JRE Editorial Office

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Published in:
Journal of Road Engineering

DOI:
10.1016/j.jreng.2023.12.001

Published: 01/12/2023

Document Version
Publisher's PDF, also known as Version of record

Please cite the original version:
JRE Editorial Office (2023). Review of advanced road materials, structures, equipment, and detection technologies. *Journal of Road Engineering*, *3*(4), 370-468. https://doi.org/10.1016/j.jreng.2023.12.001

Journal of Road Engineering 3 (2023) 370–468

Contents lists available at ScienceDirect

Journal of Road Engineering

journal homepage: www.keaipublishing.com/en/journals/journal-of-road-engineering

Review Article

Review of advanced road materials, structures, equipment, and detection technologies

JRE Editorial Office[a,*,1], Maria Chiara Cavalli[b], De Chen[c], Qian Chen[d], Yu Chen[d], Augusto Cannone Falchetto[e], Mingjing Fang[f], Hairong Gu[g], Zhenqiang Han[d], Zijian He[h], Jing Hu[i], Yue Huang[j], Wei Jiang[d,**], Xuan Li[g], Chaochao Liu[k], Pengfei Liu[l], Quantao Liu[m], Guoyang Lu[n], Yuan Ma[i], Lily Poulikakos[o], Jinsong Qian[p], Aimin Sha[d], Liyan Shan[q], Zheng Tong[i], B. Shane Underwood[r], Chao Wang[s], Chaohui Wang[d], Di Wang[e], Haopeng Wang[t], Xuebin Wang[g], Chengwei Xing[d], Xinxin Xu[g], Min Ye[g], Huanan Yu[k], Huayang Yu[u], Zhe Zeng[r], You Zhan[c], Fan Zhang[e], Henglong Zhang[v], Wenfeng Zhu[g]

[a] *Editorial Office of Journal of Road Engineering, Chang'an University, Xi'an 710064, China*
[b] *Department of Civil and Architectural Engineering, KTH Royal Institute of Technology, Stockholm 10044, Sweden*
[c] *School of Civil Engineering, Southwest Jiaotong University, Chengdu 610031, China*
[d] *School of Highway, Chang'an University, Xi'an 710064, China*
[e] *Department of Civil Engineering, Aalto University, Aalto 00076, Finland*
[f] *School of Civil Engineering and Architecture, Wuhan University of Technology, Wuhan 430070, China*
[g] *National Engineering Research Center of Highway Maintenance Equipment, Chang'an University, Xi'an 710064, China*
[h] *Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hong Kong, China*
[i] *School of Transportation, Southeast University, Nanjing 211189, China*
[j] *Institute for Transport Studies, University of Leeds, Leeds LS2 9JT, UK*
[k] *School of Traffic and Transportation Engineering, Changsha University of Science & Technology, Changsha 410114, China*
[l] *Institute of Highway Engineering, RWTH Aachen University, Aachen 52074, Germany*
[m] *State Key Laboratory of Silicate Materials for Architectures, Wuhan University of Technology, Wuhan 430070, China*
[n] *Department of Architecture and Civil Engineering, City University of Hong Kong, Hong Kong, China*
[o] *Empa, Swiss Federal Laboratories for Materials Science and Technology, Dübendorf 8600, Switzerland*
[p] *College of Transportation Engineering, Tongji University, Shanghai 200092, China*
[q] *School of Transportation Science and Engineering, Harbin Institute of Technology, Harbin 150090, China*
[r] *Department of Civil, Construction, and Environmental Engineering, North Carolina State University, Raleigh, NC 27695, USA*
[s] *Department of Road & Urban Railway Engineering, Beijing University of Technology, Beijing 100124, China*
[t] *Department of Civil and Environmental Engineering, University of Liverpool, Liverpool L69 3GH, UK*
[u] *School of Civil Engineering & Transportation, South China University of Technology, Guangzhou 510640, China*
[v] *College of Civil Engineering, Hunan University, Changsha 410082, China*

* Corresponding author.

** Corresponding author.

[1] Authors contributed equally to this paper and are listed in alphabetical order of the last names.

E-mail addresses: jre2021@126.com (JRE Editorial Office), mcca@kth.se (M.C. Cavalli), chende@swjtu.edu.cn (D. Chen), chenqian@chd.edu.cn (Q. Chen), chenyu1123@chd.edu.cn (Y. Chen), augusto.cannonefalchetto@aalto.fi (A. Cannone Falchetto), mingjingfang@whut.edu.cn (M. Fang), guhairong@chd.edu.cn (H. Gu), jasonhan029@126.com (Z. Han), steven.he@connect.polyu.hk (Z. He), hujing@seu.edu.cn (J. Hu), y.huang1@leeds.ac.uk (Y. Huang), jiangwei@chd.edu.cn (W. Jiang), lxchd@chd.edu.cn (X. Li), lcc@csust.edu.cn (C. Liu), liu@isac.rwth-aachen.de (P. Liu), liuqt@whut.edu.cn (Q. Liu), guoyanlu@cityu.edu.hk (G. Lu), 101300211@seu.edu.cn (Y. Ma), lily.poulikakos@empa.ch (L. Poulikakos), qianjs@tongji.edu.cn (J. Qian), ams@chd.edu.cn (A. Sha), shanliyan@hit.edu.cn (L. Shan), tongzheng@seu.edu.cn (Z. Tong), bsunderw@ncsu.edu (B.S. Underwood), wangchao@bjut.edu.cn (C. Wang), wchh0205@chd.edu.cn (C. Wang), di.1.wang@aalto.fi (D. Wang), haopeng.wang@liverpool.ac.uk (H. Wang), wangxuebin@chd.edu.cn (X. Wang), xingcw@chd.edu.cn (C. Xing), xuxinxin@chd.edu.cn (X. Xu), mingye@chd.edu.cn (M. Ye), huanan.yu@csust.edu.cn (H. Yu), huayangyu@scut.edu.cn (H. Yu), zzeng5@ncsu.edu (Z. Zeng), zhanyou@swjtu.edu.cn (Y. Zhan), fan.3.zhang@aalto.fi (F. Zhang), hlzhang@hnu.edu.cn (H. Zhang), zhuwenfeng@chd.edu.cn (W. Zhu).

Peer review under responsibility of Chang'an University.

https://doi.org/10.1016/j.jreng.2023.12.001

Received 27 October 2023; Received in revised form 23 November 2023; Accepted 8 December 2023

Available online 13 December 2023

HIGHLIGHTS

- Clarified the scope of road materials, structures, equipment, and detection technologies.
- Summarized the latest research findings in road materials, structures, equipment, and detection technologies.
- Envisioned the research directions for advanced road materials, structures, equipment, and detection technologies.

ARTICLE INFO

Keywords:
Road engineering
Advanced road material
Advanced road structure
Advanced road equipment
Advanced road detection technology

ABSTRACT

As a vital and integral component of transportation infrastructure, pavement has a direct and tangible impact on socio-economic sustainability. In recent years, an influx of groundbreaking and state-of-the-art materials, structures, equipment, and detection technologies related to road engineering have continually and progressively emerged, reshaping the landscape of pavement systems. There is a pressing and growing need for a timely summarization of the current research status and a clear identification of future research directions in these advanced and evolving technologies. Therefore, Journal of Road Engineering has undertaken the significant initiative of introducing a comprehensive review paper with the overarching theme of "advanced road materials, structures, equipment, and detection technologies". This extensive and insightful review meticulously gathers and synthesizes research findings from 39 distinguished scholars, all of whom are affiliated with 19 renowned universities or research institutions specializing in the diverse and multidimensional field of highway engineering. It covers the current state and anticipates future development directions in the four major and interconnected domains of road engineering: advanced road materials, advanced road structures and performance evaluation, advanced road construction equipment and technology, and advanced road detection and assessment technologies.

1. Introduction

Transport infrastructure is crucial for socioeconomic development. As a fundamental component of transportation infrastructure, road surfaces directly impact the sustainability of modern society and the quality of urban development. Technological advancements have led to phases of enhancing durability, promoting environmentally sustainable development, and fostering intelligent evolution in road engineering construction. Throughout this evolution, advanced materials, structures, equipment, and detection technologies related to road engineering have consistently emerged. To further advance road engineering technology, it is essential to comprehensively review recent progress in advanced road materials, structures, equipment, and detection technologies. This involves identifying key research focal points and cutting-edge developments while addressing current challenges and outlining future research directions.

This review focuses on the key issues encountered in practical road engineering and highly cited papers in the last 5 years from the Web of Science. The analysis systematically explores the current research status of advanced road materials, structures, equipment, and detection technologies. This encompasses 41 research directions in four major domains: advanced road materials, advanced road structures and performance evaluation, advanced road construction equipment and technology, and advanced road detection and assessment technologies. Fig. 1 shows the specific research directions and their respective authors.

This review serves as a reference and inspiration for researching and developing advanced road materials, structures, equipment, and detection technologies.

2. Advanced pavement materials technologies

2.1. Intelligent pavement materials

2.1.1. Self-aware pavement materials

Self-aware pavement materials can perceive and respond to environmental changes. For example, light-aware road materials can provide the necessary illumination for the road when road brightness is insufficient. Temperature-aware pavement materials can adjust pavement temperature by detecting changes in pavement temperature. Stress-aware pavement materials can assess the stress–strain state of the pavement to enhance road safety and reliability.

2.1.1.1. Light-aware pavement material. Light-aware pavement material is a type of functional material that incorporates self-luminescent substances into the pavement structure. It absorbs and stores natural light energy, as well as the light from lighting fixtures and other sources during the day through a process of light absorption and storage. This stored energy allows it to emit its own light in environments with insufficient or no lighting during the nighttime. In 2012, the Netherlands constructed a self-luminescent road called Oss N329 (BBC News, 2014a, b). However, during its operation, it failed to achieve the expected performance due to poor afterglow characteristics. In 2013, the UK introduced a "star road", but it was not suitable for widespread use due to its low luminescence intensity and high cost (Pratico et al., 2018). In the same year, China developed a "highway luminescent sign" marking the first application of long-lasting luminescent materials in road engineering in the country. Unlike traditional highway signs, this "luminescent" sign provides clear guidance to drivers in nighttime road conditions, thereby enhancing driving safety.

With the advancement of modern pavement materials, researchers have initiated a series of experiments focused on creating self-luminescent pavements. Currently, the self-illuminating effect on road surfaces is predominantly achieved through the following methods. (1) Utilizing artificial luminous stones to apply on road surfaces. The most commonly employed method involves the use of $SrAl_2O_4$:Eu_2+/Dy_3+ long-lasting rare earth luminescent materials. These materials have the capability to absorb energy from external sources of optical radiation and store it, subsequently emitting this energy in the form of light when in darker environments. The self-luminescent effect on road surfaces achieved by spreading fluorite primarily involves the even distribution of artificial fluorite onto asphalt or cement concrete road surfaces. Numerous successful attempts have been made in China. (2) Employing luminescent coatings. Luminescent coatings are primarily developed by harnessing the light absorption and luminescence properties of long-lasting luminescent materials, combined with the favorable light transmission characteristics of resin binders. These coatings find applications in road markings, road landscaping, and warning installations in conditions where lighting is insufficient. (3) Integrating luminescent materials with asphalt, cement concrete, and transparent resin binders, known for their excellent transparency, to form concrete. Currently, methods for blending mixtures with long-lasting luminescent materials mainly involve mixing these materials with light-colored asphalt, cement, and resin binders to create pavement binders. Alternatively, aggregates can be replaced with long-lasting

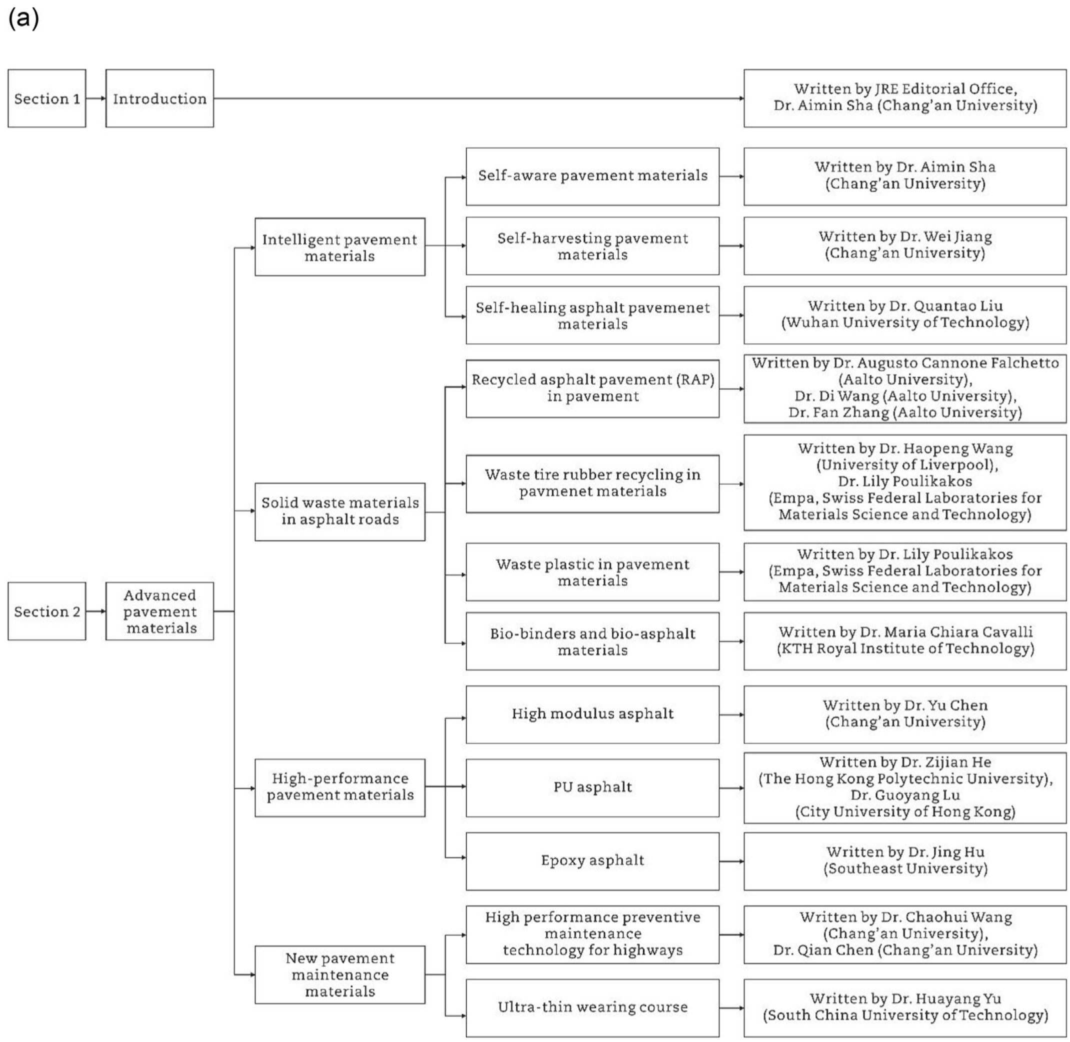


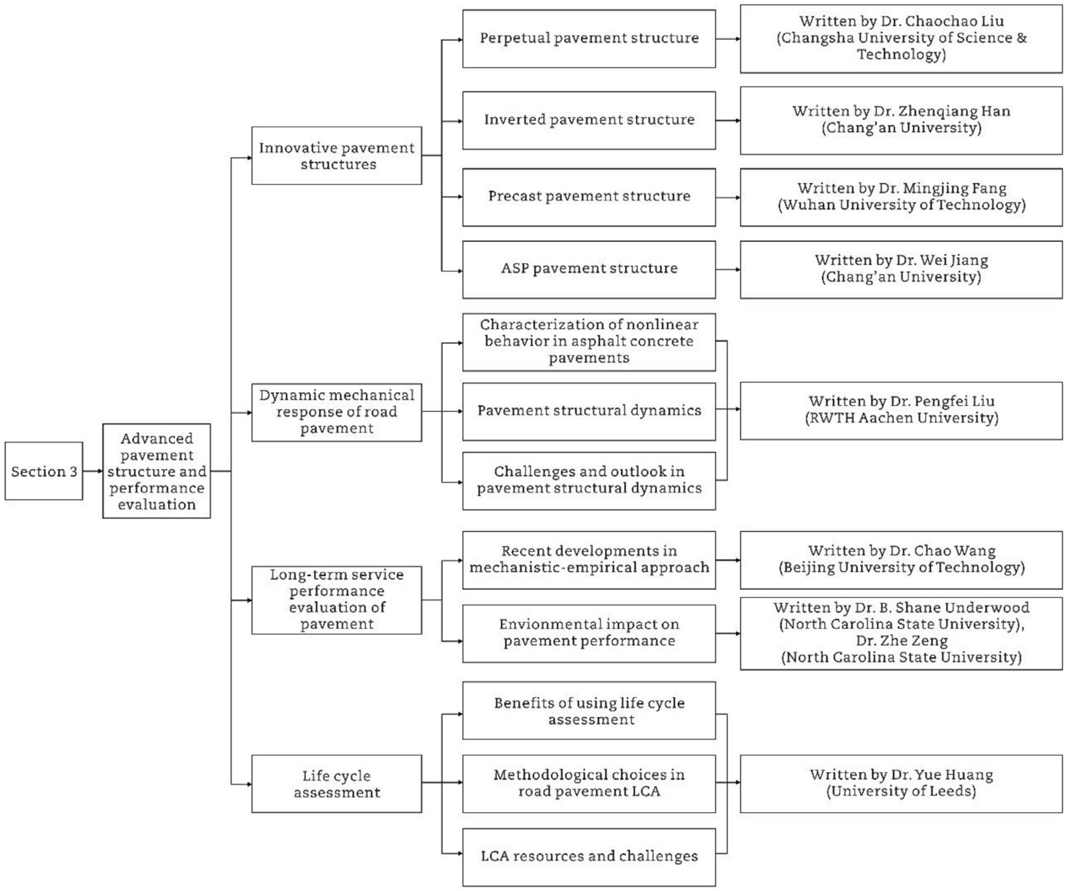
Fig. 1. Structure of the paper. (a) Sections 1 and 2. (b) Section 3. (c) Section 4. (d) Section 5.

luminescent materials to achieve the self-luminescent pavement effect (He et al., 2019; Sha et al., 2020; Wang et al., 2021c).

2.1.1.2. Temperature-aware pavement material. The implementation of temperature-ware pavement materials operates on the principle of phase transition. When these phase change pavement materials detect that the pavement temperature has reached its phase transition temperature, they initiate a phase transition process. This process either absorbs or releases heat from the pavement in the form of latent heat. As a result, it prolongs the duration of heat absorption or release on the asphalt pavement, effectively acting as a buffer for temperature fluctuations on the pavement (Sha et al., 2021). The use of phase change materials to actively manage asphalt pavement temperature has demonstrated promising applications. Phase change materials are categorized based on their phase state changes, including solid-solid phase change materials, solid-liquid phase change materials, and liquid-gas phase change materials (Fallahi et al., 2017; Wu et al., 2017). Among these, liquid-gas phase change materials exhibit a substantial volume change rate during the phase transition, limiting their practical applicability. Solid-liquid phase change materials, on the other hand, offer the benefits of high latent heat capacity and minimal subcooling (Umair et al., 2019; Xia et al., 2019). These materials can further be classified into organic and inorganic phase change materials. Compared to inorganic counterparts, organic phase change materials experience less supercooling and fewer phase separation issues during phase transitions (Mu and Li, 2019). Consequently, among various phase change materials, organic solid-liquid phase change materials find the widest application in pavement temperature control. However, it's worth noting that studies have indicated that the direct use of solid-liquid phase change materials on pavements can negatively impact the overall pavement performance. Over extended periods of use, the leakage of liquid phase change materials can gradually diminish their temperature-regulating effects (Jia et al., 2020; Chen et al., 2020c).

To address this challenge, it is imperative to implement effective measures for encapsulating solid-liquid phase change materials. Presently, research efforts predominantly concentrate on physically encapsulating solid-liquid modified materials. The encapsulation technologies primarily include the adsorption method, melt blending method, microcapsule method, and sol-gel method (Ma et al., 2016; Moises et al., 2019; Anupam et al., 2020; Guo et al., 2020a). There are three primary types of phase change materials developed using these physical encapsulation techniques: microencapsulated phase change materials, polymer-based phase change materials, and porous material-based phase change materials. Among these, microencapsulated phase change materials (PCMs) are commonly employed in pavement applications as asphalt modifiers (Kakar et al., 2019), polymer-based PCMs are typically utilized in pavements as aggregate substitutes or direct additives (Kheradmand et al., 2015; Tian et al., 2019), and porous material-based PCMs are often employed in pavements as asphalt modifiers or filler substitutes (Chen et al., 2020c). A review of the literature demonstrates that phase change materials encapsulated using physical methods can effectively slow down the asphalt pavement's rate of temperature increase, achieving the desired pavement cooling effect (Anupam et al., 2020).

(b)



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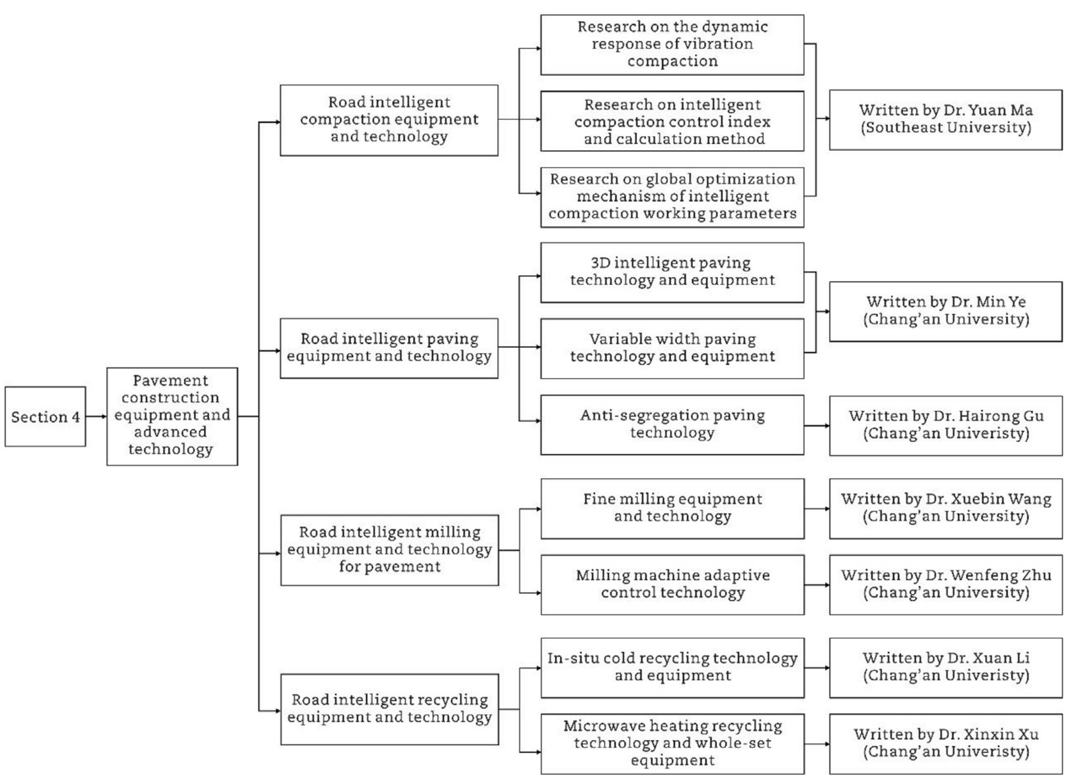


Fig. 1. (*continued*).

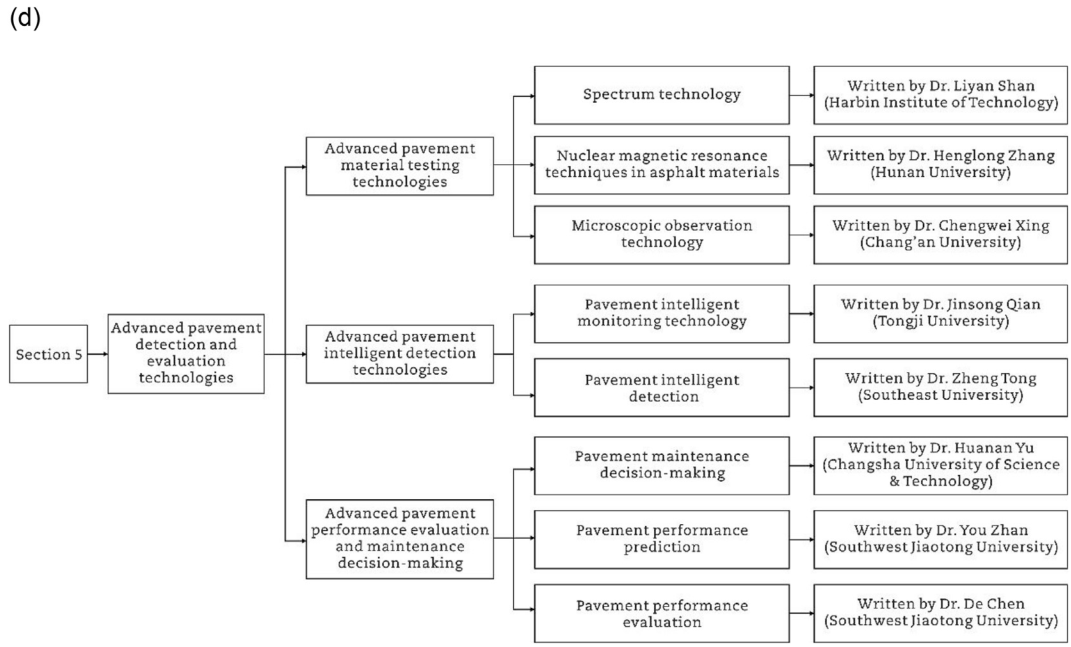


Fig. 1. (*continued*).

However, the construction and operational loads on asphalt pavements can lead to the cracking and crushing of encapsulation materials, resulting in the leakage of phase change materials. In contrast, the chemical synthesis of composite phase change materials with defined phase change properties holds promising application prospects. To realize the precise monitoring and timely adjustment of asphalt pavement temperature using PCM, further research into enhancing the thermal conductivity of PCM is also a worthwhile pursuit.

2.1.1.3. Stress-aware pavement material. Stress-aware pavement materials incorporate sensing elements with aggregates to achieve pavement stress awareness. The mechanical behavior of pavement materials fundamentally involves changes in the contact state among aggregates. To investigate the mechanical characteristics, spatial distribution, and progression of internal damage within pavement materials under load, one must essentially observe the patterns of stress and strain within the materials, as well as the variations in contact forces between aggregates and the spatial arrangement of these aggregates. In the pavement structure, pressure sensors, strain sensors, temperature sensors, distributed optical fibers, and other sensing components are installed to monitor the mechanical responses and temperature fluctuations experienced by the pavement during its service life. By capturing the pavement's mechanical responses through these embedded sensors, it becomes possible to conduct real-time assessments of changes in its modulus and overall performance, enabling long-term road health monitoring (Ma et al., 2022a). However, the installation process for these sensors is intricate, potentially disrupting the integrity of the pavement structure. Moreover, the survival rate of these sensors is often low, and their compatibility with pavement deformations is relatively limited (Miller et al., 2017). Consequently, a solution involves integrating sensor elements with various measurement functions into granular materials to create granular sensors, thereby enabling self-awareness of pavement stress.

Currently, intelligent aggregate sensors, primarily relying on the piezoelectric effect, are widely employed (Song et al., 2008; Kong and Song, 2017). These sensors employ sensing materials that can be categorized into inorganic and organic groups based on their composition. Notable representatives of the inorganic category include quartz and lead zirconate titanate (PZT), while the organic category is predominantly exemplified by polyvinylidene fluoride (PVDF). PZT piezoelectric ceramics, however, are inherently brittle and prone to breakage when subjected to high stress, significantly compromising their operational lifespan. A superior alternative is offered by piezoelectric composite sensing materials, achieved by combining PZT with polymer materials. These composites exhibit excellent attributes such as flexibility and ease of machining, making them capable of entirely replacing piezoelectric ceramics in certain applications, where they perform admirably. The piezoelectric sensing device is created by encapsulating the piezoelectric material within a specific structure. The combination of structures and the design of these enclosures profoundly impact the output of piezoelectric signals. Additionally, apart from piezoelectric smart aggregates, sensor elements with diverse functions are integrated into granules to achieve self-awareness of various functionalities. Researchers have employed 3D-printed casings to enclose components like magnetic induction meters, three-axis accelerometers, and three-axis gyroscopes, creating intelligent aggregates capable of tracking spatial motion trajectories. This development has significantly advanced the study of granular materials at the microscopic level (Al-Mansoori et al., 2018; Dan et al., 2020; Wang et al., 2018b, c).

Currently, research pertaining to the application of such sensors predominantly centers on assessing the stability of railway ballast. Conversely, there is relatively limited research focusing on their application in road engineering and the monitoring of internal stress within pavements. It holds immense significance to actualize the self-awareness capability concerning pavement mechanical behavior and its operational status by fabricating intelligent aggregates. This involves studying the perception of mechanical behavior within mixtures under load, considering the perspective of particle size.

2.1.2. Self-harvesting pavement materials

Within road infrastructures, a wealth of renewable energy sources is readily available, encompassing inherent solar energy, thermal energy, and the mechanical energy generated by vehicular movement. These energy reservoirs can be effectively tapped into by leveraging phenomena such as the Seebeck effect, piezoelectricity, and electromagnetic induction. Consequently, thermal and mechanical energies within the road environment can be transformed into electrical power. Such energy conversion mechanisms possess the capacity to notably reduce the dependence on traditional power sources for information, communication, and sensor systems.

2.1.2.1. Mechanical energy harvesting technologies.

(1) Piezoelectric conversion

The piezoelectric conversion technology employed within road traffic infrastructure entails the incorporation of piezoelectric materials into the road surface structure. It harnesses the positive piezoelectric effect to effectively convert mechanical energy derived from the road environment into electrical energy, as depicted in Fig. 2 (Wang et al., 2021d). The positive piezoelectric effect pertains to the phenomenon where a piezoelectric material's internal electric dipole moment becomes compressed when it experiences mechanical stress, as visually demonstrated in Fig. 3 (Wang et al., 2018a). This compression generates equal amounts of positive and negative charges on the material's surface, thereby converting mechanical energy into electrical energy (Cao et al., 2021b). Considering operational modes and technical capabilities, road traffic infrastructure's piezoelectric conversion technology can be classified into two categories: integrated pavement-piezoelectric material technology and embedded piezoelectric component technology (Jiang et al., 2023a). Among these, integrated pavement-piezoelectric material technology presents certain challenges, including limitations on output power, less-than-optimal road performance, intricate technical complexities during material preparation processes, and a multitude of influencing factors (Wang et al., 2019c; Li et al., 2022e). The embedded piezoelectric component technique has garnered substantial attention from researchers globally, primarily owing to its notable energy output, effective controllability, and streamlined construction process. A significant portion of the research dedicated to piezoelectric conversion technology within road infrastructure focuses on this specific approach. The crux of these methodologies revolves around the careful selection of piezoelectric materials, transducer structures, and deployment strategies (JTTE Editorial Office et al., 2021).

It's important to note that the most advanced piezoelectric materials encompass a range of substances, including monocrystalline materials (e.g., quartz), piezoelectric ceramics (e.g., PZT), polymers (e.g., PVDF), and piezoelectric semiconductors (e.g., ZnO_2). These diverse materials exhibit unique piezoelectric characteristics and mechanical properties. PZT and PVDF, renowned for their advantageous electrical and mechanical properties, have been widely applied in road traffic infrastructure. Piezoelectric transducers come in various geometric shapes and operational configurations, including concave, crescent, bridge, cantilever, stacked, and hybrid designs. Their effectiveness is contingent upon factors such as vehicle speed, road conditions, traffic flow, and vehicular loads (Xiang et al., 2013). Typical deployment methods for piezoelectric transducers mainly involve embedding them in the road surface or burying them within the internal roadbed. The former method, which entails direct vehicular load application onto the transducer structures, offers increased efficiency in force-to-electric conversion and generates substantial energy output. However, this approach demands higher mechanical performance, sealing integrity, and effective coupling between the transducer structure and the road surface. Scholarly endeavors have sought to improve this approach by incorporating an asphalt mortar layer as an intermediary, embedding the piezoelectric transducers within grooves prepared on the road surface. This enhancement significantly bolsters the connection between the road structure and the transducer coupling (Song et al., 2019). Internal roadbed burial simplifies the creation of a cohesive union between the road structure and the piezoelectric transducer. Vehicular loads are evenly distributed through the road material to the surface of the piezoelectric transducer. The ideal placement of these transducers can be determined through force analysis.

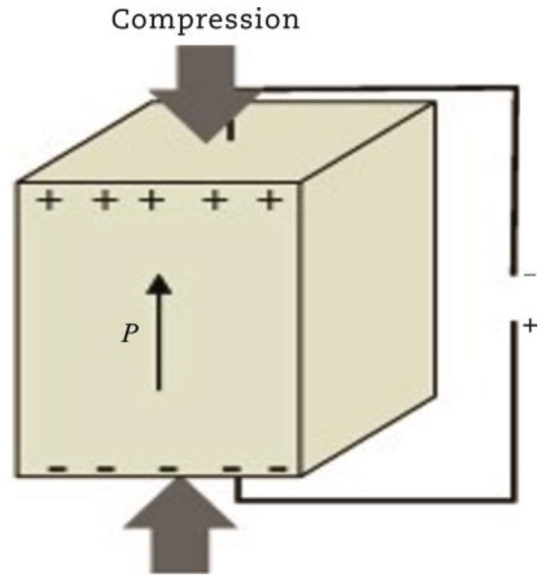


Fig. 3. Schematic diagram of the positive piezoelectric effect (Wang et al., 2018a).

(2) Electromagnetic conversion

Electromagnetic conversion technology capitalizes on Faraday's law of electromagnetic induction to convert the mechanical energy generated by vehicular loads into electrical energy. Faraday's law of electromagnetic induction stipulates that a closed-loop conductor, while in motion

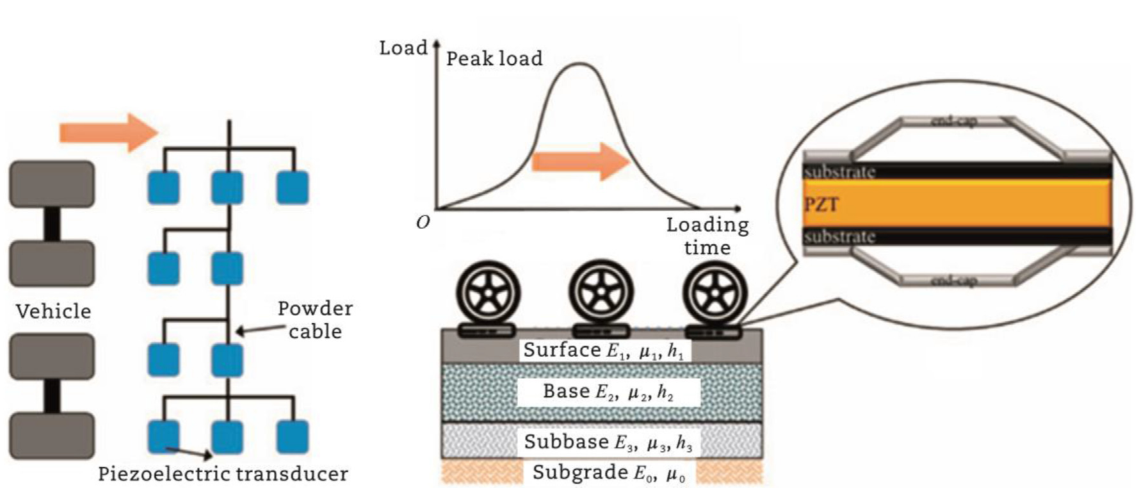


Fig. 2. Piezoelectric integration schematic (Wang et al., 2021d).

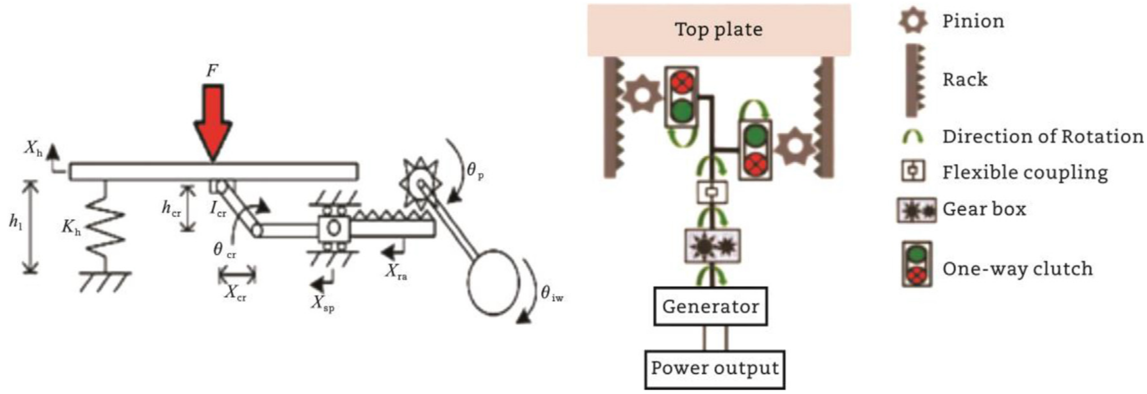


Fig. 4. Rack and pinion (Zabihi and Saafi, 2020).

through a magnetic field, changes magnetic flux, consequently engendering induced currents within the closed-loop circuit (Zabihi and Saafi, 2020). This technique boasts characteristics of higher current and output power. In terms of the energy transmission mechanism, electromagnetic conversion technology within road traffic infrastructure can be classified into three types: gear-rack, hydraulic, and drum mechanisms. Gear-rack electromagnetic conversion technology functions by translating the vertical motion of vehicular loads into rotational movement through gear-rack transmission, thereby activating a generator for power generation. Fig. 4 illustrates gear-rack mechanisms operating in both horizontal and vertical orientations. Gholikhani et al. (2019, 2020) comprehensively investigated the application of electromagnetic conversion technology within road structures. They innovated an electromagnetic speed bump energy conversion device utilizing gear-rack mechanics. This device comprises a top plate, rack, small gear, clutch, transmission shaft, spring, bracket, and electromagnetic generator. Through iterative enhancements, the maximum output power of the device reached 16.5 W, enabling a daily energy generation of 22 kW·h. Hydraulic electromagnetic conversion technology transforms vehicular load-generated mechanical energy through hydraulic systems. This energy is transmitted to displace a piston, inducing motor rotation to generate electricity, as depicted in Fig. 5. Ting et al. (2012) devised a hydraulic electromagnetic power generation apparatus aimed at capturing and harnessing the mechanical energy generated by vehicles on inclines. Research findings indicate an estimated overall operational efficiency of approximately 41.03% for this system. Fig. 6 depicts the drum-type electromagnetic conversion technology, wherein the movement of vehicles induces the rotation of the drum through friction. As a result, this rotation powers the generator, generating electrical energy. Sarma et al. (2014) engineered a road-applicable drum-type

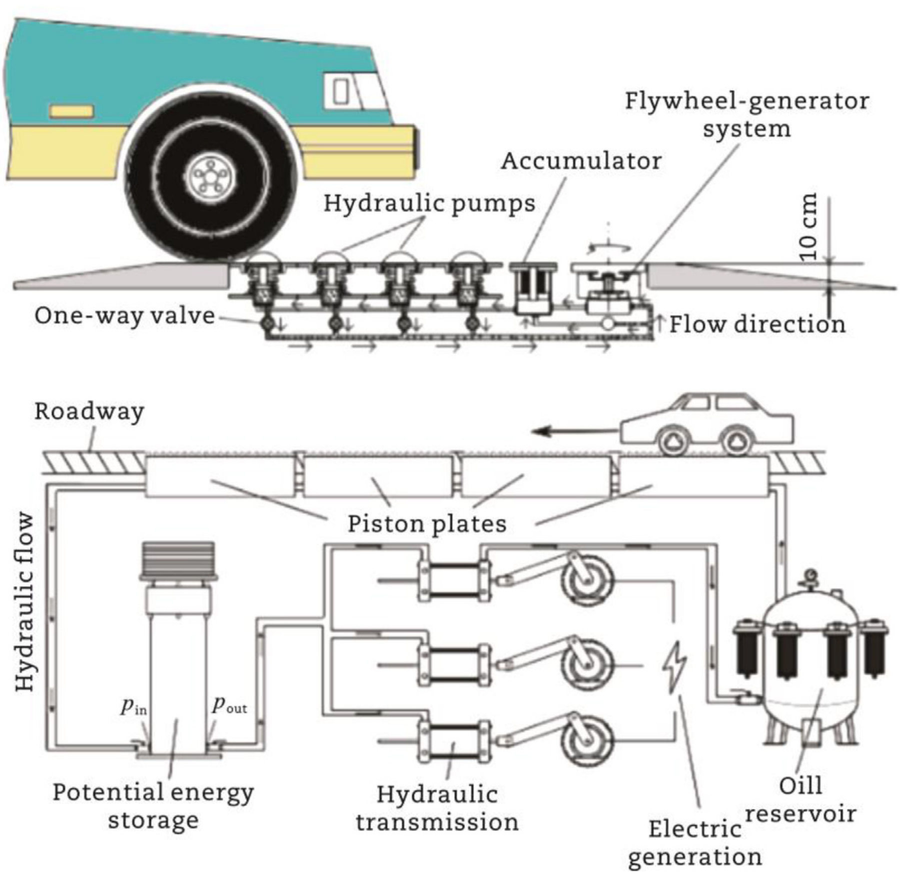


Fig. 5. Hydraulic (Obeid et al., 2014).

electromagnetic power generation apparatus, which, through testing, demonstrated a daily energy production of 2.3 kW.

(3) Triboelectric nanogenerator

Triboelectric nanogenerator (TENG) operates on the principle of friction-induced electrification coupled with electrostatic induction for power generation (Fan et al., 2012). Based on distinct operational modes, TENG can be classified into four modes: vertical contact-separation mode, horizontal sliding mode, single-electrode mode, and independent layer mode (Jin et al., 2019), as depicted in Fig. 7. Considering the distinctive characteristics of road traffic infrastructure, Pang et al. (2022) introduced an innovative friction-based nanogenerator inspired by the concept of water balloon origami. Weighing 65 g and measuring 100 mm × 50 mm × 30 mm, this device achieves an output voltage of up to 250 V. Its electrical performance surpasses fold-based TENGs by more than 67%.

2.1.2.2. Thermal energy harvesting technologies. Thermoelectric pavement embodies an emerging pavement configuration that employs thermoelectric technology based on the Seebeck effect to harness excess energy from asphalt surfaces and facilitate eco-friendly thermal energy conversion (Jiang et al., 2017). The conceptualization of thermoelectric self-capturing roadways was first introduced by Meiarashi and Ohara (1997). Over the span of two decades, the utilization of thermoelectric materials in road traffic infrastructure has evolved into two distinct approaches: one involves embedding thermoelectric conversion devices within the infrastructure for energy conversion, while the other entails the direct fabrication of road materials with inherent thermoelectric conversion properties for energy generation.

Regarding the integration of thermoelectric conversion devices into road traffic infrastructure, this can be further categorized into two modes based on the utilization of road thermal energy: the export-type and the embed-type. In the export-type, the internal thermal energy of the asphalt pavement is extracted using a heat-conductive mechanism, with external environmental media serving as the cold-side module. The thermoelectric conversion device is positioned at the roadside. In contrast, the embed-type approach involves the direct incorporation of the thermoelectric conversion device within the asphalt pavement, with appropriate protective measures in place. This configuration harnesses the inherent thermal energy of the pavement as the hot-side module, while the longitudinally cooler sections of the road structure function as the cold-side module. Regarding the export-type, Hasebe et al. (2006) incorporated water pipes as heat-conductive mechanisms within asphalt pavements and positioned thermoelectric conversion devices alongside the road. The water pipes embedded in the asphalt pavement absorb thermal energy from the road surface, providing elevated temperature as the hot side for the thermoelectric conversion device. Simultaneously, the water from the riverside serves as the cold side, ensuring a temperature gradient across the thermoelectric conversion device, thus facilitating electricity generation.

Hu et al. (2014b) advanced upon Hasebel's work by substituting heat-conductive aluminum sheets for water flow networks as the hot-side

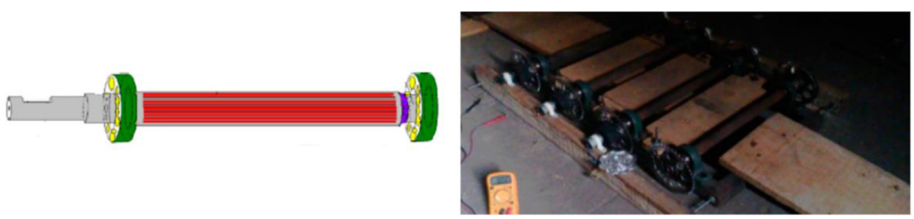


Fig. 6. Roller (Sarma et al., 2014).

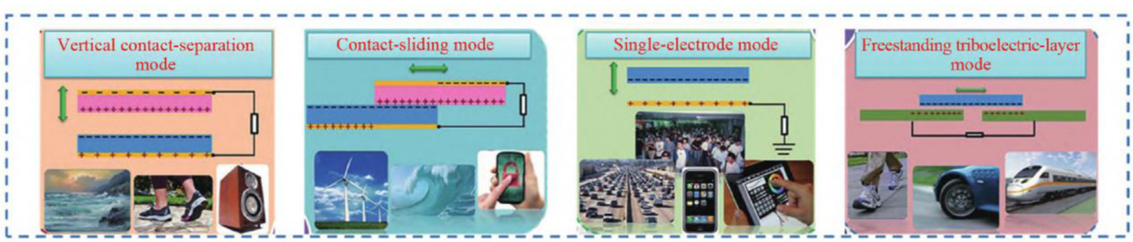


Fig. 7. Operating modes of TENG (Duarte, 2018).

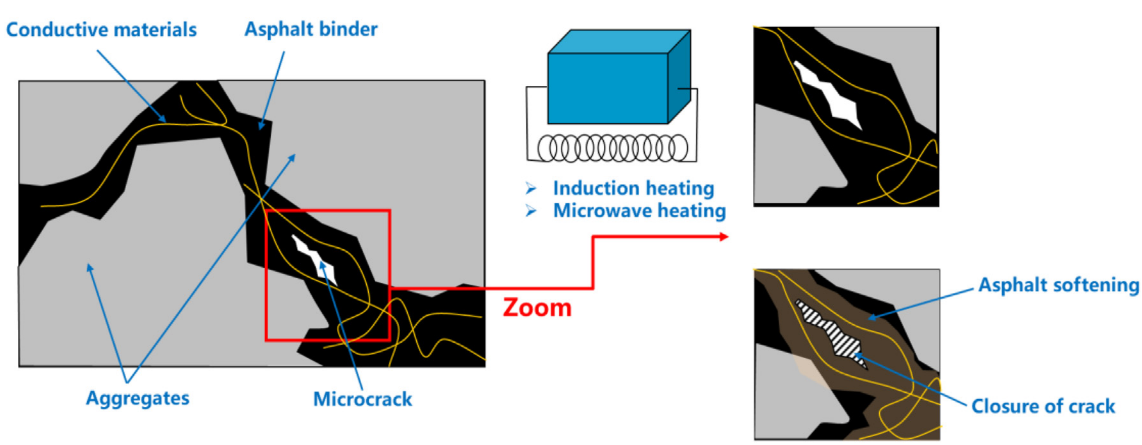


Fig. 8. The operation mechanism of thermal induced healing for asphalt materials (Tabakovic and Schlangen, 2016).

module. The thermoelectric conversion device employed a series connection of six units, with a heat sink serving as the cold side. Findings demonstrate that with a temperature gradient of 25 °C across the thermoelectric conversion device's hot and cold sides, the open-circuit voltage reaches 1.1 V. Moreover, the use of heat-conductive aluminum sheets facilitates accelerated heat transfer within asphalt mixtures. This effect contributes to a gradual temperature increase during heating and a rapid cooling during the cooling process. Since 2017, research efforts related to thermoelectric asphalt pavement structures have been spearheaded by professor Wei Jiang of Chang'an University and professor Samer Dessouky of the University of Texas at San Antonio. Professor Wei Jiang employed aluminum heat plates and steel plates as thermal energy conductors within the pavement. He introduced two innovative thermoelectric asphalt pavement configurations: one leveraging the temperature difference between the pavement and its surroundings, and the other capitalizing on the temperature differential between the pavement and the roadbed (Jiang et al., 2018; Yuan et al., 2022b, 2023a, 2023b). On the other hand, professor Samer Dessouky employed copper plates as the pavement's thermal energy conductor. He developed two distinct thermoelectric asphalt pavement structures, utilizing heat sinks equipped with water and phase change materials as the cooling-side module (Tahami et al., 2019).

The concept of embedded thermoelectric pavement was first introduced by Wu and Yu (2012). They utilized aluminum rods as thermal conductors to transfer the temperature from the deeper layers of the roadbed to the cold side of the thermoelectric conversion device. The results demonstrated the capacity of this structure to generate 0.05 mW of power. In 2014, building upon the research by Wu and Yu (2012), Park et al. (2014a) enhanced and optimized this structure by refining the selection of thermoelectric conversion devices and heat transfer mechanisms. They elevated the power generation efficiency to 40 mW and introduced a mathematical model to calculate the output power of single-layer thermoelectric conversion devices within this arrangement. Starting from 2020, Khamil et al. (2020) have conducted continuous research on buried thermoelectric energy-harvesting pavement systems. At the outset of their study, they proposed a T-shaped buried thermoelectric energy-harvesting pavement system consisting of a top plate, thermoelectric conversion devices, a bottom plate, and supports. The thermoelectric conversion devices were designed as a dual-layer structure. The findings indicated that in laboratory conditions, the system achieved a maximum temperature difference of 8.99 °C and an output voltage of 0.35 V. During field tests, the maximum temperature difference reached 7.95 °C with an output voltage of 0.32 V (Khamil et al., 2020).

Regarding the direct preparation of road materials with thermoelectric conversion properties, a primary focus lies in cement-based materials. Wei et al. (2023) employed a dry pressing method to fabricate thermoelectric cement composites for pavement heat energy harvesting. Notably, they introduced expanded graphite and metal oxides into the composite, enhancing the average electrical conductivity to 0.63 S/cm and the average Seebeck coefficient to 20.79 μV/K. Under a temperature difference of 23 °C, a thermoelectric cement pavement measuring 10 m in width and 1000 m in length generated 0.5 kW·h of electrical energy over a span of 24 h. Zuo et al. (2015) investigated the preparation of thermoelectric cement-based composites by incorporating carbon fibers and multi-walled carbon nanotubes. The study revealed that the composite exhibited the highest Seebeck coefficient and the lowest electrical resistivity when the content of carbon nanotubes was 0.5 wt%.

2.1.3. Self-healing asphalt pavement materials

Asphalt itself possesses inherent self-healing capabilities, allowing it to partially seal micro-cracks within asphalt mixtures and thereby impeding the formation of macro-cracks (Ayar et al., 2016; Tabakovic and Schlangen, 2016; Sun et al., 2018b; Zhang et al., 2023c). Nevertheless, during the actual service lifespan, the inherent self-healing capacity of asphalt often falls short in addressing the micro-cracks within the pavement. This shortfall can be attributed to the cumulative effects of temperature fluctuations, moisture exposure, traffic loads, aging, and various other factors (Alavi et al., 2016a; Yang et al., 2020b; Pszczola et al., 2022; Li et al., 2022a; Zou et al., 2023). At present, the primary approaches employed to bolster the self-healing capabilities of asphalt materials are thermal-induced healing technology and encapsulated rejuvenator-induced healing technology (Gonzalez-Torre and Norambuena-Contreras, 2020; Liang et al., 2021; Li et al., 2021c). Microwave irradiation is utilized to elevate the temperature of the asphalt mixture, thereby enhancing the diffusion rate and range of asphalt molecules. This, in turn, accelerates the process of self-repair for asphalt cracks, as illustrated in Fig. 8. On the other hand, encapsulated rejuvenator-induced healing technology involves introducing micro-carriers (either capsules or fibers) loaded with asphalt rejuvenator into asphalt mixtures. When micro-cracks form and propagate, reaching the surface of these micro-carriers, the stress concentration in that area causes a change in the permeability or rupture of the micro-carrier shell. This, in turn, prompts the internal rejuvenator to flow into the crack through capillary action, effectively sealing the crack and restoring the asphalt's performance, as depicted in Fig. 9.

2.1.3.1. Self-healing pavement materials based on thermal induced healing technology. At present, two methods for self-healing based on thermal-induced healing are widely employed: electromagnetic induction heating self-healing and microwave-induced self-healing, as illustrated in Fig. 10. These processes involve heating the conductive or microwave-absorbing elements within the asphalt mixtures using external stimuli, such as electromagnetic fields or microwaves. This elevation in asphalt temperature facilitates accelerated asphalt flow in the vicinity of microcracks, ultimately aiding in the sealing of cracks within the asphalt pavement.

Rapid self-healing of asphalt can be achieved through the thermal induced healing technology. The current research on the conductive fillers of self-healing pavement materials based on induced heating technology is mainly focused on steel fibers (García et al., 2009; Gallego et al., 2013; Norambuena-Contreras et al., 2016; Liu et al., 2017; Xu et al., 2022b), recycling metal materials (Norambuena-Contreras et al., 2018a; Fu et al., 2022a; Liu et al., 2022a), steel slag (Sun et al., 2014; Phan et al., 2018; Chen et al., 2022b; Yang et al., 2022d), carbon materials (Wang et al., 2016a; Jahanbakhsh et al., 2018) and others. Steel fiber, owing to its remarkable electrical and thermal conductivity, serves as the predominant material in the process of induction heating for repairing asphalt mixtures. Electromagnetic induction healing focuses on heating the asphalt binder rather than the aggregates and offers the advantage of selective and swift heating. Notably, in a study conducted by Liu et al. (2011a), it was discovered that the strength recovery ratio of asphalt mastic beams and the stiffness recovery ratio of porous asphalt concrete with steel wool fibers reached 85% and 100%, respectively, after undergoing electromagnetic induction heating. Gómez-Meijide et al. (2016) conducted electromagnetic induction heating on three types of asphalt mixtures with metal grift and found that the maximum healing levels of dense, semi-dense and porous asphalt mixtures could reach 92.3%, 99.7 %, and 100.4%, respectively. Besides high healing ratio, induction healing has the advantage of repeated heating to repair cracks for multiple times (Liu et al., 2012; Dai et al., 2013), which can significantly extend the service life of asphalt concrete. However, the healing depth of this method is only around 4.3 cm, and it is only applicable to the upper layer of the pavement and the abrasion layer (Li et al., 2019a). In addition, there is still an urgent need to develop induction heating equipment for field pavements.

Polar molecules within the asphalt material undergo continuous movement and collisions when exposed to microwave energy radiation, resulting in the generation of heat energy that contributes to crack closure. It's worth noting that for the same asphalt material, microwave heating offers superior uniformity but exhibits lower heating efficiency compared to electromagnetic induction heating (Norambuena-Contreras

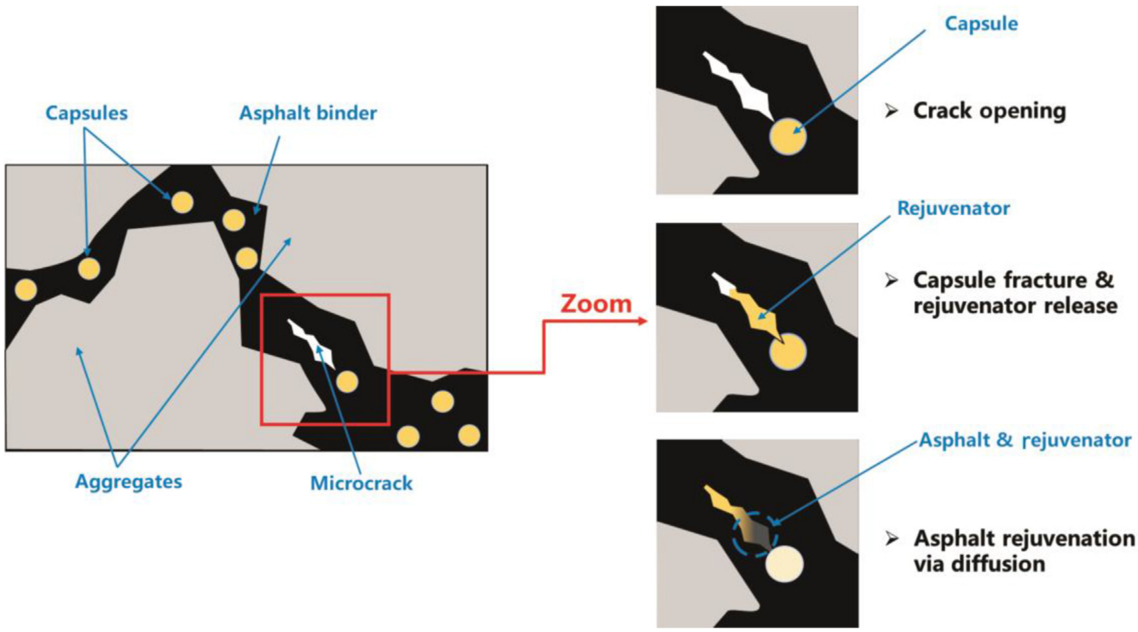


Fig. 9. The operation mechanism of rejuvenator encapsulation induced healing (self-healing capsule) for asphalt materials (Tabakovic and Schlangen, 2016).

and Garcia, 2016; Liu et al., 2018a). Sun et al. (2016) conducted an experiment involving the incorporation of steel fibers into andesite asphalt mixtures to investigate their microwave-induced healing properties. The results revealed that asphalt mixtures containing steel fibers could achieve a maximum healing level of up to 87%. Phan et al. (2018) added steel fiber into steel slag asphalt mixtures and conducted microwave heating on specimen. Result revealed that the healing level of asphalt concrete was higher than 90% after fourth heating cycle. Norambuena-Contreras et al. (2016) investigated the microwave healing property of asphalt concrete with steel fiber and found that the maximum healing level of asphalt concrete with 2% steel fiber was 95%. Microwave heating has the advantage of being reusable for healing asphalt materials multiple times. However, it's important to note that repeated heating can accelerate the deterioration of asphalt and also result in the emission of significant amounts of greenhouse gases. Research has shown that microwave radiation can damage the molecular structure of asphalt, leading to asphalt aging and a decline in its performance over time (Norambuena-Contreras and Garcia, 2016).

In summary, the intelligent road represents a comprehensive infrastructure encompassing advanced technologies such as functional road surfaces, perception, information management, and energy systems. This results in the creation of self-aware road surfaces, self-repairing road surfaces, and self-capturing energy road surfaces, as illustrated in Fig. 11.

2.1.3.2. Self-healing pavement materials based on encapsulated rejuvenator induced healing technology. It's important to note that thermal-induced healing technology, while effective in addressing certain asphalt issues, cannot completely resolve the problem of asphalt aging. Research has shown that the rejuvenator used in this technology has the capability to regenerate aged asphalt by providing essential light components (Behnood, 2019; Zhang et al., 2020c; Zahoor et al., 2021; Yan et al., 2022).

However, directly spraying rejuvenators onto asphalt pavements presents certain limitations. It has a shallow penetration depth and can reduce the pavement's skid resistance. An alternative and promising approach to address this issue is encapsulated rejuvenator-induced healing technology. To effectively enhance self-healing through rejuvenator encapsulation, the rejuvenator carrier within asphalt materials should possess specific characteristics. The shell material must exhibit excellent thermal stability, mechanical stability, and interfacial stability, ensuring it remains intact during asphalt mixture production and construction processes. The rejuvenator should have high mobility and low viscosity, enabling it to rapidly flow into cracks through capillary action once the shell is ruptured. Currently, the primary materials used as rejuvenator carriers include capsules and fibers, as illustrated in Fig. 12.

The self-healing capsules include core-shell microcapsules (in μm size) and multi-cavity capsules (in mm size). The microcapsules are mainly synthesized via in-situ polymerization method. Melamine-

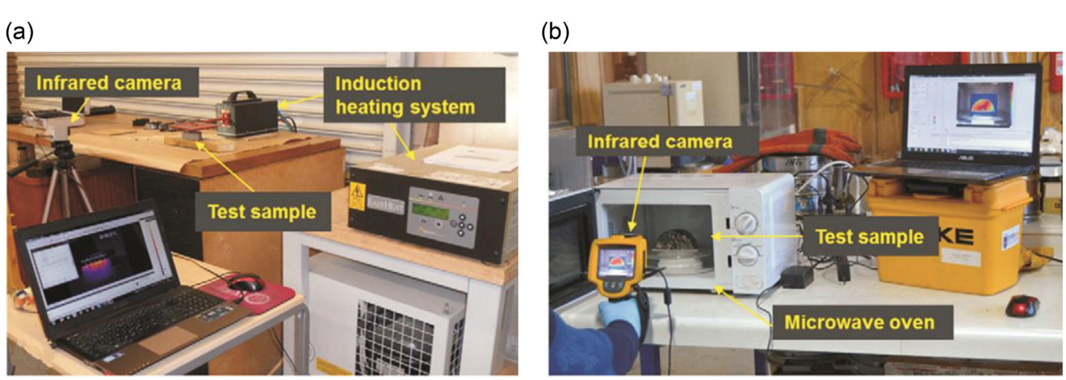


Fig. 10. Thermal induced healing technology. (a) Electromagnetic induction heating healing. (b) Microwave induction heating healing (Norambuena-Contreras and Garcia, 2016).

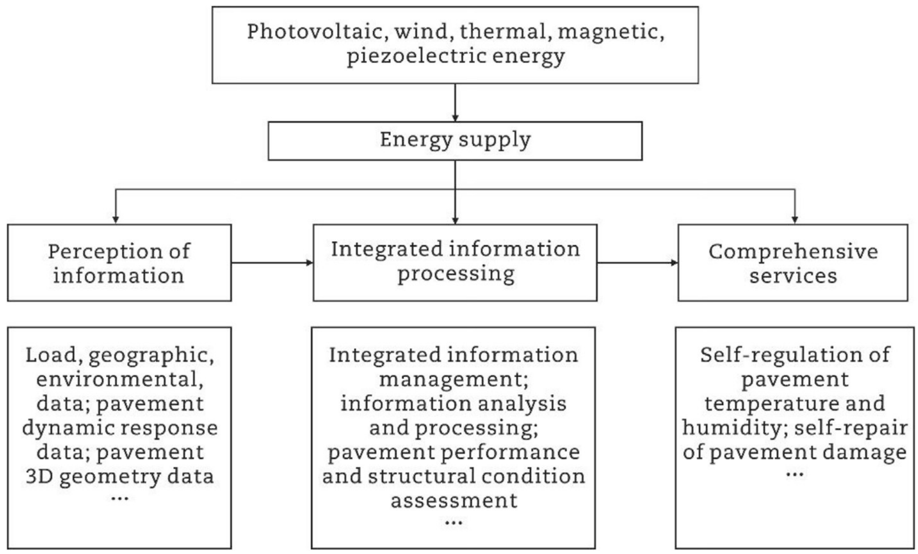


Fig. 11. Intelligent pavement architecture (Wang et al., 2019d).

formaldehyde (MF) (Sun et al., 2015; Aguirre et al., 2016), melamine-formaldehyde (MMF) (Su and Schlangen, 2012; Wang et al., 2022l), urea-formaldehyde (UF) (Li et al., 2015; Liu, 2019; Wang et al., 2022d), melamine-urea-formaldehyde (MUF) (Sun et al., 2017; Li et al., 2020b, 2021e, 2022d, 2022m), polyurethane (PU) (Tan et al., 2020a, b), isophorone diisocyanate (IPDI) (Ji et al., 2021; Chen et al., 2023a), and high methyl ether melamine-formaldehyde (HMMM) (Tian et al., 2020; Yang et al., 2022a) are selected as the shell materials. Asphalt rejuvenator is usually used as the core materials. These microcapsules enhance the healing efficiencies of asphalt binder and asphalt mixtures under the action of released rejuvenator (Ji et al., 2021; Jin et al., 2022; Li et al., 2022d, m; Sun et al., 2018b; Wang et al., 2022d; Yao and Xu, 2023). Xue et al. (2017) found that the healing ratio (ductility recovery ratio) of asphalt binder with UF microcapsules could reach 90.37%. Sun et al. (2017) found that the maximum healing level (tensile strength recovery ratio) was 83.8%. Chen et al. (2023a) incorporated the IPDI

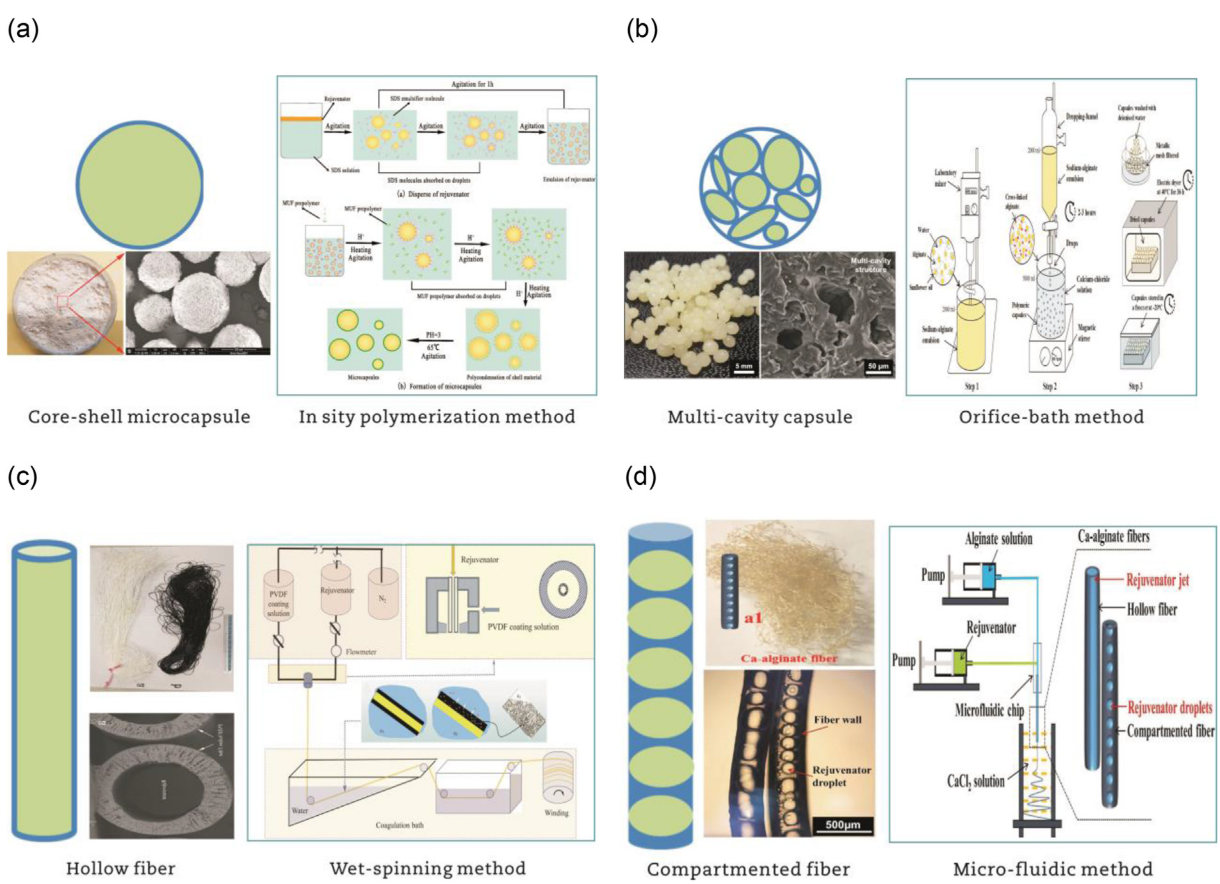


Fig. 12. Encapsulation technology for asphalt rejuvenator. (a) Core-shell microcapsule (Sun et al., 2017; 2018b). (b) Multi-cavity capsule (Norambuena-Contreras et al., 2019a, 2019b). (c) Hollow fiber (Zhang et al., 2018b; Guo et al., 2019). (d) Compartmented fiber (Shu et al., 2019a, 2019b).

microcapsules into three types of asphalt mixtures (AC-13, SMA-13, and AC-20) to explore the healing performance via SCB test. Results indicated that when the microcapsule dosage was 0.6%, the healing level (strength recovery ratio) of AC-13 was the highest, followed by SMA-13, while AC-20 was the lowest. The maximum healing ratio of AC-13 was 98% (Chen et al., 2023a).

The release mechanism of the rejuvenator in core-shell microcapsules operates intelligently by detecting the initiation and propagation of micro-cracks. However, this single-use release pattern has limitations in terms of functional lifespan and the ability to support healing when cracks reappear. Additionally, ensuring the timely release of the healing agent within the microcapsules remains a challenge, particularly in matching the strength of the microcapsules with the stress at the tip of the micro crack.

Multi-cavity capsules are created through the iron-exchange principle and the orifice-bath method. In this process, calcium alginate serves as the wall material, while vegetable oil is chosen as the asphalt rejuvenator (Micaelo et al., 2016; Al-Mansoori et al., 2017; Xu et al., 2018; Norambuena-Contreras et al., 2018b; Zhang et al., 2019b; Bao et al., 2020; Ruiz-Riancho et al., 2021; Yamaç et al., 2021; Li et al., 2021d; Kargari et al., 2022; Wang et al., 2022i; Zhao et al., 2023a). The raw materials employed in the multi-chamber capsules are entirely composed of eco-friendly, natural materials, posing no detrimental effects on the environment. Furthermore, extensive research has demonstrated that asphalt concrete containing multi-cavity capsules exhibits superior multi-crack healing capabilities and long-term healing potential. This advantage is attributed to the larger quantity of healing agent stored within separate chambers and the gradual release of rejuvenator from various cavities.

Garcia-Hernandez et al. (2020) introduced Ca-alginate capsules filled with sunflower oil into three distinct types of asphalt concrete, including dense asphalt concrete, stone mastic asphalt concrete, and porous asphalt concrete. Their investigation revealed that as the fatigue loading cycles increased, the capsules within these asphalt concrete varieties exhibited a gradual release of rejuvenator. Furthermore, all three types of asphalt concrete containing these capsules achieved a commendable healing level and demonstrated extended fatigue life when compared to plain asphalt concrete (Garcia-Hernandez et al., 2020). Zhang et al. (2019b) conducted fracture-healing-fracture test on asphalt concrete with Ca-alginate capsules and found that the strength recovery ratio and fracture energy recovery ratio of asphalt beams with the capsules could reach 92.7% and 180.2%, respectively. The initial objective behind the design of multi-chamber capsules was to leverage the traffic load on the pavement to trigger a gradual release of the rejuvenator stored within the cavities. The effectiveness of these capsules in achieving prolonged healing relies on their compatibility with traffic conditions and the degree of pavement aging. Bao et al. (2020) conducted research indicating that Ca-alginate capsules exhibited a gradual rejuvenator release pattern, with a release ratio of up to 55.2% after 64,000 loading cycles (equivalent to 4 years of service on a medium-traffic grade pavement). Rao et al. (2021) found that the rejuvenator release ratio of Ca-alginate capsules was 82.7% after 115,200 cycles of rutting loading (0.7 MPa) (equivalent to 7 years of service on a medium-traffic grade pavement). The rejuvenator within the capsules can be gradually released during the service of the pavement, which is expected to realize in-situ regeneration of aged asphalt and automatic healing of microcracks.

In terms of release mode of the rejuvenator inside the current capsules, the rejuvenator inside the core-shell microcapsule was released under the action of the tip stress of the crack (Su et al., 2013; Sun et al., 2017; Ji et al., 2021). However, the oil within calcium alginate capsules was released by the elastic contraction expansion of the shell (like the contraction-recovery of sponge before and after stress) under the action of external traffic loading (Bao et al., 2021; Wan et al., 2022b; Yu et al., 2022b). The release mechanism of rejuvenator of both core-shell microcapsules and multi-chamber capsules are based on the stress-induced (microcrack tip stress or external load stress) release mode. This passive rejuvenator release method fails to address the issue of matching the cracking and aging speed of pavement with the release speed of rejuvenator from the capsules. Moreover, this passive stress-controlled release fails to ensure timely release of the rejuvenator at due time and does not completely fit the concept of rapid maintenance of asphalt pavement. Hence, it is necessary to develop an active rejuvenator release method to match the release of the rejuvenator of the capsules with the demand of the pavement in different service condition. On the other hand, the rejuvenator released by the capsules moves into the micro crack through capillary flow, which is highly dependent on ambient temperature. Cracks are more likely to appear in cold regions. Due to the excessively low healing temperature in winter, the capillary flow rate of the rejuvenator released by the capsule is very slow, which will seriously reduce the crack repair efficiency of asphalt pavement.

Wan et al. (2021a, 2021b, 2022a) incorporated microwave absorption material (nano-Fe_3O_4) into Ca-alginate capsules and found that the composite capsules own dual-responsive feature: it can release inner rejuvenator gradually both under the cyclic traffic loading and microwave irradiation. Results indicated that after 64,000 cycles of loading, the rejuvenator release ratio of the composite capsules in asphalt concrete was 49.5%. After 40 s of microwave irradiation, the rejuvenator release ratio of the composite capsules in asphalt concrete was 26.4%. Microwave irradiation also enhanced the healing level of asphalt concrete to a very high level of 87.2%. The dual responsive feature of the composite capsule provides possibilities of active control of rejuvenator release and healing temperature, and thus is a promising strategy for low carbon maintenance of the pavement.

The self-healing fibers can be divided into hollow fiber and compartmented fiber. As shown in Fig. 12, the wet-spinning method is commonly employed in the preparation of the hollow fiber. The polyvinylidene fluoride resin (PVDF) is used as the wall material, and the oily rejuvenator is selected as the healing agent. The compartmented fiber is fabricated by the wet-spinning method (Tabakovic and Schlangen, 2016; Zaremotekhases et al., 2020) or microfluidic technology (Shu et al., 2019b; Li et al., 2022h). In this study, calcium alginate was used as the wall material, while a commercial rejuvenator and vegetable oil were chosen as the healing agents. Shu et al. (2019b) manufactured both hollow and compartmented Ca-alginate fibers and conducted research to evaluate their impact on asphalt healing properties. The results showed that when the microcapsule dosage was 5 wt%, the healing levels (measured by ductility recovery ratio) of the asphalt binder with hollow and compartmented fibers were 82.5% and 75.4%, respectively.

In the provided illustration in Fig. 13, when subjected to stress at the micro-crack tip, the entire rejuvenator within the hollow fiber is released and can heal the micro-crack once. Conversely, the compartmented fiber only releases the rejuvenator in the chamber near the crack zone. Therefore, for a single crack repair, the hollow fiber exhibits better repair efficiency than the compartmented fiber. However, in the event of subsequent cracks, the hollow fiber cannot contribute to crack repair, while the compartmented fiber can still seal the crack using the remaining rejuvenator in the separate chambers. Consequently, in terms of the ability to repair multiple cracks over time, the compartmented fiber surpasses the hollow fiber and offers long-term healing potential for asphalt materials.

2.1.3.3. Summary and recommendation. The inherent self-healing ability of asphalt presents a promising avenue to prolong the lifespan of asphalt pavements. Innovative approaches like thermally induced healing and rejuvenator encapsulation induced healing have shown significant potential in laboratory settings. Thermal induced healing technology offers superior crack repair efficiency and the capability to seal multiple cracks in asphalt concrete. However, it necessitates the incorporation of specific materials into the asphalt mix and human intervention during its service life, leading to the generation of harmful gases and accelerated asphalt aging due to repeated heating. On the other hand, rejuvenator encapsulation induced healing technology not only repairs micro cracks but

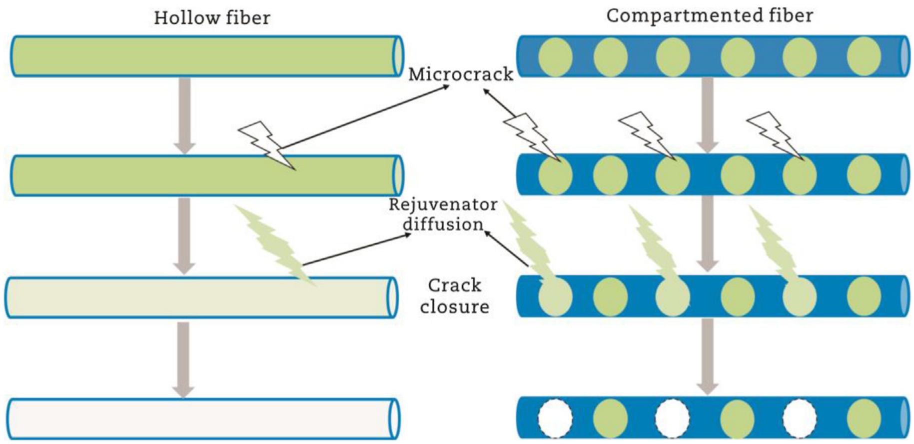


Fig. 13. The rejuvenator release mechanisms of hollow and compartmented fiber (Wan et al., 2022b).

also rejuvenates aged asphalt on-site through encapsulated rejuvenator supply. This technology demonstrates excellent curing effectiveness for damaged asphalt materials under moderate healing conditions. In real-world service conditions, the healing ratio of self-healing capsules or fibers may not match laboratory results. Moreover, controlling production costs and researching large-scale manufacturing methods for these capsules or fibers remain significant challenges.

The adoption of self-healing asphalt pavement materials has been proposed as a potential solution to address structural damage caused by the combined effects of repetitive loading and environmental factors. In the context of environmentally friendly maintenance practices, utilizing recycled materials with conductive or microwave–absorption properties can contribute to sustainable asphalt pavement through thermal-induced healing technology. Simultaneously, the development of energy-efficient electromagnetic induction and microwave transmission vehicles is urgently needed. There is also a need for optimizing the preparation processes of capsules and fibers to achieve controlled performance in production. However, the production efficiency of these capsules and fibers remains relatively low, requiring further research for industrial-scale manufacturing. Both thermal-induced healing and rejuvenator-induced healing technologies have their unique advantages and drawbacks. Exploring their synergistic effects could pave the way for the concurrent healing of asphalt materials. Collaborative efforts are essential to address the aforementioned challenges and facilitate the implementation of self-healing asphalt pavement materials in practical engineering applications. This would be a significant step toward advancing sustainable and low-carbon infrastructure for asphalt concrete.

2.2. Solid waste materials in asphalt roads

Due to the growing awareness and emphasis on sustainable development and circular economy, the examination of the feasibility of integrating various types of waste materials has emerged as a crucial research domain within the realm of engineering. The recycle and reuse approach ultimately holds the promise of enhancing resource efficiency and mitigating economic, climate, social, and environmental consequences. Nevertheless, the majority of waste materials undergo closed-loop recycling, wherein they were repurposed into the same types of products they were initially derived from; there are situations where the quality or technical specifications of these materials prevent them from being recycled into the same product. Consequently, these waste materials are disposed of in landfills or subjected to incineration. It was estimated that around 2.24 billion tonnes of solid waste are generated annually worldwide, and this number is still continuously increasing, which will further inflict a scarcity of natural resources. This presents a significant potential to repurpose waste materials, such as those generated by road pavements, as valuable resources. Roads, especially asphalt roads, are the dominating transport infrastructure worldwide, and an important contributor to the economy (JTTE Editorial Office et al., 2021). Consequently, this leads to the production of a significant quantity of asphalt mixtures and the extensive consumption of nonrenewable natural aggregates and fossil-based asphalt binders. Presently, recycled asphalt pavement (RAP) stands as the primary recycled material employed in the construction of roads (Hugener et al., 2022). Recent studies conducted on a global scale have demonstrated the successful utilization of diverse solid waste materials (Cannone Falchetto et al., 2023), including plastic, crumb rubber, steel slag, construction and demolition debris, and bio-based products (Fini et al., 2012) in the construction of road pavements. These innovative practices have resulted in significant environmental and economic advantages. However, this phenomenon is primarily observed inside intellectual circles or limited to specific nations or locations. In order to promote widespread adoption in the market, it is important to expeditiously cultivate and widely exhibit these solutions. Piao et al. (2021) conducted a comprehensive investigation of various waste materials employed in road construction. Based on the present observations, it may be inferred that the waste materials under consideration exhibit comparable or superior performance in terms of rutting, moisture, stiffness, and fatigue characteristics when compared to reference blends composed entirely of virgin materials. Simultaneously, the global technological readiness level (TRL) exhibited significant variation. The disparity can be attributed to the following factors: (a) insufficient understanding of their utility; (b) scepticism over their effectiveness; (c) absence of established criteria or benchmarks; and (d) inadequate motivation or incentives.

2.2.1. Recycled asphalt pavement (RAP) in pavement

Asphalt recycling has been demonstrated to be one of the greatest techniques to improve the sustainability of asphalt pavements. It has various advantages including preserving nonrenewable natural resources of aggregate and fossil-based asphalt binders, lowering environmental impacts resulting from the manufacturing of virgin raw materials, cutting the initial cost of asphalt, and protecting the environment from solid wastes (Guo et al., 2020b). The history of recycling and reusing RAP can be dated back to 1915. In the 1970s, it started receiving more attention due to the inflation of oil prices caused by the Arab oil ban (Kandhal and Mallick, 1998), which is especially true in Japan. Currently, RAP is well-established and practiced as one of the most reused materials around the world (Mariyappan et al., 2023). As the pavement infrastructures continue to age, the need for an established routine-based and repeated recycling process emerges as a fundamental practice to be developed and adopted in the road construction industry.

Despite the fact that recycling and reusing technologies for reclaimed asphalt pavement (RAP) have been developed for over four decades, there are several technological barriers that limit the mega-scale incorporation of RAP into unaged asphalt mixtures (Zaumanis et al., 2014; Moghaddam and Baaj, 2016; Lo Presti et al., 2016). (a) The variability of RAP properties exhibits differences among various sources and even within the same source of RAP. (b) There exists uncertainty surrounding the performance of mixtures containing RAP, particularly those with high RAP content. (c) Relatively poor performance properties and the mistrust in the performance of asphalt mixtures containing high RAP content, especially at low and intermediate temperatures, resulting in a maximum recycling limit of approximately 25% or even lower in many countries and regions. (d) The inclusion of RAP introduces heightened complexity in asphalt mix designing (Zaumanis et al., 2014; Wang et al., 2021b). To overcome these limitations, a lot of researchers conducted on the performance characterization, blending and diffusion mechanisms, reinforcement, of bituminous materials containing RAP.

2.2.1.1. Performance characterization and mix design of RAP contained materials. A high content of RAP can be incorporated into virgin/unaged asphalt mixtures to reduce the usage of raw binder and aggregate. Before adding RAP, it is essential to identify RAP's engineering properties and include them in the mix design process to ensure a comparable performance to the conventional mixture, mainly hot mix asphalt (HMA). These include, among others, RAP binder content, RAP binder properties, RAP aggregate particle size distribution, and RAP aggregate consensus properties such as the angularity of the coarse and fine particles. It is well known that the aging process (thermal oxidation and UV) ultimately leads to much stiffer and brittle binders, which can positively impact the rutting susceptibility of the pavement (Molenaar et al., 2010). However, such changes will ultimately result in susceptibility to fatigue cracking and low-temperature cracking (Petersen and Glaser, 2011). When the warm mix asphalt (WMA) technology was applied, stripping and moisture damage risks may occur due to the poor adhesion properties caused by the lower production temperatures (Guo et al., 2020b). Therefore, this represents a considerable constraint for pavement engineers and road authorities as more and more RAPs will have to be recycled in the upcoming years, possibly affecting pavement performance beyond acceptable service levels.

Hence, technologies that aim to use higher RAP content must be able to restore the lost properties of the aged binder without affecting the benefits gained with aging (Porot et al., 2017; Wang et al., 2022b). One of the commonly used methods is the use of asphalt recycling agents (ARA), such as rejuvenate additives and soft binders. Several studies have shown that some ARA can substantially restore the properties of aged asphalt binder with a limited negative impact on the binder's rheological properties and temperature susceptibility (Zaumanis et al., 2014; Grilli et al., 2017). Therefore, the optimal ARA content is one of the most important kernel factors in the performance of mixtures containing high RAP content. Besides the conventional softening point temperature and penetration values, several rheological properties based methods were proposed to determine the optimal ARA content (Alisov et al., 2020; Hugener et al., 2022). The bitumen typisierungs schnell verfahren (BTSV) (which means the binder-fast-characterization-test) (Alisov et al., 2020) principle is the alternative to softening point temperature. It was realized that the complex shear modulus $|G^*|$ at a temperature equal to softening point temperature determines a mean value of $|G^*|$ of approximately 15 kPa. Hence, $|G^*|$ equals to 15 kPa is set as a limiting threshold for the estimation of the material properties in the BTSV method. During the test, temperature, complex shear modulus $|G^*|$, and phase angle δ are recorded and reported against temperature (Fig. 14(a)). It was observed that the rejuvenator and soft binder show completely different behaviors, an example was displayed in Fig. 14(b). Such a method was further validated at the mixture level in the follow-up studies (Walther et al., 2019), and several field constructions in Europe. It should be noted that the softening point temperature based BTSV method is only related to the high temperature properties of bituminous materials. As previously mentioned, the risk of using RAP is at intermediate and low temperatures. Therefore, another method that considers a wide range of temperatures and aging conditions was proposed for this purpose under the framework of the RILEM technical committee TC-264 RAP task group 3 (Hugener et al., 2022). The target properties under different testing temperatures and corresponding aging levels between the reference and target materials were proposed at high, intermediate, and low temperatures (Table 1). Moreover, to avoid the effect of the chemical solvent, an intermediate phase asphalt mastic, between asphalt binder and mixture, was selected to avoid the extraction and recovery process of RAP binders. The asphalt mastic materials were first separated physically from the recycled asphalt plantings; and then, their mechanical properties were measured with the related DSR testing protocol (Hospodka et al., 2018; Riccardi et al., 2018). Finally, mechanistic modeling was conducted to back-calculate and predict the properties of corresponding binders and mixtures (Riccardi, 2017). More detailed information can be accessed in the related publications.

In recycled bituminous mixtures, both rejuvenation and aging occur from outside to inside. Therefore, to some extent, these two processes balance each other and deliver a relatively homogeneous asphalt binder during the blending process among virgin binder, recycled binder, and ARA. It can be considered an advantage of recycled mixtures over virgin mixtures which are less homogeneous due to inconsistent aging (Mohammadafzali et al., 2019). However, the above conclusions are based on a 100% degree of blending (DoB) among these three components, actually, it is very unlikely to reach 100% DoB (Fig. 15). Therefore, accurately capturing the degree of blending is way important to improve the performance properties and designing of asphalt mixtures. A lot of researchers conducted this topic, and it was agreed that five testing methods, indirect measurement, accountable difference, staged extraction, indicator marking, and in-situ microscopic observation, can be applied to measure the DoB based on the test principle. However, there is still a scientific debate on the improvement solutions of DoB, the proposed method may ultimately lead to a secondary aging of the blended asphalt binders (Lo Presti et al., 2020; Xing et al., 2023).

2.2.1.2. Emerging technologies and future research in RAP contained pavement. It is apparent that the application of high content of RAP in asphalt road construction could be an alternative sustainable solution for reducing the consumption of nonrenewable natural resources and greenhouse gas emissions. Even though these materials have been used for decades and have become more and more acceptable worldwide, there are still open questions to be solved. In the near future, re-recycling and multiple recycling of asphalt roads (Wang et al., 2019b, 2021b) will be issues that could not be ignored. However, only limited researchers were conducted on it, and the construction contractor treated different generations of RAP as the first generation. In addition, the evaluation methods for bituminous materials containing RAP referred to the virgin material in most of the regions all over the world, only limited standards were developed for recycled materials. Furthermore, the waste RAP in each country and region might be recycled, stored, and managed differently, such streams may affect the implementation.

2.2.2. Waste tire rubber recycling in pavement materials

With the developments in transportation and the associated increase in numbers of vehicles, approximately one billion end-of-life tires (ELTs) are produced every year worldwide (WBCSD, 2021). Due to the greater awareness of environmental issues and potential economic benefits, engineers are attempting to develop a more sustainable framework to dispose the ELTs (Sienkiewicz et al., 2012). Material recycling is the most common means of managing ELTs in the EU and has been gaining more and more attentions due to the lower processing costs and additional benefits (Torretta et al., 2015). In the paving industry, rubber materials recycled from ELTs have been successfully utilized as either the binder modifier or aggregate replacement to improve the sustainability and durability of pavement materials (Lo Presti, 2013; Shu and Huang, 2014). The size of waste tire rubber ranges from rubber chips (25–50 mm) to crumb rubber powders (4.75–0.075 mm). The following sections will

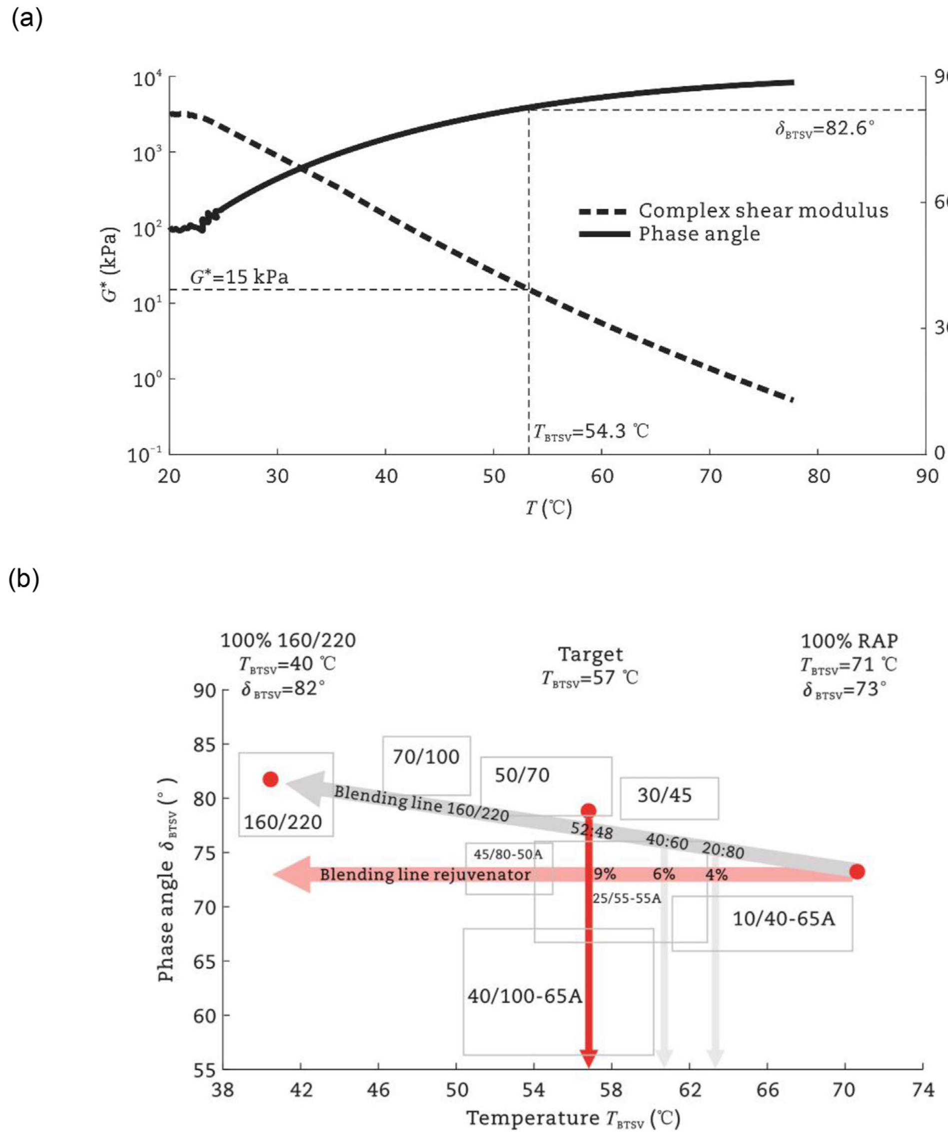


Fig. 14. Illustration of BTSV method and BTSV plane. (a) Example for BTSV method to determine softening temperature T_{BTSV} and corresponding phase angle δ_{BTSV}. (b) BTSV plane and illustration of recycled binders blending with soft binder and rejuvenator (Alisov et al., 2020).

review the production and construction technologies, interaction mechanisms, and performance evaluation of rubberized pavements.

2.2.2.1. Waste tire rubber as binder modifier. **Process.** Acting as binder modifiers in the wet process, crumb rubber (CR) particles are blended with asphalt binder and a predetermined reaction time is required before mixing the modified binder with aggregates. According to the different wet processing technologies (State of California Department of Transportation, 2003; Lo Presti, 2013; Shu and Huang, 2014), rubberized asphalt has various technical terminologies, such as asphalt rubber (AR), terminal blends (TB), crumb rubber modified binder (CRMB), etc.

Table 1
Recommended target properties (Hugener et al., 2022).

Temperature range	Recommended condition	Ageing state
High	DSR $\|G^*\|$ @ 58 °C, 1.59 Hz	Short-term
Intermediate	DSR $\|G^*\|$ @ 28 °C, 1.59 Hz	Unaged, short- and long-term
Low	G'' @ 6 °C, 1.59 Hz (with 8 mm plate) or DSR G'' @ −20 °C, 1.59 Hz (with 4 mm plate)	Long-term

Rubber-asphalt interaction mechanism. The interaction of CR and asphalt binder has a critical effect on the rheological properties and storage stability of rubberized asphalt binder. Some findings demonstrated that CR had no influence on the functional groups and molecular structures of asphalt binder based on the analysis of infrared

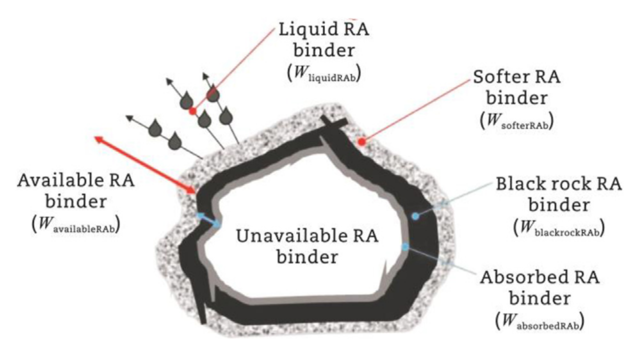


Fig. 15. Example of the blending between recycled and unaged binders (Lo Presti et al., 2020).

spectroscopy. It has been suggested that the modification process of CR with asphalt binder is a physical reaction (Ghavibazoo and Abdelrahman, 2013). However, this depends on the variables of CR (e.g., type, percentage, size, etc.) and asphalt binder (e.g., grade, SARA, etc.) as well as different interaction parameters (e.g., temperature, time, mixing technique, etc.). There are two main mechanisms involved in the interaction process of CR and asphalt binder: rubber particle swelling and chemical degradation (Abdelrahman and Carpenter, 1999; Wang et al., 2020a).

Wang et al. (2019b) reported four stages of rubber-asphalt binder interactions with increasing time at elevated temperatures in detail in Fig. 16. CR particles were just immersed in asphalt binder at Stage 0. The maleness in asphalt binder diffused into and were absorbed by CR. This caused the swelling of CR particles and the formation of a gel-like structure adjacent to the rubber-asphalt binder interface (Stage 1) (Peralta et al., 2010; Wang et al., 2020c). Since the process of swelling reduced the free spaces among the CR particles, the swollen CR had less mobility in the binder matrix (Shen et al., 2009), which further led to the increment of viscosity of asphalt binder and negatively affected the workability (Billiter et al., 1997b). A finite element model was also introduced in Wang's research to quantitatively simulate the multiphasic swelling phenomenon including mass diffusion and volume expansion (Wang et al., 2020e). With the increase of interaction time and temperature, rubber swelling reaches its equilibrium at a certain point (Stage 2). After that, extending interaction time at elevated temperatures will cause disintegration of the vulcanized network structure of CR and splitting into small individual particles (Stage 3). The small rubber particles can be fully dissolved into asphalt binder, but the high temperatures also cause the aging of asphalt binder (Billiter et al., 1997a; Ghavibazoo et al., 2013).

Rheology development and performance. Many studies have been conducted to investigate the effects of CR on rheological responses and performance of asphalt binder, including viscoelasticity (e.g., viscosity, complex modulus and phase angle), rutting resistance at high temperatures, cracking resistance at low temperatures, fatigue resistance at intermediate temperatures, etc. The incorporation of CR into base asphalt improves the rheological properties of base asphalt with enhanced stiffness and elasticity provided by the cross-linking polymer network. The stiffening of the asphalt phase and the inclusion of swollen rubber particles in the asphalt matrix together contribute to the peculiar viscoelastic response of rubberized asphalt binder, i.e., stiffer and more elastic at high temperatures, softer and more elastic at low temperatures. This modification mechanism explains the superior rutting, fatigue and thermal cracking resistance of rubberized asphalt binder (Wang et al., 2020d, 2021b). The improvement of high- or low-temperature performance is more prominent at higher rubber concentrations.

The effects of rubber modification on the asphalt mixture (AM) performance reported by different researchers are not always consistent or even contradictory as there are too many factors (raw materials properties, mix gradation, mixing conditions, etc.) contributing to the final mixture performance. Table 2 indicates qualitatively the performance tendency of the different types of rubberized asphalt mixture compared with conventional and non-conventional mixtures (Picado-Santos et al., 2020).

2.2.2.2. Waste tire rubber as aggregate replacement. **Process.** Recycled waste tire rubber can be used as partial replacement of aggregates in HMA and Portland cement concrete (PCC). In the dry process for HMA, granulated crumb rubber is typically used to substitute for a small portion of aggregates, typically 1%–3% of the total aggregate weight. The rubber particles are blended with heated aggregates through conduction prior to the addition of hot asphalt binder. The interaction between rubber and asphalt binder occurs during the time that these components come into contact in the mixer and during transport to laydown, with around 90 min generally being necessary before compaction (da Silva et al., 2018). Similar to the wet process, the rubber-asphalt interaction has great impact on the performance of dry mixed rubberized asphalt mixture.

Performance. Rubber particles can swell to twice to five times their original size with rubber-asphalt interaction and may resist later mixture compaction effort (Gawel et al., 2006). This swelling effect as well as the inherent resilient nature of rubber particles can prevent the mixture from achieving its target density, consequently leading to premature failure, such as cracking and raveling (Rahman et al., 2010). Mechanical test results show that the addition of crumb rubber in asphalt mixture through dry process method reduces the resilient modulus and creep modulus compared to the conventional mix which could probably be considered for low-volume road (Farouk et al., 2016).

The addition of waste tire rubber into PCC significantly alters the properties of the concrete. Due to the hydrophobic nature of rubber, the bond between the untreated rubber and hydrated cement is weak, which results in the significant reduction of both compressive and tensile strength of rubber modified PCC (Güneyisi et al., 2004; Huang et al., 2004). On the other hand, concrete becomes more ductile, as illustrated by the limited viscoelasticity and higher post failure toughness (Li et al., 2004). In addition to environmental benefits, the most significant advantages of rubber modified PCC have been their excellent energy absorbing characteristics and light weight (Siddique and Naik, 2004; Thomas and Gupta, 2016).

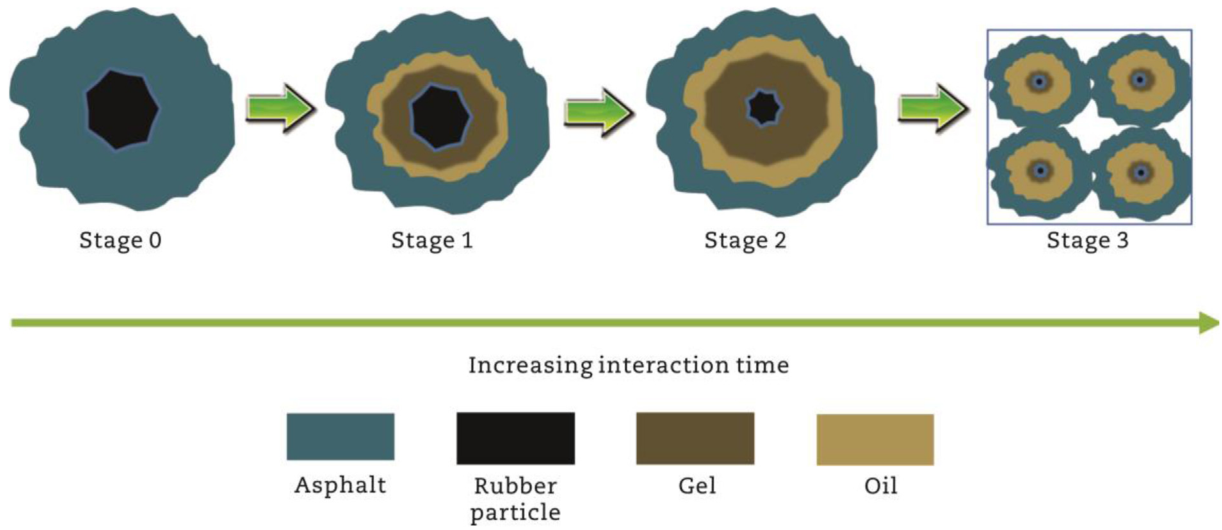


Fig. 16. Schematic representation of the asphalt binder–rubber interaction process (Wang et al., 2019b).

Table 2
The effects of rubber modification on the asphalt mixture (AM) performance.

Mixture comparison	Stiffness	Rutting resistance	Fatigue resistance	Moisture resistance	Thermal cracking resistance
Dense-graded rubberized AM vs. dense-graded virgin AM	⇧	⇧	⇧	⇩	⇧
Gap-graded rubberized AM vs. dense-graded virgin AM	※	⇧	⇧	★	⇧
Gap-graded rubberized AM vs. similar blends with other polymer-modified binder (e.g., SBS)	⇩	⇨	★	★	⇨

Note: ⇧ means usually increase; ※ means usually decrease; ★ means may increase; ⇩ means may decrease; ⇨ means usually unchanged.

2.2.2.3. Emerging technologies and future research in rubberized pavements. The importance of rubber-binder interaction in controlling the property development and mixture performance has been demonstrated in both wet process and dry process rubberized asphalt concrete. The inconsistency of long-term performance of rubberized pavements stems from issues including poor storage stability, poor workability and compaction, which are primarily dependent on rubber-asphalt interaction (Nanjegowda and Biligiri, 2020). Therefore, further efforts, which are listed below, are needed to understand the intrinsic connections among CR preparation process, swelling and degradation degree of rubber within asphalt, as well as the service performances of rubberized asphalt.

(1) Developing new pretreatment/activation methods on rubber particles by combining physical and chemical technologies to improve the compatibility with asphalt, such as microwave irradiation, low temperature plasma (LTP) treatment, light pyrolyzation by twin-screw extruder, etc.
(2) Establishing a comprehensive evaluation framework (including thermodynamics and kinetics) for quantifying the swelling and degradation degree of rubber in asphalt to control the binder property development more effectively.
(3) Establishing a micromechanics-based modelling framework to predict the long-term performance of rubberized asphalt pavements more accurately.
(4) Developing more advanced rubberized asphalt products, such as reacted and activated rubber (RAR), activated crumb rubber pellets, etc.

2.2.3. Waste plastic in pavement materials

Increasing amounts of plastic waste are an important challenge to the urban environment. According to the United Nations environmental programme (UNEP), plastic use has come with severe environmental, social, economic and health consequences. According to their report worldwide one million plastic bottle and five trillion plastic bags are used mostly for single use purposes. This results in 400 million tonnes of plastic waste every year. The properties of plastics that make them durable and resistant to degradation result in them not breaking down completely over time. Therefore, new avenues need to be developed for their reuse. The use of plastics in asphalt is a viable solution for reuse of this material (Poulikakos et al., 2017). The available data shows that similar performance can be expected in comparison to conventional materials from waste plastic modified mixtures (Piao et al., 2021; Wu and Montalvo, 2021; Poulikakos et al., 2023). RILEM Technical Committee TC 279 WMR on waste and secondary materials for roads investigated the use of plastic waste in asphalt as binder additive and mixture additive. The results are discussed in the sections below. Various types of plastics have been used in asphalt mixtures, however this chapter is using polyethylene (PE) for the purpose of demonstration.

2.2.3.1. Waste plastic as binder modifier. Kakar et al. (2021) used waste PE as binder modifier. The results showed that compared to conventional polymer modified binders, high temperature performance such as rutting could improve substantially with adding waste PE. Special attention should be paid to storage stability of the PE blended at high temperatures. As part of the work of RILEM TC 279 WMR, Wang et al. (2022a) investigated the rheological properties of PE modified binders. Their results showed that the use of plastic modifiers led to a higher complex shear modulus and softening point temperature while decreasing the penetration value. In addition, as part of TC WMR work, Tušar et al. (2023) showed that the blending of PE waste with bitumen is primarily physical and it does not alter the chemistry of bitumen. The multiple stress creep recovery (MSCR) tests indicated that the PE blends were less sensitive to permanent deformation in comparison to the neat binder. The fatigue performance using the linear amplitude sweep (LAS) test showed a better performance in terms of stress and fatigue life for the PE blends. Due to the reduced storage stability it is recommended to use the binder blend experiments for laboratory scale investigations only.

2.2.3.2. Waste plastics in asphalt mixtures. Based on the binder bled experimental results discussed above it is recommended to add the plastic modifiers to the mixture using the dry process that is the plastics are added to the aggregates before the binder and filler. Alternatively, one can use the semi wet process that is the plastics are added to the binder and immediately added to the hot aggregates. Microscopic evaluation of the PE modified mixtures (Fig. 17) indicate that although the melting temperature of PE is ca 120 °C and the mixing temperature ca 160 °C, the plastic pieces do not melt within the mixture, they are rather present as elastic bodies. This helps the high temperature performance when the binder becomes viscoelastic the plastic remains elastic. As part of the work of RILEM TC WMR PE modified mixtures were investigated (Poulikakos et al., 2022). Eleven laboratories participated in this international round robin study of PE modified AC16 mixtures. The results showed that compared to the control mixtures, PE modified mixtures were easier to compact, had less time dependence of stiffness, had higher elastic behavior, lower creep rate, and higher creep modulus. Furthermore, cyclic compression test results showed that the resistance to permanent deformation was improved when using PE, whereas the wheel tracking tests showed relatively similar or better results when 1.5% PE was added to the control mixture. The wheel tracking test results in water showed an increase in deformation with increasing PE content.

2.2.3.3. Emerging technologies and future research in plastic pavements. It is apparent that plastic modified asphalt mixtures could be an

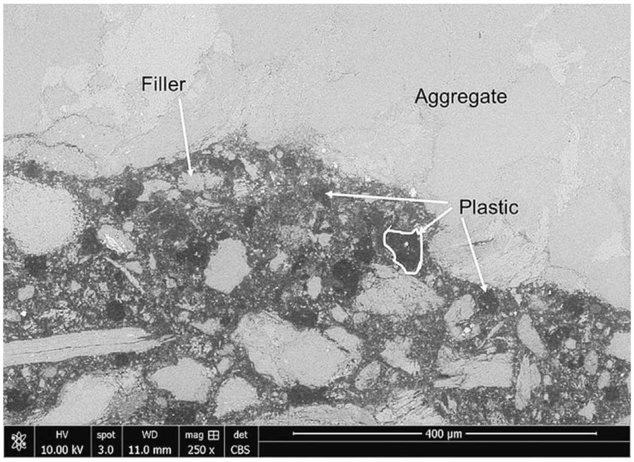


Fig. 17. Environmental scanning electron microscopy (ESEM) image of a PE Modified mixture at 250 × (Kakar et al., 2022).

environmentally friendly solution for reducing polymer modification in asphalt and using an abundant waste material. The sections above show that this new composite material can provide the mechanical performance needed. However, if using plastic modified mixtures makes sense environmentally has to be determined through environmental analysis such as leaching and determination of microplastics within the environment as well as greenhouse gas emissions and energy use through a complete life cycle assessments (LCA). Furthermore, the waste stream in each country and region might be treated differently. If the waste stream is landfilled then the use of the material in asphalt makes environmental sense. However, if the waste stream is used as fuel then it should be determined if alternative fuels exist to replace the plastic.

2.2.4. Bio-binders and bio-asphalt materials

Over the past decade, asphalt binder has emerged as a widely used construction material (Ashimova et al., 2021). As a result, extensive research efforts have been dedicated to exploring innovative binders and additives that can enhance the mechanical properties of asphalt pavement, extend its lifespan, reduce bitumen viscosity, and minimize carbon emissions during application (Mousavi et al., 2016a). However, a significant limitation of asphalt lies in its dependence on petroleum-based resources for procurement. Therefore, the search for a nonpetroleum alternative that not only addresses this limitation but also enhances the material's properties has become a crucial endeavor. Nevertheless, identifying a cost-effective and high-performing replacement has proven to be a challenging task.

2.2.4.1. Type of bio-based products. Fortunately, bio-oils have emerged as a promising solution. These bio-based binders are derived from renewable resources, such as wood sources. The utilization of bio-oils offers a viable path to overcome the petroleum dependence in asphalt production while simultaneously improving its properties (Cavalli et al., 2019).

- Vegetable oils. Vegetable oils, such as soybean oil, can be used as bio-based additives in asphalt to improve its properties. These oils can enhance the viscosity and stiffness of the binder, leading to improved performance (Elkashef et al., 2018).
- Bio-oils. Bio-oils obtained from biomass sources like wood pallets, corn stover, miscanthus, or animal waste can be used as a substitute for petroleum-based binders in asphalt. These bio-oils offer a renewable and sustainable alternative while maintaining or even enhancing the performance of the asphalt mixture (George et al., 2016).
- Lignin. Lignin, a natural polymer found in plant cells, has gained attention as a potential bio-based additive for asphalt. It can improve the cohesion and adhesion properties of the binder, leading to enhanced pavement performance (Xie et al., 2017).
- Bio-polymer modifiers. Bio-based polymers, such as bio-based polyethylene or bio-based polypropylene, can be used as modifiers in asphalt. These polymers can enhance the mechanical properties, rut resistance, and durability of the asphalt mixture (Ku et al., 2011).
- Waste byproducts. Various waste byproducts from industries, such as recycled tires or recycled plastics, can also be utilized as bio-based additives in asphalt. These materials contribute to waste reduction and offer performance benefits in terms of improved elasticity and resistance to cracking (Leng et al., 2018; Eskandarsefat et al., 2019).

Bio-asphalt is produced by replacing or modifying petroleum asphalt with bio-binder. Huang and Di Benedetto (2015) showed that bio-asphalt is generally produced by the following three ways: (1) bio-binder directly replaces petroleum asphalt (100% replacement rate); (2) bio-binder is used as modifier to modify petroleum asphalt (replacement rate is less than 10%); (3) bio-binder is used as diluent to blend petroleum asphalt (25%–75% replacement rate).

2.2.4.2. Chemical analysis. Chemical analysis plays a crucial role in understanding the composition and behavior of bio-based binders. Researchers have used various analytical techniques, such as Fourier-transform infrared spectroscopy (FTIR) and nuclear magnetic resonance (NMR), to characterize the chemical structure and functional groups present in bio-based binders. These analyses provide insights into the compatibility of bio-based binders with asphalt and their potential for improving mixture performance. In a different study, Elkashef et al. (2018) investigated the chemical composition and rheological properties of plant oil-based bio-asphalts. The researchers used FTIR to analyze the molecular structure of the bio-asphalts and found that the introduction of plant oil improved the flexibility and thermal stability of the asphalt binder. This research demonstrated the chemical changes induced by bio-based products and their impact on the performance of asphalt mixtures.

NMR Spectroscopy: NMR spectroscopy provides insights into the molecular composition and structure of bio-based asphalt binders. It can be used to analyze the different chemical components, quantify their relative concentrations, and study their interactions within the binder matrix (Mullins et al., 2012).

Elemental analysis techniques, such as energy-dispersive X-ray spectroscopy (EDX) can be employed to determine the elemental composition of bio-based asphalt binders. This analysis helps in assessing the presence of specific elements, such as metals or trace elements, which may influence the binder's performance (Cavalli et al., 2016).

Thermal analysis techniques, including thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC), are used to study the thermal behavior and stability of bio-based asphalt binders. These techniques can provide information on the binder's thermal degradation, phase transitions, and oxidation characteristics (Soenen et al., 2014).

Gas chromatography-mass spectrometry (GC-MS): GC-MS analysis allows for the separation, identification, and quantification of the individual compounds present in bio-based asphalt binders. It is useful in characterizing the volatile and semi-volatile components, identifying degradation products, and assessing the overall chemical profile of the binder (Yang et al., 2017).

The majority of researchers have focused on studying the rejuvenation of bitumen using rheology-based metrics. However, it is important to recognize that oxidative aging can lead to morphological changes in bitumen that may not be detectable through rheometry. Recent studies utilizing atomic force microscopy (AFM) have revealed the presence of micrometer-sized bee-like structures within bitumen (Bhasin and Ganesan, 2017). These bee structures have been observed to be larger in aged bitumen compared to their counterparts in virgin bitumen (Cavalli et al., 2019). Additionally, it has been reported that the number of these bee structures decreases with aging (Hung et al., 2017). Furthermore, Yu et al. (2015) discovered that the bee structures in unmodified binders became more elongated following aging in a pressure aging vessel.

2.2.4.3. Rheological analysis. Rheological analysis helps in understanding how asphalt materials flow and deform under different conditions, such as temperature and stress. This information is crucial for designing asphalt mixtures with optimal workability during construction processes like mixing, compaction, and placement. By studying parameters like complex modulus, phase angle, and creep behavior, it becomes possible to predict how the asphalt will behave under different environmental and loading conditions, helping in the design of durable and long-lasting pavement structures.

Dynamic shear rheometer (DSR): DSR analysis is commonly employed to evaluate the viscoelastic properties of bio-based asphalt binders. It measures the complex shear modulus (G^*) and phase angle (δ) as a function of temperature and frequency, providing information about the binder's stiffness, resistance to deformation, and flow characteristics (Cavalli et al., 2019).

Multiple stress creep recovery (MSCR): MSCR testing is used to assess the rutting resistance and recovery properties of bio-based asphalt binders. It involves subjecting the binder to a constant stress for a certain duration, followed by stress removal and measurement of the recovery response. MSCR parameters, such as permanent deformation and recovery percentage, provide insights into the binder's resistance to rutting (Yang et al., 2017).

Bending beam rheometer (BBR): BBR analysis helps evaluate the low-temperature cracking potential of bio-based asphalt binders. It measures the stiffness and creep behavior of the binder under bending stress at low temperatures, providing information on the binder's ability to resist cracking in cold climates (Mousavi et al., 2016b).

Rotational viscometry: rotational viscometry is used to determine the viscosity and flow behavior of bio-based asphalt binders at different temperatures and shear rates. It provides insights into the binder's resistance to flow, which is crucial for evaluating its workability during mixing, compaction, and application processes (Xu et al., 2017a).

Rolling thin film oven (RTFO) test: the RTFO test is performed to simulate short-term aging of bio-based asphalt binders by subjecting them to elevated temperatures and oxidative conditions. It measures the changes in viscosity and rheological properties, such as the softening point, ductility, and elastic recovery, after the simulated aging process (Ongel and Hugener, 2015).

2.2.4.4. Performance evaluations. Performance evaluation of bio-based asphalt is crucial to assess its suitability for various applications in the field of road construction. Researchers have conducted extensive studies to investigate the mechanical properties, durability, and environmental performance of bio-based asphalt.

One aspect of performance evaluation is the assessment of mechanical properties. Studies have shown that bio-based binders, such as those derived from vegetable oils or bio-oils, can improve the stiffness and rutting resistance of asphalt mixtures (Zhu et al., 2017). Additionally, bio-based additives, such as lignin, have been found to enhance the cohesive and adhesive properties of asphalt (Xie et al., 2017). These improvements contribute to the overall strength and performance of bio-based asphalt pavements.

Durability evaluation is another important aspect. Researchers have examined the resistance of bio-based asphalt to aging, moisture damage, and thermal cracking. It has been observed that bio-based additives can enhance the aging resistance and moisture susceptibility of asphalt mixtures (Gong et al., 2016). Furthermore, bio-based binders have demonstrated good resistance to thermal cracking, which is crucial for asphalt pavements in regions with extreme temperature variations (Porot et al., 2017).

Environmental performance evaluation focuses on the sustainability and carbon footprint of bio-based asphalt. Life cycle assessments (LCAs) have been conducted to evaluate the environmental impacts of bio-based asphalt compared to conventional asphalt. LCAs have shown that bio-based asphalt can reduce greenhouse gas emissions and energy consumption during production (Samieadel et al., 2018). Moreover, the use of renewable resources in bio-based asphalt aligns with sustainable development goals, promoting a more environmentally friendly infrastructure.

Performance evaluations of bio-based asphalt mixtures include also tests such as Marshall stability, resilient modulus, and fatigue life. These tests assess the mechanical properties and durability of the mixtures. Studies have shown that bio-based asphalt mixtures can exhibit comparable or even superior performance compared to conventional asphalt mixtures.

For example, a study by Xu et al. (2017c) evaluated the performance of asphalt mixtures containing lignin, a bio-based additive derived from plant materials. The research investigated the effects of lignin content on the mechanical properties of the mixtures, including stiffness, rutting resistance, and fatigue life. The results indicated that the incorporation of lignin improved the performance of the asphalt mixtures, particularly in terms of rutting resistance and fatigue life.

Finally, the performance evaluation of bio-based asphalt encompasses mechanical properties, durability, and environmental performance. Through comprehensive studies, it has been demonstrated that bio-based asphalt exhibits favorable performance characteristics, making it a promising alternative to conventional asphalt in road construction.

In conclusion, the use of bio-based products in the asphalt field offers promising opportunities for sustainable road construction. These products, obtained from renewable sources, show potential improvements in mechanical properties, chemical analysis, and performance evaluations of asphalt mixtures. Proper characterization and understanding of the chemical structure and functional groups of bio-based binders contribute to the development of high-performing asphalt mixtures. Further research and development in this area will continue to advance the utilization of bio-based products, contributing to more sustainable and environmentally friendly road infrastructures.

2.3. High-performance pavement materials

2.3.1. High modulus asphalt

High modulus asphalt concrete (HMAC), originally developed in France the 1960s, was intended to withstand the increasing plastic deformation of the base course caused by heavy traffic. Although these mixtures were initially designed for base or binder courses, they have later been extended to surface layers.

The objective of this review is to investigate the pavement performance of HMAC. This paper can be divided into four sections, primarily reviewing the pavement performance of HMAC in the following areas: (1) rutting resistance, (2) fatigue resistance, (3) low-temperature cracking, (4) water stability.

2.3.1.1. Rutting resistance. Dynamic stability, which measures the number of loading cycles required to generate a 1 mm rut depth in the last 15 min of a 1 h test, has been widely used to characterize the rutting resistance performance of HMAC. HMAC typically exhibit better rut resistance performance compared to traditional mixtures (Yang and Wei, 2011; Zou et al., 2015a, 2015b, 2017). It has been reported that dynamic stability significantly decreases when the test temperature is raised from 60 °C to 75 °C (Zou et al., 2015a, b). Regarding the effect of temperature on rutting resistance, the relative deformation rate, defined as the rut depth divided by the original slab thickness, also significantly increases when the test temperature rises from 45 °C to 75 °C (Fig. 18).

Despite the widespread use of dynamic stability testing, there is a relatively high coefficient of variation in the test results. This has raised valid concerns about the suitability of using dynamic stability for assessing rutting resistance of HMAC (Xia et al., 2018). According to

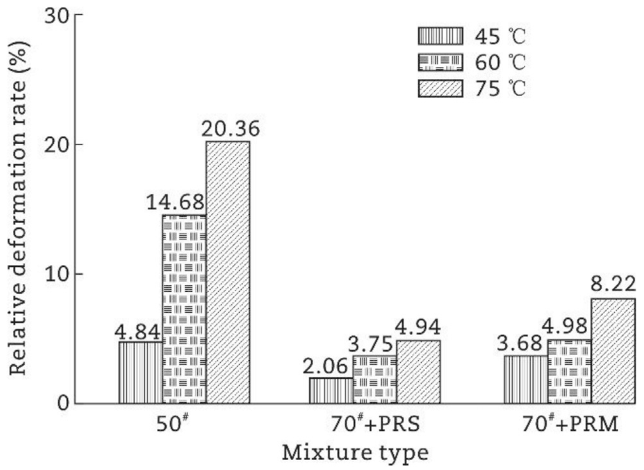


Fig. 18. Comparison of relative deformation rates of 3 asphalt mixtures (Huang et al., 2016).

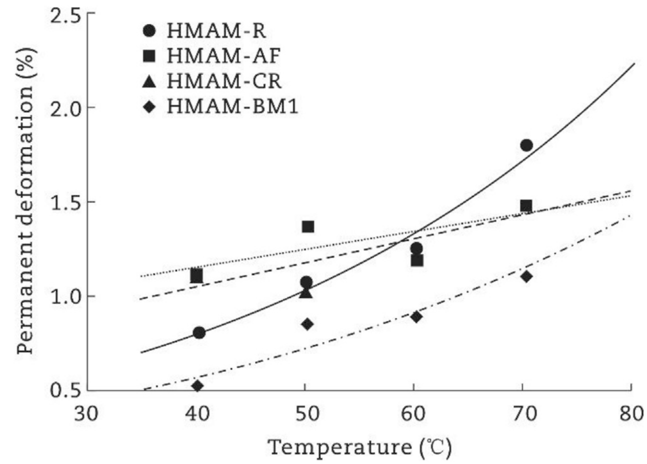


Fig. 19. Triaxial tests results (Moreno-Navarro et al., 2014).

AASHTO TP 79-13, the flow number, which is a rut resistance parameter obtained using the asphalt mixture performance tester (AMPT), is significantly higher for HMAC mixtures compared to traditional mixtures (Leiva-Villacorta et al., 2017). The repeated load axial test (RLAT) is employed to assess the permanent deformation resistance of HMAC. The performance parameters obtained from this test include the rutting rate in the quasi-linear region of the curve, permanent vertical strain after 3600 loading cycles (ε_p), permanent vertical strain in the quasi-linear region of the curve (ε_{p2}), stress (S_{mix}(ax)) and strain relationship parameters, as well as the mean viscosity parameters (h_1) (Capitão and Picado-Santos, 2006a, b). The test results indicate that with an increase in asphalt content (Capitão and Picado-Santos, 2006a, b; Khiavi and Naseri, 2019) and a decrease in air void content (Capitão and Picado-Santos, 2006a, b), rutting resistance increases, especially with regards to the 10/20 penetration grade asphalt content, which has a significant impact on permanent deformation. Restricted cyclic triaxial tests were also employed to assess the plastic deformation of high-modulus mixtures. The results indicated that HMAC containing acrylic fibers and latex particles outperformed SBS-modified mixtures and traditional mixtures in terms of permanent deformation (Fig. 19).

To assess the rutting resistance of HMAC for intersections, repeated load triaxial tests were conducted to simulate the slow-speed loading at intersections. The results showed that the EME mixture with a 15/25 penetration grade exhibited 100 times greater rutting resistance compared to other traditional mixtures, which required a certain number of cycles to reach a specific rut depth or permanent strain value (Arnold et al., 2017). The study found that a high content of TLA can significantly enhance the rutting resistance of HMAC, particularly when combined with 3‰ polyester fibers. Immersion wheel tracking tests were used to assess the rutting resistance of high modulus mixtures under hot and humid climatic conditions (Moreno-Navarro et al., 2016; Zou et al., 2015a, b). The test results indicate that HMAC containing PRM and PRS improves its resistance to permanent deformation compared to SBS-modified mixtures and traditional mixtures (Zou et al., 2015a, b). High modulus asphalt mixtures with acrylic fibers exhibit a more stable response to resisting plastic deformation, whereas controlling high modulus mixtures does not possess this characteristic. This implies that acrylic fibers can enhance the mechanical response of asphalt mixtures and disperse stress generated in the material effectively (Moreno-Navarro et al., 2016). The excellent performance of HMAC in resisting rutting was also confirmed through wheel tracking tests and LCPC accelerated loading tests (Brosseaud and Spernol, 1998; Caroff et al., 1994).

2.3.1.2. Fatigue resistance. Fatigue cracking in asphalt pavements is generally considered one of the most challenging issues in the field of pavement engineering today. Two-point bending, three-point bending, four-point bending tests, and indirect tensile tests are commonly used to assess the fatigue resistance of asphalt mixtures (BSI, 2001). Strain-controlled two-point bending tests on trapezoidal specimens are conducted to assess the fatigue resistance of HMAC. The results reveal that due to its higher binder content and lower porosity, HMAC exhibits better fatigue resistance compared to traditional asphalt mixtures (Corté, 2001; Xia et al., 2018). Specimens extracted from field test sections typically perform better than those compacted with lower energy (Capitão and Picado-Santos, 2006a, b). Interestingly, early failures were reported in beams with low porosity percentages (2.06%–2.49%) when subjected to sinusoidal loading, which may be attributed to stress concentrations induced in the beam specimens due to their low porosity content (Botes, 2016). On the other hand, within the porosity range of 2.92%–3.69%, beams subjected to sinusoidal loading exhibited the best fatigue resistance. It can be concluded that compaction plays a crucial role in the fatigue life of asphalt mixtures. Lower compaction efficiency was also found to result in increased low-temperature cracking in HMAC base layers (Judycki et al., 2016). The typical fatigue curves for HMAC and conventional asphalt mixtures were shown in Fig. 20. In Fig. 20, one traditional base AC, two HMACs having the same composition but different hard asphalt.

The fatigue resistance of HMAC is better than that of the original asphalt mixture when tested using stress-controlled three-point bending beam tests at 15 °C. This is attributed to the increased stiffness modulus of high-modulus mixtures, primarily due to the increased viscosity resulting from the addition of PRM and PRS particles, leading to a longer fatigue life (Zou et al., 2017). Under stress-controlled cyclic loading, a higher stiffness modulus will reduce the strain levels within the mixture, thus extending the fatigue life. A similar conclusion, where EME mixtures exhibited better fatigue resistance compared to traditional mixtures, was drawn by Albayati and Lateif (2017) in stress-controlled loading conditions of three-point bending beam tests. Four-point bending beams have also been used to assess the fatigue resistance of prism-shaped specimens of high-modulus mixtures under strain-controlled cyclic loading. A comparison of fatigue resistance between two-point bending and four-point bending has been confirmed (Jaczewski et al., 2016).

In order to study the crack propagation behavior of HMAC, a semi-circular bending test was conducted using digital image correlation methods to monitor the crack propagation process (Montepara et al., 2004). The results indicate that HMAC exhibits linear elastic behavior within the temperature range of 10 °C–15 °C, while above this range, elastic-plastic behavior can be observed. The crack propagation characteristics of HMAC were studied using compact tension (CT) tests, and a smooth crack growth curve between the crack tip opening displacement and the measured crack length was generated using linear regression

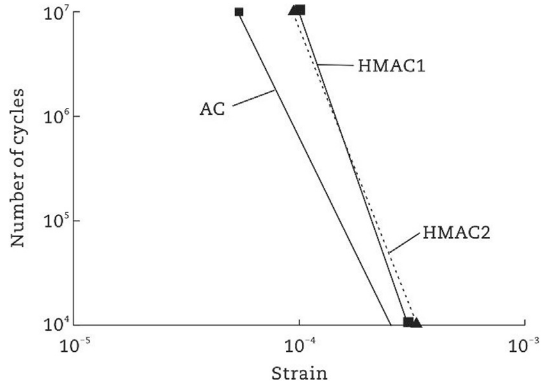


Fig. 20. Two-point bending fatigue tests (Corté, 2001).

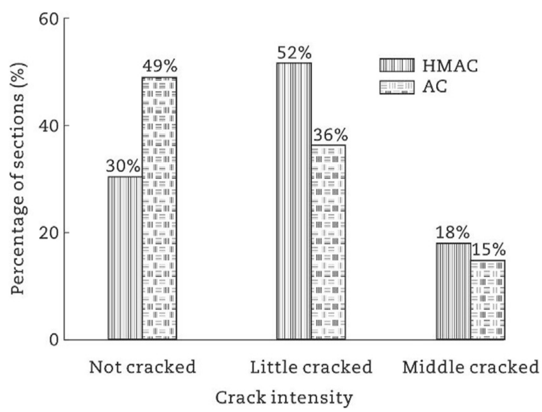


Fig. 21. Percentage of sections with HMAC and AC pavement base courses in three groups of cracks intensity, according to observations in 2014 (Rys et al., 2017).

(Sewell, 2017). Lyu et al. (2022) developed a fatigue model for HMAC by unifying its characterization and considering the influence of loading rate under various loading modes, which eliminates the specimen size effect.

2.3.1.3. Low temperature cracking. Ultimate flexural strain from bending beam tests mixture (Cheng, 2016; Cui et al., 2014; Song et al., 2018; Yang and Wei, 2011; Yang and Zhang, 2012; Zou et al., 2015a, b), J-Integral (Cui et al., 2014), single-edge notched beam (SENB) (Gen et al., 2018), thermal stress restrained specimen test (TSRST) (Vervaecke and Vanelstraete, 2008; Cheng, 2016; Moreno-Navarro et al., 2016) and SCB (Vacková et al., 2017) have been employed by researchers to study the low temperature cracking resistance of HMAC. Better performance for HMAC with modifiers than conventional asphalt mixture (Yang and Wei, 2011; Yang and Zhang, 2012; Cui et al., 2014; Zou et al., 2015a, 2015b, 2017; Cheng, 2016), but lower performance than SBS-modified asphalt mixture (Yang and Zhang, 2012; Zou et al., 2015a, 2015b, 2017) were reported based on ultimate flexural strain from bending beam tests. However, HMAC produced from hard-grade binder often showed lower low temperature cracking resistance than conventional asphalt mixture (Cui et al., 2014; Gen et al., 2018).

In addition to the bending beam test, J-Integral testing also confirmed the excellent low-temperature performance of HMAC with modifiers. However, HMAC prepared with hard bitumen exhibited lower performance compared to conventional asphalt mixtures (Cui et al., 2014). Fracture energy (G_f), from SENB was successfully employed to assess the low-temperature cracking resistance of HMAC. The results indicated that HMAC prepared with Gilsonite rock asphalt and hard bitumen exhibited lower resistance compared to mixtures using SBS and 70 penetration-grade bitumen (Gen et al., 2018).

Cui et al. (2014) indicated that there was no correlation between the critical temperature from BBR testing and the critical values of strain energy density and fracture toughness from the bending beam test. However, there was a strong correlation between BBR stiffness and TSRST critical temperature. There was no correlation between the critical temperature based on BBR *m*-value and TSRST critical temperature (Vervaecke and Vanelstraete, 2008). Vacková et al. (2017) also reported a certain connection between binder and asphalt mixture properties. For example, higher softening points and smaller complex shear moduli were associated with better low-temperature characteristics.

Rys et al. (2017) revealed that road pavements using high modulus asphalt in the base course were more prone to cracking compared to pavements using conventional asphalt concrete in the base course, as shown in Fig. 21. Colder usage temperatures (Fig. 22) and longer pavement aging (Fig. 23) also increased the likelihood of low-temperature cracking. In Fig. 22, A represents the coldest (maximum depth of frost penetration h_z=1.2 or 1.4 m); B represents the medium (maximum depth of frost penetration h_z=1.0 m), C represents the warmest (maximum depth of frost penetration h_z=0.8 m).

In subsequent research, Pszczola et al. (2022) conducted a study evaluating four test sections using HMAC in the base and binder courses. Field investigations of the number of low-temperature cracks were performed over several years. The results indicated that the number of new low-temperature cracks is influenced by many random factors, and the statistical term “reversion to the mean” should be considered. A new factor named “increase in cracking index” was developed to analyze the resistance of the pavement to low-temperature cracking.

2.3.1.4. Water stability. Freeze-thaw splitting tests and Marshall immersion tests have been widely used to evaluate the moisture resistance

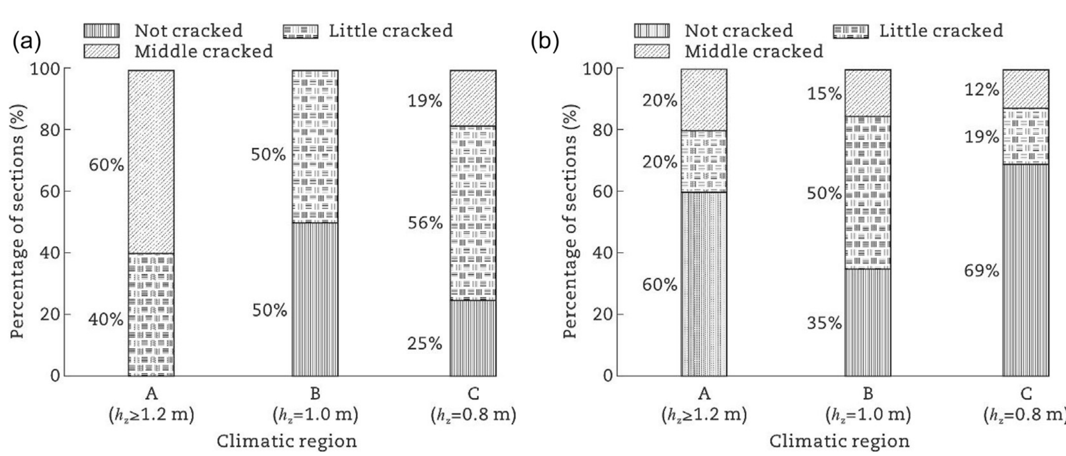


Fig. 22. Relationship between the intensity of cracking with the depth of frost penetration (h_z) in regions A, B, and C in Poland. (a) Pavement with HMAC base. (b) Pavement with AC base (Rys et al., 2017).

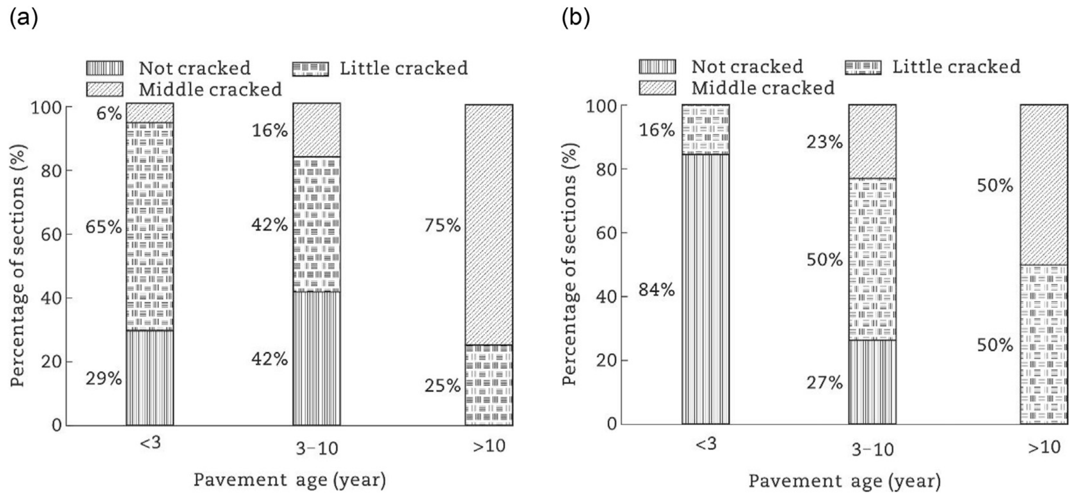


Fig. 23. Relationship between the intensity of cracking with the age of pavements. (a) Pavement with HMAC base. (b) Pavement with AC base (Rys et al., 2017).

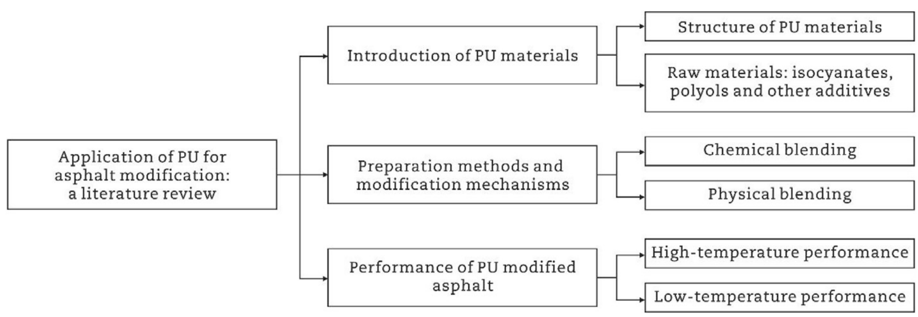


Fig. 24. Structure of this review paper.

of HMAC (Zou et al., 2015a, b). It has been reported that high modulus mixtures containing PRM and PRS exhibit better moisture resistance compared to high modulus mixtures containing SBS and pure binder (Zou et al., 2015a, b). Results from the indirect tensile strength test indicate that HMAC mixtures produced using hard-grade binders also exhibit better moisture resistance compared to traditional mixtures (Albayati and Lateif, 2017).The moisture-induced damage evaluation method specified by AASHTO T283 can be used as a replacement for the Duriez method in France because it offers better repeatability, whereas the simple freeze-thaw splitting test has lower reliability (Xia et al., 2018). High modulus mixtures with a composite modification of PE and SBS exhibit better water resistance compared to mixtures containing only SBS particles (Yang and Zhang, 2012).

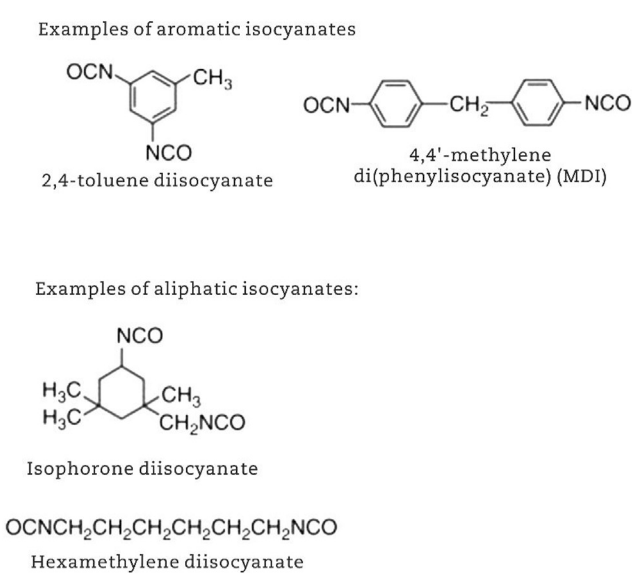


Fig. 25. Chemical structures of some common isocyanates.

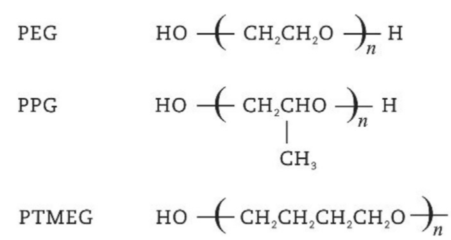


Fig. 26. Chemical structures of some common polyols.

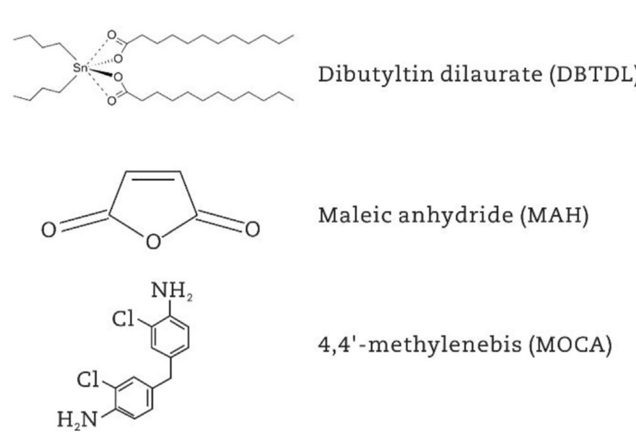


Fig. 27. Chemical structures of some common additives.

For the composite modification of TLA and polyester fibers, concerning moisture resistance, the optimal addition of TLA is 30% when a polyester fiber content of 3‰ is selected (Wang et al., 2018b). The improved water resistance is primarily attributed to the increased viscosity of the modified binder (Zou et al., 2015a, b), reduction in air voids within the mixture and the enhancement of the bond between the asphalt and aggregates in the mixture contribute to the improved water resistance (Song et al., 2018), which can effectively prevent moisture from infiltrating the interface.

The overview finds that HMAC typically exhibits improved water resistance, better resistance to rutting, reasonable fatigue resistance, but there are concerns regarding its resistance to thermal cracking. Its application in pavement structures can reduce pavement layer thickness, thus saving construction costs.

2.3.2. PU asphalt

Asphalt binder, also known as asphalt cement or asphalt cement binder, is a by-product of petrol refining (Speight, 2016). Due to excellent road performance, low production cost, and comfortable driving conditions, asphalt binder has been widely used in pavement engineering (Zhang et al., 2020a). Therefore, asphalt will have significant impacts and contributions on the performance of asphalt pavement. Recently, due to increasing traffic volume, traditional asphalt binders have been unable to satisfy the requirements of existing pavement design. In order to ensure the asphalt pavement can withstand the increasing traffic volume, various additives, such as rubber, SBS, PP, and PET, have been added to asphalt to improve its mechanical performance (Singh et al., 2013; Li et al., 2021f, 2022f). Although these modifiers can effectively enhance the mechanical properties of base asphalt, there are still some problems when using these modifiers, including poor storage stability problems, high energy consumption during both the production process and construction process, and severe air pollution (Zhu et al., 2014; Behnood and Gharehveran, 2019; Yu et al., 2021a; Zhou et al., 2023). Recently, a thermosetting material, polyurethane (PU), was applied to partially substitute conventional asphalt binder, which was found to effectively improve the mechanical properties of asphalt. In addition to the performance improvements, the PU-modified asphalt also has excellent storage stability and significant environmental benefits, such as less energy consumption and air pollution.

Various studies have been conducted on the preparation, mechanical performance, and modification mechanism of PU-modified asphalt and its mixture. Singh et al. (2013) evaluated the effect of isocyanate production waste particles on the thermal and rheological properties of waterproofing bitumen. Xia et al. (2016) applied the castor oilpolyurethane prepolymer (C-PU) to modify both high and low-temperature properties of asphalt, and the Fourier-transform infrared spectroscopy (FTIR) analysis conducted in the research can partially illustrate the chemical interaction between C-PU and active hydrogen in asphalt. Bazmara et al. (2018) utilized synthesized PU as the modifier additive to improve the high-temperature performance of asphalt, and it was found higher rutting and cracking resistance can be achieved by PU modification. In the latest research, PU modifier was also incorporated with rock asphalt to effectively improve the low-temperature performance of base asphalt (Jin et al., 2020). Although the mechanical and chemical performance of PU-modified asphalt has been reported in some previous studies, the results of these studies are still messy, and the application of PU is still developing. Hence, this paper will give a systematic literature review of current research progress for PU-modified asphalt. The paper structure is shown in Fig. 24 and this review paper is composed of three parts: (1) introduction of PU materials and the raw materials for PU synthesis; (2) summary of different modification methods and their modification mechanisms; (3) performance of PU-modified asphalt,

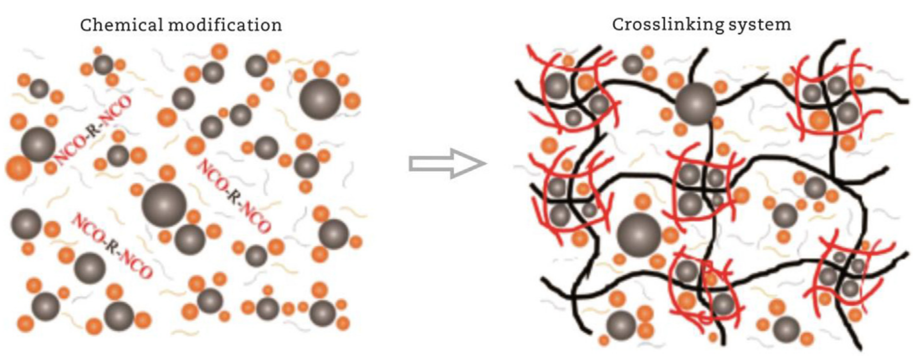


Fig. 28. Schematic diagram of PU precursor modified asphalt.

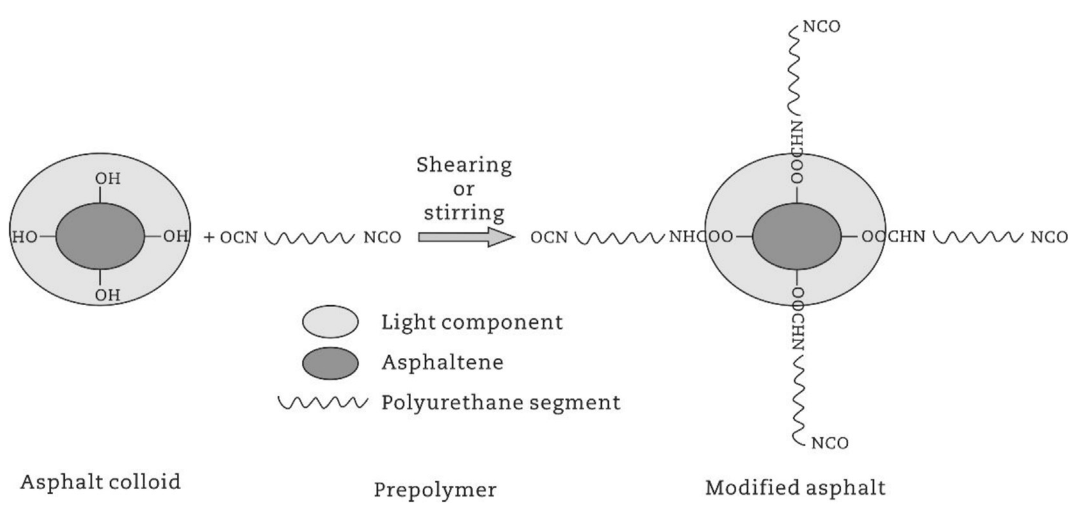
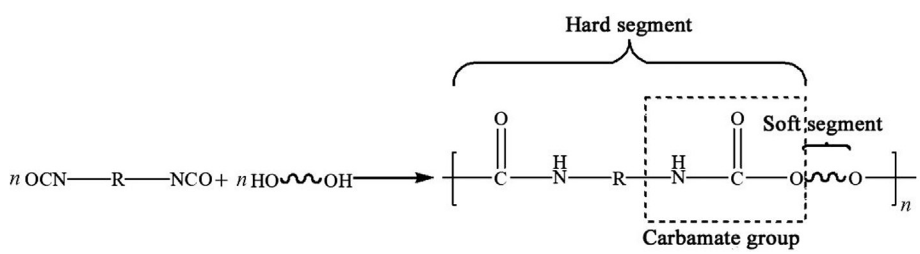


Fig. 29. Schematic diagram of PU prepolymer modified asphalt.

including high-temperature performance and low-temperature performance.

2.3.2.1. Introduction of PU materials. PU is a class of polymers containing urethane groups (–NHCOO–) in molecule chains stemming from the reaction of isocyanate-based materials (contain –NCO functional groups) with polyols (contain –OH groups). The reaction mechanism of PU is shown in Eq. (1) (Hong et al., 2021). It is shown that the molecular structure of PU is divided into hard segments and soft segments. In the PU molecular structure, the soft segments provide elasticity, toughness, resiliency, and low-temperature performance while the hard segments decide strength, hardness, and high-temperature performance.



(1)

2.3.2.2. Raw materials

2.3.2.2.1. Isocyanates. Isocyanates can be divided into two types, aliphatic isocyanates, and aromatic isocyanates. Aromatic isocyanate uses cheap toluene as a raw material, which has developed rapidly and currently dominates the market. The typical examples of aromatic isocyanates include toluene diisocyanates (TDI) and methylene diphenyl isocyanate (MDI) while the typical examples of aliphatic include diisocyanate (HDI) and isophorone diisocyanate (IPDI) (Padsalgikar, 2017). The chemical structures of some common aliphatic isocyanates and aromatic isocyanates are shown in Fig. 25. The structure of isocyanate affects the rigidity of the hard segment, so the type of isocyanate has a great impact on the performance of polyurethane materials. PU prepared from aromatic isocyanate usually has higher mechanical strength than that from aliphatic isocyanate due to the presence of rigid aromatic ring (Rahman et al., 2019). However, aromatic polyurethane generally has poorer resistance to ultraviolet irradiation, resulting in yellow and degradation of PU (Rosu et al., 2009). For aromatic isocyanates, MDI polyurethane usually has higher mechanical strength and modulus than TDI polyurethane because the molecular structure of MDI is more orderly which promotes the crystallization of the polymer (Fink, 2013).

2.3.2.2.2. Polyols. Oligomer polyols such as polyether and polyester constitute the soft segment, which accounts for a major part of polyurethane. The properties of ammonia prepared by different oligomer polyols and diisocyanate are different. The strength, oil resistance, and thermal oxidation stability of polyester polyurethane are higher than those of polyether polyurethane, but the hydrolysis resistance is worse than that of polyether polyurethane (Das and Mahanwar, 2020). The commonly used polyols for PU synthesis include PEG, PPG, and PTMEG, and the chemical structure of these polyols are shown in Fig. 26.

2.3.2.2.3. Other additives. In addition to the isocyanates and polyols, other additives such as catalysts, compatibilizers, chain extenders, and crosslinkers. The chemical structures of some additives are shown in Fig. 27 catalyst is used to accelerate the chemical reaction between isocyanates and polyols, and the commonly used catalyst for PU is dibutyltin dilaurate (DBTDL) and triethylamine (TEA). Compatibilizers can improve the compatibility between PU and asphalt, and one of the most used compatibilizers is maleic anhydride (MAH). Chain extenders and crosslinkers play an important role in determining the performance of PU because they affect the hard segments and soft segments of PU. The most used chain extender and crosslinker are 1,4-butanediol (BDO) and 4,4′-methylenebis (MOCA).

2.3.2.3. Preparation methods and modification mechanism:. The preparation method of PU can be divided into two main types, chemical blending, and physical blending. For chemical blending, PU precursor/prepolymer is added to asphalt for blending. In this situation, due to the high activity of NCO groups in the PU precursor/prepolymer, the free NCO groups will react with the active atoms such as –OH groups in the asphaltenes and form a strong chemical bond between PU and asphalt

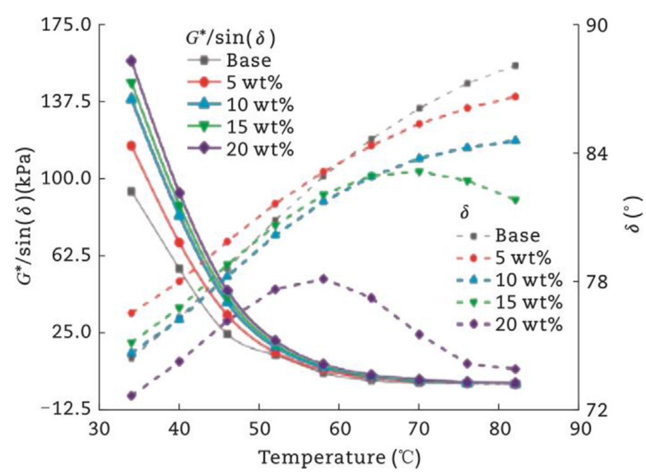


Fig. 30. Temperature sweep test results of binders containing various contents of PU (Zhang et al., 2023d).

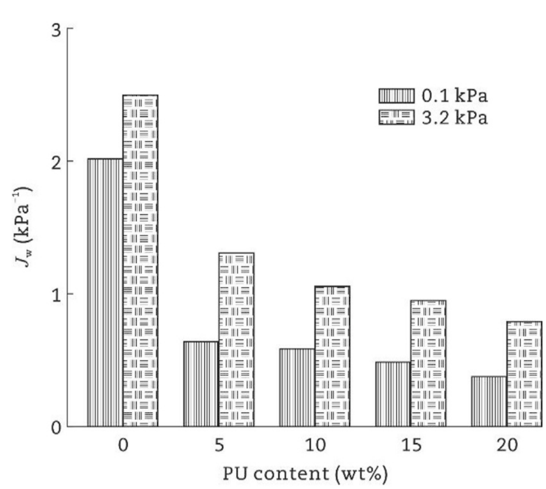


Fig. 31. J_{nr} values of various asphalt systems at different stress levels (Zhang et al., 2023d).

(Sun et al., 2018c; Li et al., 2022c). Hence, the properties of asphalt are greatly enhanced. The modification mechanism of PU precursor/prepolymer is showed in Figs. 28 and 29. The other method is adding PU elastomer for physical blending, which is similar to traditional asphalt modification (Zhang et al., 2021f).

2.3.2.4. Performance of PU modified asphalt

2.3.2.4.1. High-temperature performance. Previous results have shown that PU can significantly improve the high-temperature performance of asphalt. Xia et al. (2016) performed a frequency sweep test on PU-modified asphalt with PU content from 0 to 40%. The Master curve constructed using the CAM model indicated that at lower frequencies, 30 % PU-modified asphalt presented the highest values of shear modulus, showing that 30% PU has the best effects on the high-temperature performance of asphalt. Recently, Zhang et al. (2023d) conducted the temperature sweep test and multiple stress creep recovery (MSCR) test on the PU modified asphalt with different PU content ranging from 0 to 20%. The results showed that $G^*/\sin(\delta)$ values increased and J_{nr} values decreased with the increase of PU content as shown in Figs. 30 and 31, which indicated that PU can effectively enhance the high-temperature performance of asphalt. In addition, the MD simulation results also verified the experimental results.

2.3.2.4.2. Low-temperature performance. In previous studies, the bending beam rheology (BBR) test and differential scanning calorimeter (DSC) analysis were used to evaluate the low-temperature performance of asphalt. The results of most studies showed that asphalt's low-temperature performance was improved with the addition of PU. However, this improvement decreased when the high PU content was used. Fig. 32 presents the BBR test results of PU-modified asphalt containing different amounts of PU, the creep stiffness (S) had a decreasing trend and then increased with the increase of PU concentration. The Improvements in the low-temperature performance of PU-modified asphalt were stopped when the PU concentration exceeded 15%. Fig. 33 exhibits the results of DSC analysis of PU-modified asphalt with different PU content, which also showed similar results to the BBR test. The glass transition temperature (T_g) of PU-modified asphalt increased first and then decreased with increasing PU content.

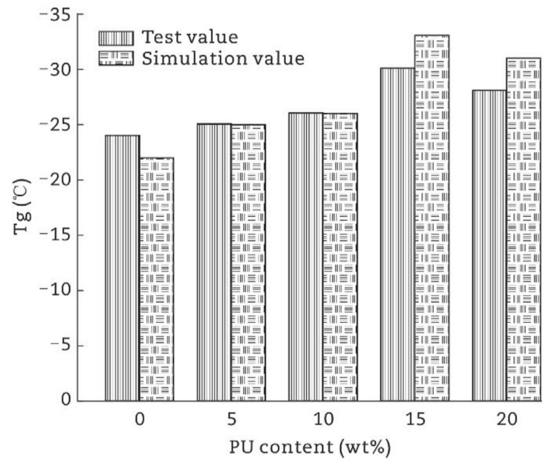


Fig. 33. Experimental and simulated T_g results (Zhang et al., 2023d).

2.3.3. Epoxy asphalt

Epoxy asphalt (EA) is a composite material consisting of epoxy resin, curing agent, and base asphalt (Xiao et al., 2019; Luo et al., 2022). As shown in Fig. 34, the epoxy resin undergoes an irreversible curing reaction with the curing agent to form a two-phase system with the epoxy resin as the continuous phase and the asphalt as the dispersed phase, thus fundamentally changing the inherent thermoplastic behavior of the asphalt (Yu et al., 2016a; Xu et al., 2020c; Sun et al., 2022a). As a result, EA exhibits excellent mechanical properties, deformation resistance, and corrosion resistance (Ai et al., 2017; Liu et al., 2018b).

2.3.3.1. Research and development history. The development of EA can be dated back to the 1950s. The effects of heavy aircraft wheel loads and fuel spills led to permanent deformation, potholes, and other defects in airport pavements. In order to solve this dilemma, Shell Oil Company developed an EPON epoxy asphalt, but there were deficiencies such as incomplete curing and poor performance stability (Simpson et al., 1960). Consequently, to improve the curing effect and performance stability of EA, researchers began to improve the selection and utilization of curing agents. Novel curing agents such as anhydrides, amines, and their derivatives were successively used to improve the reactivity and compatibility between epoxy resin and asphalt, and the performance of the material after curing was enhanced (Hijikata and Sakaguchi, 1982; Roberts, 1982). In the research and development of EA, the most representative products are from the ChemCo Systems Co., Ltd. in the United States and TAF Corporation in Japan. ChemCo Systems invented a novel EA material utilizing a pioneering two-component method, in which component A was a bisphenol-A epoxy resin and component B consisted of base asphalt, curing agent, and other additives. Meanwhile, the product was easily used by simply mixing components A and B according to the specified ratios after heating them to (87 ± 5) °C and (128 ± 5) °C, respectively (Apostolidis et al., 2019; Chen et al., 2020a). In contrast, the EA produced by TAF consisted of three components. In particular, component A was the base asphalt, component B was the epoxy resin, and component C was the curing agent. Moreover, the TAF epoxy asphalt required heating component A to 150 °C and components B and C to 60 °C for application, which was quite different from ChemCo Systems (Zhu, 2013). At present, these two products have been widely used in bridge deck pavement in many countries around the world.

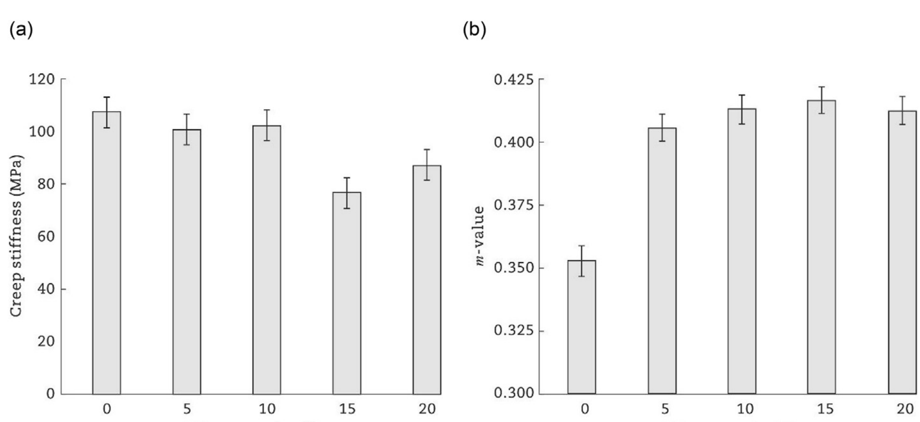


Fig. 32. BBR test results of asphalt samples at −12 °C. (a) Stiffness. (b) *m*-value (Zhang et al., 2023d).

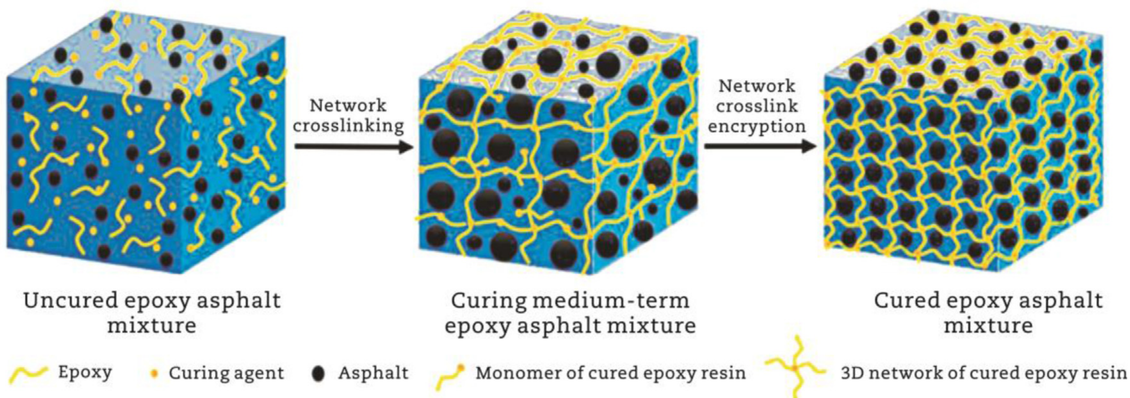


Fig. 34. Curing cross-linking process of EA (Xu et al., 2020c).

The research on EA in China began in the 1990s. Although imported EA had excellent properties, its high price was prohibitive and not conducive to the promotion in China (Jamshidi et al., 2022; Sun et al., 2023a). Hence, scholars were committed to the research and development of domestic EA, and Southeast University was one of the earliest institutions to conduct the investigation. Huang et al. (2020) and his colleagues developed various domestic EA products to facilitate the localization of EA applications. Additionally, the domestic EA generally lacks compatibility, poor toughness, and other deficiencies. The researchers used asphalt maleic anhydride, hyperbranched polymer grafting, composite modification, and other methods to optimize its performance. The flexibility, storage stability, abrasion resistance, and corrosion resistance stability of EA were further improved (Kang et al., 2015; Xu et al., 2016; Zhang et al., 2021e).

2.3.3.2. Application status. The epoxy asphalt mixture (EAM) is prepared using EA and aggregates and has significantly enhanced high-temperature stability, water stability, and fatigue resistance compared to ordinary pavement asphalt mixtures (Xiao et al., 2013; Apostolidis et al., 2020; Sun et al., 2023b). The EAM was used in the orthotropic steel deck pavement of the San Mateo Hayward Bridge in the United States in 1967, which was the first time the EAM was used in a physical project. Its excellent service performance quickly attracted attention and was subsequently widely used in countries such as the United States, Netherlands, Canada, and Australia (Lu and Bors, 2015). However, due to the high cost of EAM, their application scenarios are limited to special pavements such as steel bridge decks and airport pavements (Jamshidi et al., 2023; Sun et al., 2023c).

Although the application research in EAM bridge deck pavement started relatively late in China, with the rapid development of the economy, the demand for transportation infrastructure increased dramatically. Large-scale construction also accumulated abundant experience and developed EAM pavement compatible with China's climate. EAM was first used in China in 2001 on the Nanjing Yangtze River Bridge, which has been in service for 22 years and still exhibits favorable performance (Lu and Bors, 2015; Luo et al., 2015). After that, the EAM was successively applied to the Runyang Yangtze River Bridge, Jiangyin Yangtze River Bridge, Zhejiang Zhoushan Taoyao Gate Bridge, and other national key projects (Huang et al., 2020; Xiang and Xiao, 2020; Luo et al., 2022). From the service condition and construction quality inspection, the effect of EAM bridge deck pavement was satisfactory, symbolizing the growing maturity of this technology. In 2007, the domestic EAM was first paved on the Tianjin Guotai Bridge. After that, it was also used in the Wuhan Tianxingzhou Yangtze River Bridge. The test results demonstrated that, on the basis of all technical indicators reaching the international level, the domestic EAM has the significant advantages of a wide construction temperature range and lower price (Zhang, 2014).

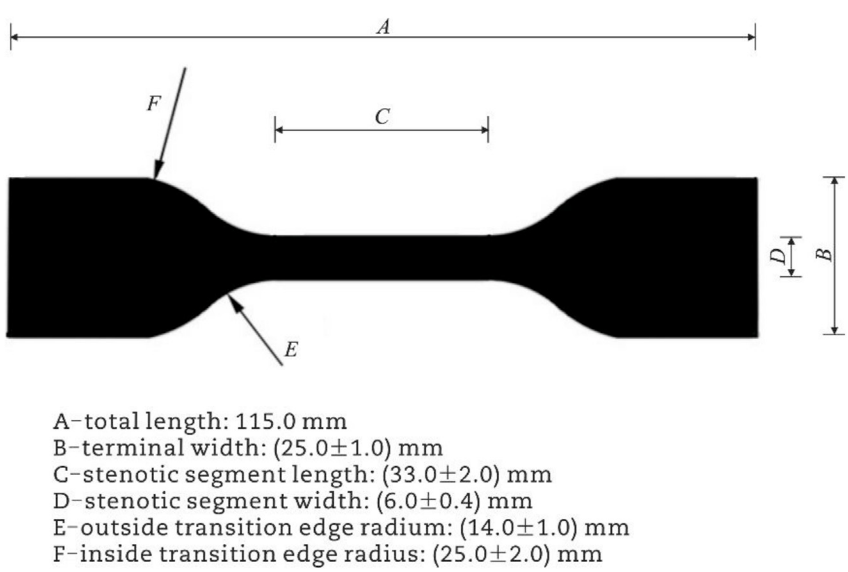


Fig. 35. Dogbone-shaped tensile specimen of EA.

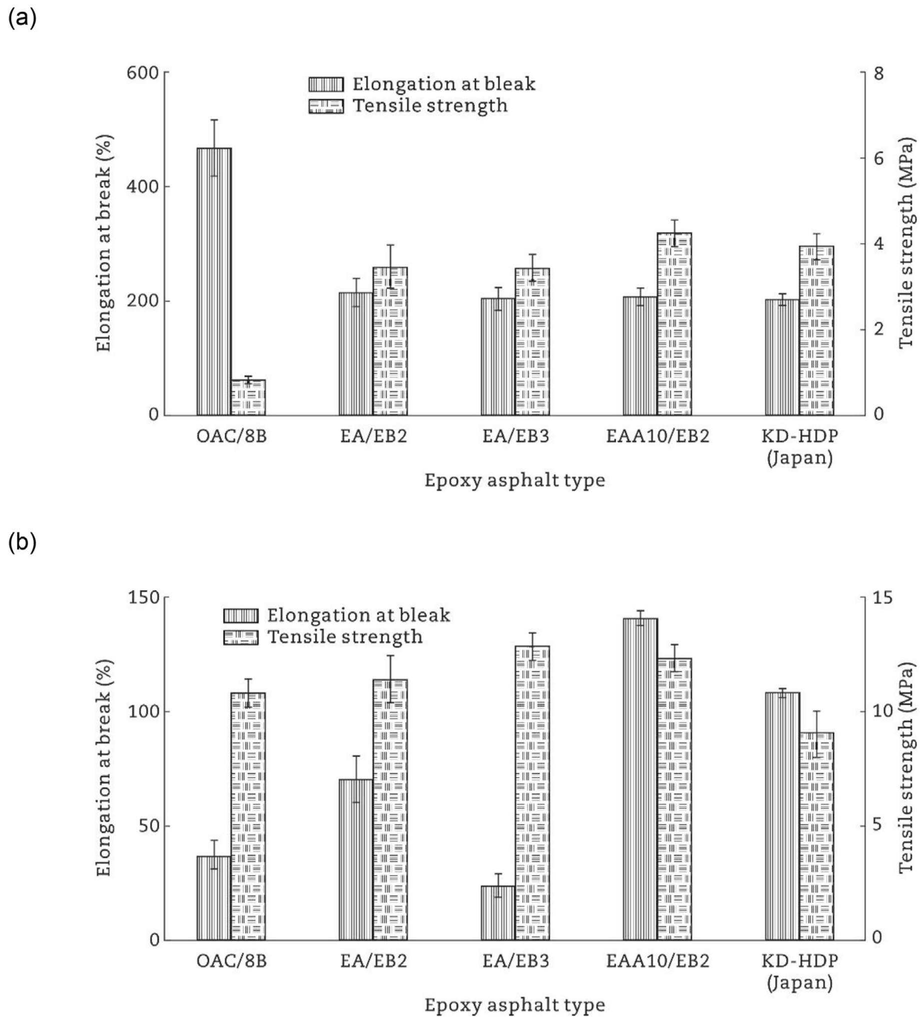


Fig. 36. Tensile test results of EA. (a) 23 °C. (b) −10 °C.

The transportation industry is one of the major consumers of non-renewable resources and emitters of greenhouse gases. Road infrastructure consumes large quantities of mineral materials throughout its life cycle of construction, operation, and maintenance (Marinković et al., 2010; Peng et al., 2015). With the primary strategic goal of carbon neutrality and carbon peaking in China, it has become a significant challenge to seek ideal substitutes for natural mineral materials, promote low-carbon and green transportation transformation, and comprehensively improve the utilization efficiency of solid waste resources. In this context, the team of Wei Huang developed a variety of new EA systems suitable for pavement engineering, including "OAC curing agent and 8B epoxy resin", "EA curing agent and EB2/EB3 epoxy resin" and "EAA10 curing agent and EB2 epoxy resin" system. While promoting the application of EA materials in highway pavement, they also actively push the reuse of solid waste resources such as steel slag and RAP materials, which achieves the replacement of more than 60% of solid waste materials in the aggregates of new pavements. The outcomes are relevant to facilitating long-life, low-carbon pavements and sustainability in transportation infrastructure development.

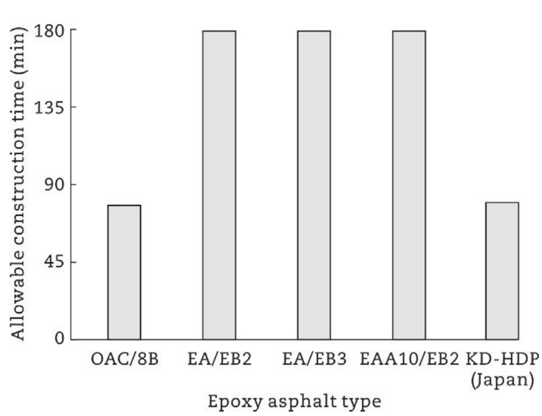


Fig. 37. Construction allowable time for different EA.

2.3.3.3. *Latest domestic epoxy material properties.*

(1) Tensile property

The thermosetting characteristic of EA leads to the difficulty of evaluating its physical properties by the traditional softening point,

Table 3
Pavement performance data for different EAM

Mixture type	Pavement performance indicator			
	Marshall stability (kN)	Dynamic stability (times/mm)	Maximum bending strain (με)	Freeze-thaw splitting strength ratio (%)
EA/EB2	75.8	> 63,000	2652	92.5
EA/EB3	81.1	> 63,000	2732	88.7
EAA10/EB2	> 100	> 63,000	3178	89.9
KD-HDP (Japan)	50.8	31,500	2803	89.1

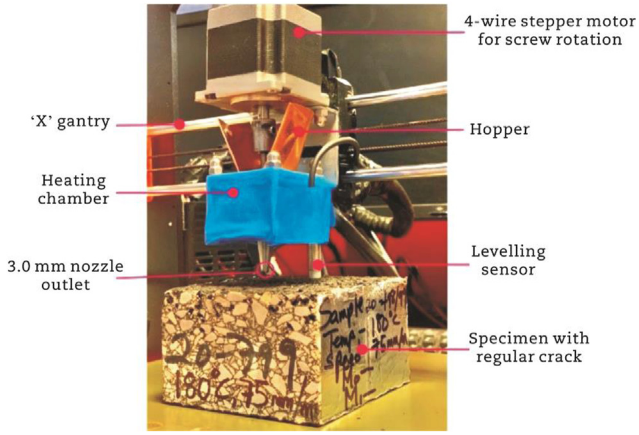


Fig. 38. Crack repair equipment based on 3D printing (Awuah and Garcia-Hernández, 2022; Liu et al., 2022e).

needle penetration, and ductility tests (Zhang et al., 2021e). As a result, dogbone-shaped specimens, as shown in Fig. 35, are usually fabricated according to ASTM D638 to evaluate the mechanical properties of EA using two indexes, tensile strength and elongation at break, obtained from tensile tests (ASTM, 2014). The tensile test results of domestic EA are shown in Fig. 36. The mechanical strength of OAC/8B epoxy asphalt is insufficient at room temperature. In contrast, the EA/EB2, EA/EB3, and EAA10/EB2 epoxy asphalt are comparable to those of KD-HDP epoxy asphalt. Under low-temperature conditions, the tensile properties of EAA10/EB2 epoxy asphalt are significantly better than those of KD-HDP, indicating that it has satisfactory low-temperature flexibility and high potential for application.

(2) Viscosity characteristics

Viscosity tests were used to evaluate the construction allowable time for EA. Adequate construction allowable time plays a vital role in the successful preparation, transportation, paving, and compaction of the mixture (Luo et al., 2022; Sun et al., 2022b). The curing reaction causes the viscosity of EA to gradually increase with time. In order to ensure that the pavement construction has enough time, the construction allowable time of EA was stipulated. Strategic highway research program (SHRP) protocols require that the viscosity of the asphalt binder used for construction should be ≤3000 mPa·s and that the construction allowable time should be ≥45 min (Asphalt Institute, 2003). Fig. 37 illustrates the results of the construction allowable time of the domestic EA developed by Wei Huang's team and compared with the KD-HDP epoxy asphalt from TAF, Japan (Huang et al., 2020). OAC/8B and KD-HDP epoxy asphalt have similar construction allowable times. In contrast, EA/EB2, EA/EB3, and EAA10/EB2 epoxy asphalt have significantly longer construction allowable times, which are all higher than 180 min. This can effectively avoid the construction organization chaos caused by the short construction allowable time and ensure the quality of pavement construction.

(3) Mixture pavement performance

The pavement performance of asphalt mixtures determines the service quality of the constructed pavement. Table 3 lists the pavement performance data of the latest domestic EAMs (40 wt% epoxy content) and compares them with the Japanese product. Obviously, compared with KD-HDP EAM, domestic EAM had significantly improved mechanical strength and high-temperature rutting resistance. The highlight is that the low-temperature performance of the EAA10/EB2 EAM was significantly improved, with the maximum bending strain reaching 3178 με, which was a big breakthrough. The performance of the domestic EAM improved, and the cost dropped significantly, laying the foundation for developing long-life pavements in China.

2.4. *New pavement maintenance materials*

2.4.1. *High performance preventive maintenance technology for highways*

Preventive maintenance of highway pavement is a proactive maintenance technology adopted to prevent the occurrence or expansion of minor diseases, slow down the degradation of pavement performance, and improve service functions. At present, high performance pavement preventive maintenance technologies that are widely studied and applied include crack filling or crack sealing, fog seal, chip seal and fiber chip seal, slurry seal and micro-surfacing, thin overlays and ultra-thin overlays, etc.

2.4.1.1. Crack filling or crack sealing. Cracks are one of the common diseases on pavement, and crack treatment can seal the cracks and prevent rainwater from seeping into the interior of the pavement structure. Timely and effective crack treatment can prevent further damage to the pavement and extend its service life, including technical means such as crack filling, crack sealing and crack banding. Existing research mainly improves the effectiveness of pavement crack treatment by developing high performance crack treatment materials and optimizing construction methods. The types of crack treatment materials mainly include asphalt and polymer, which can be divided into room temperature and heating type based on their construction temperature. Heating type crack filling or sealing materials mainly include modified asphalt prepared using SBS, rubber powder, and polyurethane (Gong et al., 2022), room temperature type includes modified emulsified asphalt, as well as polymers such as epoxy resin, polyurethane, polysiloxane, and polysulfide (Fang et al., 2021). Normally, the room temperature type has better permeability and is less affected by the environment during construction. Polymer crack filling or sealing materials exhibit better mechanical strength, adhesion, and impermeability. In addition, to improve the repeated repair ability of crack filling or sealing materials, crack filling or sealing materials containing self-healing microcapsules were prepared (Tan et al., 2020b), and

Fig. 39. Field application of fog seal technology (Xu et al., 2022a).

the repeated repair ability index was proposed. However, in the existing industry standards in China, the performance evaluation indicators for road crack filling or sealing materials are still relatively single, and their performance evaluation system needs further optimization.

In terms of crack repair technology, relevant research results (Mazumder et al., 2019) indicate that the average effect of slot filling is 37% higher than that of non slot filling, which has higher economic benefits. With the continuous development of automation and intelligence technology, rapid and non-destructive automated crack treatment technology is the future development trend. 3D laser scanning and 3D printing technology, as well as intelligent optimization algorithms, have been studied and applied in road crack identification, automated crack filling, and path optimization (Awuah and Garcia-Hernández, 2022; Liu et al., 2022e). The crack repair equipment based on 3D printing is shown in Fig. 38. Compared with crack filling or crack sealing, crack banding is simple in operation, efficient in construction, and can avoid secondary diseases such as side joints and edge gnawing caused by slotting. It is gradually being promoted and applied in China. However, the crack banding technology also has the possibility of easy detachment, internal detachment, and causing jumping. There is relatively little research and application on it, and the crack banding technology needs further in-depth research.

2.4.1.2. Fog seal. The fog seal is formed by using specialized high-pressure spraying equipment to spray the fog seal material on the asphalt pavement, which plays a role in waterproofing, sealing cracks, restoring and protecting aged asphalt, consolidating loose aggregates, and updating the appearance of the pavement. The field application of this technology is shown in Fig. 39. With the development of fog seal technology, on the one hand, polymer modifiers (Chen et al., 2020b; 2021c; 2022c), penetrating agents (Gao et al., 2022), reducing agents (Feng et al., 2020), and fine aggregates (Tian et al., 2021; Ma et al., 2023b) are added to improve their bonding, waterproofing, permeability, durability, and anti-slip performance. At the same time, TiO_2 based photocatalytic degradation materials (He et al., 2020; Zhang et al., 2021d) low freezing point fillers (Chang et al., 2021; Zhu et al., 2022a), phase change materials, and self-healing microcapsules are added to endow the fog seal with functions such as purifying automotive exhaust, anti-freezing, snow melting, and self-healing. Waterborne resin polymers such as waterborne epoxy resin, waterborne polyurethane and waterborne acrylate can effectively improve the adhesion, strength and anti-aging properties of emulsified asphalt fog seal materials (Liu et al., 2021e; Xu et al., 2022a; Chen et al., 2022c), and silicone resin can improve the permeability, water stability and other properties of fog seal materials (Gao et al., 2022). Compared with the fog seal, the sand fog seal exhibits better anti-slip and wear resistance properties (Tian et al., 2021; Ma et al., 2023b). The influence of the type, particle size, grading, and dosage of anti-slip granular materials on the anti-slip and other properties of the sand fog seal has been studied. Some testing methods and evaluation indicators for the anti-slip and durability properties of the sand fog seal have been proposed, but there is still a lack of unified technical requirements for the adhesion and durability of the fog seal material, the design method for the composition of fog seal and sand fog seal.

In addition, the application of photocatalysis materials such as TiO_2 in fog seal can achieve the purification of automotive exhaust, but the compatibility between photocatalysis materials and binders (He et al., 2020; Zhang et al., 2021d), as well as the greater realization of their purification effect, require further research. At the same time, slow-release anticoagulant ice materials and microencapsulated snow melting agents have been developed and applied in fog seal (Chang et al., 2021; Zhu et al., 2022a), but the durability of the anti-freezing and snow melting effects of fog seal needs to be further clarified.

2.4.1.3. Chip seal and fiber chip seal. Chip seal is formed by spraying asphalt binder on the pavement and immediately spreading a certain particle size of coarse aggregate, which is then compacted. It can improve the skid resistance, waterproofing, and impermeability of the pavement. In existing research, improving the performance and quality of chip seal mainly involves optimizing the composition of binder (Rahman et al., 2020; Zhang et al., 2021g; Fu et al., 2022b), regulating the particle size and coverage of crushed stone, adding fibers and adjusting its composition structure (Vargas-Nordcbeck and Jalali, 2020; Nair and McGhee, 2022). At the same time, the application of recycled resources (Wei et al., 2020; Shamsaei et al., 2023) such as steel slag and building recycled aggregates in chip seal, as well as functional chip seal with low noise and degradation of automotive exhaust (Cao et al., 2021a), has also been studied. In order to improve the problems of bleeding, aggregate peeling, and insufficient bonding performance in the chip seal, rubber powder or waterborne epoxy resin modified emulsified asphalt have been developed (Rahman et al., 2020; Zhang et al., 2021g; Fu et al., 2022b). Among them, the interlayer bonding and anti-stripping performance of waterborne epoxy resin modified emulsified asphalt chip seal is 2–3 times higher than that of other chip seals, demonstrating better comprehensive

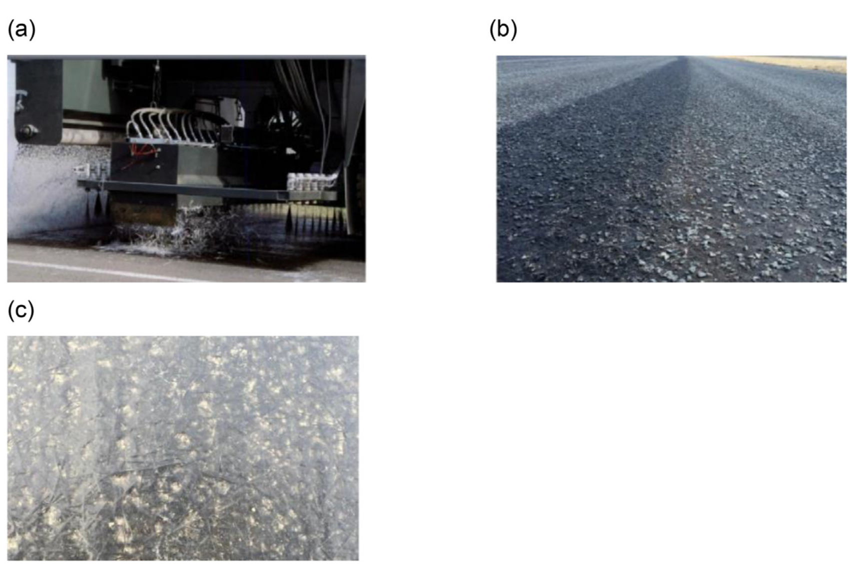


Fig. 40. Field application of fiber chip seal technology. (a) Paving construction. (b) Curing. (c) Open to traffic (Vargas-Nordcbeck and Jalali, 2020; Nair and McGhee, 2022).

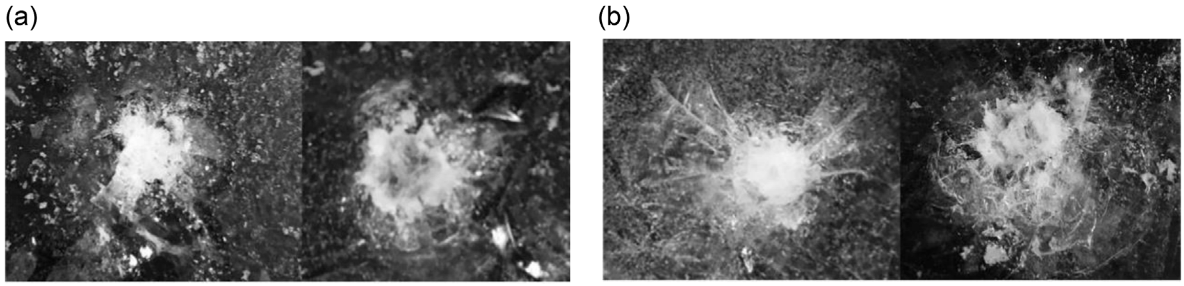


Fig. 41. Anti-icing performance test results. (a) Ordinary emulsified asphalt micro-surfacing. (b) Waterborne epoxy resin modified hydrophobic emulsified asphalt micro-surfacing (Han et al., 2020).

performance. In addition, researchers developed road energy absorbing materials with energy absorption characteristics and buffering effects (Chen et al., 2022a; 2023c), and their application in pavement preventive maintenance technology has also been explored to some extent.

Fiber chip seal is a composite structure composed of "asphalt binder-fiber-asphalt binder", which is sprayed synchronously with asphalt binder and fibers. Then, coarse aggregate is immediately spread, and after rolling, a new wear layer or stress absorption layer is formed. The field application of this technology is shown in Fig. 40. The relevant research results show that (Vargas-Nordcbeck and Jalali, 2020; Nair and McGhee, 2022) compared with ordinary chip seal, its interlayer adhesion, wear resistance, crack resistance, and other properties are improved by more than 30%. The fibers fully play the roles of adsorption, stability, reinforcement, crack resistance, and toughening. In addition to single-layer chip seal, some research has also been conducted on double-layer chip seal and "asphalt binder-crushed stone-asphalt binder" chip seal. At present, chip seal and fiber chip seal are still mainly suitable for lower level highway preventive maintenance, and their performance requirements and applications in higher level pavement preventive maintenance need further research.

2.4.1.4. Slurry seal and micro-surfacing. Micro-surfacing is developed on the basis of slurry seal, using specialized mechanical equipment to mix modified emulsified asphalt, coarse and fine aggregates, fillers, water, and additives according to the design ratio to form a slurry mixture and spread it on the old pavement. It is a type of preventive maintenance seal that can quickly open up traffic, improve the performance of pavement permeability, skid resistance, wear resistance, and repair rutting diseases. At the same time, it has higher requirements for raw materials and construction technology, and is also suitable for higher level pavement preventive maintenance. At present, relevant research mainly focuses on optimizing the road performance and noise reduction effect of micro-surfacing by using high performance modified emulsified asphalt (Alavi et al., 2020; Liu et al., 2021d; Huang et al., 2023), regulating aggregate gradation (Chen et al., 2021d), adding rubber powder, fibers (Luo et al., 2019) or functional materials (Han et al., 2020; Sun et al., 2020; Meng et al., 2022a; Zhang et al., 2022a; Li et al., 2022b), and endowing it with functions such as anti-freezing, snow melting, cooling, and purifying automobile exhaust. Natural asphalt, rock asphalt, and waterborne epoxy resin can effectively improve the adhesion, mechanical strength, high and low temperature, water stability, fatigue, and other properties of emulsified asphalt, thereby improving the road performance of micro-surfacing. Among them, waterborne epoxy resin modified emulsified asphalt micro-surfacing has better comprehensive road performance (Alavi et al., 2020; Liu et al., 2021d; Huang et al., 2023), and the WTAT after immersion 1 h and 6 d can be lower than 200 g/m^2 and 400 g/m^2, and the PLD can be lower than 2%.

The current relevant research mainly adopts measures such as optimizing aggregate gradation, adding elastic materials such as rubber powder and fiber to improve the problem of high noise at the micro-surfacing that affects driving comfort (Luo et al., 2019; Chen et al., 2021d). Usually, as the surface structure and texture depth of the micro-surfacing increase, the noise value will increase. The noise reduction effect of obtaining a suitable surface structure and macroscopic texture for micro-surfacing by adjusting the mineral aggregate gradation is more excellent than that of adding rubber powder and fiber. The addition of rubber powder and fiber can improve the damping and vibration reduction of micro-surfacing, thereby achieving noise reduction effects. However, the addition of rubber powder has a certain negative impact on the wear resistance of micro-surfacing. Fiber can form a stable network structure inside the slurry mixture, which plays a reinforcing role and can enhance the performance of micro-surfacing. Currently, many studies have been conducted on noise reduction micro-surfacing and fiber micro-surfacing, but there is still a lack of unified noise testing and evaluation methods, as well as technical requirements for fiber and fiber micro-surfacing.

Micro-surfacing, as a commonly used and mature pavement preventive maintenance technology, is often used as a functional carrier to achieve pavement ice melting and snow melting (Han et al., 2020; Meng et al., 2022a), cooling, and purifying automobile exhaust (Sun et al., 2020; Zhang et al., 2022a; Li et al., 2022b). The focus of future research is to incorporate slow-release ice and snow melting agents, low freezing point fillers, hydrophobic materials, phase change materials, and nano-TiO_2 photocatalytic materials into micro-surfacing to efficiently achieve their functionality while reducing their impact on road performance. In addition, the feasibility of using waste resources such as steel slag (Cui et al., 2020; Apaza et al., 2021), recycled asphalt mixture (Wang and Shen, 2020), coal gangue (Ziari et al., 2022), and waste glass (Cheng et al., 2021) in micro-surfacing has been verified. The superior surface structure, texture, and wear resistance of steel slag can improve the anti-slip and wear resistance of micro-surfacing. The color micro-surfacing with functions of beautifying the environment and guiding traffic (Xu et al., 2023), as well as the composite seal formed by adding micro-surfacing on chip seal or fiber chip seal, have also been studied to some extent (Chen et al., 2021b). Anti-icing performance test results are shown in Fig. 41.

2.4.1.5. Thin overlays and ultra-thin overlays. The current industry standard in China uses 25 mm as the boundary thickness between "thin" and "ultra-thin". The thin overlays is an asphalt overlays with a thickness of 25–40 mm. The thickness of the ultra-thin overlays is less than 25 mm. They can prevent or repair some pavement diseases and improve the skid resistance and other performance of the pavement. Under the premise of meeting the performance requirements, the ultra-thin overlays has a thinner thickness, can save more resources, and has more significant economic benefits. Its research and application are more extensive. The current research mainly focuses on the optimization of binder performance (Li et al., 2021i; Wang et al., 2022k, n), grading design (Yu et al., 2020, 2022a; Ai et al., 2022; Jiang et al., 2022), mechanical analysis, and interlayer optimization (Kim et al., 2021; Zhao et al., 2023b) to improve the pavement performance of the overlays, as well as its drainage and noise reduction functions. Due to the thinning of the structural thickness, the stress

Fig. 42. Field application of cold mix cold lay ultra-thin overlays technology. (a) Original pavement milling. (b) Mixture production. (c) Paving construction. (d) Paving surface details. (e) Roller construction. (f) Rolled surface details. (g) Pavement after six months. (h) Pavement details after six months (Yu et al., 2021b).

generated inside the structural layer under load is relatively greater, making it more prone to diseases such as peeling, cracking, and displacement. Especially for the overlays with high porosity such as OGFC-10 and Nova-Chip, higher requirements are put forward for the viscoelasticity, water stability, and other properties of the binder. Commonly used binders include SBS-modified asphalt, rubber powder modified asphalt, and high viscosity modified asphalt. Currently, the Marshall stability, freeze-thaw splitting strength ratio, and dynamic stability of the overlay mixture can reach 15 kN, 10,000 cycles/mm, and 90%, respectively (Yu et al., 2020, 2022a; Li et al., 2021i; Wang et al., 2022n; Ai et al., 2022). In addition to the hot mix asphalt mixture overlay, polyurethane or waterborne epoxy resin modified emulsified asphalt cold mix cold lay ultra-thin overlays that can be mixed, spread, and rolled at room temperature has also been studied and applied (Fu et al., 2021; Li et al., 2022j, k; Wang et al., 2022h; Yang et al., 2020c, 2021a; Yu et al., 2021b). The performance that existing cold mix cold lay ultra-thin overlays can achieve can be comparable to that of hot mix asphalt mixture ultra-thin overlays such as AC-10 and Nova-Chip. The field application of this technology can be seen in Fig. 42. There are significant differences in the performance of different grading types of the overlays, and suitable grading types can be selected according to different functional needs. The relevant research results show that adjusting the mineral material grading can effectively ensure the high-temperature stability, low-temperature crack resistance, and fatigue performance of thin and ultra-thin overlays, as well as better surface performance such as skid resistance, wear resistance, and drainage and noise reduction.

Insufficient interlayer bonding can easily cause displacement and swelling diseases of thin and ultra-thin overlays, leading to premature failure. Existing research mainly improves the quality of thin and ultra-thin overlays by optimizing interlayer treatment methods, optimizing interlayer bonding materials, and construction techniques. Different overlay types and structural combinations cause significant differences in interlayer contact and stress conditions. It is necessary to choose interlayer bonding materials that match the type and performance of the overlay mixture. In addition, the application of fiber reinforced thin overlay mixtures (Zhao et al., 2022a) and regenerated resources such as steel slag and barium slag (Pazzini et al., 2023; Skaf et al., 2023) in thin overlay mixtures has also been studied to some extent.

2.4.1.6. Development trend of preventive maintenance. Preventive maintenance technology plays an important role in maintaining the condition and service level of the pavement, extending the service life of the pavement, and reducing the maintenance cost of the pavement life cycle. At the same time, preventive maintenance technology has gradually become more safe, reliable, economically applicable, convenient for construction, and green for environmental protection. The main development trends are as follows. (1) Modified emulsified asphalt is widely used in various preventive maintenance techniques. How to achieve intelligent design and selection of modified emulsified asphalt based on different application scenarios and working conditions, according to functional requirements, so as to further improve the quality and engineering applicability of preventive maintenance technology. (2) How to innovate traditional preventive maintenance technology, so that it can significantly increase the bearing capacity of the original road structure while improving the surface function of the pavement and enhancing its own durability, thereby further extending the service life of the road. (3)

Preventive maintenance technology is often used as a carrier for pavement to achieve functions such as purifying automobile exhaust and melting ice and snow. How to adjust and prepare more efficient functional materials to reduce the impact on the road performance of preventive maintenance technology while efficiently achieving and maintaining functionality.

2.4.2. *Ultra-thin wearing course*

With the rapid economic growth of China, the scale of road construction and maintenance is also expanding. The pavement structure is a multi-layer system, the upper-most layer is called the wearing course which directly contacts with UV radiation, oxygen and vehicle loading. Within 3–5 years of operation, the wearing course deteriorates quickly, leading to problems like cracking, raveling and insufficient skid-resistance which greatly impact the driving comfort and safety (Liu et al., 2019a; Zhang et al., 2021c). In fact, the service life of wearing course is less than 10 years, maintenance is required to extend its service life in this situation (Hu et al., 2019).

Facing these problems, researchers and managers gradually adopt preventive maintenance techniques to prolong the service life of asphalt pavement. Previous research has shown that when the pavement reaches 75% of its design life and its mechanical performance declines by approximately 40%, it presents the most proper time for preventive maintenance. It is believed that postponing maintenance beyond this point results in an overhaul cost that is 4–5 times higher than the cost of achieving the same pavement condition through preventive maintenance. Preventive maintenance methods include slurry seal, micro-surfacing, fog seal, and ultra-thin asphalt overlay (Liu, 2014). Recently, the ultra-thin wearing course (UTWC) is widely used as an efficient preventive maintenance method with good mechanical properties and long service life.

UTWC is a new type of surface functional layer with thickness of 15–30 mm. UTWC has proven its efficiency in extending the service life of asphalt pavements. This technique swiftly solves mild issues such as rutting, cracking, and raveling, offering notable advantages in terms of enhancing pavement smoothness, skid resistance, and noise reduction. UTWC proves to be a cost-effective strategy when considering the life cycle analysis of pavements, primarily due to the reduction in thickness to approximately 1/3 to 1/2 of traditional wearing courses. Ultra-thin asphalt overlays result in a material cost reduction of 30%–40% and a decrease in energy consumption during pavement construction (Yu et al., 2020).

The wearing course had its origins in France in the 1970s and was subsequently adopted and popularized in Europe. In the 1970s and 1980s, the United States developed an OGFC to replace the traditional road surface-treatment technology, and further developed SMA-5. Since then, with the increasingly severe situation of highway maintenance and the increasing shortage of non-renewable resources such as asphalt and high-quality aggregate, the development and application of ultra-thin wearing course has continued progress, and gradually derived some new types such as SMA-10, Nova-Chip and GT-8 (Lou et al., 2021). UTWC can restore the functional performance of the road surface and delay the strength attenuation of the original pavement structure, which will become the best choice of preventive maintenance treatment for pavement in the future.

2.4.2.1. *Materials composition of UTWC.*

UTWC is a type of surface-functional layer that undergoes long-term and frequent vehicle loading. It also serves as a critical layer directly exposed to environment. As a result, there are typically stricter technical requirements for its material composition compared to conventional asphalt pavements, which are reflected in the selection of asphalt binder, aggregate, filler and additives.

2.4.2.1.1. Asphalt binder. The performance of UTWC pavement heavily depends on the quality of the asphalt binder. UTWC is prone to deformation under vehicle loads, resulting in higher tensile and shear stresses within the pavement structure compared to traditional asphalt pavement layers with a thickness of 4–5 cm. However, commonly-used virgin asphalt and modified asphalt often have low viscosity, which makes it challenging to provide adequate support to the aggregate skeleton. This limitation can significantly impact the performance and durability of UTWC pavement. It is necessary to use high-viscosity and high-elasticity asphalt binders to effectively restrain the course aggregate skeleton, ensuring overall mechanical and functional performance of the wearing course. In China, SBS-modified asphalt, high-viscosity, high-elastic modified asphalt, and crumb rubber modified asphalt can be used as binders for hot mix ultra-thin asphalt pavement (Liu et al., 2019c; Zhao et al., 2022b).

Scholars have conducted a series of research studies on the asphalt binder used in UTWC. Yu et al. (2020) prepare a high-viscosity asphalt binder used for UTWC and the binder exhibits great performance on elastic recovery, high temperature performance and dynamic viscosity. Liu et al. (2019a, c) employed various modifiers and prepare a high-viscosity asphalt for porous ultra-thin asphalt overlays. The results demonstrated the excellent performance of the asphalt binder and mixture. According to the research, it is prepared that a high-strength-modified asphalt binder for HWU-10 and explored its laboratory and field performance. Researchers used 60 °C dynamic

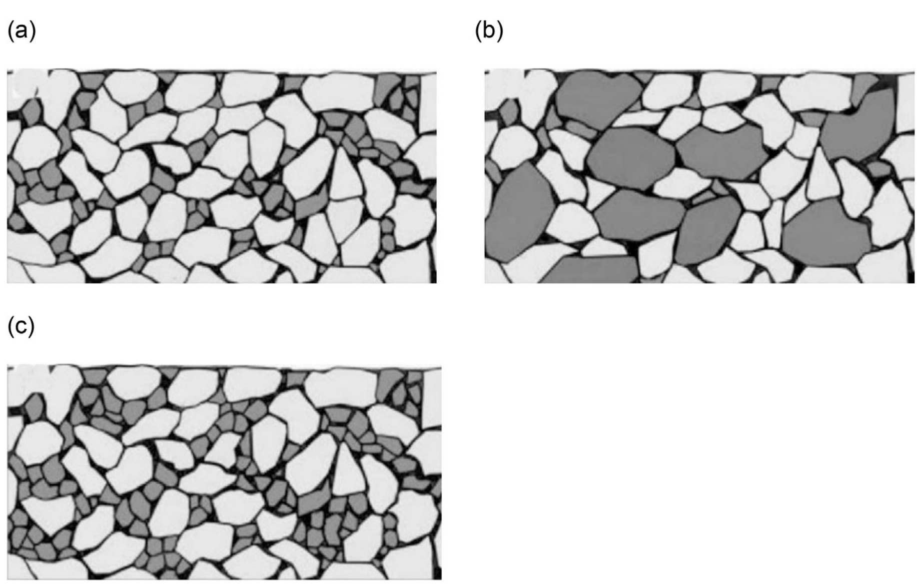


Fig. 43. Typical ultra-thin friction course structure. (a) SMA-10. (b) Nova-Chip. (c) GT-8.

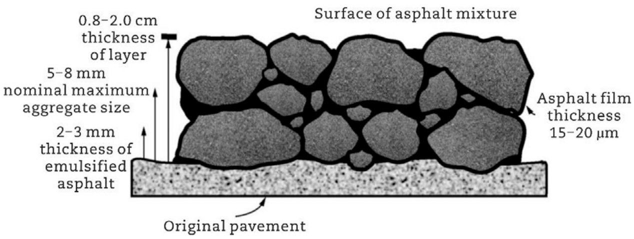


Fig. 44. High-toughness ultra-thin friction course (GT-8).

Table 4
Part of technical index of ultra-thin wearing course.

Technical index	SMA-10	Nova-Chip	GT-8
Gradation type	Dense-graded	Open-graded	Dense-graded
Marshall stability (kN)	≥6	≥6	≥8
Retained Marshall stability (%)	≥85	≥80	≥85
Tensile strength ratio (%)	≥80	≥85	≥85
Asphalt film thickness (mm)	–	≥9	15
Dynamic stability (cycles·mm^{-1})	≥3000	≥3000	≥5000
Pull strength (MPa)	–	–	≥0.4
Shear strength (MPa)	–	–	≥0.4

viscosity as a crucial parameter index for UTWC, which exhibits a strong correlation with the resistance to high temperature. Meanwhile, the binder is required to have high elasticity that can restore deformation and resist the shrinkage and expansion effect caused by high temperature (Qin et al., 2018; Li et al., 2019b).

2.4.2.1.2. Emulsified asphalt. In order to prevent delamination of the UTWC wearing course and ensure the continuity between the layers (Zuo et al., 2022), it is necessary to use high-viscosity emulsified asphalt between the layers. On the other hand, emulsified asphalt needs to have good fluidity and penetrate into the fine gaps of the original pavement to avoid water intrusion into the underlying bearing layers (Yu et al., 2020). Compared to traditional coatings, the design of the adhesive layer requires careful consideration of its enhanced shear resistance. Therefore, it is crucial to focus on the viscosity of its evaporative residues at high temperatures, such as dynamic viscosity at 60 °C and the softening point which ensures that no delamination or migration occurs under vehicle loads.

Zuo et al. (2022) added a certain proportion of high molecular polymers and latex to prepared emulsified asphalt and the interlayer shear and tensile strengths exceeding 0.4 MPa. Yu et al. (2020) prepared coupling SBS polymer modifier emulsified asphalt which has higher softening point (> 80 °C) and superior dynamic viscosity (> 20,000 Pa·s at 60 °C). The strong bonding effect between UTWC and the lower layer ensures the durability of the asphalt pavement.

2.4.2.1.3. Aggregates. The UTWC consists of coarse aggregate, fine aggregate and filler, which require a uniform texture and no other impurities. Previous studies have shown that the mechanical performance and functional performance of UTWC are greatly influenced by the choice of aggregates (Beyene et al., 2016). The properties of aggregate and filler influencing skid-resistance, noise reduction and high-temperature performance.

As the main factor in forming the skeleton of UTWC, the coarse aggregate must have sufficient strength. It is essential to consider the shape and angularity of coarse aggregate, as poorly shaped aggregate often indicate lower mechanical performance, subsequently affecting the skeleton strength of UTWC. It is advisable to choose high-quality basalt, diabase, or high-quality diorite aggregate with superior abrasion resistance and particle shape. As for the fine aggregate, it is recommended to use clean and inclusion-free mechanical sand or impact-breaking stone chips.

2.4.2.1.4. Additives. Some modifiers can improve the properties of asphalt binder and significantly enhance the mechanical properties of UTWC. Previous studies have shown that the use of SBS material and crumb rubber to prepare modified asphalt can improve the overall performance of the binder, thus strengthening the performance of high-temperature and noise reduction (Chen et al., 2019; Li et al., 2020a). Besides, materials such as Sasobit, polyethylene wax and SMC are applied to reduce the viscosity of asphalt at low temperature (Yu et al., 2016b), thereby reducing the energy consumption in the road construction process. It is noteworthy that some additives such as carbon fiber, basalt fiber, steel fiber and steel slag were used in the asphalt mixture (Nejad et al., 2014; Wan et al., 2018; Lou et al., 2021). Adding fiber in mixtures led to better properties under high-temperature.

2.4.2.2. Gradation design of UTWC. While ultra-thin wearing course technology has been widely used today, it faces certain technical limitations that hinder its broader adoption. Firstly, the minimal layer thickness leads to increased tensile stress at the bottom of ultra-thin coatings, rendering them more susceptible to fatigue cracking, stripping, and shoving. Besides, traditional open gradation or semi-open gradation in ultra-thin wearing course tend to raise concerns about clogging, resulting in reduced durability for drainage and noise reduction functions. To address the mentioned concerns, studies have aimed at enhancing the durability of ultra-thin layers, primarily by improving the bonding materials and optimizing gradation designs. The aggregate gradation significantly influences the road performance of UTWC. A stable skeleton structure, for instance, proves to be effective in enhancing skid-resistance and mechanical strength of UTWC (Xu et al., 2017b; Garcia-Gil et al., 2019). The key aspect of ultra-thin asphalt pavement structure design lies in the selection of gradation based on functional requirements. This article mainly introduces three common types of gradations used in UTWC: SMA-10, Nova-Chip, and GT-8, as shown in Fig. 43.

2.4.2.2.1. SMA-10. Stone mastic asphalt (SMA) is widely employed in pavement construction and maintenance to enhance the surface layer performance of UTWC. SMA exhibits excellent rutting resistance due to its stone-to-stone aggregate skeleton structure. Derived from SMA, SMA-10 is particularly renowned for its exceptional durability and resistance to rutting and cracking, making it the preferred choice for high-traffic areas and road surfaces that demand superior performance. SMA-10 employs a discontinuous dense-graded design method characterized by high content of coarse aggregates, substantial amount of mineral filler, and high asphalt content. The mineral powder, bonding with other materials, stabilizes the asphalt binder, forming a dense skeleton structure that enhances its strength and resilience. In SMA-10, coarse aggregate

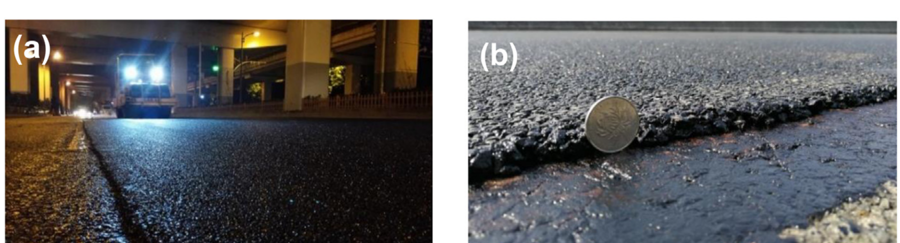


Fig. 45. Application of high-toughness ultra-thin friction course (GT-8). (a) Application of GT-8 in Yanan Road, Shanghai. (b) Thickness of GT-8.

makes up approximately 70% of the mixture, while mineral filler comprises around 10%, resulting in an asphalt-aggregate ratio exceeding 6%. These unique attributes set SMA-10 apart from other asphalt concrete mixtures, giving it increased texture depth, improved compaction properties, and superior durability.

2.4.2.2.2. Nova-Chip. Nova-Chip is one of the earliest UTWC products in America. This is an efficient and fast curing treatment solution using Nova bond emulsified asphalt as material of bonding layer and Nova binder as asphalt binder, which is realized by the special paving equipment-Nova paver. Nova-Chip ultra-thin wear layer technology has a broad development prospect in the preventive maintenance of high-grade asphalt pavement and cement pavement. In contrast, for other ultra-thin wear courses, Nova-Chip has special requirements for raw materials and their design methods. This technology was introduced to South Africa in 1998, and the Nova-Chip ultra-thin wearing course was also widely used in Russia, Sweden, Poland, Spain and other countries.

Nova-Chip technology uses discontinuous gradation and relies on the asphalt binder of coarse aggregate to form a bond to provide good mechanical properties. Compared with SMA, the content of coarse aggregate and fine aggregate in Nova-Chip grading design is less than other structure. Nova-Chip has good skid resistance, anti-wearing properties and noise reduction performance. The Nova-Chip ultra-thin wear layer is divided into three different gradations, Types A, B and C (Chu et al., 2017).

2.4.2.2.3. GT-8. GT-8 is a kind of pavement wearing course with a thickness of 0.8–2.0 cm, as shown in Fig. 44. It adopts high-viscosity and high-elastic modified asphalt to bond aggregates of UTWC. SBS-modified emulsified asphalt with high viscosity is used as the bonding materials of interlayer of UTWC. GT-8 gradation design and optimization follows coarse aggregate voids filling method (CAVF), by adjusting the 2.36 mm key screen pass rate to increase the amount of coarse aggregate, using the skeleton formed by stone extrusion and asphalt mortar to fully fill the ore gap to form a dense structure, it is a continuous grading design with dense structure. Its field application is shown in Fig. 45.

Compared with SMA-10, the GT-8 wear layer has relatively less coarse aggregate and mineral powder content and no fiber, but the asphalt-aggregate ratio is above 7.2%. The key to the success of this design is the application of high-viscosity and high-elastic modified asphalt which ensure the high-temperature performance of the asphalt mixture. The coarse aggregates are interlocked to form a stable aggregate skeleton, while the asphalt mortar acted as the connection and fills the void for the aggregate skeleton. Meanwhile, more asphalt binder was filled to replace part of fine aggregate, which reduced and increased the asphalt film thickness ($\geq$15 μm) to achieve a stronger stress absorption effect. The overall performance of GT-8 UTWC have good crack resistance, skid resistance and noise reduction effect. GT-8 UTWC technique has been applied in Hong Kong-Zhuhai-Macao Bridge, Baiyun International Airport and other projects in south China.

2.4.2.3. Performance evaluation index of UTWC

2.4.2.3.1. Mechanical performance of UTWC.

(1) Mechanical performance of asphalt mixture

As a surface improvement layer known for its thin thickness and direct exposure to traffic loads, the ultra-thin wearing course should exhibit both excellent pavement durability and high structural strength. The UTWC incorporates high-performance asphalt binders and high-quality aggregates in its asphalt mixture, resulting in superior mechanical performance compared to standard asphalt mixtures with equivalent gradations. Part of the technical index of UTWC are shown in Table 4.

Previous studies focused on the mechanical performance evaluation of UTWC. But some researchers believed that traditional experiments cannot accurately characterize the actual mechanical properties of the UTWC due to the difference in thickness between the UTWC and normal Marshall test specimen. Scholars created thinner rutting specimen or employed double-layer structures to analyze the real mechanical behavior of UTWC. Yang et al. (2020a) analyzed the rutting performance of asphalt mixture by evaluating the mechanical properties of the double-layer composite specimen which consisted of cement slab and asphalt layer. Yu et al. (2022a) studied the performance of typical UTWC products (SMA-10, Nova-Chip-B, and GT-10). They designed a new composite specimen which was made by a 20 mm UTWC slab and a 30 mm PCC slab and then evaluated the rutting performance of it.

(2) Interface bonding performance

Poor shear resistance between layers of asphalt pavement frequently leads to shear failures at the interlayer interface. The UTWC, serving as the uppermost asphalt layer, is exposed to vehicle loads, making the bonding strength between the newly constructed UTWC and the underlying layer a vital factor that affect its service life. Yu et al. (2020) evaluated the interfacial bonding stability of HUFC-8 with the "PosiTest AT" debonding strength tester, the result indicated that bonding effect between layers was reliable. The existing research indicates that the properties of emulsified asphalt, the dosage of emulsified asphalt, and the paving process of the interlayer can influence the interlayer bonding performance.

2.4.2.3.2. Functional performance of UTWC.

(1) Skid-resistance

Insufficient skid-resistance of asphalt pavement caused by traffic loads and environmental factors is the main cause of car accident. About 70% of the wet weather crashes can be avoided with improved pavement surface texture or friction. The skid-resistance and durability of the surface layer can be improved by UTWC. The anti-skid properties of pavement are characterized by the texture depth and the friction coefficient. Liu et al. (2011b) demonstrated that variations in macro-texture significantly impacted the level of skid resistance at various driving speeds during wet weather conditions. Guan et al. (2011) conducted a study to assess the long-term anti-skid performance of pavement using SMA16. Cong and Wang (2018) conducted research on fine aggregate angularity and discovered that it played a crucial role in affecting the macro-texture of skid resistance, while exerting only a minimal influence on micro-texture. The existing research results show that UTWC can significantly improve the anti-skid performance of asphalt pavement.

(2) Water-sealing performance

UTWC is a water-sealing asphalt layer that prevents water from the bottom of asphalt pavement. Yu et al. (2020) demonstrated that the HUFC-8 greatly enhanced the water sealing performance. The water-sealing function of ultra-thin asphalt pavement is essential for protecting road surfaces from water-related damage and ensuring safe driving conditions, particularly during wet weather. This type of pavement serves as a cost-effective and efficient solution for road maintenance and improvement while addressing critical water-sealing needs.

(3) Noise reduction

UTWC asphalt overlays have a significant positive impact on reducing road noise. It provides a relatively smooth and uniform road surface compared to original pavement. Improved smoothness reduces noise generated by tire-pavement interaction. Vehicles traveling on a smoother surface produce less noise from tire-road contact, resulting in lower road noise levels. Some ultra-thin asphalt overlays, such as SMA-10 or open-graded mixes, are designed to have specific surface textures that help reduce noise. Open-graded mixes, for example, have a porous structure that can dissipate sound energy, reducing noise levels.

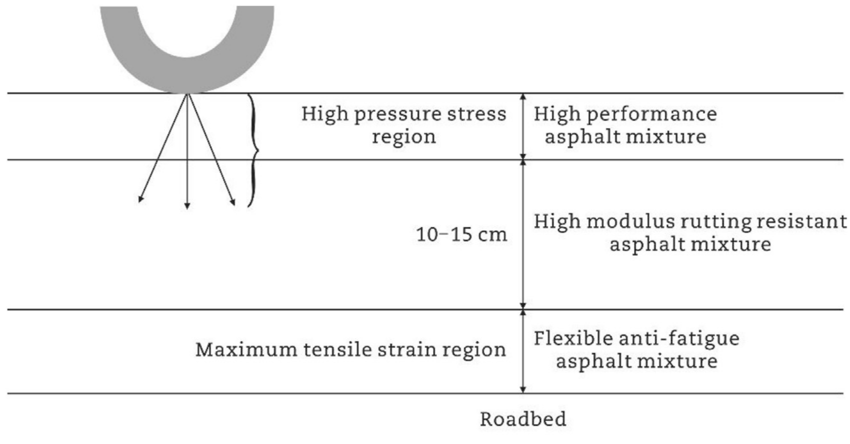


Fig. 46. Main ideas of full-thickness long-life pavement.

2.4.2.4. Existing problems and future research. Currently, ultra-thin wearing course technology is widely used in road maintenance in China, with Nova-Chip being the most extensively applied thin layer at the present stage. Emerging technologies such as GT-8 UTWC offer superior road performance and functional performance. UTWC improves the overall performance of the road surface while saving a lot of non-renewable resources. They also deliver notable economic and environmental benefits, making them poised for broader application in the future.

Many scholars have done some research related to UTWC, but there are still some certain problems that urgently need to be solved (Ding et al., 2021).

(1) Due to the reduction in structure thickness, the functional performance degradation of the overlay accelerates under the influence of loading and external environmental conditions.
(2) The ultra-thin friction course is characterized by its thin thickness, which adds complexity to the construction process. The asphalt mixture cools rapidly, resulting in a significantly shortened window for effective rolling during construction, thus leading to compaction challenges.
(3) There remains a lack of comprehensive performance evaluation system and methodology for UTWC. It is necessary to form a standardized and well-established norm and guidelines in the construction and design of UTWC.

In the future, research on UTWC can focus on various aspects, including the analysis of the mechanical performance mechanisms in wearing course, optimizing the overall performance of asphalt binder, and refining gradation designs. These efforts should aim to further reduce the thickness of UTWC while ensuring their mechanical performance and functional performance. On the other hand, there is a potential transition from hot mix UTWC asphalt pavement to cold-mix ultra-thin asphalt friction courses. This transition can contribute to enhanced economic and environmental benefits associated with UTWC.

3. Advanced pavement structure and performance evaluation

Traditional asphalt or cement concrete pavement structures are widely used around the world. However, the related pavement structure has certain limitations in the multi-functional integration and expansion of pavement. To this end, scholars from various countries are also committed to developing new pavement structures. Typical new structures mainly include perpetual pavement structures, inverted pavement structures, prefabricated pavement structures, and asphalt steel plastic (ASP) pavement structures. Meanwhile, in terms of pavement structure behavior and performance evaluation, compared with the traditional and simple road performance test and evaluation, the current research has paid more attention to the dynamic mechanical response of pavement, long-term service performance, and life cycle evaluation of pavement. In this chapter, the corresponding advanced research and applications are comprehensively reviewed.

3.1. Innovative pavement structures

With the rapidly increasing demands of multi-functional integration and expansion of pavement, conventional pavement structures cannot meet the requirements of modern and future transportation infrastructure. Accordingly, innovative structures for road pavement are deeply in need. For example, a perpetual road pavement is hopefully designed and

Table 5
Typical full-thickness perpetual asphalt pavement structures in different countries.

Highway designation	Pavement structure
Michigan long-life asphalt pavement test road	65 mm SMA asphalt concrete + 150 mm medium grained asphalt concrete + 190 mm asphalt crushed stone base + 430 mm grained base
Wisconsin long-life asphalt pavement test section	50 mm asphalt concrete + 130 mm asphalt concrete + 100 mm asphalt crushed stone base
British high-speed M25	38 mm hot pressed asphalt concrete + 68 mm coarse-grained asphalt concrete + 63 mm hot pressed asphalt concrete + 190 mm lean concrete + 200 mm graded gravel
German High-speed A5	37 mm cast asphalt concrete + 200 mm asphalt concrete + 150 mm stable base
Hamburg Highway, Germany	35 mm cast asphalt concrete + 265 mm asphalt concrete + 150 mm graded sand gravel + antifreeze layer
Stered Highway, France	70 mm asphalt concrete + 160 mm asphalt gravel + 100–350 mm cement graded gravel + 150 mm sand layer
Italian Del Sole Highway	30 mm medium grained asphalt concrete + 70 mm coarse-grained asphalt concrete + 150 mm asphalt gravel + 360 mm graded gravel + 300–400 mm sand layer
Austrian Brenner Highway	100 mm asphalt concrete + 140 mm dense graded asphalt gravel + 160 mm open-graded asphalt gravel + 300 mm antifreeze layer
Kyushu Expressway, Japan	40 mm dense graded asphalt concrete + 60 mm coarse-grained asphalt concrete + 80 mm asphalt gravel + 270 mm granular material
Yokohama Expressway Line 2, Japan	50 mm dense graded asphalt concrete + 50 mm coarse-grained asphalt concrete + 160 mm coarse-grained asphalt mixture + 210 mm granular material

Table 6
China Highway Society's "Long-Life Pavement Award" road section.

Road name	Pavement structure
Beijing Section of Jingjintang Expressway (G2)	40 mm LH-20 + 60 mm LH-30 + 80 mm LH-30 + 300 mm cement stabilized macadam + 300 mm limestone stabilized soil
Shandong–Jiqing Expressway (G20) Jinan East Section	4 cm medium grain asphalt concrete + 6 cm coarse graded bituminous concrete + 8 cm coarse graded bituminous concrete + 30 cm cement stabilized macadam + 30 cm limestone stabilized soil
Beijing–Hong Kong & Macao Expressway (G4) Guangzhou–Shenzhen Section	40 mm LH-20II + 80 mm LH-30 + 100 mm LH-40II + 100 mm LH-40 + 270 mm unscreened crushed stone

Table 7
Typical structure of inorganic binder stabilized base asphalt pavement of expressway.

		Structure 1		Structure 2		Structure 3		Structure 4	
		Thickness (cm)	Material type	Thickness (cm)	Material type	Thickness (cm)	Material type	Thickness (cm)	Material type
Surface	Upper class	15–20	AC/SMA	20–26	AC/SMA	15–20	AC/SMA	20–26	AC/SMA
	Intermediate layer		AC		AC		AC		AC
	Under layer		AC		ATB		AC		ATB
Foundation course	(1)	50–60	Inorganic binder abilization class	50–60	Inorganic binder stabilization class	30–55	Inorganic binder stabilization class	30–60	Inorganic binder stabilization class
	(2)					15–20	Graded granular material	15–20	Graded granular material
Roadbed improvement layer			15–20 cm, unscreened crushed stone or natural aggregate, recommend			–	–	–	–

built to last longer than 50 years without requiring major structural rehabilitation or reconstruction, and needing only periodic surface renewal in response to distresses confined to the top of the pavement. To achieve the goal of long-life service of pavement, the inverted pavement as an unconventional type of flexible pavement structure is developed. In which, an unbound aggregate base (UAB) with a low initial modulus is sandwiched (layered) between two stiffer layers, a thinner asphalt concrete layer (AC) and a cement-treated base layer (CTB). In addition, precast pavement as a unique solution for pavement construction that utilizes prefabricated concrete panels is applied primarily for very fast rehabilitation or reconstruction of existing pavement but can also be used for new construction as well. In recent years, a new asphalt steel plastic (ASP) pavement structure was proposed with an asphalt mixture forming the surface layer, and steel plate and plastic materials functioning as the main load-bearing layers. In this section, four types of innovative pavement structures, perpetual pavement structure, inverted pavement structure, precast pavement structure, and ASP pavement structure, will be introduced from the views of essential design conception and engineering applications.

3.1.1. Perpetual pavement structure

3.1.1.1. Overview of perpetual asphalt pavement. Perpetual asphalt pavement, also known as long-life asphalt pavement or durable asphalt pavement, is a new technology proposed by the international road engineering community in the 1990s based on the principle of the most economical total cost of the entire life cycle. It refers to the design service life of asphalt pavement over 40 years (UK Department for Transport, 2011; Newcomb, 2002), with the basic idea of controlling deep pavement diseases and limiting pavement diseases to the surface layer of the pavement. This maintenance is mainly focused on road surface diseases, without the need for deep disease treatment, that is, the road surface a long enough time (30–50 years) does not cause deep structural damage (mainly asphalt layer fatigue cracking, serious rutting, etc.). Then, the United States, Japan, and other countries further developed and improved the durability of the asphalt pavement and built many durability of the asphalt pavement test section. It has provided valuable information and accumulated rich practical experience for the promotion, application, and long-term development of durable asphalt pavement (Murayama et al., 2003).

3.1.1.2. Foreign long-life pavement structure. The structural types of foreign long-life asphalt pavements are mainly divided into two categories (Moriyoshi et al., 2014; Coppola, 2020). One type uses a mixed base structure, generally consisting of asphalt crushed stone base and granular stabilized base, mainly represented by Japan and European countries. The other type is the use of fully flexible or full-depth asphalt pavement structure, mainly represented by the United States.

The mixed base and full-thickness long-life asphalt pavement in foreign countries have a common feature: the asphalt layer thickness is relatively thick. The asphalt layer thickness of the mixed base long-life asphalt pavement is generally 250–400 mm and the thickness of the

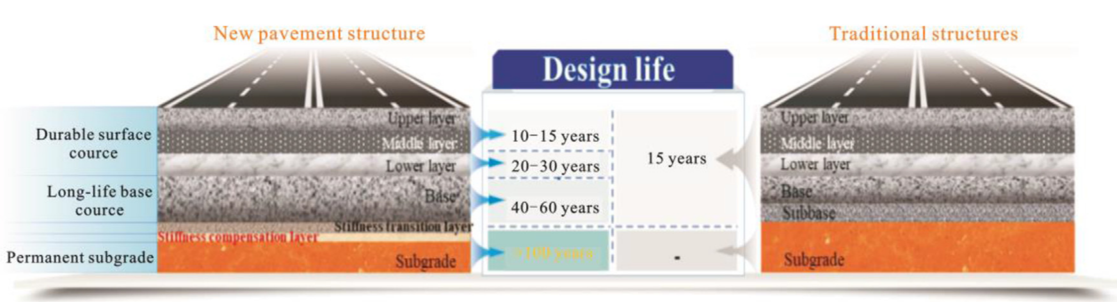


Fig. 47. Structure layer life layer by layer increasing long-life asphalt pavement structure system.

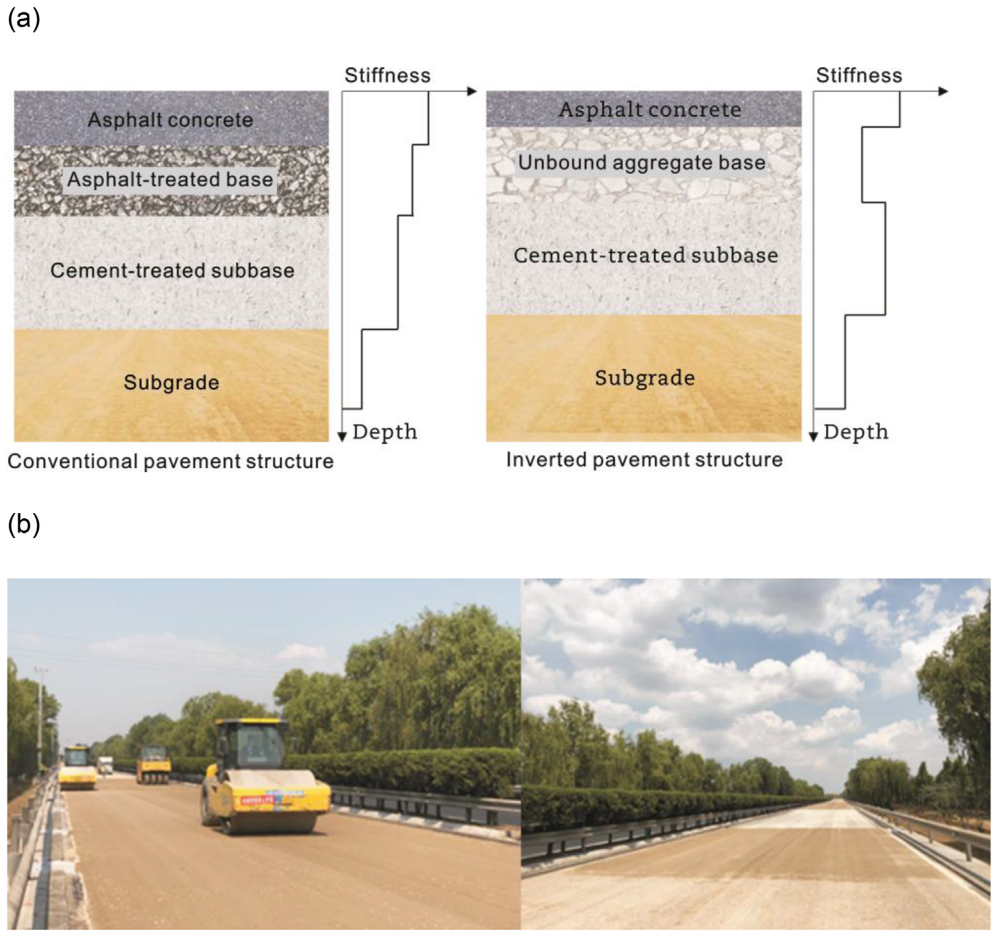


Fig. 48. Comparison and application. (a) Comparison of conventional and inverted pavement structure. (b) Application of high quality unbound aggregate base in Taian, Shandong Province.

asphalt layer on the entire thickness asphalt pavement. As shown in Fig. 46, the main design concept for the full-thickness long-life pavement structure proposed by the United States is that the upper layer is anti-wear, the middle layer is anti-rutting, and the lower layer or base layer is anti-figure. Table 5 shows typical full-thickness long-life pavement structures from various countries worldwide.

From the research and actual pavement structure of long-life asphalt pavement abroad, developed countries such as Europe and America mainly use asphalt crushed stone and granular materials as the base material for long-life pavement, and more use granular base structure. Usually, technical measures such as increasing the thickness of the asphalt layer or increasing the strength and stiffness of the middle and lower layers are taken, and it is unanimously believed that using a non-binder structural layer can reduce the structural and functional damage of asphalt pavement, and improve the service life of the pavement. Although much research has been carried out on long-life asphalt pavement in countries such as Europe, America, and Japan, methods such as optimizing structural combinations and reducing bending and tensile fatigue stress of structural layers have yet to be proposed. Various countries unanimously recognize no typical type of long-life asphalt

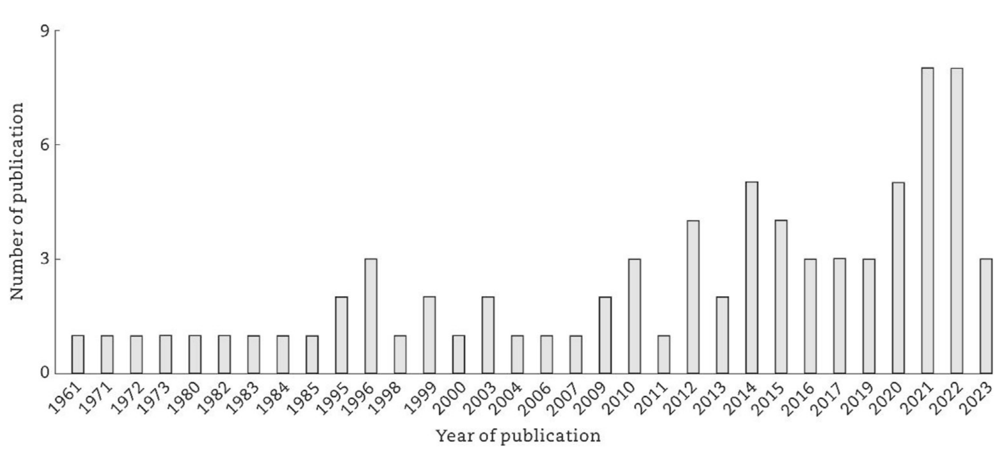


Fig. 49. Annual publication number of research regarding the inverted pavement since 1961.

pavement structure. Long-life asphalt pavement is still in an essential stage of development and improvement.

3.1.1.3. Chinese long-life pavement structure. According to the definition of long-life asphalt pavement, if the standard of 40 or 50 years of service life of asphalt pavement is used, no expressway in China meets the durability standard requirements. However, based on the critical indicator of cumulative standard axle load action times, some high-speed highways in China have already met the standard of durability asphalt pavement service life (Li et al., 2019), such as Jinan-Qingdao Expressway, Beijing-Tianjin-Tanggu Expressway, Beijing-Shijiazhuang Expressway and so on. According to the actual traffic load capacity, the cumulative number of standard axle loads on the single lane of these expressways has been more than 100 million times, which is equivalent to the traffic load capacity of the US high-speed for more than 50 years and meets the standard of the service life of durable asphalt pavement (Wang et al., 2022m).

China's long-life asphalt pavement structure is developed based on the large-scale use of semi-rigid base asphalt pavement structure. The representative pavement structures are the Beijing–Tianjin–Tanggu Expressway (G2) Beijing Section, Shandong–Jiqing Expressway (G20) Jinan East Section, Beijing–Hong Kong & Macao Expressway (G4) Guangzhou–Shenzhen Section, etc., as listed in Table 6, all of which were awarded the "Long-Life Pavement Award" by the China Highway Society in 2020. In addition, Jiangsu, Hebei, Fujian, and other provinces have also carried out a lot of work on long-life pavement structures, and the summary of pavement structure is listed in Table 7.

At the same time, in terms of the design theory and method and structural system of long-life asphalt pavement in China, academician Jianlong Zheng of Changsha University of Science and Technology and his team have made significant contributions and proposed a long-life asphalt pavement structure system with increasing life of structural layer (Zheng, 2014; Zheng and Zhang, 2015; Zheng et al., 2020). The structure comprises a permanent subgrade + stiffness compensation layer + stiffness transition layer + long-life base layer + durability surface layer, as shown in Fig. 47. The structural system has broken through the traditional concept of equal life design of each structural layer of asphalt pavement at home and abroad. It has doubled the service life of the overall structure of the pavement and the period of large and medium repair. It has been successfully applied in over 10 highway construction projects in 6 provinces and regions, such as Huaizhi (Hunan), Guangfozhao (Guangdong), Yudeng (Henan), etc.

3.1.1.4. Development prospect of long-life pavement structure.

(1) Research on new durability pavement structure system and design theory and method.

(2) Study on the long-term evolution law of service performance of pavement structure.

(3) Research on life-increasing maintenance technology of in-service pavement.

3.1.2. Inverted pavement structure

The inverted pavement (IP) was developed and widely applied as a viable alternative to conventional asphalt pavements in South Africa. By adopting the unbound aggregate base materials and thin AC layer, IP could help reduce the consumption of expensive asphalt materials and decrease the life-cycle cost of asphalt pavements. Related research and applications were also conducted by countries such as the United States, France, China, India, Iran, the United Kingdom, Italy, Pakistan, Canada, etc. The three aspects including the structural characteristics, the research evolution, and the future perspectives regarding IP are summarized and shown as follows.

3.1.2.1. Structural characteristics and benefits of inverted pavements. The main difference between IP and conventional pavement structure is the sequence of layers and the quality of the UAB layer. To spread the traffic loads downwards to the subgrade, materials with higher moduli are generally selected for layers close to vehicle loads, resulting in the continuous decrease of layer moduli from top to bottom. In contrast, IP utilizes the well-compacted unbound aggregate materials in the base course between two stiffer courses of AC on top and CTB at the bottom. The CTB limits the deformation of the stress-sensitive unbound aggregate mixture which allows the UAB, which is shown in Fig. 48. To develop increased stiffness during the construction and service stage. A thin AC layer is usually adopted to utilize the property of stress-dependent stiffness of UAB by providing a higher level of confining stress in the base and avoiding excessive rut deformation developed in the AC layer. Therefore, IP could make full use of the bearing capacity of unbound aggregate materials to reduce the thickness of the AC layer, which decreases the construction cost. The thin AC layer is mainly used as a functional layer providing a smooth, waterproof, and anti-skidding driving surface rather than the primary load-bearing course. By adopting routine maintenance for the AC layer, IP could provide an acceptable level of service within the design life without structural capacity restoration or rehabilitation. Hence, the IP technology illustrates significant economic benefits while providing desirable long-term performance.

3.1.2.2. Research evolution of inverted pavement design and application. Publications regarding IP can be found since the early 1960s, and the annual publication number so far is presented in Fig. 49. According to the literature investigation results, research before 1980 mainly focused on the structural response properties of asphalt pavements with an untreated aggregate base and the comparative analysis with conventional pavements (Johnson, 1961; Ahlvin et al., 1971; Barker et al., 1973). Documented research results illustrate that the quality of UAB significantly affects the mechanical property and long-term performance of IP. Therefore, the emphasis of the research was on improving the design and construction technologies of UAB in the 1980s (Freeme et al., 1980; Barksdale and Todres, 1983; Barksdale, 1984). Meanwhile, the accelerated pavement test (APT) technology was developed and extensively applied in the life-cycle performance investigation and validation of full-scale and in-suit IP structures, which facilitates the establishment of mechanistic-empirical design guidelines and leads to the wide application of IP in high-traffic roads in South Africa (Freeme et al., 1982; Maree et al., 1982; Theyse et al., 1996). Meanwhile, French pavement design guidelines also recommended IP as the alternative pavement design to prevent the reflection cracking from the base course (Corté and Goux, 1996).

More publications can be found since the U.S. Federal Highway Administration scanning tour to South Africa in 1996 (Horne, 1997). To improve the accessibility of rural areas in South Africa, IP was used to upgrade the in-suit gravel roads with a relatively inexpensive gravel bonding surface (Steyn et al., 1998). In Louisiana, the performance, failure modes, and design method of IP were investigated in the first full-scale APT experiment (Li et al., 1999; Metcalf et al., 1999; Rasoulian et al., 2000). Afterward, the in-situ stiffness of UAB in IP was characterized and different construction methods were compared in a quarry haul road in Georgia (Terrell et al., 2003). The development and achievements of IP research in South Africa before 2006 were analyzed and summarized to facilitate the improvement of design and application methods (Hugo and Martin, 2004; Du Plessis et al., 2006). The nonlinear and stress-dependent properties of UAB were characterized to improve the material constitutive models and the accuracy of mechanical response calculation in the numerical modeling of IP structure (Kim et al., 2009b). Design guidelines suitable for the mechanical behavior and performance characteristics of IP were proposed based on field tests and simulation results (Avellaneda, 2010). The benefits of IP compared with traditional asphalt pavements were evaluated based on the simulation

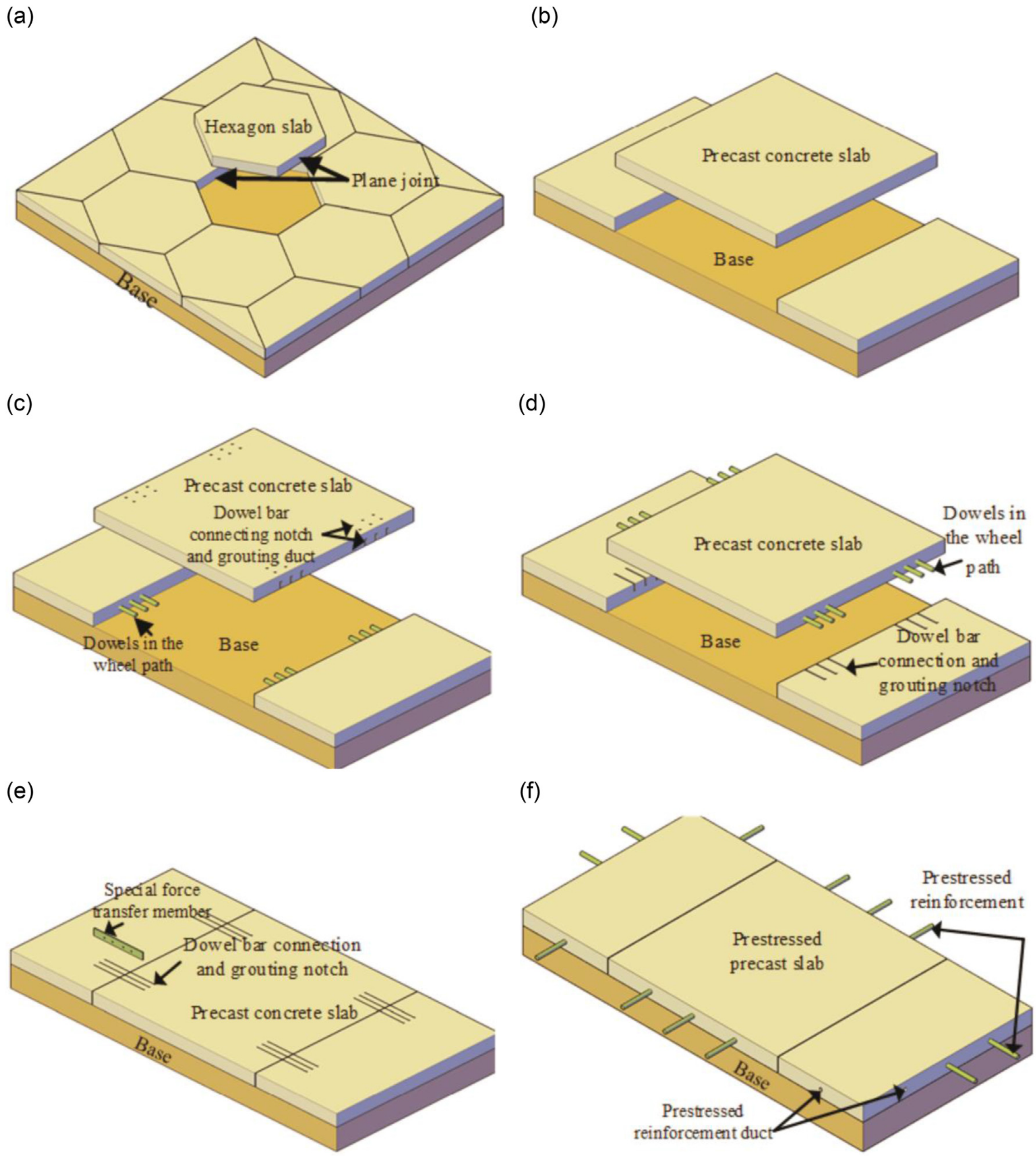


Fig. 50. Typical precast slab systems. (a) Hexagon slab. (b) Rectangular slab. (c) Super-slab. (d) Michigan slab. (e) Uretek stitch slab. (f) Prestress slab.

results and long-term performance monitoring results of test sections built in the U.S. (Agostinacchio and Olita, 2007; Cortes et al., 2012; Lewis and Jared, 2012; Cortes and Santamarina, 2013) and South Africa (Theyse et al., 2011; Kleyn, 2012; Maina et al., 2013). However, researchers also found that the cross anisotropy of UAB in numerical simulation resulted in greater pavement responses and less estimated service life for fatigue and rutting distresses (Al-Qadi et al., 2010; Li et al., 2011). Therefore, the ability of IP under different traffic and environmental conditions needs to be verified even though IP could outperform traditional flexible pavements in some cases.

In the recent decade, there has been a renewed interest in the research of IP due to the increase in construction and maintenance costs and the decrease in the funds allocated to transportation infrastructure by the government (Tutumluer, 2013; Han et al., 2019a; Biswal et al., 2020; De Almeida, 2021). The design method optimization and cost-effectiveness of IP were further investigated by countries to verify the adaptability and promote the application of IP (Chen and Zhang, 2014; Etzi et al., 2014; Papadopoulos, 2014; Papadopoulos and Santamarina, 2014; Santamarina, 2014). More research has been conducted to investigate the feasibility of using local resources for IP construction (Contu, 2016; Ghaaowd et al., 2022; Ghanizadeh et al., 2022; Khan et al., 2022a, 2022b) and improve the accuracy of mechanical response calculation by optimizing the parameters and numerical models of IP (Ghanizadeh and Padash, 2019; Zhang and Lei, 2021; Han et al., 2021b; Jiang et al., 2021b). Besides, the performance prediction models of typical IP distresses such as fatigue and rutting were investigated to consider the differences in building materials and environment conditions of different countries (Ahmed et al., 2021a, b; Han et al., 2023; Jiang et al., 2022).

3.1.2.3. Future perspectives. In summary, there have been numerous researches in the area of materials composition design, structure design, and construction technique of IP using material tests, field tests, APT, and

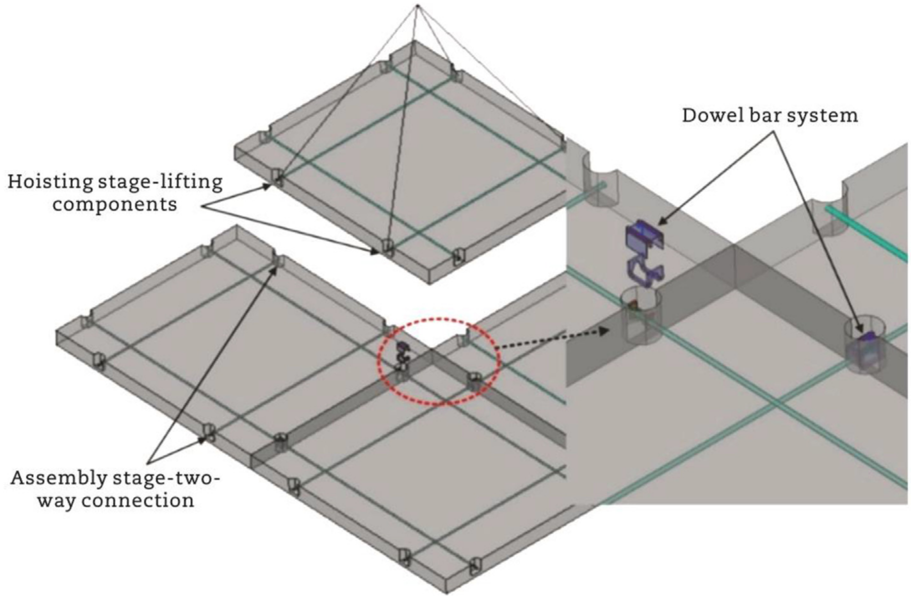


Fig. 51. Two-way hoisting and connection slab system.

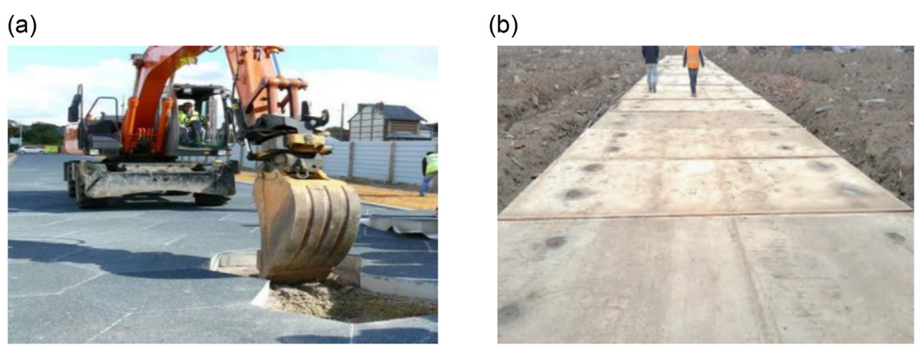


Fig. 52. Application of assembly pavement slab with non-force transmission type. (a) Hexagonal slab. (b) Rectangular slab.

numerical simulation. Especially, the nonlinearity and stress-dependent properties of UAB have been characterized and incorporated into the numerical models for more accurate simulation of IP. In the future, the novel mix design and construction technology of high-performance unbound aggregate materials will continue to be the key to the successful application of IP since the UAB is the primary load-bearing course. Considering that the unbound materials cannot fully bond with concrete layers, proper characterization, and simulation of interlayer bonding between AC, UAB, and CTB are necessary for the accurate calculation of mechanical responses and prediction of distresses. To realize a more reliable design of IP, it is vital to establish the dataset of property parameters of typical road materials and life-cycle performance monitoring data of APT or field test sections. The dataset could provide critical fundamental data for the construction of more reliable fatigue damage and rut depth prediction models, which could facilitate the design and maintenance of IP.

3.1.3. *Precast pavement structure*

The prefabricated or precast pavement is made with precast slabs and then transported to the construction site for assembly and connection. Prefabricated pavement has various advantages of short construction time, quick opening traffic, good durability, and low influence by climatic conditions (Tomek, 2017), making it one of the

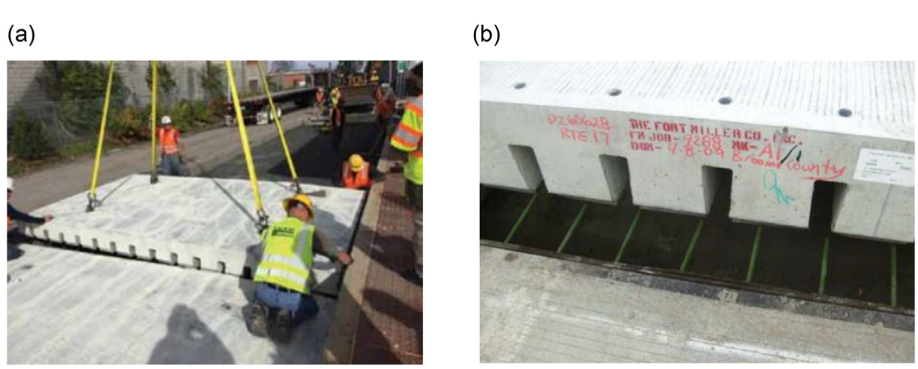


Fig. 53. Typical applications of the super-slab system. (a) Repairing the bus stop. (b) Placing slab over anchor rods.

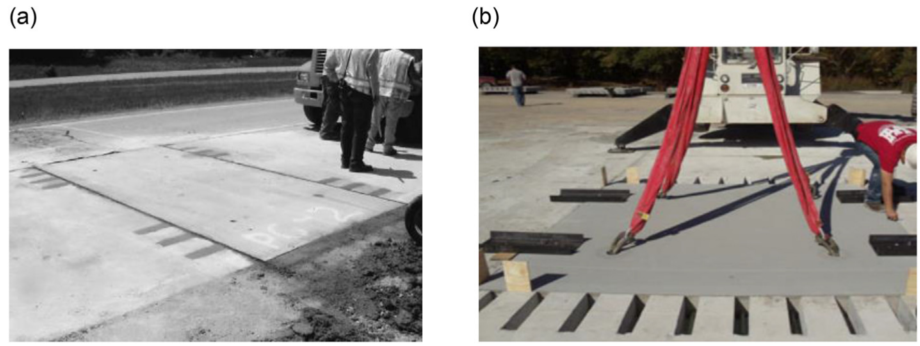


Fig. 54. Typical applications of the Michigan slab system. (a) Repairing road. (b) Repairing airport pavement.

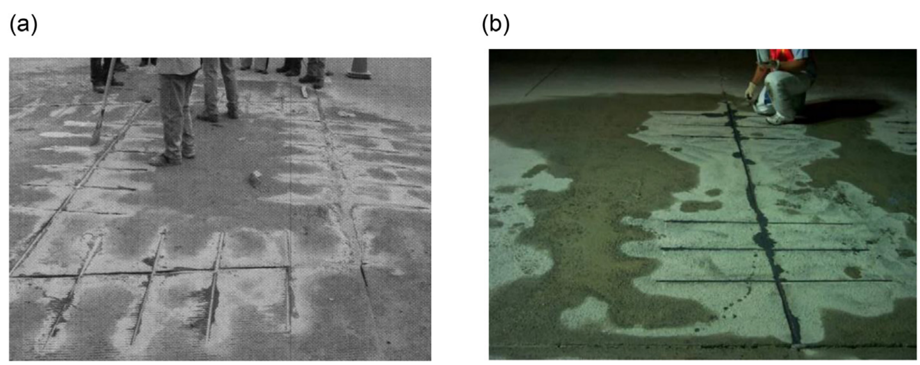


Fig. 55. Typical application of Uretek stitch slab system. (a) Repairing the pavement. (b) Reinforcing the road.

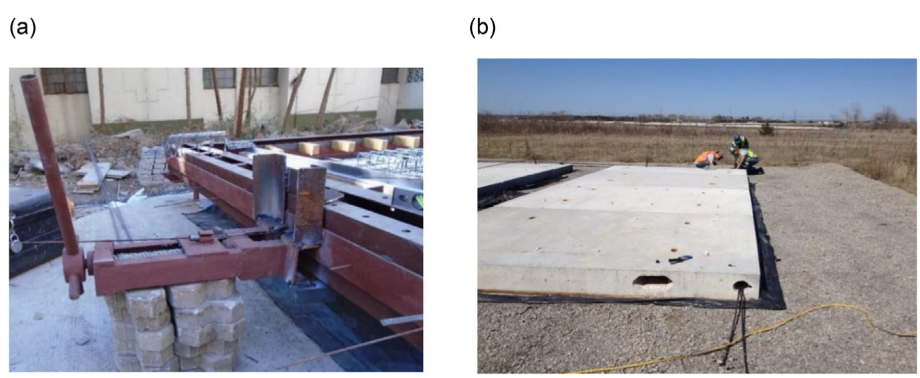


Fig. 56. Typical application of prestress slab system. (a) Pre-tensioning. (b) Post-tensioning.

Fig. 57. Prefabricated pavement base layer. (a) Sand cushion course (Tayabji, 2016). (b) Dry-mixed mortar (Tang, 2019).

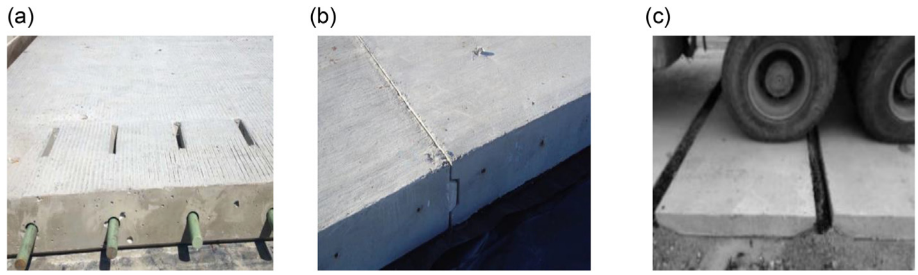


Fig. 58. Prefabricated pavement connection forms. (a) Super-slab groove. (b) Tongue-and-groove. (c) Aggregate interlock.

current focus in road engineering. However, unlike conventional continuous cast-in-place concrete pavement, prefabricated pavement is formed by continuous splicing of pavement slabs. After splicing, the prefabricated pavement inevitably forms actual joints. The existence of joints acts as expansion and contraction joints of pavement. Meanwhile, the force transmission connection, sealing, and waterproofing of the joints inevitably decrease the pavement service level if no effective measurements are taken. Therefore, driving comfort is critically limited by the road elevation difference and width of the pavement slab joints (Zhao, 2015). Up to today, prefabricated pavement tests have been implemented in more than ten countries. The research on prefabricated pavement in several countries is over the stage of engineering application (Kamali and Hewage, 2017). These countries are already using prefabricated pavement technology to pave municipal roads, airport pavement, etc. However, most applications are still in field verification (Editorial Department of China Journal of Highway and Transport, 2020). In the below, three aspects including the design system, applications on-site, and future perspectives regarding precast pavement are summarized.

3.1.3.1. Design system. From the previous research, six design types of precast pavement slabs, in general, could be found, and the design schemes can be depicted in Fig. 50 (Fang et al., 2022). Based on the existing design, a new form considering common reinforcement for hoisting and connection was developed in Wuhan (Ke et al., 2023), as shown in Fig. 51. Research regarding the corresponding material review has also been conducted (Fang et al., 2023). From the material review, the toughness of the precast pavement slab must be enhanced, and the fibers and rubber particles are the recommended materials for the concrete mix design.

3.1.3.2. Applications on-site. For the application, precast pavement can be used for the intermittent repair of damaged pavement and the continuous laying of new pavement (Delatte, 2018). The structural connection of the transmission rod can be divided into force and non-force types. The force transmission rod connection is mainly used for rectangular slab systems, including super-slab systems, Michigan slab systems, Uretek stitch systems (Tayabji et al., 2013; Novak et al., 2017), and prestress slab systems (Liu and Zhang, 2006). The non-force transmission rod connection adopts the tongue-and-groove type of aggregate interlocking type. Due to the complex structure, the hexagonal slab system is mainly connected by the tongue-and-groove type and aggregate interlocking type. This section will summarize the prefabricated pavement system from the general applications of precast slabs.

The application of assembly pavement slab with non-force transmission type for hexagonal slab (De Larrard et al., 2013) and rectangular slab (Sun et al., 2018a) are shown in Fig. 52(a) and (b), respectively. The typical applications of the super-slab system could be repairing the bus stop (Tayabji and Tyson, 2017) and placing the slab over anchor rods (Tayabji, 2016), which are seen in Fig. 53(a) and (b), respectively. For the Michigan slab system, the typical applications of repairing roads (Buch et al., 2003) and repairing airport pavement (Priddy et al., 2014) are shown in Fig. 54(a) and (b), respectively. The typical applications of the Uretek stitch slab system could be found in repairing the pavement (AASHTO, 2001) and reinforcing the road (Anderson et al., 2007), as shown in Fig. 55(a) and (b), respectively. The typical applications of prestress slab systems also can be found, such as pre-tensioning (Syed and Sonparote, 2020) and post-tensioning (Alwehaidah, 2013), which are shown in Fig. 56(a) and (b), respectively. Before assembling, the base layer must be treated for a required level, and the typical usages are sand cushion course and dry-mixed mortar (Tang, 2019) as seen in Fig. 57(a) and (b), respectively. For the connection between slabs in the application, the groove (Tayabji, 2016), tongue-and-groove (Alwehaidah, 2013), and aggregate interlock (Xu et al., 2020a) are often applied, which are shown in Fig. 58(a)–(c), respectively.

From the applications of different design forms, the same focus of assembling on-site is the connection between slabs and layer interaction processing. In one word, the basic requirement of a successful precast pavement technology is the road performance must be equal to the conventional way at least.

3.1.3.3. Future perspectives. Prefabricated pavement is applied increasingly in road engineering due to the increased requirements of time-saving especially for urban traffic infrastructure construction and

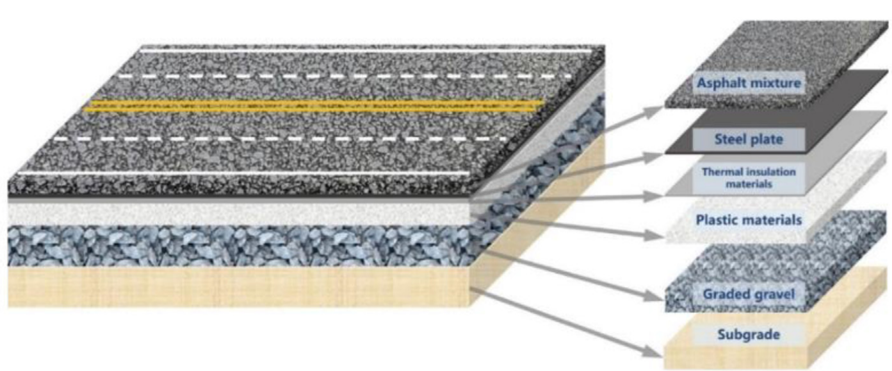


Fig. 59. Typical pavement and ASP pavement (Jiang et al., 2021a).

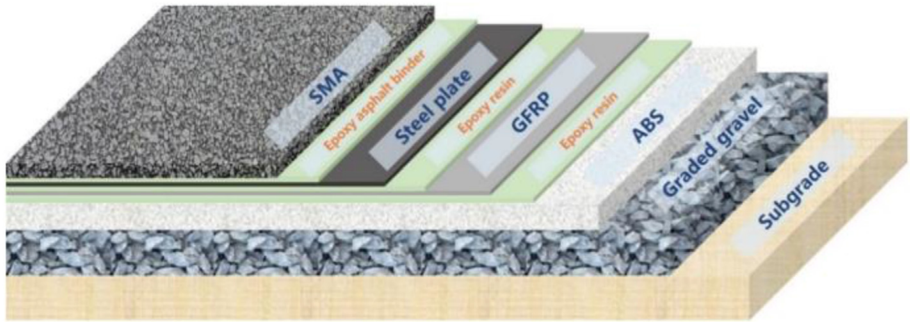


Fig. 60. Proposed materials and thickness for ASP pavement structural layer (Jiang et al., 2021a).

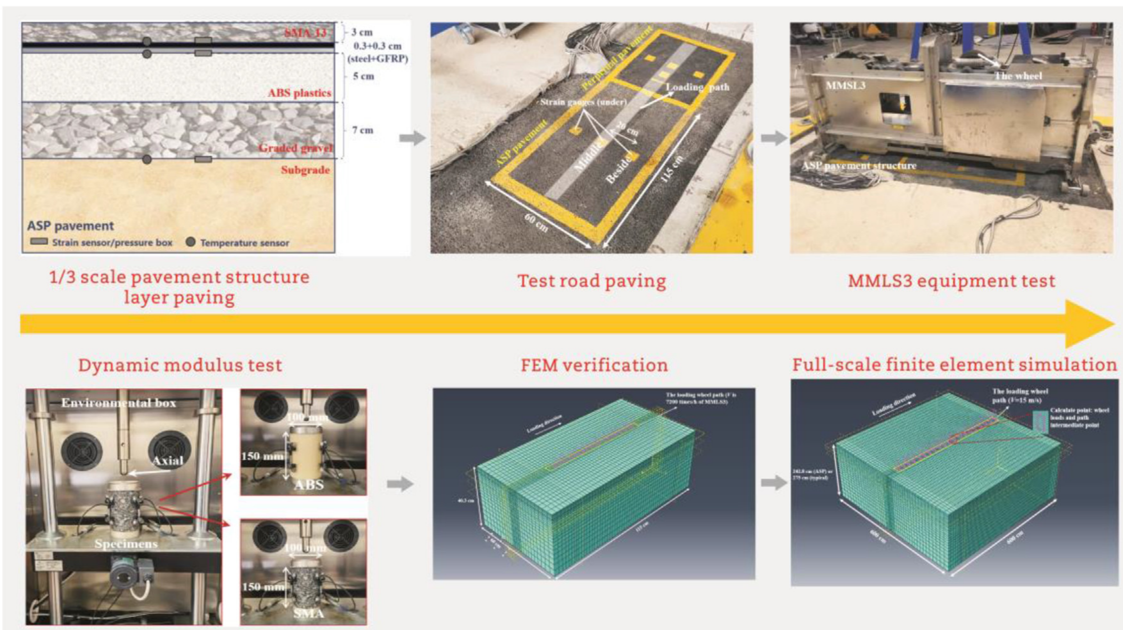


Fig. 61. Test process (Jiang et al., 2023b).

maintenance. Therefore, innovative designs and construction processing are still in rapid development. For example, a study on pavement functionalization and multi-layer composite slabs integrating permeation, water collection, and drainage functions is needed. Also, developing mechanization to improve the paving efficiency of slabs and reduce construction costs is recommended. Besides, promote the intelligence applied to the precast pavement slabs to realize the intelligentization of pavement infrastructure with sensing equipment into the prefabricated pavement. In addition, apply new concrete materials limiting the specified density concrete and recycled aggregate concrete and more acceptable but low-cost construction materials for slab precast. This includes the development of flexible concrete precast slabs to adapt to subgrade deformation. Meanwhile, processing the sealing of slab joints to improve the waterproofing, and smoothness

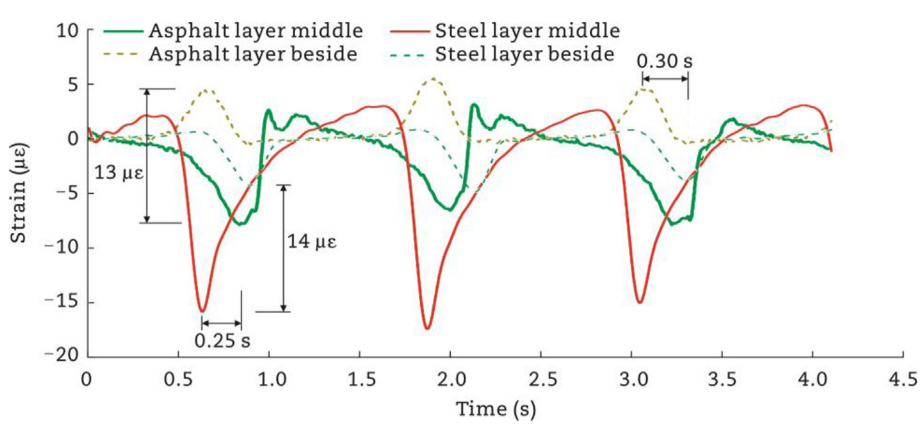


Fig. 62. Comparison of ASP pavement interlaminar strain (Jiang et al., 2023b).

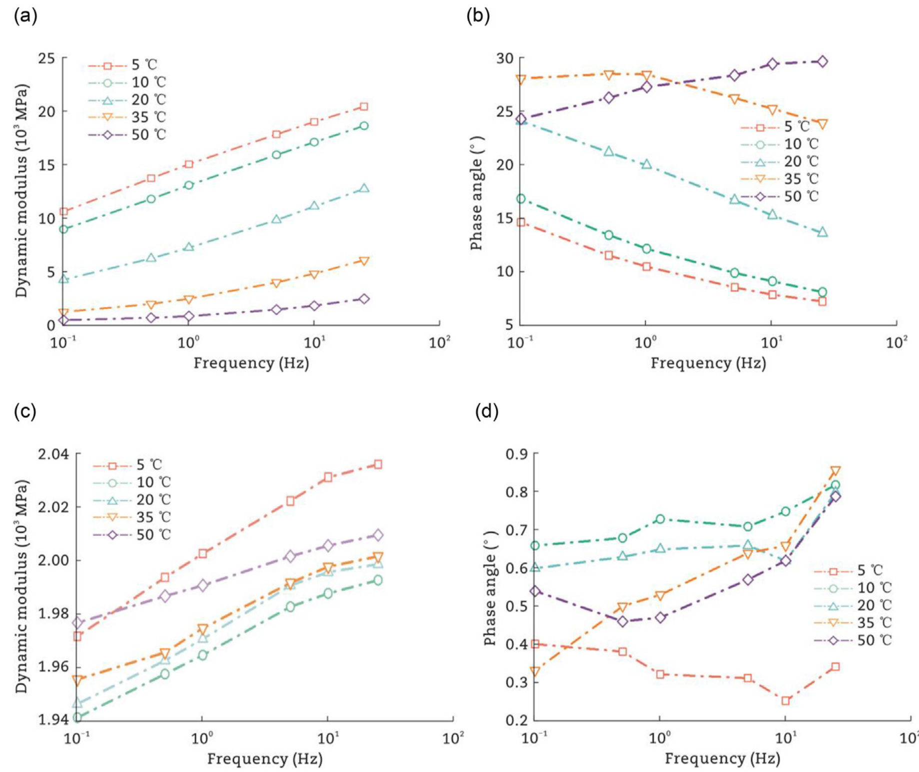


Fig. 63. Experimental results at different frequencies and temperatures. (a) Dynamic modulus of SMA-13. (b) Phase angle of SMA-13. (c) Dynamic modulus of ABS. (d) Phase angle of ABS (Jiang et al., 2023b).

between pavement slabs is also significantly important for high-quality prefabricated pavement assembling.

3.1.4. *ASP pavement structure*

Exploring low-carbon, environmentally friendly, and durable road materials and structures constitutes one of the research directions for the sustainable development of road engineering (Jiang et al., 2022; Sha et al., 2021; Yuan et al., 2023a). In recent years, novel materials such as plastic and steel have garnered widespread research and application in road infrastructure (Gu and Ozbakkaloglu, 2016; Gurjar et al., 2018; Bhagat and Savoikar, 2022; Sha et al., 2022a). (1) Polymer plastics in asphalt modification: polymers, plastic particles, and solid waste materials have been extensively studied for asphalt modification to enhance properties like high-temperature resistance, low-temperature performance, and fatigue resistance in asphalt mixtures (Grady, 2021; Jia et al., 2023; Wang et al., 2022f; Xu et al., 2021a; Yuan et al., 2022a, 2022c). (2) Alternative materials for improved stability: materials like steel slag, plastics, and solid waste have been investigated as partial substitutes in road composition to enhance the stability and functionality of road structures (Aziz et al., 2014; Tulashie et al., 2020; Pai et al., 2021; Liu et al., 2022c). However, traditional road materials or structures have encountered challenges in achieving performance breakthroughs. As depicted in Fig. 59, this study introduces a novel asphalt steel plastic (ASP) pavement structure (Jiang et al., 2021a; 2023b). In this structure, asphalt mixture forms the surface layer, while steel plates and plastic materials constitute the primary load-bearing layers, replacing the load-bearing layer in conventional pavement structures.

3.1.4.1. ASP pavement structure design. The design of the ASP pavement adheres to core principles of road durability and serviceability, encompassing two essential components: (1) the surface functional layer (Wu et al., 2021b; Lu et al., 2022), with a service life of 5–10 years, boasting excellent skid resistance and safety; and (2) the load-bearing structural layer (Han et al., 2019b; Yuan et al., 2022b), providing a stable and durable framework to withstand vehicular loads. Furthermore, both layers of materials should exhibit ample temperature stability, water resistance, and aging resistance. Additionally, they should possess renewability or reusability at the end of their design lifespan. As depicted in Fig. 60, the road materials and structure are designed from bottom to top, comprising five distinct layers.

(1) Graded gravel material (first layer: distributes loads from the upper structure).
(2) Acrylonitrile-butadiene-styrene (ABS) engineering plastic material (second layer: high strength, wear resistance, impact resistance, etc.).
(3) Glass fiber reinforced polymer (GFRP) insulation material (third layer: insulates against construction heat transfer from the upper structure).
(4) Q345D steel plate (fourth layer: high isotropic stiffness, high toughness).
(5) SMA-13 asphalt mixture (fifth layer: provides skid resistance and functional road characteristics).

High-viscosity binding material is utilized between structural layers to ensure a continuous integrated system. Based on preliminary performance assessments and cost-benefit analysis, the pavement's structural thickness and material selection entail surface layer thicknesses of 4, 6, and 8 cm, steel plate thicknesses of 0.6, 0.8, 1.0, and 1.2 cm, ABS layer thicknesses of 12, 14, 16, 18, and 20 cm, graded gravel layer thickness of 20 cm, subgrade soil thickness of 200 cm, and relatively small GFRP layer thickness of approximately 0.5 cm.

3.1.4.2. ASP pavement performance test. Currently, methods for investigating the mechanical response of road pavement structures primarily encompass field tests and finite element simulations. Field tests effectively reveal the mechanical response state within the structure, while

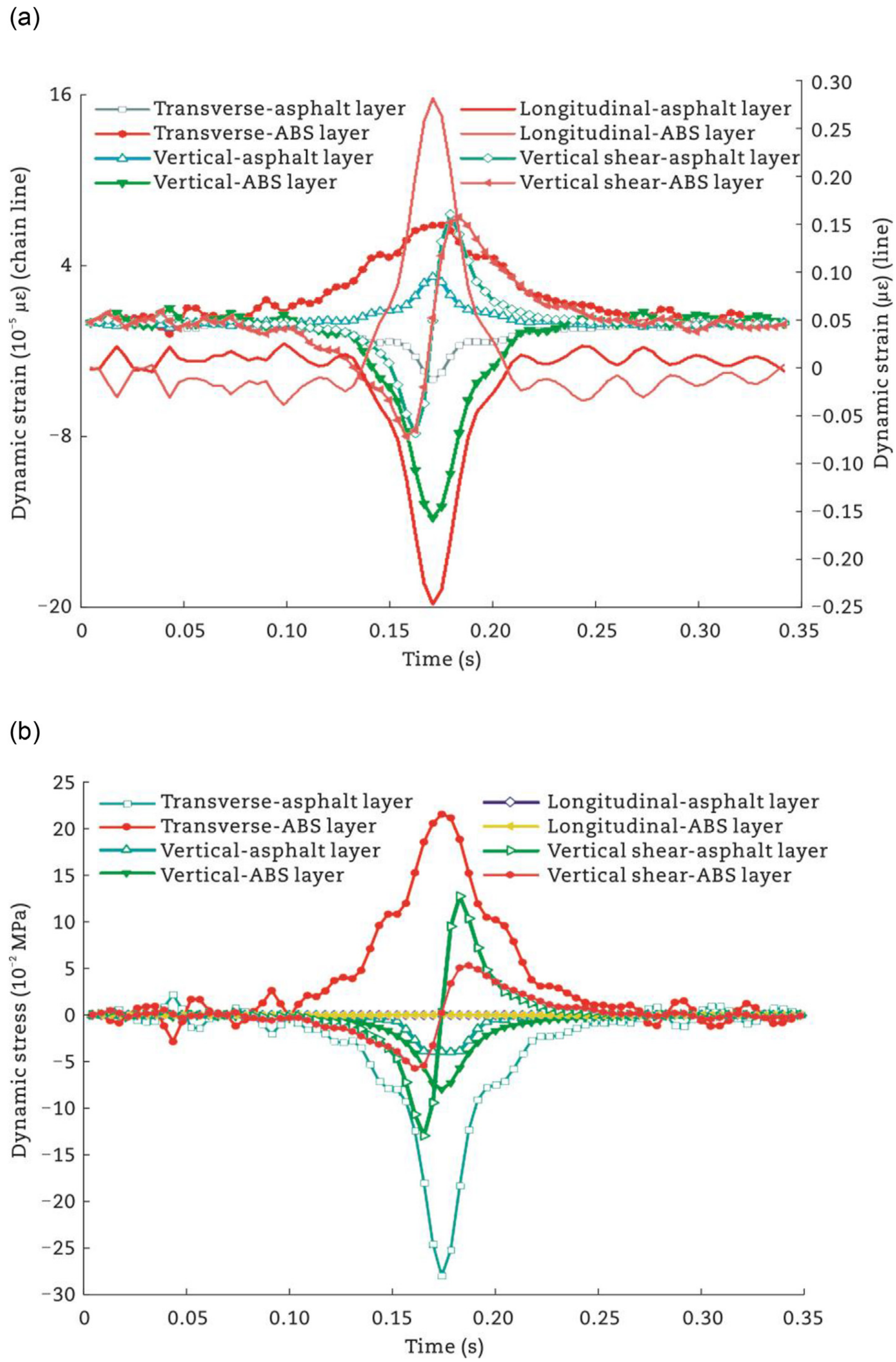


Fig. 64. Time histories of strain and stress at different layers bottoms of ASP pavements during the moving load. (a) Dynamic strain. (b) Dynamic stress (Jiang et al., 2023b).

finite element simulations comprehensively depict variations in mechanical responses between different layers and validate them against field test data. This substantiates the rationality and effectiveness of studying the mechanical response of road pavement structures. Hence, as illustrated in Fig. 61, this study establishes 1/3-scale test (MMLS3 (Bhattacharjee et al., 2008; Lee et al., 2011)) pavement structures: ASP pavement (3 cm SMA-13 + 0.3 cm steel plate/GFRP + 5 cm ABS plastic + 7 cm graded gravel + subgrade). This analysis explores the internal response characteristics, road performance, and long-term behavior of the novel pavement structure. To comprehensively analyze the mechanical response variations in each structural layer of the ASP pavement, a full-scale finite element simulation model is established for the pavement structures: (1) ASP pavement: 8 cm SMA-13 + 0.8 cm steel plate + 14 cm ABS plastic + 20 cm graded gravel + subgrade; (2) typical pavement: 5 cm SMA-13 + 25 cm Superpave mixture + 5 cm ATB-30 + 40 cm graded gravel + subgrade. This analysis contrasts the internal mechanical response of the ASP pavement structure under load, including the dynamic modulus of SMA-13 asphalt mixture and ABS plastic. These measurements serve to determine material model parameters for finite element modeling and material properties under different temperatures and frequency loading conditions.

3.1.4.3. ASP pavement performance evaluation. Fig. 62 presents strain results at different locations on the ASP pavement. From the graph, it is

Table 8
Maximum mechanical properties of each layer of two pavement structures (Jiang et al., 2023b).

Index	ASP pavement				Typical pavement			
	Asphalt	Steel	ABS	Gravel	Asphalt	Superpave	ATB	Gravel
Vertical stress (MPa)	−0.04	−0.13	−0.08	−0.03	0.05	−0.06	−0.04	−0.01
Transverse stress (MPa)	−0.28	−0.96	0.22	0.06	−0.36	0.15	0.21	0.02
Longitudinal stress (MPa)	−0.25	0.93	0.28	0.06	−0.24	0.18	0.23	0.02
Vertical shear stress (MPa)	0.13	0.12	0.06	0.01	0.03	0.06	0.02	0.00
Allowable stress value (MPa)	0.20–9.93	174.00	24.50	–	0.20–9.93	–	–	–
Vertical strain (με)	32.25	2.12	−136.89	−216.13	55.09	−38.50	−54.37	−71.94
Transverse strain (με)	−40.03	−5.60	68.71	126.71	−66.15	24.98	40.05	47.13
Longitudinal strain (με)	−29.96	5.40	114.37	136.98	−32.98	32.90	48.23	48.54
Vertical shear strain (με)	−64.06	1.59	74.28	−82.92	17.10	35.83	18.16	−26.53
Allowable strain salue (με)	–	844	11,100	–	–	–	–	–

evident that the difference in maximum strain between the bottom of the asphalt layer and the steel plate layer is 13 με and 14 με, respectively, with opposing strains observed at the bottom of the asphalt layer. The combination of the "asphalt layer + steel plate layer + ABS plastic layer" structure is not conducive to interlayer bonding under the coupling effect of load and temperature.

Fig. 63 depicts the experimental results of the dynamic modulus and phase angle for the SMA-13 asphalt mixture and ABS plastic. The dynamic modulus of the SMA-13 asphalt mixture varies within the range of 620 to 20,000 MPa, while the phase angle remains between 7.2° and 29.7°. In contrast, the dynamic modulus of ABS plastic remains primarily within the range of 1914–2036 MPa, and the phase angle remains below 1°. This suggests that ABS plastic exhibits minimal viscous behavior at the tested temperatures and frequencies, possibly due to the material not reaching a plastic state at the experimental temperature. Notably, at a test temperature of 5 °C, the dynamic modulus of ABS plastic is higher compared to other test temperature conditions. It is evident that both the SMA-13 asphalt mixture and ABS plastic exhibit consistent trends in dynamic modulus variations with temperature and loading frequency. In comparison to the SMA-13 asphalt mixture, ABS plastic is less affected by temperature and loading frequency, demonstrating better temperature stability. As a result, ABS plastic can meet the material requirements of road surfaces under complex conditions involving loads and temperature.

Fig. 64 illustrates the finite element simulation results of various structural layers within the ASP pavement. Analyzing the three-directional stress and strain at the bottom of each structural layer reveals that as the moving load reaches the calculation point, lateral, vertical, and vertical shear strains and stresses at the bottom of the asphalt layer and ABS layer fluctuate within a certain range. However, longitudinal strains are relatively larger, and longitudinal stresses are smaller at the bottom of the two structural layers. Higher stress levels are observed in the lateral direction of the structural layers, which could potentially impact the interlayer bonding over the long term. In other directions, stress and strain maintain good coordination. Table 8 presents the maximum stress and strain values at the bottom of each structural layer for both ASP and typical pavement structures. Comparing the maximum stresses of the two pavement structures, the stress at the bottom of the ABS layer is comparable to that of the typical pavement structure, while the stress at the bottom of the steel plate layer averages 75% higher than that of the typical pavement structure. However, the maximum stress generated within the ASP pavement structure's load-bearing layer remains within 1% of the allowable stress of the materials. Comparing the maximum strains of the two pavement structures, the strain at the bottom of the ABS layer averages 50% higher than that of the typical pavement structure's load-bearing layer, while the strain at the bottom of the steel plate layer is significantly lower than that of the typical pavement structure's load-bearing layer. The analysis indicates that, compared to the typical pavement structure, the load-bearing layer composed of Q345D steel plate and ABS plastic accounts for less than 1% of the allowable stress, effectively bearing irregular stress and strain and enhancing the load-bearing capacity of the structural layers. Consequently, the pavement structure utilizing steel plates and plastic materials exhibits clear advantages.

As a result, the ASP pavement demonstrates reliable load-bearing capacity and durability under the influence of moving axle loads. However, further research is needed regarding the design of structural layer thickness and interlayer bonding treatment (Chun et al., 2015; Yang and Li, 2021). Moreover, the cost of ASP pavement materials is approximately 1.2–1.5 times that of materials used in perpetual pavements, with carbon emissions being only 1/6 of those in perpetual pavements. This innovation aligns with the environmentally friendly nature of prefabricated pavement construction (Qu et al., 2017; Sha et al., 2022b), making it more environmentally friendly. This innovation holds the potential to offer practical solutions for enhancing pavement performance and aligns well with the engineering development goals of low-carbon and environmental sustainability.

3.2. Dynamic mechanical response of road pavement

The study of the dynamic mechanical response of road pavement stands as a pivotal field within civil engineering, encompassing a multifaceted investigation into the mechanical behavior and performance of road pavement materials under dynamic loading conditions. This crucial research area is driven by the continuous strive to enhance the durability, safety, and sustainability of transportation infrastructure, given the profound impact of road networks on societal progress and economic growth. Dynamic mechanical response analysis, as a core pillar of pavement engineering, involves subjecting pavement specimens to cyclic or dynamic loads that simulate the repetitive stresses induced by vehicular traffic. By scrutinizing the intricate interplay between material properties, structural design, and environmental factors that collectively influence the pavement's response to dynamic loads, researchers endeavor to uncover mechanisms governing pavement distress and deterioration under real-world conditions. Two primary research domains emerge within this topic: material characterization and modeling, and pavement structural dynamics. Each plays a distinct role in unraveling the complexities of dynamic pavement behavior.

3.2.1. Characterization of nonlinear behavior in asphalt concrete pavements

At the foundational forefront of dynamic mechanical response research lie endeavors to meticulously characterize the mechanical properties of pavement materials and formulate reliable constitutive models capable of describing their dynamic behavior. Asphalt binders, along with aggregates, undergo intricate mechanical interactions that evolve over time due to varying stress magnitudes and loading rates. Advanced testing techniques empower researchers to quantify essential material parameters, including the complex modulus, phase angle, and dynamic shear viscosity. These parameters provide a crucial foundation for the development of sophisticated viscoelastic and viscoplastic material models. The integration of various viscoelastic and viscoplastic material models, combined with laboratory testing, further aids in constructing material models that accurately capture the time-dependent, nonlinear material response observed under dynamic loading.

3.2.1.1. Material testing methods for nonlinear behavior. The quest to understand the nonlinear behavior of asphalt concrete pavements has been a pivotal focus in pavement research. To accurately represent and predict the mechanical behavior of pavement materials under dynamic loads, a plethora of methodologies and techniques have been adopted by researchers. In the recent past, aiming for a deeper insight into the nonlinear behavior of asphalt concrete, a series of advanced indoor and outdoor testing methods have been introduced. The dynamic shear rheometer (DSR), for instance, has emerged as an essential indoor testing tool, facilitating measurements of the complex modulus and phase angle of asphalt materials across a spectrum of temperatures, stress levels, geometries, and frequencies (Motamed and Bahia, 2011). In parallel, the falling weight deflectometer (FWD) has been widely adopted in outdoor settings to gauge the linear and nonlinear response of pavement structures (Nega et al., 2016).

Venturing beyond the conventional realms of DSR and FWD tests, researchers have explored a variety of other testing methodologies. The triaxial compression test, tailored to assess the mechanical performance of materials under multiaxial stress conditions, mirrors the stress state of pavement materials in the laboratory and under real-world traffic loads (Blanc et al., 2015; Zheng and Huang, 2015). Beam bending tests predominantly target the evaluation of fatigue performance and crack propagation tendencies of asphalt concrete when subjected to bending loads (Adhikari and You, 2010; Sudarsanan and Kim, 2022).

3.2.1.2. Development of constitutive models. In the bid to encapsulate the nonlinear behavior of asphalt concrete, researchers have pioneered several constitutive models. Rooted primarily in viscoelastic or viscoplastic theories, these models accommodate the time and stress dependencies inherent to the material. Among these, the Burgers and generalized Maxwell models, which are prominent viscoelastic models, have been instrumental in portraying the nonlinear behavior of asphalt concrete under dynamic loads (Cheng et al., 2019). Beyond these models, the academic community has recognized models such as the five-parameter model, the Zener model, and the Prony series. These models present robust frameworks for understanding the nonlinear behavior of asphalt concrete (Li et al., 2022i). The five-parameter model, which accounts for both the viscous and elastic behaviors of the material, is adept at representing its response across varied load and temperature conditions (Wang et al., 2013b). The modified Zener model, a streamlined viscoelastic model, is particularly suited for characterizing the asymmetry of dynamic viscoelasticity (Zhang et al., 2023b). The Prony series, a mathematical construct, is harnessed to elucidate the relaxation and creep tendencies of asphalt mixtures (Zhang and Sun, 2022).

In the ever-evolving landscape of pavement research, the past few years have witnessed the emergence of more sophisticated viscoelastic and viscoplastic models tailored for asphalt concrete. These models aim to capture the intricate nonlinear behavior of the material with enhanced precision, especially under varying environmental conditions and loading scenarios. The extended Burgers model, an extension of the traditional Burgers model, incorporates additional elements to better represent the rheological parameters of asphalt concrete which strongly depend on temperature (Judycki, 2018). Another noteworthy model is the fractional derivative model, which employs fractional calculus to capture the phase lag between stress and strain in asphalt materials, offering a more accurate representation of their viscoelastic behavior, especially in the high-frequency region (Xu et al., 2019). Schapery's nonlinear viscoelastic model has also gained traction in recent research. This model is particularly adept at describing the time-dependent behavior of asphalt concrete, especially when subjected to prolonged loading (Chen et al., 2023d). On the visco-plastic front, the Perzyna visco-plastic model stands out. It integrates viscoelasticity with plasticity, making it suitable for materials like asphalt concrete that exhibit both these behaviors under certain conditions. Furthermore, the integration of machine learning and artificial intelligence in model development has opened new avenues. Artificial neural network-based models, for instance, leverage historical data and learning algorithms to predict the nonlinear behavior of modified asphalt concrete with remarkable accuracy (Zhong et al., 2022).

3.2.2. Pavement structural dynamics

Pavement structural dynamics is a pivotal domain that delves into the dynamic interactions between vehicular loads and the foundational pavement structure. Research in this field primarily branches into two main trajectories: understanding tire-pavement interaction mechanisms and the numerical modeling and analysis of pavements' dynamic response to vehicular loading.

3.2.2.1. Tire-pavement interaction mechanisms. This segment seeks to understand the intricate mechanisms through which vehicular loads interact with various pavement materials and structures. Central to this exploration are factors such as tire pressure, tread design, and vehicle speed.

Fluctuations in tire pressure can significantly alter the contact stress distribution on the pavement. For instance, under-inflated tires can lead to heightened contact stress areas, potentially causing premature pavement damage (Xue et al., 2015). Conversely, over-inflated tires might reduce the effective contact area, leading to increased stress concentrations (Arshad et al., 2018). The design intricacies and patterns of tire treads play a pivotal role in modulating the frictional dynamics between the tire and pavement. Recent studies have probed into various tread designs, evaluating their impact on skid resistance and the overall longevity of pavement (Kumar and Gupta, 2021). Innovative tread patterns and materials have been shown to improve water dispersion on wet pavements, reducing hydroplaning risks (Fwa et al., 2009; Cao et al., 2019). The speed at which vehicles navigate pavements significantly influences the dynamic loading and the ensuing pavement response. Elevated vehicular speeds have been linked to a decrease in elastic pavement response in flexible pavements (Mshali and Steyn, 2022). A recent study emphasized the nonlinear relationship between speed and dynamic load impact (Wang et al., 2020f).

3.2.2.2. Numerical modeling and analysis. At the core of pavement structural dynamics is the evolution and application of sophisticated numerical models. These models are meticulously crafted to capture the holistic dynamic response of pavements under vehicular duress. FE modeling offers insights into the structural nuances of pavements under vehicular loads. Recent applications of FE modeling have underscored the ramifications of heavy vehicle loads on rigid and flexible pavements, pinpointing critical stress points and potential areas of failure (Kabir and Hiller, 2021). Fast Fourier transform (FFT) transitions time-domain signals into their frequency-domain counterparts, proving invaluable in discerning the vibrational nuances of pavements under dynamic loads (Li et al., 2020c). FFT has been instrumental in analyzing the resonance frequencies in pavements subjected to varying load types and other parameters (Tang et al., 2020). The wavelet transform has been harnessed to pinpoint and categorize damage in rigid pavements (Das et al., 2022). Combining the wavelet transform with deep learning algorithms has shown promise in detecting pavement distress patterns with remarkable accuracy (Li et al., 2022a, h).

Drawing from these tools and investigative studies, a profound understanding of pavement dynamics is achieved, propelling the objective of refining pavement designs and bolstering the durability of transportation infrastructure.

3.2.3. Challenges and outlook in pavement structural dynamics

The pursuit of understanding the dynamic mechanical response of road pavements, while having made significant strides, is not without its challenges. As the transportation sector evolves with the introduction of heavier vehicles, higher traffic volumes, and the demand for longer-lasting infrastructure, the complexities in pavement dynamics research intensify.

The dynamic behavior of pavements is influenced by a myriad of factors. Natural variability in materials, particularly aggregates, and binders as well as testing methods, results in a variability in pavement characterization and thus leads to challenges in crafting universally applicable models (Dinegdae, 2022). Changing environmental conditions, including temperature shifts, moisture levels, and freeze-thaw cycles, significantly modify pavement material properties, yet their full impact and the establishment of comprehensive databases remain an ongoing research focus (Titus-Glover et al., 2019). Technological advancements, while promising, come with their own set of challenges. Advanced testing and modeling techniques necessitate specialized equipment and expertise, and replicating the vast array of real-world conditions in labs is still a formidable task (JTTE Editorial Office et al., 2021). Furthermore, even with cutting-edge modeling, accurately forecasting long-term pavement performance is a complex endeavor. Various elements, such as the historic state of the pavement, construction standards, and unpredictable traffic loads, add layers of uncertainty and nonlinear relationships (Bukharin et al., 2021).

The horizon of pavement structural dynamics research is expanding with promising prospects. The integration of cutting-edge technologies, such as artificial intelligence (AI), big data, and the internet of things (IoT), is poised to redefine data acquisition, analysis, and predictive modeling in the realm of pavement studies (Dong et al., 2021). In conclusion, while challenges persist, the continuous evolution of technology and research methodologies, combined with a collaborative and holistic approach, will drive the next wave of innovations in pavement structural dynamics.

3.3. Long-term service performance evaluation of pavement

Effective and accurate performance simulation and evaluation is a fundamental tool to establish the performance-based specification (PBS) or performance-related specification (PRS) for pavement infrastructure. Currently, it is still challenging to achieve a reliable approach for long-term service performance prediction under the complicated traffic loading and various environmental impacts (temperature, precipitation, etc.). Compared with the empirical methodology several decades ago, various advanced mechanistic-empirical approaches have been gradually developed, calibrated, and verified with field performance in the past 20 years. This section briefly reviewed the recent progress on the pavement performance simulation approach and its application for long-term service performance assessment. Several mechanistic-empirical approaches and corresponding software (MEPDG, CalME, and FlexPAVETM) are first reviewed, followed by a discussion on the aging and long-term climate impacts on the performance evaluation. It should be noted that various environmental factors could influence the long-term pavement performance although the aging and climate change perspectives are addressed in this work.

3.3.1. Recent developments in mechanistic-empirical approach

3.3.1.1. MEPDG update and related case studies. The mechanistic-empirical pavement design guide (MEPDG), proposed by NCHRP Project 01-37A, has been the primary document for designing new and rehabilitating highway pavements for nearly 20 years (TRB, 2004; Hallin et al., 2004). It utilizes the mechanistic-empirical (M-E) numerical model to analyze input data related to traffic, climate, materials, and structure, estimating damage accumulation and predicting performance over the service life (AASHTO, 2020). Compared to the AASHTO 1993 guide, MEPDG has expanded the range of applicable models and their types, along with advancements in the sophistication of the modeling approaches (TRB, 2004). While empiricism continues to play a role in various aspects of MEPDG, researchers are actively working to incorporate a stronger foundation of fundamental mechanics into its framework. In recent years, new developments have expanded the performance prediction models of the MEPDG. Notably, the introduction of the top-down cracking model and the reflective cracking model. For top-down cracking prediction: in NCHRP Project 1-42A, the VECD-based model has been proposed for predicting crack initiation, while the hot mix asphalt fracture mechanisms (HMA-FM) model has been developed to predict crack propagation (Roque et al., 2009). Furthermore, NCHRP Project 1-52 has presented a fracture-mechanics-based approach for predicting top-down cracking performance, which involves pseudo-J-integrals determination and Paris law calculation, and has been validated and integrated into the MEPDG design process (Lytton et al., 2018). This model comprises various developments covering a mixture of material properties, aging, traffic stress, load spectrum, pavement temperature, thermal stress, crack initiation, crack propagation, finite element analysis, artificial neural network models, and cumulative damage. In addition to the top-down cracking model, one more mechanistic-based model has been integrated to predict reflective cracks in asphalt overlay layers, enhancing the predictability of the MEPDG design software (Lytton et al., 2010). This model utilizes the stress intensity factor-based Paris law to simulate reflective cracking under both traffic and thermal conditions, resulting in a performance evaluation tool for asphalt pavement rehabilitation design (Lytton et al., 2010). After these advancements, extensive research has been conducted globally to promote and apply the MEPDG, encompassing regions such as Ontario, Wyoming, Iowa, and others (Zhou et al., 2013; Kim et al., 2014; Ng et al., 2021; Abdelfattah et al., 2022). The MEPDG has found wide application in predicting the long-term performance of roadways. Notable applications include predicting the low-temperature cracking performance of rubber-modified asphalt pavements, assessing the impact of glass fiber reinforcement on flexible pavements, simulating the effect of polymer-modified asphalt on the rheological properties, etc. (Al-Khateeb et al., 2020; Rabab'ah et al., 2021; Zborowski and Kaloush, 2011).

3.3.1.2. Consider other 2nd generation analysis methods. While the MEPDG has undergone significant development and has been extensively used for pavement performance prediction, various other analysis methods have also been developed and employed for this purpose. Two notable design systems in this context are CalME and the Texas asphalt concrete overlay design system (TxACOL). CalME, the mechanistic-empirical structure analysis program for flexible pavement developed by the pavement program's office of asphalt pavements in collaboration with the University of California Pavement Research Center (UCPRC), is utilized for designing new and rehabilitated asphalt pavements. Using the damage mechanics, the Incremental-Recursive models in CalME were validated and calibrated using performance data from heavy vehicle simulator (HVS) tests completed by UCPRC between 1995 and 2004 and WesTrack experiment from a closed-circuit test road facility constructed at the Nevada Automotive Test Center (NATC) (Ullidtz et al., 2005, 2006; Wu et al., 2021a). Mateos et al. (2012) successfully utilized the CalME model to replicate the evolution of asphalt layer stiffness during a full-scale test. This replication considered factors such as damage, traffic-induced densification, and aging. TxACOL was developed for the Texas Department of Transportation (TxDOT) under Research Project 0-5123 (Zhou et al., 2008). The system integrates the M-E reflection cracking model based on Paris law and the VESYS rutting model (Zhou et al., 2009). Hu et al. (2014a, b) further developed and calibrated the performance prediction models within the TxACOL system. Karki et al. (2022) applied the TxACOL model to simulate reflective cracking performance across 2700 asphalt overlays under various conditions, encompassing different climates, traffic levels, overlay thicknesses, pavement types, and aggregate/binder combinations. The simulations aimed to assist in selecting appropriate asphalt types for pavement overlay projects, and the new PG binder selection catalog was recommended for asphalt overlays from their study.

3.3.1.3. FlexPAVE development and its application in PRS technology. In parallel with the MEPDG effort, another pavement analysis tool named FlexPAVE was developed from layered viscoelastic pavement analysis for critical distresses (LVECD). Initially, the program proposed the multiaxial viscoelastoplastic continuum damage (MVEPCD) model for asphalt concrete to predict its behavior under both compression and tension (Kim et al., 2009a). Subsequently, a performance prediction model for pavement design and maintenance was introduced, based on the LVECD approach (Park et al., 2014b). Furthermore, the Fourier finite element (FFE) method was integrated to predict crack and rut evolution under moving loads (Eslaminia and Guddati, 2016). In a following-up study, Wang et al. (2016b) conducted a comparative analysis between the predictive outcomes of LVECD and Pavement ME, demonstrating that the simulation results of LVECD exhibited a stronger correlation with field performance data. To date, researchers from various countries have extensively utilized the FlexPAVE program for pavement performance prediction studies. For instance, in China, Cao et al. (2016) identified a dependency between the fatigue performance of asphalt pavement and its thickness. In Brazil, Bueno et al. (2022) research highlighted that increasing the thickness of the asphalt layer effectively reduced the cost-to-fatigue life ratio through the FlexPAVE simulations. In Italy, Spadoni et al. (2022) investigated the fatigue resistance of polymer-modified asphalt mixtures using FlexPAVE as a performance evaluation tool.

Moreover, FlexPAVE serves as a crucial performance evaluation tool in PRS in which the primary objective is to establish a link between volumetrics and performance, thereby accentuating the significance of performance in a more pronounced manner when compared to the conventional Superpave mixture design approach (Wang et al., 2019a). The performance-volumetric relationship, which is a pivotal relationship requiring calibration during balanced mix design (BMD), can be established through analysis of cracking and rutting simulation outcomes obtained from FlexPAVE (Wang et al., 2022c). Currently, the PRS methodology formed based on FlexPAVE simulations has undergone thorough investigation and widespread application in both research and engineering contexts (Jeong et al., 2020; Wang et al., 2021a; Saleh et al., 2023).

3.3.2. Environmental impact on pavement performance

3.3.2.1. Aging effect. Aging has long been recognized as a major driver of distress for asphalt concrete and pavement. Either short- or long-term aging causes the asphalt material to be stiffer with more embrittle, which further affects the pavement's durability. In past decades, an important effort has been made to quantify the aging impact on the multiscale properties of asphalt concrete from the material level, which can be found elsewhere (Zhang et al., 2021a). More importantly, the need to model the pavement structure performance with the aging in progress is becoming significant for a better understanding of the field pavement deterioration over its service life.

One recent systematic effort completed in the NCHRP 09-54 project addressed this concern, in which a pavement aging model (PAM) is developed, verified, and compared to the global aging system (GAS) model used in the MEPDG approach (Saleh et al., 2022). The PAM applies to both conventional hot mix asphalt (HMA) and other materials (i.e., warm mix asphalt (WMA), reclaimed asphalt pavement (RAP), and polymer-modified asphalt (PMA)). For most of the evaluated pavement sections, the PAM-based performance predictions agree reasonably well with the field core measurements, except for some field sections that contained RAP and/or WMA (Saleh et al., 2022). Generally, the proposed PAM approach can capture the material aging impact on the structure level and promising to be implemented into the FlexPAVETM software.

Meanwhile, a long-term aging model for asphalt pavements using a morphology-kinetics-based approach has also been proposed in recent years (Zhang et al., 2019a). This methodology focuses on the binder viscosity as the target property and makes use of combined kinetics and mixture morphology framework for the model development. The new model also provides more reliable binder viscosity prediction under long-term aging than the traditional GAS model.

3.3.2.2. Climate change impact. Growing research from the earth science field has demonstrated that the global climate is changing negatively and a common challenge has been recognized among countries in the world. Several government agencies and transport administrations already conducted a preliminary study on the potential climate change impact on the transportation system in the early 2000s (Norwell, 2004; Gaspard et al., 2007; Humphrey, 2008; Willway et al., 2008). Especially, with expecting long-life infrastructure engineering (i.e., asphalt pavement), the transportation infrastructure faces inevitable risks from the climate change impact. In this subsection, the impacts of both the long-term evolution of the climate environment (temperature, precipitation, etc.) and extreme climate events (floods, heat waves, etc.) are presented.

Firstly, global warming is one of the main features of future climate change. The long-term exposure of road infrastructure to the environment negatively impacts its service performance with future temperature increases. The evaluation of the impact of rising temperatures on the performance of road infrastructure is currently addressed in terms of rutting and cracking of asphalt pavements (Miao et al., 2022; Zhang et al., 2022b). Furthermore, the impact of the future rising temperatures under various scenarios on the cost increase of road infrastructure maintenance is also addressed, if the climate change concern is not taken into account at the initial stage of the pavement project plan and design (Mallick et al., 2014; Underwood et al., 2017). Secondly, climate change also causes changes in the rainfall trends and material design and structure design should be adjusted to the significant increase in precipitation due to climate change (Swarna et al., 2022). Some scholars have proposed a method to quantitatively evaluate the risk of pavement under extreme precipitations based on risk analysis, brittleness modeling, and cost estimation (Lu et al., 2018). In addition, the road infrastructure in coastal areas is susceptible to the impacts of climate change-induced sea level rise, resulting in a reduction in its service life (Knott et al., 2017).

The occurrence of extreme weather caused by global climate change also increased in recent years. The increase in the frequency of floods and heat waves can lead to the accelerated potential of pavement distress and pose a serious challenge to the reliability of flexible pavement (Matini et al., 2022). There is an increasing need to adequately design pavement thickness and drainage systems and implement post-flood traffic control (Wang et al., 2015a). The subgrade materials with appropriate gradation to ensure adequate hydraulic conductivity and/or thicker surface layers are to avoid serious degradation and keep pavement resilient in flood-prone areas (Nivedya et al., 2020).

3.4. Life cycle assessment

3.4.1. Benefits of using life cycle assessment (LCA)

Environmental life cycle assessment (LCA) was developed in the 1970s by the chemical industry which adhered to the ‘polluters pay’ principles and believed the high-polluting products or processes in the supply chain should be held accountable for their environmental footprint. This calls for a holistic approach to assessing the many environmental impacts that a product or a service may have over its lifecycle. Pavement construction and maintenance are known for their high demand for mineral resources. Their long service life and profound effects on user costs require their design and procurement to be considered by much wider stakeholders. Using LCA, the high-impact product or process can be identified, such that actions can be prioritized to reduce their impacts. This will ensure the 'hot spot' area can be tackled effectively where changes in practice will make a substantial difference. This is necessary to use the R&D resources efficiently to tackle climate change and other environmental problems. For that purpose, a simplified LCA is frequently undertaken.

Another strength of LCA compared to a single criterion assessment such as carbon accounting, is the holistic approach that includes all, instead of one or few, environmental impacts. It is not difficult to understand that trade-offs often exist when comparing two products. For instance, one product may have less carbon but give more atmospheric pollutants. Claims of sustainable pavement based simply on one aspect such as materials saving or energy reduction are disputable and hard to compare. In the 3rd phase of LCA, different impacts are quantified and characterized by pre-defined conversion factors, such as global warming potential (GWP). In doing so, decisions can be made on an informed basis. For new materials (e.g., warm mix asphalt) and emerging construction techniques (e.g., pre-fabricated pavement), contractors need to ensure that reduction in the construction impacts will not be offset by potentially higher impacts at the operation/maintenance stage or through the supply chain.

In addition to research in bio-fuels which deems a promising alternative to fossil fuels, there is also experimental work in the field of bio-binders that process waste from agriculture (e.g., animal waste) or industry (e.g., tire rubber or plastics) into binders that replace bitumen to bond aggregates in pavement. LCA of this kind of pavement will inevitably expand the system boundary to include the upstream harvesting and refining activities. The gains in saving petroleum and using "carbon-neural" products will be assessed against the burdens incurred from the upstream, and perhaps more importantly impacts from land use change. In doing so, LCA will help to avoid shifting problems from one sector to another and to provide evidence for policy making that often influences multiple sectors of transport, energy, and farming.

3.4.2. Methodological choices in road pavement LCA

There are four phases in an LCA study, namely goal and scope definition, inventory analysis, impact assessment, and interpretation. The main work includes the development of a lifecycle inventory, in which all the significant environmental inputs (e.g., aggregates in tonnes, diesel in litres) and outputs (e.g., CO_2 in kg) will be quantified and compiled. Road pavement projects differ from one another in terms of materials and equipment use, transport, and placement methods. In general, the inventory results are difficult to interpret or compare, thus a LCA often proceeds to the impact assessment phase (although not every study will), such that results can be presented in a predefined way that supports comparison or further analysis. In the development of functional pavement, the novel products (e.g., self-healing agents) or processes (e.g., energy harvesting modules) may give rise to environmental impacts in the production or create legacy issues at the end-of-life (EOL). It is therefore necessary to quantify the additional impacts as well as savings. Some examples that LCA can help with the functional pavement include.

1) Choose the materials, such as recycled vs. virgin.
2) Compare the design and intervention, such as pavements of different design life or maintenance profile.
3) Evaluate the construction techniques, such as recycling in-situ, modular pavement.

The key to the success of using LCA in comparative studies is the definition of a functional unit that can best represent the role of the product. The functional unit in road pavement LCAs can be defined as the length by the width of the carriageway carrying the design traffic. Durability, or pavement service life, is another important element to ensure a fair comparison. An example of a well-defined functional unit can, therefore, be a surface area of pavement to carry the design traffic for a defined period (including necessary maintenance and rehabilitation). Road pavement LCAs can be cradle-to-gate (from raw materials to the product, e.g., asphalt, concrete), to-laid (including construction), or to-grave (the whole lifecycle including maintenance, use, and demolition). The choice of a cradle-to-grave LCA needs to deal with the complexity of the use phase and uncertainty in disposal scenarios. The boundary setting needs to be transparent and it takes a lot of subject knowledge to set an appropriate boundary. It is important to consider the goal of the study, and for which its results may be used in making decisions.

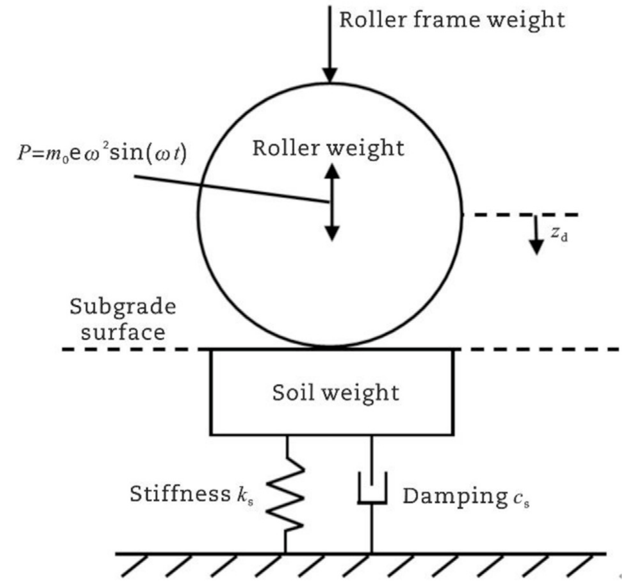


Fig. 65. Single-degree-of-freedom dynamics model.

Allocation of environmental burdens, among co-products or at end-of-life (EOL) recycling, should be declared because they too can make a significant difference to the results of an LCA study. ISO14040 specifies that allocation can be made based on physical property (e.g., mass, volume) or economic value of the products. In general, energy-related emissions can be calculated with relatively high accuracy, by tracing the consumption back to the generation process (e.g., electricity from a power station) and using standard emission factors. Non-energy-related emissions, however, are difficult to measure and quantify, and they are generally not included in the life cycle inventory because relevant data are not available. However, the omission of non-energy use emissions such as CO_2 could lead to substantial over/under presentation of the inventory results. Recent studies are paying increasing attention to the emissions from brake and tire wear, the latter is directly related to pavement mix design, aggregate mineralogy, and surface condition. This should warrant new research aiming to reduce non-exhaust emissions.

3.4.3. LCA resources and challenges

The LCA of road pavements has been developing for more than 25 years. The first application of LCA to road pavements was made in Europe in the late 1990s. Since then, a number of life cycle inventories of pavement materials, such as bitumen and Portland cement, have been developed by material associations. It is a challenge to use the findings from different LCA studies and maintain comparable levels of accuracy and industrial consensus. The early work has been strengthened by including recycled and secondary materials, a growing practice in response to stakeholders' calls for sustainable construction. More recent LCA research is focused on methodological choices, the use of novel binders or aggregates, and integration with pavement asset management.

Commercial LCA software will assist in the modelling of data and presentation. The use of these tools will improve the efficiency of modelling, and provide a means of communication between LCA practitioners. Standard (sets of) rules, known as product category rules (PCR), need to be further developed and accepted by the road sector, as in EN 15804. When time and budget allow, it is always advisable to cross-check the results from different tools, test and calibrate the LCA model, and verify any benchmark figures for a typical practice in a specific technical, environmental, and economic context.

In summary, the main challenges of applying LCA to road pavement include the following aspects, many of which also represent areas for further work.

1) Define the functional unit, consider which lifecycle stages to include (cradle-to-gate, to-laid, or to-grave).
2) Decide what environmental impacts to be considered, being careful of limitations may lead to decisions that risk other impacts increasing.
3) Include, where data permits, the non-energy related emissions in the modelling, be transparent in the data source and validity.
4) Establish the inventory data on secondary materials, investigate the appropriate allocation methods.
5) Predict the life expectancy, and the end-of-life disposal, of pavement layers made using recycled and other innovative materials.
6) Include the effects of road maintenance works on traffic flow and the additional fuel use and emissions that result, helped by traffic simulation modelling.
7) Explore the relations between pavement condition and vehicle fuel consumption.
8) Assess data quality. Primary data when available should be used, which however may make the study very specific to one situation if not representative. Sensitivity analysis helps to identify the effects of data, assumptions, and methodological choices on the final results.
9) Consider which tool to use, either using an existing tool or creating a bespoke one. Whatever the decision, understand what the underlying assumptions are, including in-built datasets.
10) Explore the development of PCRs or the use of LCA results in the environmental product declaration (EPD), which is possibly the most important step in allowing comparable and transparent pavement LCA results to be used in decision-making.

4. Pavement construction equipment and advanced technology

Pavement construction equipment includes paving, compacting, milling, regenerative, and other related equipment. Many new pavement construction equipment and technologies have developed in the past years.

4.1. Road intelligent compaction equipment and technology

Compaction is general in road construction for the roadbase, stable layer, and surface layers. Intelligent compaction technology is developed and used in road construction to improve quality and productivity. The research mainly concentrates on the compaction model, compaction degree detection, and compaction parameters control in the intelligent compaction area, and compaction degree detection is the base of intelligent compaction control. Adjusting the roller's operation parameters according to the compaction degree is the typical method in intelligent compaction control. Although the compaction degree detection method has achieved significant progress in the past ten years, more research should be done to extend intelligent compaction because of the variety of construction materials.

4.1.1. Research on the dynamic response of vibration compaction

Based on the dynamic theory, the dynamic model of "roller-compacted material" is established to obtain the response of the compacted structural layer. It is a meaningful way to study the dynamic response of vibratory compaction and analyze its characteristics. Since the 1970s, experts and scholars have carried out a large number of research on the dynamics model of different road structure layers, the dynamics model under different vibratory roller motions, and the multi-degree-of-freedom dynamics model.

4.1.1.1. Dynamic model of different road structure layers. The roadbed usually consists of a specific gradation of soil and gravel materials. Its mechanical properties are less affected by temperature. The dynamic model of the interaction between the wheel and the roadbed (Fig. 65) is the earliest proposed and is comparatively mature (Raper et al., 1995). The development process of the roadbed dynamic model has gone through three stages: elastic, viscoelastic, and viscoelastic-plastic. In the elastic principal model, Foster (1980) proposed a two-degree-of-freedom dynamic model based on the assumption that the vibrating wheel always acts on the elastic soil body and simplifies the dynamic system into two concentrated weights: the upper frame and the vibrating wheel. The interactions between the upper frame and the vibrating wheel and between the vibrating wheel and the soil are described by the parallel combination of springs and dampers (Foster, 1980). In viscoelastic intrinsic models, two asymmetric hysteresis models based on the triangular hysteresis model and Bouc-Wen model of soil were established by Grabe (1993) and Shen and Lin (2008) respectively, for the case where the different mechanical properties of the roadbed soil cause material nonlinearity in the process of loading and unloading.

Asphalt mixtures have complex nonlinear rheological properties and are affected by temperature changes in the compaction process. It is also affected by the characteristics of the sub-layer, such as stiffness and structural integrity. However, considering the influence of the above factors in modeling will significantly increase the complexity of the model. So, the dynamic interaction model between the vibrating wheel and the asphalt surface layer is still in the primary stage. Liu et al. (2009) selected the Burgers model to describe the rheological properties of asphalt mixtures to reduce the number of parameters and the difficulty in solving the dynamic model. They designed the loading test to solve the parameters of the rheological model (Liu et al., 2009). Beainy et al. (2013, 2017) simulated the periodic deflation of the vibrating wheel by adding degrees of freedom. They established multiple regression relationships between the model parameters and void ratio and temperature to simulate the real-time variation of the parameters. The mixture

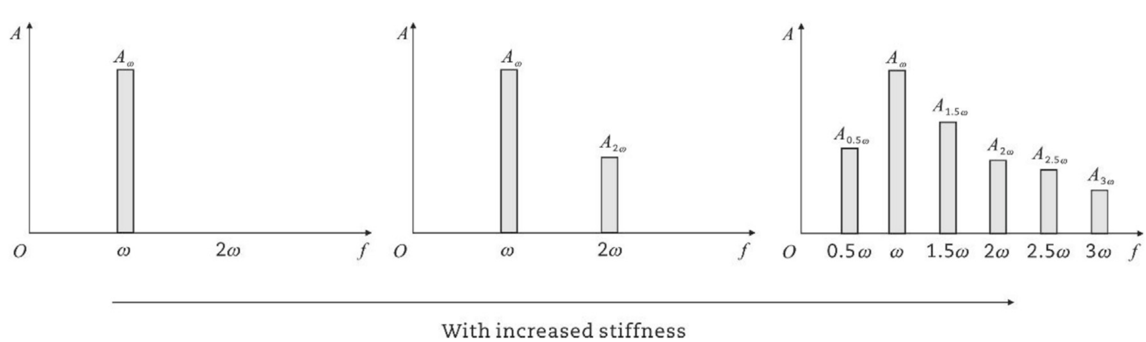


Fig. 66. Harmonic and subharmonic components of the acceleration signal.

under the vibrating wheel was segmented to simulate the roller travel process, and spring elements were added under the asphalt layer to simulate the stiffness of the sub-layer. At the same time, spring elements were added between adjacent blocks to simulate the horizontal shear resistance. After considering the influence of the above factors, a more realistic dynamic model is constructed. Based on the dynamics model solution, the critical influencing factors on compaction quality are analyzed (Beainy et al., 2013, 2017; Imran et al., 2015).

4.1.1.2. Dynamic modeling of different roller motion modes. Fukami et al. (2006) investigated the friction coefficient of the vibratory wheel and the compacted material and the deformation characteristics of the vibratory wheel weight on the compacted material by modeling the dynamics of the vibratory wheel in the two cases of driving and traction. The results showed that the self-weight of the vibratory roller is the most important factor affecting the compacted structural layer (Fukami et al., 2006). Tian et al. (2003) summarized several oscillatory compaction dynamics models, including the single-degree-of-freedom oscillating roller vibratory wheel-roadbed system dynamics model, the staged vibratory roller-roadbed system dynamics model, and the staged oscillating roller-roadbed system dynamics model (Tian et al., 2003).

4.1.1.3. Multi-degree-of-freedom dynamics model. Gong (2013) took the 12-ton intelligent vibratory roller as the analysis object and constructed a four-degree-of-freedom overall dynamic model. He also analyzed the relationship between soil compaction and the vibrating wheel acceleration of the roller, and the influence of vibration frequency, line load, and other parameters on the compaction performance of the roller (Gong, 2013). By summarizing the classical dynamic model, Tong (2007) made a reasonable simplification of the "roller-soil" system, established a five-degree-of-freedom dynamic model, and derived the "roller-soil" system through the Lagrangian dynamic equation. Huang et al. (2012) established a seven-degree-of-freedom dynamics model and differential equations of vibratory roller motion based on Newton's laws of motion. They transformed the differential equations of the roller into a model that can be simulated through the state-space method in Matlab/Simulink. The result showed that using state space method modeling simplified the programming process and improved the quality and reliability of programming (Huang et al., 2012).

In summary, the application of dynamic modeling in road compaction has been developed so far, and the dynamic models of vibratory rollers in two cases of driving and traction and the dynamic models of various oscillating rollers have significantly been developed. Several experts and scholars have studied the dynamic models of the roadbed system and the asphalt surface layer. The dynamic interaction model between the vibrating wheel and asphalt pavement is constantly improved. Existing research has also initially obtained the change rule of compaction effect under different temperatures, asphalt layer thickness, and nature of the base layer.

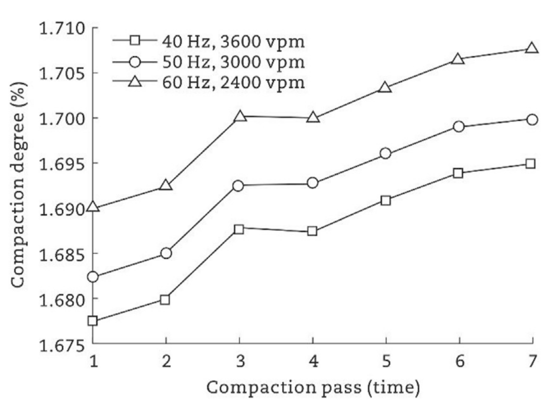


Fig. 67. Variation of compaction quality with excitation frequency.

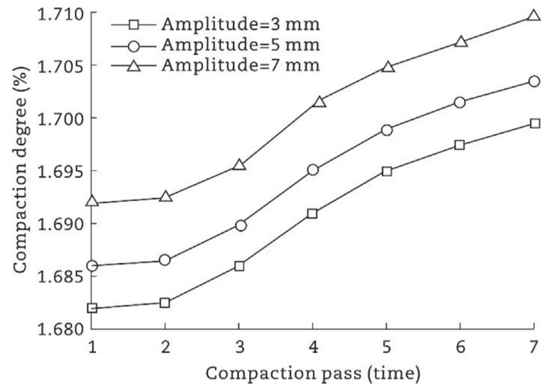


Fig. 68. Change of compaction quality with the amplitude.

4.1.2. Research on intelligent compaction control index and calculation method

The basic principle of intelligent compaction quality detection is to characterize the compaction degree based on the relationship between dynamic response and compaction quality. Therefore, the core of intelligent compaction technology is to calculate the corresponding compaction quality index based on the dynamic response (Zhao, 2015). At present, there are various compaction quality control indexes in intelligent compaction technology, which can be divided into two categories. One is the relative compaction index, which is not an independent parameter only reflecting the nature of the compaction material, and its value is also affected by the working parameters of the compaction equipment (Zhao, 2016). The other is the absolute compaction index, which is theoretically removed from the influence of the relevant parameters of the roller, and it is an independent parameter only related to the nature of the compaction material (Zeng, 2016).

4.1.2.1. Relative compaction index. Relative compaction indexes include CMV (Yu et al., 2014a, b), CCV, and THD (Ma et al., 2018; Wang et al., 2019a, b, c, d). CMV is a compaction index proposed by Dynapac, and it is also the earliest continuous compaction index. In 1976, Dynapac first proposed the compaction meter method to realize continuous compaction monitoring. This compaction meter can be directly assembled on the roller, and its needle can indicate the compaction degree of the crushed material. The compaction meter's index is called compaction meter value (CMV). CMV is calculated as the ratio of the amplitude of the second harmonic component in the spectrogram of the acceleration signal to the amplitude of fundamental frequency, reflecting the degree of distortion of the acceleration signal (Yu et al., 2014b). The CMV calculation formula is shown in Eq. (2). Considering that there may be more spectral components in the acceleration spectrogram at the later stage of compaction, using only the second harmonic component may not be accurate enough. Therefore, more spectral components are introduced into the expression, resulting in the CCV of Sakai, Japan, and the THD proposed by Mooney (Wang et al., 2019d), and the formulas for the calculation of CCV and THD are shown in Eqs. (3) and (4). Harmonic ratio type calculation principle is shown in Fig. 66.

$$\mathrm{CMV}= C\frac{A_{2\omega}}{A_{\omega}} \tag{2}$$

$$\mathrm{CCV}= C\frac{A_{0.5\omega}+A_{1.5\omega}+A_{2\omega}+A_{2.5\omega}+A_{3\omega}}{A_{0.5\omega}+A_{\omega}} \tag{3}$$

$$\mathrm{THD}= C\frac{\sqrt{A_{2\omega}+A_{3\omega}+\cdots+A_{N\omega}}}{A_{\omega}} \tag{4}$$

where C is coefficient, A is the amplitude, ω is the angle frequency.

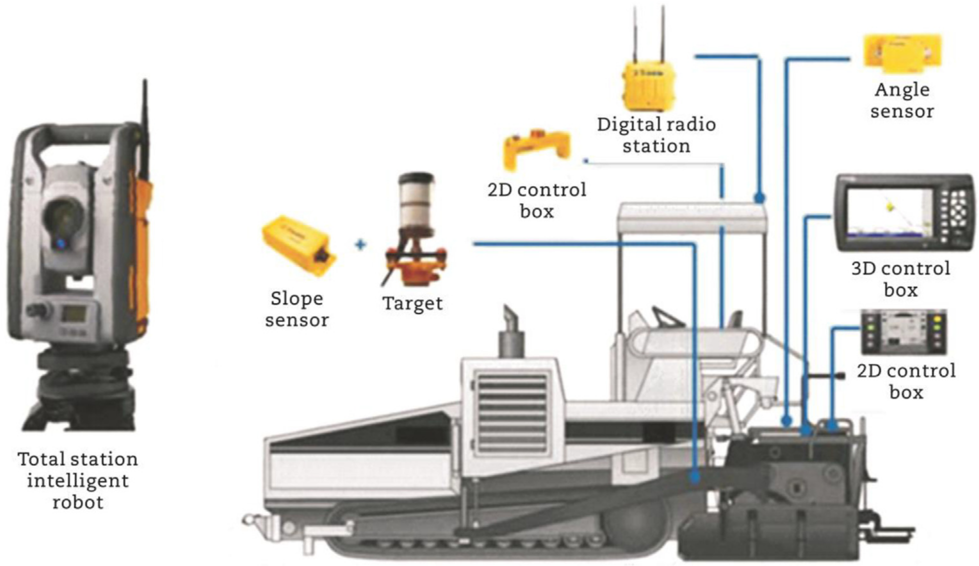


Fig. 69. 3D paving system composition.

4.1.2.2. Absolute compaction index. The absolute compaction index mainly refers to the vibration modulus Evib, which is transformed from the stiffness coefficient k_s based on the Lundberg solution (Foster, 1980). The vibratory modulus index has two main advantages. One is that the calculation results are theoretically not affected by the working parameters of the roller. Fang (2021) combined the finite element method and orthogonal experimental design and verified the index value under different combinations of excitation parameters. The results show that in the common range of the project, the change of the excitation parameters does not significantly affect the accuracy of back-calculating the vibratory modulus. The second is that the vibratory modulus reflects the modulus characteristics of the compacted material, and theoretically, it is related to the material's elastic modulus.

In summary, the absolute compaction index Evib has better application prospects than the relative compaction index (Xu et al., 2012; Kenneally et al., 2015). However, at present, the accuracy of Evib is insufficient and not widely used.

4.1.3. Research on global optimization mechanism of intelligent compaction working parameters

The global optimization mechanism of compaction parameters can give the optimal values of current working parameters according to the real-time changes of mechanical properties of compaction materials, thus improving the quality and efficiency of compaction. The global optimization mechanism of working parameters mainly consists of establishing the constraint method of operating parameters and the global optimization model.

4.1.3.1. Working parameter constraint methods. Working parameter constraints based on machine-material decoupling avoidance are a prerequisite for using global optimization methods, and they can be used in conjunction with construction parameter global optimization methods (Mooney et al., 2010). Both Ammann's ACE Plus System and BOMAG's Variocontrol System introduce "machine-material" decoupling monitoring while using a global optimization method based on a target pass value, i.e., as soon as the compaction metrics reach the preset target value, the amplitude is reduced in the pass zone to avoid over-pressurization (Anderegg and Kaufmann, 2004). In addition, Ammann provides a set of optimization methods for excitation parameters based on contact force control: according to the preset three contact force levels, one of them is selected as the contact force target value according to the compaction degree in practice, and the amplitude of excitation force is adjusted based on this level.

4.1.3.2. Global optimization mechanism. The global optimization method focuses on optimizing the excitation parameters (amplitude of excitation force, frequency of excitation) and travel parameters (number of passes, speed of rolling) of the roller, ignoring the influence of the type of mixture and environmental conditions on the compaction quality. The current research has formed a unified conclusion on the influence mechanism of each parameter on compaction quality. The effect of excitation frequency on compaction quality is related to the intrinsic frequency of the asphalt mixture. The variation of compaction quality with excitation frequency is shown in Fig. 67. According to the resonance theory, when the excitation frequency is consistent with the intrinsic frequency of the mixture, the mixture resonates, the aggregates separate from each other, and the internal friction is significantly reduced. The compaction effect reaches the best (Shen et al., 2021).

The internal frequency of asphalt mixture is usually 40–70 Hz and increases with compaction (Zhao et al., 2021a, b). Therefore, in compacting the asphalt surface layer, the natural frequency of the mixture is the best reference for excitation frequency, and its value needs to be adjusted continuously with the compaction process. The amplitude of the excitation force also affects the compaction quality, as shown in Fig. 68.

After determining the relationship between compaction quality and compaction parameters, such as excitation frequency, excitation amplitude, number of rolling passes, and rolling speed, the compaction quality prediction model considering the roller working parameters is further constructed to establish the mapping relationship between the roller working parameters and compaction quality. Finally, the global optimization model of construction parameters is established. The current study mainly establishes the compaction quality prediction model by the empirical regression method. The empirical regression method can be subdivided into two types. One type is adopting a multiple regression analysis method to establish the relationship between compaction parameters and compaction density, and then adopting a nonlinear regression method to establish the correlation between compaction energy density and compaction degree, to indirectly realize the real-time prediction of compaction quality by compaction parameters (Cao et al., 2021c; Ma et al., 2022c, d). The other type, including artificial neural networks and other algorithms, is used to establish the empirical regression relationship between compaction parameters and compaction quality, which directly realizes the real-time prediction of compaction quality by compaction parameters (Xue et al., 2021; Zhao et al., 2022c).

In summary, the global optimization mechanism based on empirical regression circumvents the complex mechanical analysis. However, it is difficult to ensure the complex engineering universality of the model

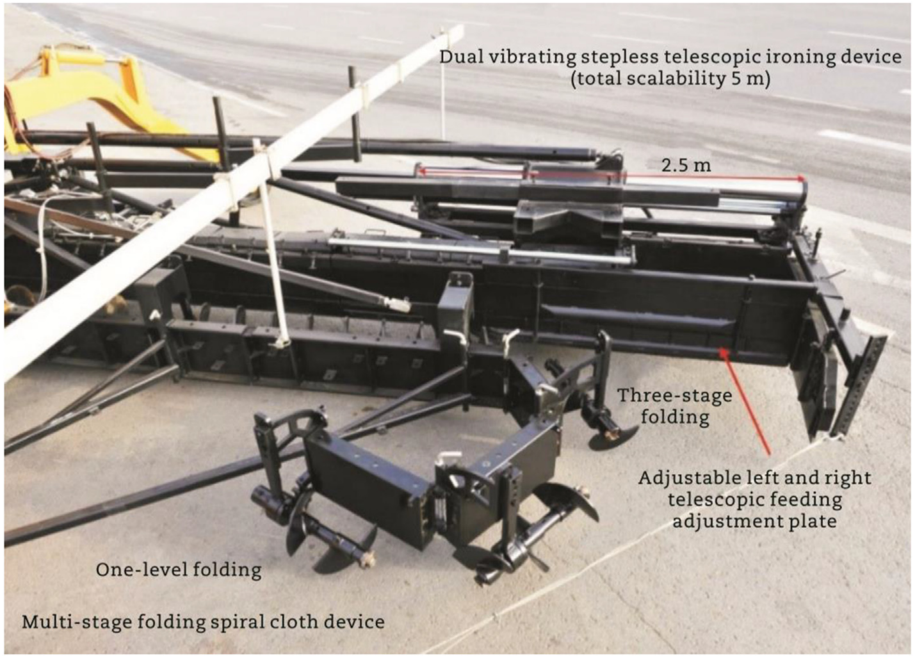


Fig. 70. Anti-segregation extension screed with multi-stage folding screw conveyor.

under the condition of lacking mechanical principle support. It restricted the application of the global optimization model in practice and led to the apparent severance between the existing optimization model and the global optimization requirements of practical applications.

4.2. Road intelligent paving equipment and technology

Asphalt concrete paver is the leading mechanical equipment for asphalt paving operations. It spreads the mixture evenly on the roadbed or pavement base according to the shape and thickness and gives preliminary tamping and leveling to form a pavement base or surface layer. In mechanized construction, the asphalt paver is one of the indispensable machines widely used in asphalt paving of highways, urban roads, docks, and large parking lots (Jiao, 2002). In the past several years, paving equipment and technology have made significant progress, such as 3D intelligent paving technology and equipment, variable-width paving technology and equipment, and anti-segregation paving technology. Unmanned pavers and rolls have been adopted in asphalt pavement construction in some projects in China.

4.2.1. 3D intelligent paving technology and equipment

3D, also known as three dimensions, refers to the three dimensions of space. 3D paving relates mainly to three directions: elevation, thickness, and width. 3D paving technology uses an electronic total base station to track the optical targets installed on the paver, obtaining millimeter-level positioning accuracy. The positioning data is transmitted in real-time to the paver control system through a radio station. The control system compares the airborne 3D design elevation with the actual value and transmits the generated elevation correction information to the hydraulic control system. The hydraulic system drives the hydraulic cylinder to pull the screed to the designed elevation and slope, thus achieving automatic control of the paver (Gao et al., 2022).

4.2.1.1. Research actuality. As early as the 1990s, developed countries, such as Germany and the United States, began researching digital construction technology. Topcon invented the first generation road 3D digital construction control systems in 1999, with positioning signals provided by a total station. In 2005, Topcon invented the second-generation road 3D digital construction control system. VOGELE Navitronic Plus 3D automation control technology can fully automatically control the walking direction of the paver, which means the paver can travel automatically along the designated route as a laser total station or GPS locates it. Swiss Leica has innovated the pave smart 3D control system based on traditional paving technology, widely used in Europe and America. Some highway projects in China have used 3D paving technology in asphalt pavement construction. However, there are still certain limitations in the 3D intelligent paving construction technology,

Fig. 71. Continuous widening paving of Hong Kong–Zhuhai–Macao Bridge.

Fig. 72. Installation of rubber baffle in screw gearbox.

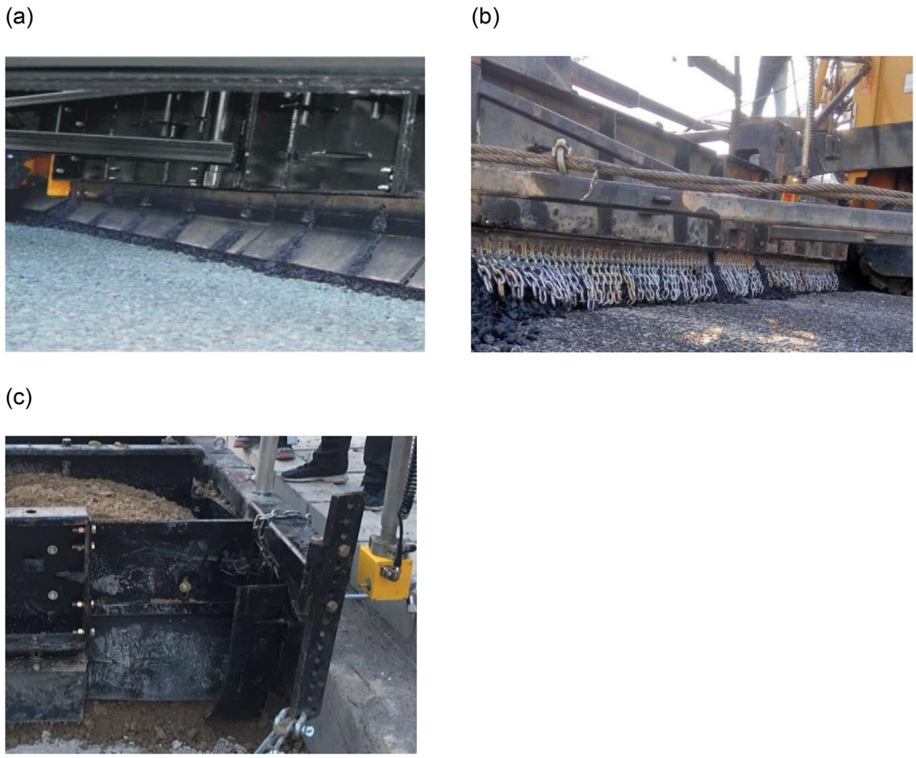


Fig. 73. Anti-segregation device of paver. (a) Flexible rubber sheet. (b) Chain baffle. (c) Anti-segregation baffle for unloading port.

such as being susceptible to the compaction quality of roadbeds and the construction environment.

4.2.1.2. System composition. The 3D paving system mainly consists of three parts: mechanical part (paver), hydraulic system, and automatic control system, as shown in Fig. 69.

The automatic control system includes an intelligent total station, slope sensor, angle sensor, 2D control box, target, 3D control box, digital radio, etc. The 3D control paver uses an intelligent total station as the positioning device, mechanical structure as the support, onboard computer as the core, control converter as the processing amplifier, engine as the power, hydraulic system as the power conversion device, and screed as the work tool. The leveling operation is divided into three stages: establishing a 3D road surface model, benchmark measurement, and paving operation.

4.2.1.3. Technical advantages and development trends. 3D paving technology can accurately control different construction stages to reduce engineering errors and has the characteristics of high precision, intelligence, and pilelessness. Many problems in traditional paving technology can be solved by intelligent and automated operation.

3D paving technology has been widely used in new highway, airport, and square pavement projects (Gu et al., 2021). With the development and application of 5G technology, 3D paving technology can also be integrated with wireless communication technology and big data platforms to control the entire project construction.

4.2.2. Variable width paving technology and equipment

Road construction, especially on mountainous roads, often encounters tunnels, bridges, and culverts. The width of the road inside and outside the tunnel, bridge, and culvert is different, so variable-width paving is necessary. The variable width paving needs the paver to change the screed width according to the requirements. The screed extension forms include mechanical extension and hydraulic extension. The mechanical extension screed has high paving accuracy, but the width cannot be changed continuously. The width of the hydraulic extension screed can be adjusted continuously by the hydraulic cylinder, which is easy to operate and labor-saving and has superior performance in variable-width paving. However, the width of the screw conveyer in front of the screed can only be mechanically changed, usually set according to the width of the tunnel. The paving quality is guaranteed in the tunnel, bridge, and culvert. However, due to the short screw conveyer, there is a lack of materials at both ends when paving a wider pavement, affecting the pavement's flatness and compactness.

The DT2000 paver, developed by Shaanxi Zhongda Machinery Co., Ltd., adopts an anti-segregation extension screed with a multi-stage folding screw conveyor (Fig. 70). The screw conveyor can realize three-stage folding when the screed is retracted. The total extension width is 5 m, which solves the defect of the traditional paver in variable-width paving without a screw conveyor.

The traditional asphalt paver can only retract within a small range (less than 0.75 m). However, the dynamic widening and anti-segregation paver have a more widely variable width paving capacity (more than 2.5 m on both sides). At the same time, the original disassembly and assembly time is reduced to 2 min from at least 2 h, which ended the history of frequent disassembly and assembly of screeds for variable width paving at bridges, tunnels, fork of median separators, parking bay, drainage pipe, and other locations. This technology has been applied in the bridge deck paving of the Hong Kong–Zhuhai–Macao Bridge, which realizes the continuous widening paving of the bridge-island-tunnel connection part with the super width state (Fig. 71), ensuring construction quality and improving construction efficiency.

4.2.3. Anti-segregation paving technology

One of the important reasons for the pavement's early damage is the uneven pavement structure, and the main reason for the uneven pavement structure is the segregation of the mixture. In the area where the fine aggregate is concentrated, there is a lack of skeleton support from large particle aggregate, which is prone to rutting, pushing, and embracing. In the area where large particle aggregate gathers, there is a lack of filling of fine materials, which is prone to water seepage, slurry pumping, potholes, and other distress, reducing the durability of the pavement and even affecting the service life. Material segregation can be

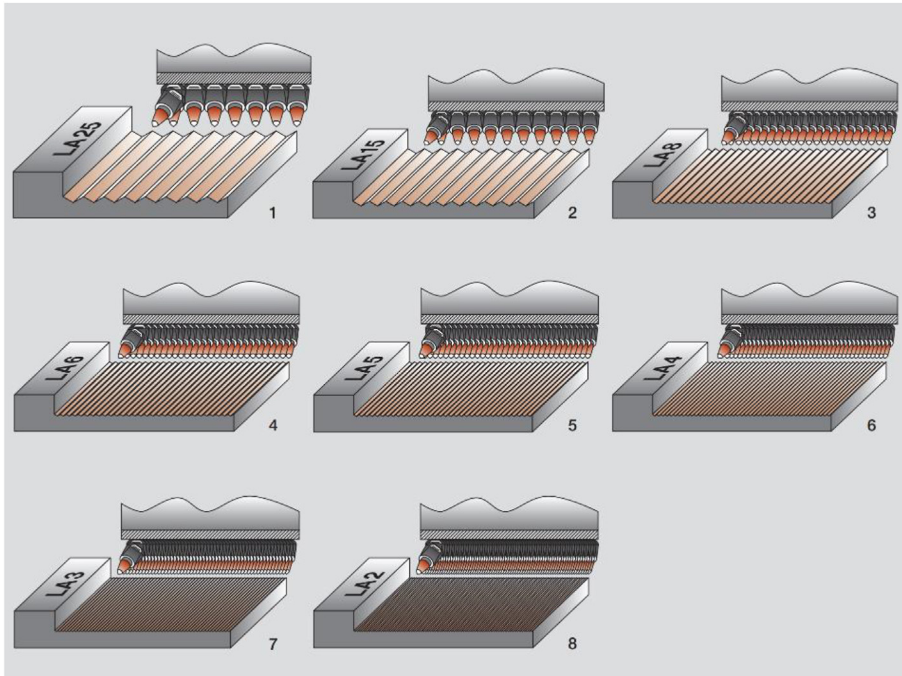


Fig. 74. Road surface texture milled with different cutter spacing.

subdivided into transverse, longitudinal, vertical, and flake segregation (Tang, 2017; Xu, 2018).

4.2.3.1. Lateral segregation control. To meet the performance requirements of "different feeding capacities at different positions", the screw conveyor of the paver must have a different pitch or screw diameter. In theory, the paving uniformity can be improved by using the screw conveyor with variable pitch or variable pitch structure (Li et al., 2008; Ma et al., 2010b), but the processing and production are inconvenient, and the interchangeability is poor. Shaanxi Zhongda Machinery Co., Ltd. puts forward an equal pitch stepped variable screw diameter screw conveyor based on material level stability, effectively improving lateral segregation on the road surface. Meanwhile, the lateral segregation of wide pavement can be effectively improved by increasing screw conveying capacity, reducing screw driving speed, increasing screw secondary mixing function, full-burying screw with material, and so on.

The gearbox of the screw conveyor is equipped with a rubber baffle (Fig. 72) to prevent the large particle aggregate from being thrown to the rear of the gearbox and the longitudinal segregation caused by the concentration of the large particle aggregate in the middle.

Reverse screw blades with adjustable angles and variable quantity are installed on both sides of the screw gearbox and adjusted according to the paving thickness and material. The different sizes of aggregates can be uniformly filled in the area below the screw gearbox, keeping the mixture spreading layer uniform, sufficient, and dense at the seam area to avoid longitudinal belt segregation.

4.2.3.2. Vertical segregation control. A front guide plate is installed under the front baffle, and the ground clearance can be adjusted according to the paving thickness and type of material. The bottom of the front guide plate adopts a flexible rubber sheet structure (Fig. 73(a)), which can minimize the ground clearance and prevent the vertical segregation caused by the large particle aggregate falling from the bottom opening part of the screw. Meanwhile, the external tension effect of the elastic plate can reduce the conveying resistance of the screw. Several strip-shaped flexible chain baffles can also be used to anti-rolling and unload materials (Fig. 73(b)). The chain is in flexible contact with the ground to effectively prevent vertical segregation, and the impact force of the material is effectively unloaded by multiple flexible chain baffles, which significantly reduces the conveying resistance of the screw. At the unloading port on both ends of the screw, the hanging structure of the elastic rubber plate (Fig. 73(c)) is adopted, which can prevent the vertical segregation caused by the large particle aggregate rolling down, avoid the screw stuck, and avoid the poor roughness caused by the low discharge capacity.

4.2.3.3. Flake segregation control. The five-discharge method is usually adopted in the finished product discharge process to reduce flake

Fig. 75. Fine milling rotor with 672 cutters.

Fig. 76. Pavement texture after fine milling.

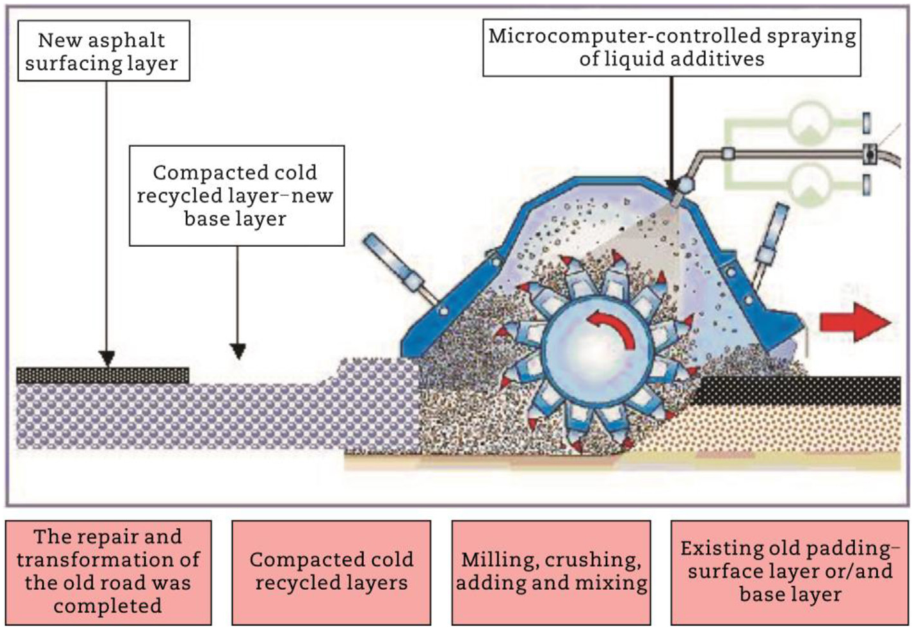


Fig. 77. In-situ cold recycling of asphalt pavement.

segregation in the mixing station. When the mixture is unloaded to the hopper from the dump truck, the horizontal distance between the dump truck box and the side plate of the paver hopper should be reduced to decrease the large particle aggregate falling between them. When a truck of material is unloaded into the paver hopper, it is not paved when the next truck of material is transported to the construction area, which can also reduce flake segregation.

4.3. Road intelligent milling equipment and technology for pavement

The cold milling machine is designed to quickly and efficiently remove asphalt or concrete pavements to form a flat and defined profile base layer for paving a new surface layer with uniform thickness. In addition, milling operation layer by layer ensures the material can be selectively regenerated and classified into different mixtures. The milling and resurfacing are uneconomical if the disease only exists on the road surface. Fine milling can be used to mill the rut and bloated package. After the fine milling, the road surface can restore smoothness and open traffic quickly. Otherwise, Fine milling technology is widely used to improve skid performance, remove traffic markings, and treat rutting disease on the road surface.

4.3.1. Fine milling equipment and technology

Fine milling operation mainly deals with road sections threatening traffic safety due to backpacking, rutting, or smooth road surfaces. Unlike the standard milling process, the fine milling operation can get a higher flatness and finer texture road surface by increasing the number of cutters and decreasing the cutter spacing. It is a fast and economical method to reduce the risk factors of roads without deep excavation and repair.

If the cutter spacing is less than 8 mm, the milling rotor is called the fine milling rotor, which aims to achieve a specified new road surface texture. Although the fine milling rotor cannot repair the damaged parts deep into the road structure, it can get a flat, non-skid surface. The road surface texture milled with different cutter spacing is shown in Fig. 74.

Wirtgen invents the fine milling machine. An ultra-precision rotor with 672 cutters is installed on the 2 m milling machine, as shown in Fig. 75. The milled surface texture is shown in Fig. 76. The fine-milled pavement can obtain a good skid performance and combination between the milled surface and the seal layer.

First, it is necessary to have a high-level fine milling rotor to obtain a high smoothness and good texture road surface. Secondly, the whole machine control system should perform well, especially the automatic leveling system. Zhao and Gao (2022) adopt 3D fine milling technology in bridge deck treatment. Three technologies, e.g., shot blasting, conventional fine milling, and 3D fine milling, were studied, and several performance indexes, e.g., the elevation change, structural depth, friction coefficient, and flatness, were compared. The results show that the 3D fine milling has the best performance. Compared with untreated bridge deck pavement, fine milling treatment can increase the drawing strength and shear strength of resurfacing by 50% and 87%. Furthermore, one year after construction, all pavement performance parameters are better than the original bridge deck pavement.

The fine rotor's cutter layout and geometric parameters were analyzed and discussed. An integral tool holder was designed to explore a new production process and simplify the operation. It tried to solve the problems of difficult tool positioning, heavy workload, and difficulty ensuring accuracy in the rotor manufacture. The developed fine rotor makes the fine milling operation more energy-saving and efficient, and the surface flatness index IRI $\leq$1.8 m/km (Zuo et al., 2021). After fine milling, tunnel concrete pavement's skid resistance and structural depth are improved, and the smoothness of the pavement and driving safety are also enhanced (Wang, 2018; Fu, 2019).

The above research mainly focuses on analyzing and testing the effect of fine milling, the influence of fine milling on the skid resistance of pavement, and the improvement of interlayer bonding performance. However, the design and manufacture of fine milling rotors are less involved. There is no technical literature on fine milling technology abroad, and most of them are news reports.

4.3.2. Milling machine adaptive control technology

The control system of a milling machine can be divided into the driving control system, steering control system, engine management control system, power control system, fan control system, milling depth and automatic leveling control system, auxiliary control system, and so on.

Ma et al. (2010a) analyzed the load characteristics of the cold milling machine and the shortcomings of the traditional engine power control technology with the mechanical governor. He suggested a power adaptive control method for cold milling machines with multi-power mode EFI engines. The method, combining torque and speed characteristics of the engine, achieves the power adaptive control by adjusting the engine's output power.

Zhou (2015) suggested a power adaptive control method for the milling machine by maintaining the total power output near the engine's rated power. Based on the analysis of the factors affecting the power consumption of the walking and rotor systems, the walking speed was proposed as the power adaptive control parameter of the milling machine. The control system detects the engine speed in working. If the engine's speed is less than the set speed, decrease the displacement of the walking pump to reduce the walking speed of the machine. If the engine's speed is higher than the set speed, increase the displacement of the walking pump to raise the walking speed of the machine. Finally, the engine will work in a set state to ensure that the rated power of the engine can be fully utilized. When the walking pump is increased to the maximum, the engine still cannot operate at the rated power. It is considered to adjust the maximum output power of the engine by adjusting the opening of the throttle to save energy.

Wu et al. (2023) proposed power adaptive control and limit load control to solve the problem of high energy consumption of milling machines, considering the characteristics of the milling operation and cutting force model. The engine power is adjusted to match the change of milling load during medium and low load mode to ensure the engine's operation in the economic working area. The milling load is adjusted to match the engine power to ensure the stable operation of the milling machine under the heavy load mode.

Guo (2010) investigated the relationship curve between the traction force and the slip rate of the milling machine by analyzing the kinematics and dynamics of the walking mechanism, determined the target slip rate that satisfies both the higher traction efficiency and the higher production of the milling machine, proposed the walking speed control strategy of the milling machine.

Because the speed of the milling machine is proportional to the working load, Zhang (2008) judged the load change by the engine speed and controlled the displacement of the walking pump or the walking motor to achieve an adaptivity milling machine's speed.

In summary, the adaptive control technology can help to improve the operation efficiency of the milling machine, reduce the engine power loss, and improve the fuel economy.

4.4. Road intelligent recycling equipment and technology

The asphalt pavement maintenance industry faces the rapid growth of raw material costs, increased recycled materials yearly, and increasingly severe environmental protection. To achieve the sustainable development of asphalt pavement, the key problem is to add as many recycled materials as possible in the recycling process and to realize the in-situ utilization of recycled materials. The recycling technologies include in-situ cold recycling, in-situ hot recycling, plant mix cold recycling, and plant mix hot recycling.

4.4.1. In-situ cold recycling technology and equipment

In the process of pavement maintenance, the in-situ cold recycling technology of asphalt pavement can reuse 100% of the waste pavement materials, which significantly reduces the resources waste and environmental damage, and also effectively reduces the maintenance cost and shortens the construction period (Liu et al., 2022d). The disadvantage of in-situ cold recycling is that the old asphalt mixture unsuitable for recycling cannot be removed, and the gradation adjustment range is small. It is difficult to control the construction quality, and it is usually necessary to overlay another asphalt layer. In-situ cold recycling technology is suitable for repairing pavement diseases such as loose pavement surface, pit and groove, unstable rutting, structural rutting, subsidence, wave, huddle, block crack, longitudinal crack, and so on (Jones et al., 2020; Ma et al., 2023a). In-situ cold recycling of asphalt pavement (Fig. 77) is to mill and crush the materials of damaged asphalt pavement, then add new asphalt and new aggregate, add a certain amount of additives according to a certain proportion, mix them in-situ at room temperature, and then compact the mixture to form road by roller.

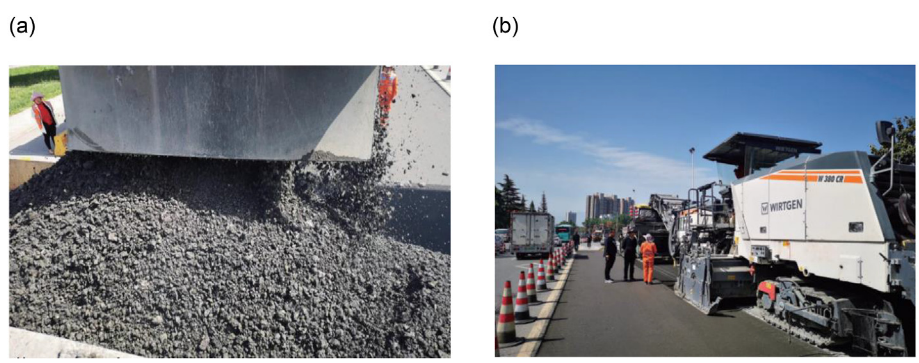


Fig. 78. Construction site of W380CR foam asphalt cold in-situ recycling unit. (a) Homogeneous foamed bitumen cold recycling mixture. (b) Intelligent and efficient regeneration.

Fig. 79. XLZ230II pavement cold recycling machine.

According to the different additives, it can be divided into cement cold recycling, foamed asphalt cold recycling, emulsified asphalt cold recycling, lime cold recycling, fly ash cold recycling, etc (Ogbo et al., 2022; Zhao, 2022b). The in-situ cold recycling of asphalt pavement can also be divided into cold recycling technology of pavement surface layer and deep remixing recycling technology.

The pavement surface layer cold recycling technology aims at the pavement whose structure strength meets the bearing requirements, the drainage facilities are intact, and only the road structure layer is deformed or damaged. Before cold recycling, the pavement structure layer is reinforced first. The cold recycling thickness is 8–15 cm to form the bottom layer of asphalt pavement. The deep remixing recycling technology aims at the road stability layer. The mixing depth is 10–20 cm when the pavement base is recycled, and the mixing depth can reach 40 cm when the soil base stability layer is treated (Cong et al., 2015; Zhao, 2022a).

Cold in-situ recycling technology has been gradually promoted in the United States since the 1970s. Since 1984, the U.S. Department of Transportation has carried out more than 120 in-situ cold recycling projects and conducted continuous research on construction technology and performance. By 1996, IOWA had implemented and completed 97 in-situ cold recycling projects (Jahren et al., 1999). In 1997, Kansas launched a cold in-situ recycling project called US-283 and paved two test sections (Thomas et al., 2000). In 1999, the British Transportation Laboratory issued the "Design Guidelines and Specifications for Structural Maintenance of Pavements Using In-Situ Cold Recycling Technology". Australia also formulated the asphalt stabilized in-situ recycling specification in 2002 (Transport Research Laboratory, 1999). In 2002, Minnesota adopted the cold in-situ recycling technology in the "Blue Earth County Aid Highway 20" project. In 2013, three different cold recycling technologies were used to pave the test section in a road project, and their energy consumption, greenhouse gas emissions, pavement performance, and engineering costs were compared and evaluated (Forsberg et al., 2002).

In 1997, asphalt pavement's cold in-situ recycling technology was first applied in a pavement reconstruction project in Handan, Hebei Province, China. It is also the first time to use large-scale modern recycling machinery to complete the whole recycling construction process of the old pavement at one time (Li, 2023). In 2004, emulsified asphalt was successfully used for cold in-situ recycling of asphalt pavement for the first time in the overhaul project of the first-class highway of Yingda Line in Liaoning Province. In the following two years, the pavement performance tracking monitoring showed promising results (Chen, 2012). In 2007, China introduced the WR4200 in-situ cold recycling machine produced by Germany and completed the in-situ cold recycling construction of 28,000 square meters in the overhaul project of the Beijing-Shenyang Expressway. Its application has gradually expanded with the continuous deepening of the emulsified asphalt cold recycling technology research. Beijing–Shanghai Expressway, Beijing–Harbin Expressway, Shanghai–Nanjing Expressway, Xihan Expressway, Tonghuang Expressway, and Huihe Expressway and other overhaul projects have paved emulsified asphalt cold recycling test sections and achieved good results.

4.4.1.1. Development status of in-situ *cold recycling equipment.* Foreign production companies on cold in-situ recycling equipment mainly include CMI company in the United States, Caterpillar company in the United States, Bomag company in Germany, Panien company in France, Marini company in Italy, and Wirtgen company in Germany. The world's largest manufacturer of road recycling equipment is Wirtgen, whose cold recycling machine has the highest market share. Fig. 78 is the construction group diagram of W380CR foam asphalt cold in-situ recycling equipment. W380CR in-situ recycling machine has the characteristics of high flexibility, uniform mixing of recycled materials, accurate spraying of blinders, and good matching of the unit. The maximum recycling depth of the W380CR cold in-situ recycling machine can reach 30 cm, and the maximum operating capacity can reach 800 t/h. The equipment can cooperate perfectly with the paver to continuously implement 100% in-situ recycling of the original pavement material and the paving of the recycled mixture. The material can be mixed, paved, and rolled simultaneously to ensure the timeliness of the material. So, the recycled pavement has good uniformity and stability, which can significantly improve the durability of the pavement. Recycled roads can significantly eliminate reflective cracks, reduce the temperature sensitivity of concrete, and significantly extend the service life of roads (Wirtgen Group, 2021).

In recent years, Chinese construction machinery manufacturers have gradually attached importance to the research, development, and production of cold recycling machines. Shandong Highway Machinery Factory has developed LZS2400 in-situ cold recycling machine with an international advanced level, Xi'an Road Construction Machinery Company has developed CR2500 in-situ cold recycling mixer, and Xuzhou Construction Machinery Group Co., Ltd. (XCMG) has developed a new type of recycling equipment XLZ230II pavement cold recycling machine (Ma et al., 2018). Through years of research development and improvement, the cold recycling machine can realize the step-less speed regulation between the maximum and minimum speed of the milling rotor, increasing the maximum cold recycling depth. Fig. 79 shows the XLZ230II pavement cold recycling machine of XCMG. The XLZ230II pavement cold recycling machine has the functions of intelligent control of rotor speed, power self-distribution, lateral slip of cab, high-pressure flushing, rapid replacement of milling rotor tool, etc. It is suitable for the in-situ mixing of base and subbase stabilized soil in highways, urban and rural roads, airports, docks, and parking lots (XCMG, 2015).

4.4.1.2. Development trend of in-situ *cold recycling equipment.* There is still ample development requirement for in-situ cold recycling equipment, for example, studying the reasonable matching of working parameters such as engine power, milling rotor speed, and walking speed. It can reduce the crushing of stone to improve the bearing capacity of recycled base and reduce the amount of new stone added.

4.4.2. Microwave heating recycling technology and whole-set equipment

Microwave maintenance technology for asphalt pavement started in the 1970s. Through experiments, Al-Ohaly and Terrel (1988) found that microwave-heating asphalt mixture can improve the adhesion between asphalt and aggregate, meanwhile improving the quality of pavement repair. Osborne and Hutcheson (1989) proposed that microwave heating reduced the asphalt mixture heating time from 240 to 45 s. Similarly, Howard (1986) also noticed that the asphalt mixture with good microwave absorption performance has faster speed and efficiency in microwave repair.

The Chinese highway maintenance department introduced in-situ hot recycling technology with the increase in asphalt pavement maintenance quantity. In 1998, a set of hot in-situ recycling units was first imported from Niigata Ironworks in Japan and used in the pavement renovation project of Jingjintang Expressway. In 2002, North China Expressway Co., Ltd. introduced the first set of asphalt pavement hot in-situ recycling equipment from Wirtgen to the Chinese market (Fan and Wu, 2002). However, the problems of expensive equipment, high use cost, and immature processes seriously affect China's popularization and application of in-situ hot recycling technology. In 2004, Zoomlion designed and produced China's first asphalt pavement heating machine (Fu, 2004). In 2008, Zoomlion officially launched the first set of comprehensive in-situ hot recycling equipment (two heating machines, one remixer) in China to the market (Xu, 2008), using hot air circulation heating technology to heat and recycle asphalt pavement. Since then, Chinese enterprises, such as Anshan Senyuan, Nanjing Yingda, Jiangsu Aoxin, and Wuxi Xitong, have gradually developed their own in-situ hot recycling units (Ren, 2008; Wang, 2008, 2013, 2015).

In 2004, Chang'an University began to develop the world's first microwave maintenance equipment for asphalt pavement in cooperation with

Media Group Weite Highway Maintenance Equipment Co., Ltd. It successfully launched the market in 2005 (Liu, 2008). Subsequently, the microwave maintenance technology of asphalt pavement is widely used in the pavement maintenance of high-grade highways. Some Chinese construction and maintenance machinery manufacturing enterprises also developed microwave maintenance products. Jiangsu Weituo is the first to apply microwave heating technology to in-situ hot recycling construction. In 2018, Jiangsu Provincial Road Technology and Equipment Research Institute independently developed the JCM100W intelligent asphalt road microwave maintenance vehicle, which adopted a single engine, high-frequency switching power supply, variable power, high-performance anti--microwave leakage, "one file for every pit" digital intelligent management system and other technologies (Jiao and Ren, 2020). In 2019, XCMG developed a new generation of asphalt road microwave maintenance vehicles. Compared with the previous maintenance vehicles, it has achieved technological breakthroughs and innovations in microwave uniform heating, efficient power supply, microwave shielding, intelligence, and process adaptability (Gao et al., 2019). In 2020, Jicui Road innovatively designed a microwave heating silo mechanism to solve the synchronous heating problem of pavement to be repaired and asphalt to be added to improve pavement maintenance performance (Cheng et al., 2020). In 2022, Ma et al. (2022b) analyzed the heating conditions of 915 MHz and 2450 MHz microwave and concluded that the 915 MHz microwave heating asphalt mixture had better uniformity and a smaller temperature gradient in the depth direction. Changing antenna spacing, heating height, and mixture thickness will change microwave mutual interference in the heating box. In 2023, based on the characteristics of asphalt pavement pothole repair, Hunan Expressway Maintenance Engineering Co., Ltd. developed mobile microwave heating equipment consisting of the magnetron, microwave transmission system, microwave resonance system, microwave control system, and other parts (Zhang et al., 2023e).

China has studied some equipment for this combined heating technology in recent years. In 2020, the microwave heating technology was creatively integrated into the complete set of equipment for in-situ hot recycling technology. The form of hot air plus microwave composite heating has better solved the material temperature problem and has been better applied in constructing the Xuzhou section of G30 Lianhuo Expressway (Xie and Xia, 2020). In 2021, the JCM100E vehicle-mounted microwave hot air curing device developed by Jiangsu Jicui Engineering Technology and Equipment Research Institute Co., Ltd. completed the construction demonstration on the Jiawang construction site of G206 national highway in Xuzhou, and completed the rapid and high-quality recycling of old asphalt mixture (Yang and Lin, 2021). In the same year, Shaanxi Zhonglin Group Engineering Design and Research Co. (2021) disclosed a microwave hot air composite heating equipment for asphalt mixture. The power control system is placed outside the box. The power control panel reserves the control switches for the transmission motor, microwave generator, and hot air system. The mixture is heated in the form of a microwave hot air combination, which has high heating efficiency, and the hot air is recycled, effectively preventing the waste of resources. In 2022, "5G+ unmanned hot in-situ recycling construction" and "international first asphalt pavement aging layer removal device and process application" technologies were staged in Hengshui Daguang Expressway (G45) in Hebei Province and Wulanchabu Erguang Expressway (G55) in Inner Mongolia. The group maintenance equipment adopts the digital management system of hot air microwave composite heating in-situ hot recycling unit with unmanned driving technology. Compared with the traditional in-situ hot recycling maintenance operation, it has high productivity, good operation quality, and low construction cost (Cheng, 2022).

5. Advanced pavement detection and evaluation technologies

5.1. Advanced pavement material testing technologies

This section reviews the advanced pavement material testing technologies, including spectrum technology in Section 2.1.1, nuclear magnetic resonance (NMR) technology in Section 2.1.2, and microscopic observation technology Section 2.1.3. These technologies effective tools for characterizing asphalt and cement materials in recent years due to their rapid testing and non-destructive nature. Spectroscopic techniques involve the study of the interaction between materials and light waves, followed by the measurement of specific properties of light, such as wavelength, intensity, frequency, and polarization. This process provides insights into the composition, structure, and properties of materials. NMR technology allows qualitative and quantitative analysis of the composition, structure and properties of asphalt, while being applied to research on asphalt modification, aging and rejuvenation. Microscopic observation technology explains some specific phenomenon of asphalt material through collecting the microstructure maps, including microscopic observation technology consists of fluorescence microscopy (FM), scanning electron microscopy (SEM), environmental scanning electron microscopy (ESEM), atomic force microscopy (AFM).

5.1.1. Spectrum technology

Spectroscopic techniques involve the study of the interaction between materials and light waves, followed by the measurement of specific properties of light, such as wavelength, intensity, frequency, and polarization (Silverstein et al., 2005). This process provides insights into the composition, structure, and properties of materials. Over the years, spectroscopic techniques have emerged as a valuable tool for the study and analysis of asphalt materials due to its advantages of convenience, speed, no damage, and no pollution. The common spectroscopic methods include infrared spectroscopy (IR), ultraviolet-visible spectroscopy (UV-Vis), and Raman spectroscopy.

5.1.1.1. Infrared spectroscopy. Infrared spectroscopy (IR) is used to analyzes molecular vibrational and rotational modes by measuring the absorption, emission, or reflection of infrared radiation by the sample, particularly useful for determining the structure and functional groups of organic molecules. Fourier transform infrared spectroscopy (FTIR) is widely used for qualitative or quantitative analysis of functional group in asphalt materials, facilitating the modifier identification, modification mechanism, aging and regeneration mechanism research, rapid identification of asphalt oil sources and rapid evaluation of asphalt performance.

(1) Modifier identification and modification mechanism

For modifier identification, the absorption peak at the C=C bond in unsaturated alkanes (966 cm^{-1}) is usually used to characterize the presence and content of styrene-butadiene-styrene (SBS) (Zhao et al., 2010). Two special adsorption peaks at 966 cm^{-1} and 700 cm^{-1} can respectively identify the polybutadiene (PB) and polystyrene (PS). Canto established the relation model between absorbance ratio at 966 cm^{-1} vs. 700 cm^{-1} and PB/PS ratio and achieved the prediction of the PB/PS ratio using FTIR (Canto et al., 2006). Luo et al. (2020) employed a similar method to propose a prediction model for SBS content. For crumb rubber (CR), it can be identified by the absorption peaks at the N–H and NH_2 groups (Hou et al., 2018). Vulcanization can reduce the strength of the C=C absorption peak in SBS and CR modified asphalt, and generate weak absorption of C–S and S–S bonds between 500 cm^{-1} and 700 cm^{-1} (Zhang et al., 2023f). Three absorption bands between 1300 cm^{-1} and 1400 cm^{-1} assignable to CH_2 and CH_3 groups can identify the branching degree of polyethylene (PE) (Gulmine et al., 2002). The study of polyphosphate (PPA) by FTIR showed that there are two absorption peaks near 1726 cm^{-1} and 1073 cm^{-1}, attributed to the vibration of P–O and P=O bonds (Fu et al., 2023). In addition, researchers also identified functional groups present in various other modifiers based on FTIR, such as ester bonds, N=C=O, –NH, etc. (Elkashef et al., 2018; Meng et al., 2022b).

By comparing the FTIR of virgin asphalt, modifiers, and modified asphalt, the physical and chemical changes involved in the modification process can be determined. For modifiers such as SBS, CR, graphene, nano-Al_2O_3, carbon nanotubes, bio-oil, the modification process is physical modification due to the absence of new peaks or shift in the peak position (Nivitha et al., 2016; Dong et al., 2019; Wang et al., 2021e; Li et al., 2021h; Ji et al., 2022). Meng et al. (2022b) reported a combination modification mechanism of physical modification (effect of bio-based polyurethane) and chemical modification (chemical crosslinking between bio-based polyurethane and virgin asphalt). Wang et al. (2022j, m) found that with the addition of PPA, new absorption peaks were generated, which is attributed to the reaction between PPA and asphalt to generate inorganic phosphates.

(2) Aging and regeneration mechanism

Researchers reported through FTIR analysis that the functional groups formed by aging are mainly carbonyl (1700 cm^{-1}) and sulfoxide (1030 cm^{-1}) (Liu et al., 2014a). Petersen (2009) believe that the oxidation degree during asphalt aging is directly related to the carbonyl and sulfoxide areas in FTIR. Therefore, the carbonyl and sulfoxide indexes obtained by FTIR are usually used to indicate the aging degree of asphalt binder (Herrington, 1995; Petersen, 2009; Liu et al., 2021b). Liu et al. (2022b) showed that a small amount of sulfone (1107 cm^{-1}) and associated carbonyl (1730 cm^{-1}) groups were formed during asphalt aging based on FTIR. Hung and Fini (2019) combined SARA fractions and FTIR analysis to believe that asphalt aging is not only related to changes in the carbonyl content, but also accompanied by loss of saturates, carbonation, and degradation of the poly-aromatic cores of asphaltenes and resins. In addition, aliphatic and aromatic indexes were also monitored to study the aging degree of asphalt (Lamontagne et al., 2001; Yao et al., 2016; Jamal and Giustozzi, 2022). Typically, the aliphatic index decreases while the aromatic index increase (Jamal et al., 2022). For SBS-modified asphalt, the butadiene index (966 cm^{-1}) can used to monitor the aging degree of modifiers (Zhang et al., 2011). Xu et al. (2021b) and Wei et al. (2019) pointed out through FTIR analysis that aging can cause oxidative degradation and fracture of the butadiene chain and methyl index can be applied to evaluate the aging of SBS modifier. Researchers also studied the effects of various modifiers on the aging degree of asphalt by tracking the changes in carbonyl and sulfoxide indexes (Tang et al., 2023). Researchers usually analyze the regeneration effect based on the carbonyl and sulfoxide indexes. It's found from the FTIR analysis that the oil rejuvenators diluted the carbonyl and sulfoxide groups in the aged asphalt, soften asphalt and restore asphalt pavement performance (Li et al., 2023a, b; Yi et al., 2022). However, several researchers warned that using sulfoxide indexes to evaluate the aging degree may lead to misleading conclusions, especially when rejuvenators are employed (Herrington, 1995; Elkashef et al., 2018, 2020; Liang et al., 2019). Camargo et al. (2023) found that the carbonyl and sulfoxide indexes are not suitable to capture the real oxidative aging experienced by dilauryl thiodipropionate rejuvenators and proposed the normalized carbonyl index to quantify the aging sensitivity of rejuvenators.

(3) Identification of asphalt oil sources and evaluation of asphalt performance

Researchers establish the relationship between characteristic absorption peaks and oil sources and performance of asphalt binder combined FTIR, principal component analysis, partial least squares discriminant analysis and linear discriminant analysis techniques achieving rapid identification of asphalt oil sources and rapid evaluation of asphalt performance. Some studies explored the asphalt fingerprint regions of different oil sources and established the rapid identification method for asphalt oil sources (Ren et al., 2019; Hashemi-Nasab and Parastar, 2020). Lima and Leite (2004) study the relationships between absorption and asphalt properties such as penetration value, viscosity and flash point to accomplish a fast and accurate estimation in asphalt grade. Weigel and Stephan (2017) modeled the chemical and rheological parameters and predicted the asphaltene content, softening point, permeability, complex shear modulus and phase angle of asphalt. Soenen and Redelius (2014) used the absorption peak area at 1600 cm^{-1} to represent the aromatic content of asphalt, establishing a relationship between the aromaticity and elasticity. Due to the extreme complexity of asphalt composition, the applicability of the above prediction models is limited. With the development of artificial intelligence, technologies such as artificial neural networks, data-driven and machine learning have also been applied establish more universal models (Wang et al., 2020b; Ren et al., 2022; Shan et al., 2023).

To sum up, FTIR plays an important role in asphalt composition analysis, making significant contributions to asphalt performance rapid evaluation, oxidation, regeneration, and modification mechanisms. However, the above studies are both qualitative and semi-quantitative. This is because the composition of asphalt is extremely complex, making it difficult to purify individual compounds and test their absorbance, thus preventing accurate quantitative studies based on FTIR and Beer-Lambert law (Mayerhöfer et al., 2020; Liu et al., 2022b).

5.1.1.2. Ultraviolet-visible spectroscopy. Ultraviolet-visible spectroscopy (UV-Vis) is used for analyzing the absorbance of different compounds in asphalt and modifiers to understand their composition and chemical properties. In terms of composition and performance of asphalt, Chu et al. (2000) used UV-Vis to quantitatively analyze the SARA fractions of asphalt. Aguiar et al. (2014) determined the solubility parameter range of different asphaltenes and crude oil samples through UV-Vis. In terms of UV aging resistance, researchers usually study the UV light blocking and UV absorption abilities of materials based on UV-Vis. Li et al. (2018) found that sodium stearate can enhance the UV aging resistance by blocking UV light. Liu et al. (2015) studied the improvement effect of two types of layered double hydroxides (LDHs) on the UV aging resistance of asphalt, and found that Zn-Al-LDHs have better UV aging resistance due

Table 9
Categories and chemical shift of H atom in ^{1}H NMR (Zhang et al., 2020b).

Name	Position	Chemical shift (δ, ppm)
H_A	Hydrogen directly linked to aromatic carbon	6.0–9.0
H_α	Hydrogen linked to the C_α of the aromatic ring	2.0–4.0
H_β	Hydrogen linked to C_β of the aromatic ring and beyond CH_2, CH	1.0–2.0
H_γ	Hydrogen linked to C_γ of the aromatic ring and beyond CH_3	0.5–1.0

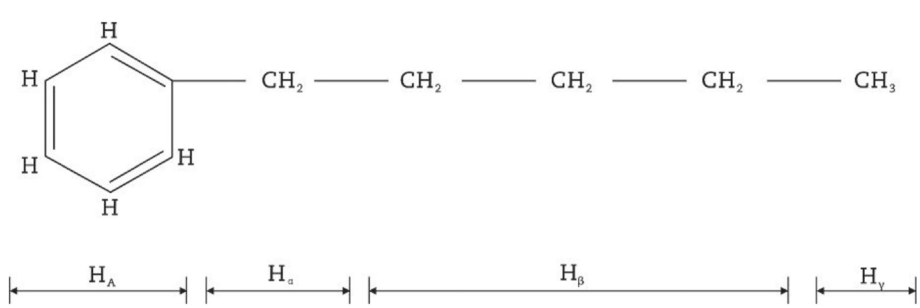


Fig. 80. Schematic diagram of attribution of H_A, H_α, H_β and H_γ (Zhang et al., 2020b).

to their high UV reflectance. Li et al. (2021g) reported that ternary compound carbon nitride has high absorbance in both the UV and visible regions, which can be used to improve the aging resistance of asphalt. Xu et al. (2015) studied the improvement of aging resistance by intercalating layered double hydroxides with UV absorbers based on UV-Vis. In addition, UV-Vis is also applied in the in the purification of automobile exhaust gas by ion-doped titanium dioxide (Lei et al., 2021; Zhang et al., 2021d).

5.1.1.3. Raman spectroscopy. Raman spectroscopy (RS) provides information about molecular vibrations by measuring the scattering of photons by the sample, often used in chemical composition analysis. For carbon nanomaterial asphalt modifiers, RS is commonly used to determine the content and number of layers of graphene derivatives (i.e., carbon materials) in modified asphalt (Caputo et al., 2020; D'Angelo et al., 2022; Gulisano et al., 2022; Nciri et al., 2016; Polo-Mendoza et al., 2023). Therefore, the diffusion or coupling degrees of carbon molecules within graphene modified asphalt can be estimated (Liu et al., 2014b; Zhang et al., 2017). For graphene oxide (GO), the G band at 1580 cm^{-1} is attributed to the lamellar structure of graphene oxide (stretching sp2); the D band at 1355 cm^{-1} is attributed to the oscillation of the hexagonal carbon chains that occurs when the symmetry, linked to the functional groups and defects present on the plane and on the edge of the GO, is broken (D'Angelo et al., 2022). RS is also used to study the structure (such as diameters and number of layers) of carbon nanotubes (Liu et al., 2007; Xu et al., 2013). The D band at 1336.2 cm^{-1} is related to defects and disordered carbon structures, while the G band at 1581.2 cm^{-1} is attributed to ordered carbon structures (Liu et al., 2007). Similarly, RS has also been applied to other carbon nanomaterials, such as carbon microfibers (CMFs), carbon porous materials, graphene nanoparticles (GNPs), reduced graphene oxide (RGO) and composite modifiers (Xu et al., 2007; Wang et al., 2018d, 2021e; Duan et al., 2019; Ma et al., 2020; Chen et al., 2021a; Gorbunova et al., 2022).

For the study of virgin asphalt, RS can provide information about the crystallinity (or the crystalline domain dimension) of the system (Caputo et al., 2022). Caputo et al. (2022) determined the asphaltene molecular sheet dimensions combined RS and X-ray powder diffraction and studied the impact of aging. Qiu et al. (2023) achieved a richer Raman spectral structural information by introducing silver nanoparticle colloids (Ag NPs) as surface-enhanced Raman scattering substrates to quench autofluorescence. The results demonstrate that Raman spectroscopy can effectively identify different aging states of asphalt based on characteristic peaks.

5.1.2. Nuclear magnetic resonance techniques in asphalt materials

Nuclear magnetic resonance has become a powerful non-destructive tool for scrutinizing the molecular structure and dynamics of materials, including the complex composition of asphalt (Siddiqui and Ali, 1999; Zhang et al., 2020b). NMR has become an effective tool for characterizing asphalt materials in recent years due to its rapid testing and non-destructive nature. NMR technology allows qualitative and quantitative analysis of the composition, structure and properties of asphalt, while being applied to research on asphalt modification, aging and rejuvenation (Huang, 2010).

NMR is mainly due to the spin motion of atomic nuclei. Spin nuclei have two energy states, reverse aligned and forward aligned nuclear energy. When a spin nucleus receives electromagnetic radiation of a certain frequency in an external magnetic field, if the radiation energy is exactly equal to the difference between the two energy states, the spin nucleus in the lower energy state absorbs the electromagnetic radiation and jumps to a higher energy state, a process known as NMR (Filippelli et al., 2012; Baldino et al., 2017). The most common NMR spectrum are the hydrogen spectrum (^{1}H NMR) and carbon spectrum (^{13}C NMR). Based on the analysis of the spectrum, it is possible to distinguish between various types of atoms and quantify the content of each type of atom (Rossi et al., 2018a). Fig. 80 and Table 9 demonstrate the chemical shifts of ^{1}H NMR hydrogen atoms on different carbon chains.

This section discusses the application of NMR techniques to the analysis of asphalt materials, including the structural analysis of matrix and modified asphalt, the evaluation of asphalt aging, and the exploration of structural changes in rejuvenated asphalt.

5.1.2.1. Structural analysis of matrix asphalt. The properties of asphalt are highly correlated with its composition, but it is difficult to accurately identify the molecular composition and structure of asphalt. The analysis of NMR spectrum, especially ^{1}H NMR, allows distinguishing different hydrogen containing functional groups and determining the molecular composition and structure, thus contributing to the understanding of the viscoelastic properties of asphalt materials (Ramsey et al., 1967; Cardozo et al., 2016) were the first to use ^{1}H NMR to determine the structure of asphalts and used the results to correlate with elemental analyses from obtaining the structural distribution in the asphalt. After the appearance of Fourier transform infrared spectrometer, ^{13}C NMR has also begun to be applied to the analysis of asphalt structure, combined with ^{1}H NMR to further grasp the complex composition and structure of asphalt (Cardozo et al., 2016).

Lu and Redelius (2006) characterized the composition and structure of waxes isolated from different sources of asphalt, and analyzed the detailed features of the molecular structure changes of the components by NMR. Nciri et al. (2016) compared the hydrogen content attributed to different species of petroleum asphalt and natural asphalt by ^{1}H NMR and found that the concentration of aliphatic hydrogen in natural was higher than that in petroleum asphalt. Nciri and Cho (2017) compared ^{13}C NMR of two different sources of natural asphalt, they found that Trinidad Lake asphalt contains a high concentration of oxygenated compounds and an aromatic fraction with protonated carbons, and that the alkyl chains in

Table 10
Applications for characterizing structural changes in asphalt aging by NMR.

Reference	NMR technique	Application
Menapace et al. (2016)	T_2 and RHI	LF-NMR was applied to evaluate asphalt mixture samples in different states of deterioration on the pavement. The aging degree of asphalt concrete cores was estimated without binder extraction.
Zhang et al. (2021b)	^{1}H NMR and ^{13}C NMR	The aging resistance mechanism of asphalt modified with multidimensional nanomaterials was investigated, and it was found that the internal friction between asphalt molecules decreases with the reduction of the straight chain length after the addition of multidimensional nanomaterials to asphalt.
Wang et al. (2022g)	T_2 and RHI	The effects of the two modifiers (SBS and crumb rubber) on the aging level of asphalts were investigated. After aging, the characteristic peaks of the modifiers disappeared, and the addition of modifiers changed the law that the larger the asphalt viscosity, the shorter the T_2 relaxation time.
Wu et al. (2022)	^{1}H NMR	Quantification and characterization of the chemical structure of five different oil source matrix asphalts before and after aging in combination with chemometric analysis. Differences in asphalt structure depend on the different oil sources, and although aging leads to changes in asphalt structure, it does not alter the overall structural framework of the asphalt.
Pei et al. (2022)	^{1}H NMR	Changes in asphalt structure during thermal-oxidative and UV aging were investigated. After thermal-oxidative aging, the length of the fatty side chains tends to increase. And after UV aging, the fatty side chains undergo some degree of cleavage reaction.
Di et al. (2023)	^{1}H NMR	The anti-aging mechanisms of TiO_2 modified asphalt and ZnO modified asphalt were explored, and found that TiO_2 can inhibit the loss of aromatic carbon in asphalt, and ZnO can induce sufficient arylation to counteract the effects of asphalt aging to varying degrees.

Trinidad Lake asphalt are more susceptible to oxidation and vulcanization than Gilsonite asphalt.

5.1.2.2. Structural analysis of modified asphalt. Modifying asphalt to enhance specific properties is a common practice. NMR techniques play an important role in analyzing the effect of modifiers on the molecular structure of asphalt. Whether polymers or additives are introduced, NMR techniques help to identify changes in molecular mobility, interactions and distribution (Varanda et al., 2016; Liu et al., 2020) investigated the modification mechanism of polyphosphoric acid-modified asphalt by ^{1}H NMR, ^{13}C NMR, and phosphorus spectrum (^{31}P NMR), and found that polyphosphoric acid underwent grafting, phosphate esterification, and cyclization reactions with asphalt, thus changed the carbon chain structure of asphalt and made the asphalt more viscous. Yu et al. (2014a) have demonstrated by NMR and Fourier transform infrared spectrometer that there is no complex chemical reaction between Evotherm DAT (a typical warm mixing agent) and crumb rubber modified asphalt. Further, Evotherm DAT modifies the rheological properties of modified asphalt by affecting the aggregation state of crumb rubber.

NMR techniques can reveal the effect of modifiers on the properties of asphalt such as elasticity, viscosity and temperature sensitivity. In addition, by NMR techniques, researchers can gain insight into the dynamics of modified asphalt, revealing the movement and relaxation times of molecular fragments. Therefore, by predicting the chemical reactions that occur, it is possible to reveal the modification mechanism and predict changes in asphalt properties (Haghshenas et al., 2018).

5.1.2.3. Asphalt aging evaluation. The aging of asphalt affects its properties, which seriously affects the performance of asphalt pavement (Zhang et al., 2018a). NMR techniques provide methods of evaluating the asphalt aging in terms of the microstructure. NMR techniques include high field NMR (HF-NMR) for testing the chemical structure of molecules and low field NMR (LF-NMR) for providing information on the dynamics between molecules (Madeira et al., 2022). Table 10 shows applications for characterizing structural changes in asphalt aging by NMR in recent years.

By comparing the ^{1}H NMR and ^{13}C NMR before and after aging of the matrix asphalt, it is possible to analyze the compositional changes of the asphalt and to speculate on the chemical reactions that occurred (Uchoa et al., 2021). It has been studied by the differences in hydrogen and carbon content of the different types and it is proposed that oxidation, isomerization and hydrogenation reactions occur during the aging process (Siddiqui, 2010). In addition, NMR spectrum can detect the characteristic peaks of styrene-butadiene-styrene copolymer (SBS) modifiers (hydrogen on methene (alkene) and methine (alkyne)) and thus analyze the degradation of SBS modifiers after aging process (Guo et al., 2018).

As for LF-NMR, asphalt parameters can be measured directly without separating the asphalt mixture and are independent of aggregates and voids (Menapace et al., 2017a, b). The LF-NMR parameters that are mainly applied in the evaluation of asphalt aging research are the transverse relaxation time T_2 and the relative hydrogen index (RHI), which are strongly related to the viscosity of asphalt. The T_2 values tend to increase as the temperature increases, which indicates that a decrease in the T_2 values indicates an increase in the viscosity of the asphalt (Menapace et al., 2016, 2017a, 2017b; Zhang et al., 2021b). The RHI (AI_{oil}/AI_{water}) specifies that the amplitude index of any fluid at the same temperature is normalized to AI water, as the viscosity of the asphalt increases, the NMR amplitude measured in the fluid decreases and the value of the RHI decreases (Menapace et al., 2016).

By investigating the composition of NMR spectra, transverse relaxation time T_2 and RHI, researchers can quantify the changes in molecular mobility and oxidation levels during asphalt aging. This comprehensive analysis can help predict the long-term performance of materials and in designing asphalts with excellent resistance to aging. In addition, LF-NMR can detect the aging level of asphalt without extraction of the asphalt, allowing non-destructive on-site measurement of pavement deterioration.

5.1.2.4. Structural analysis of rejuvenated asphalt. The rejuvenation of aged asphalt has attracted attention as a sustainable method of extending pavement life. NMR technology is a tool for evaluating the properties of rejuvenated asphalt at the molecular level and determining the effect of rejuvenators on the rejuvenation process of aged asphalt. Through

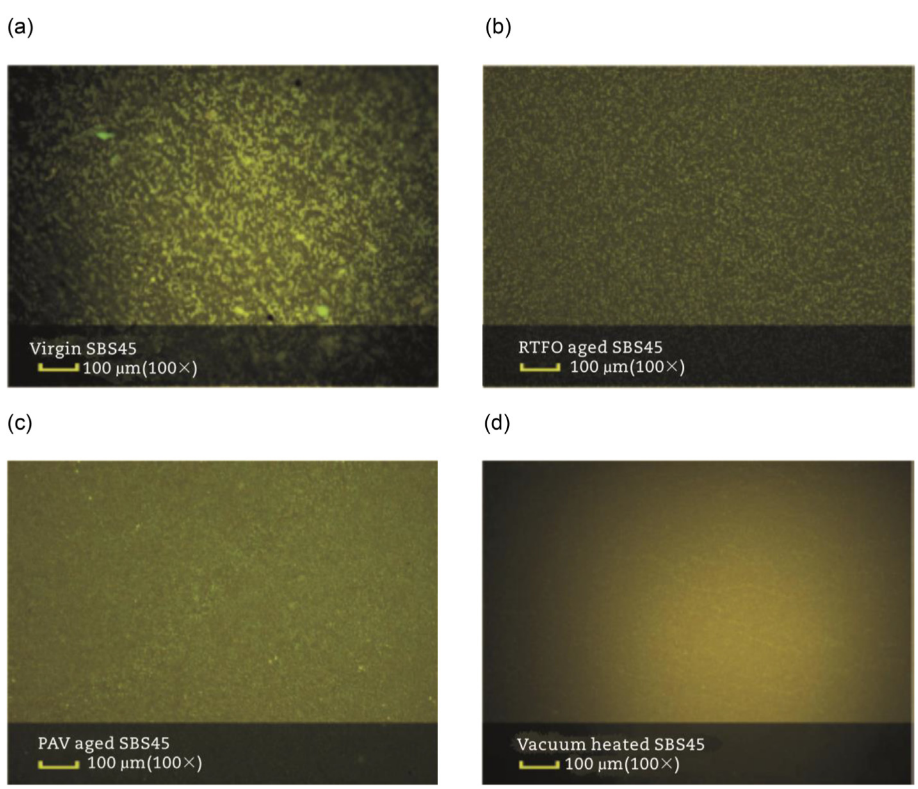


Fig. 81. Fluorescence maps of SBS-modified bitumen before and after aging. (a) Virgin. (b) RTFO. (c) PAV. (d) Vacuum heating (Yan et al., 2019).

relaxation and diffusion studies, researchers can quantify improvements in asphalt constituent mobility post-rejuvenation (Haghshenas et al., 2018). In addition, NMR techniques can reveal the interactions between rejuvenators and aged asphalt, providing an in-depth understanding of the rejuvenation mechanisms (Menapace et al., 2018). Caputo et al. (2019) distinguished between rejuvenators and fluxes (softeners) using inverse Laplace transform NMR. They found that softeners can only reduce the viscosity of aged asphalt, while rejuvenators are beneficial in restoring the physical properties, rheological properties and chemical structure of asphalt, as well as restoring the aggregation of asphaltenes to its original state. Rossi et al. (2018b) used NMR techniques to determine the effect of a new green rejuvenator on aged asphalt. They also noted that vegetable oils are only used as fluxes to soften aged asphalt, matching the macroscopic physical parameters to specific requirements.

5.1.3. Microscopic observation technology

Microscopic observation technology has been widely used to investigate bituminous materials, which mainly explains some specific phenomenon through collecting the microstructure maps. Currently, the commonly used microscopic observation technology consists of fluorescence microscopy (FM), scanning electron microscopy (SEM), environmental scanning electron microscopy (ESEM), atomic force microscopy (AFM), and so on (Du et al., 2021b). This section reviews the state-of-the-art development and application of specific microscopic observation technology on bituminous materials.

5.1.3.1. FM. FM can capture the morphology of the fluorescent substance in the sample through collecting the fluorescence of samples irradiated by ultraviolet light. Generally, the FM map of base bitumen shows black. Commonly used modifiers appear in different colors. For example, styrene-butadiene-styrene (SBS) modifiers show yellowish green, and sulphur modifiers present red (Qu et al., 2022). Currently, this technology is always used to characterize the blending system between modifiers and base bitumen. With the help of FM, Kou et al. (2020) found that star SBS modifiers presented a complete and complex network structure in bitumen. Increasing the SBS content and prolonging the shearing time can significantly improve the dispersion and network structure of modifiers. Similarly, a network structure appeared between ethylene vinyl acetate (EVA) and bitumen (Xiao et al., 2016). In contrast, recycled polyethylene (PRE) modifiers were difficult to dissolve uniformly in the base bitumen according to the research conducted by Sun et al. (2021).

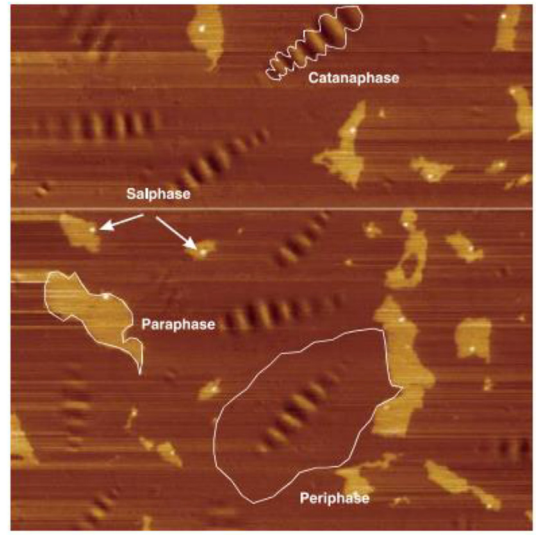


Fig. 83. Various phases on the bitumen surface (Masson et al., 2006).

In recent years, some scholars also adopted FM to evaluate the aging and reclamation of bitumen (Ding et al., 2017, 2018; Yan et al., 2019; Chen et al., 2020d; Xing et al., 2023) used FM to characterize the fluorescence degree of base bitumen incorporated by fluorescent powders before and after aging and found that bitumen was aged from the outside to the inside. As for SBS-modified bitumen, Yan et al. (2019) observed that the polymer gradually showed a point distribution and the particle size of that decreased after aging, which can be attributed that aging destroyed the network structure of modifiers in base bitumen, as shown in Fig. 81. Xiao et al. (2016) attributed the improved aging resistance of the organic montmorillonite (OMMT) and EVA modified bitumen to the exfoliated structure in the modified bitumen. This structure prevented the evaporation of light fractions and weakened the aging damage of bitumen. With regard to the reclamation of aged bitumen, the research conducted by Ding et al. (2017, 2018) built a blending chart in terms of

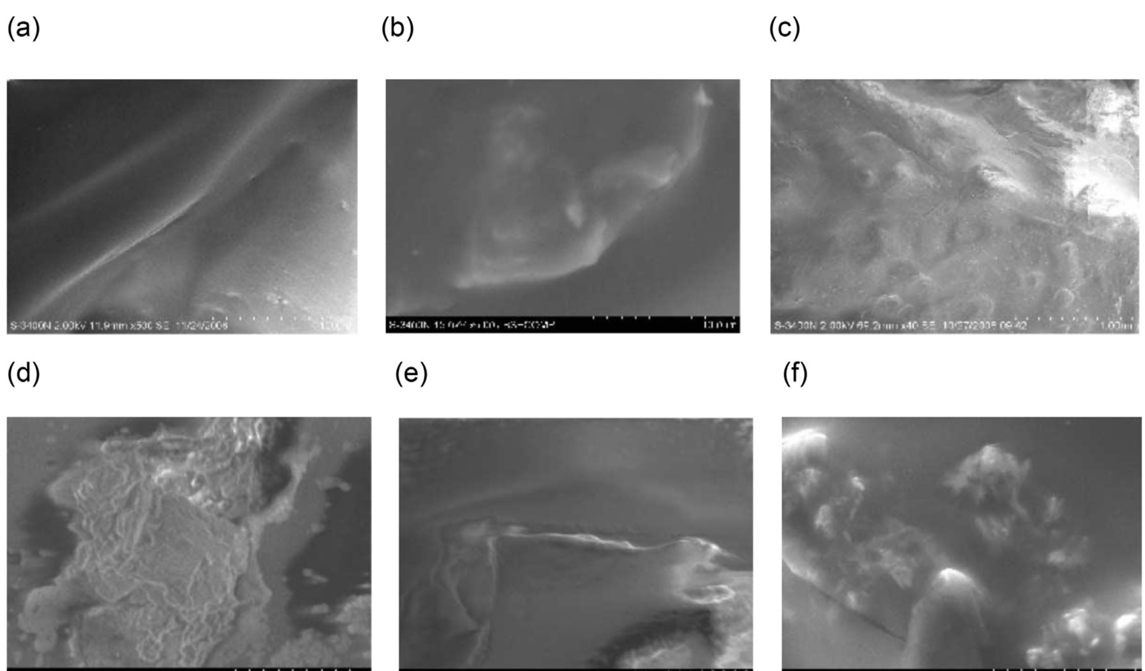


Fig. 82. ESEM maps of bitumen. (a) Virgin crumb rubber modified bitumen. (b) Aged crumb rubber modified bitumen. (c) Virgin SBS-modified bitumen. (d) Aged SBS-modified bitumen. (e) Virgin modified bitumen prepared by crumb rubber and SBS. (f) Aged modified bitumen prepared by crumb rubber and SBS (Wang et al., 2015b).

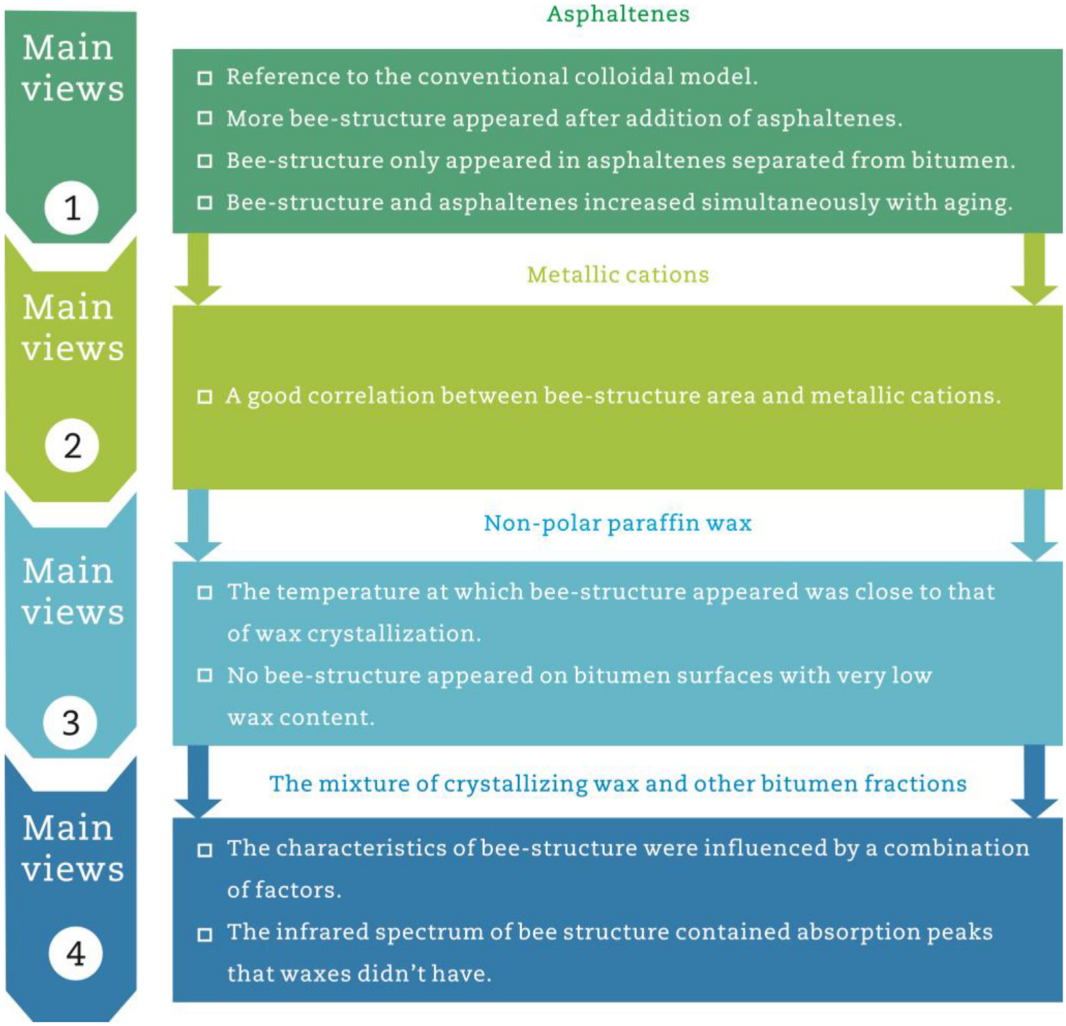


Fig. 84. The cognitive process of bee structures (Xing et al., 2022).

mean gray values according to the difference of gray values of FM maps between virgin bitumen and reclaimed asphalt pavement (RAP) bitumen, which was used to evaluate the blending degree of virgin and RAP bitumen.

5.1.3.2. SEM and ESEM. SEM and ESEM have been widely used to characterize the microstructure of bituminous materials because of their high resolution. Given that SEM imaged samples using electron beam in the ultra-high vacuum environment, the surface of non-conductive bitumen samples usually needs gold spray treatment to improve the conductivity of samples for the purpose of good imaging quality. However, this treatment may affect the real morphology of bitumen. Besides, bitumen is volatile under ultra-high vacuum. Therefore, there may be some deviation in the evaluation of bitumen by SEM. In contrast, ESEM has more advantages than SEM in the study of bituminous materials because no conductive coating is required and the detection can be carried out in the natural state.

Specifically, SEM and ESEM has been used in the research on the modification, aging, and reclamation of bitumen (Cui et al., 2011; Fang et al., 2012; Wang et al., 2015b; Mikhailenko et al., 2017, 2019). Cui et al. (2011) captured the SEM maps of base bitumen and rubber modified bitumen. It can be found that the rubber powder was insoluble in bitumen and the volume of that became small, which can be attributed to the desulfurization and depolymerization of rubber in the process of high-speed shearing and stirring. Fang et al. (2012) observed that the nano-lamellas of OMMT were exfoliated into individual lamellas. Beneath the large lamellas, some small lamellas were grouped together in a stacked fashion. These exfoliated lamellas facilitated full contact with bitumen during modified bitumen preparation. In terms of the research on bitumen aging, Mikhailenko et al. (2019) evaluated the microstructure of bitumen before and after aging through comparing the ESEM maps. The fingerprints of bitumen evolved with aging. After long-term aging, the fiber structure of base bitumen became dense and vertically arranged, and the average diameter of fibers became smaller. Mikhailenko et al. (2017) observed a similar phenomenon. Furthermore, according to the ESEM maps of three kinds of modified bitumen before and after aging, Wang et al. (2015b) found aging can lead to the poor continuity at the bitumen-modifier interface, causing the worse interface adhesion, as shown in Fig. 82. Among them, SBS-modified bitumen was obviously affected, followed by modified bitumen prepared by crumb rubber and SBS. In order to recover the performance of aged bitumen, Mikhailenko et al. (2017) added virgin base bitumen into aged bitumen to prepare reclaimed bitumen. Then, with the help of ESEM, it can be found that when the content of aged bitumen was high, it was difficult to restore to the microstructure of virgin bitumen.

5.1.3.3. AFM. AFM is a surface observation tool, which captures the morphology of samples through the interaction between probes and samples (Munz et al., 1998). Conventional AFM can obtain the topographic maps and phase maps at the nanoscale. With the development of technology, a series of advanced functional detection modes have been developed based on the basic imaging modes. Among them, the peak force-quantitative nanomechanical mode (PF-QNM) has been used to study the nanomechanical properties of bituminous materials because it is suitable for collecting nanomechanical maps of soft and sticky samples (Nahar et al., 2014, 2016). Loeber et al. (1996) first used AFM to collect topographic maps of bitumen and observed rippled microstructures on surface of thin-film bitumen. Masson et al. (2006) named various phases of bitumen surface as catanaphase, periphase, paraphase, and salphase, respectively, as shown in Fig. 83. Among them, the bee structure of bitumen surface at the nanoscale has attracted the widespread attention of scholars. Blom et al. (2018) found that the spacing between adjacent peaks was approximately 0.5 μm, which was independent of bitumen types. Regarding the chemical composition and formation mechanism of bee structures, the cognitive process has gone through four stages, as shown in Fig. 84 (Xing et al., 2022). At present, it is generally believed that the formation of bee-structures was most likely driven by the interaction between the wax crystallization and other chemical composition in bitumen (Xing et al., 2020a, b).

In recent years, AFM has been used in the research on the modification, aging, reclamation, and interfacial interaction of bitumen (Huang and Pauli, 2008; Wu et al., 2009; Nahar et al., 2013; Wang and Liu, 2017; AbuQtaish et al., 2018; Zhang et al., 2019c; Ji et al., 2020; Xing et al., 2020a, 2020b, 2020c, 2022; Xu et al., 2020b; Yang et al., 2020d). Specifically, Zhang et al. (2019c) found that compared with base bitumen, the addition of SBS modifiers increased the area and proportion of bee structures. Furthermore, the research conducted by Wang and Liu (2017) revealed that linear SBS-modified bitumen had larger Derjaguin-Muller-Toporov (DMT) moduli and adhesion compared with base bitumen. With regard to crumb rubber modified bitumen, another commonly used polymer modified bitumen, Huang and Pauli (2008) observed small particulate matters on the surface. In terms of the effect of aging, Wu et al. (2009) found that base bitumen and SBS-modified bitumen after aging have larger and more bee structures. However, some research came to the opposite conclusion that aging led to the decrease of bee structures and roughness (Ji et al., 2020; Wang and Liu, 2017; Xing et al., 2020a, b). Furthermore, with the help of AFM PF-QNM, research conducted by different scholars demonstrated that aging resulted in the decrease of adhesion and the increase of moduli of bitumen surface (Wang and Liu, 2017; Yang et al., 2020d). Aged bitumen is usually reclaimed to achieve reuse. Nahar et al. (2013) captured the topographic maps of the blending zone between aged and virgin bitumen and observed that the blending zone presented the microstructure characteristics between virgin and aged bitumen. Besides, the blending zone was related to the temperature and time of blending. Similarly, the research conducted by AbuQtaish et al. (2018) demonstrated that the modulus of the blending zone was lower than that of the aged bitumen but higher than that of virgin bitumen, which proved that the nanomechanical properties of blending zone were affected by virgin and aged bitumen. In the study of the interfacial interaction between bitumen and mineral materials, Xu et al. (2020b) prepared three kinds of mastics including limestone, diabase, and granite, respectively and found that the bee-structure area and roughness of bitumen surface in mastics were less than that of single bitumen surface. To better clarify the effect of fillers on the bitumen microstructure, Xing et al. (2020a, b, c) adopted AFM PF-QNM to collect the nanomechanical maps of bitumen interiors in mastics and mixtures prepared by frozen-storage and low-temperature-cutting methods. It can be found that bitumen far from the interface had less A-phase and more B-phase in comparison with single bitumen.

5.2. Advanced pavement intelligent detection technologies

This section introduces the advanced pavement intelligent detection technologies, including pavement intelligent monitoring technology in Section 4.2.1 and pavement intelligent detection technology in Section 4.2.2. The former recalls road performance monitoring technologies and traffic flow monitoring technologies, and the internet of things (IoT), including laser systems, mobile on-board devices, in-situ pavement sensors, fiber optic sensing, and embedded wireless sensor. The latter introduces the pavement surface and internal detection technologies. The surface detection technology uses image- or laser-based devices to collect pavement surface distress and macro-texture information and then uses machine learning-based models to perform the detection task.

5.2.1. Pavement intelligent monitoring technology

With urbanization progressing and transportation becoming busier, the safety, reliability, and efficiency of road infrastructure are gaining significance. Road conditions play a pivotal role in influencing traffic flow and driving safety. Consequently, real-time intelligent monitoring of road surfaces has emerged as a pivotal strategy to enhance the overall performance of transportation systems. While traditional monitoring approaches often demand substantial resources and time, hindering their adaptability to swiftly changing road dynamics and traffic demands, the rapid evolution of information technology and artificial intelligence has paved the way for intelligent road surface monitoring. This segment delves into pivotal techniques in the realm of intelligent road monitoring.

5.2.1.1. Road performance monitoring. Pavement performance monitoring involves quantitatively assessing the quality, structure, and condition of road surfaces. Over time, road surfaces can deteriorate due to factors like traffic loads, climate conditions, and wear, resulting in issues like cracks, potholes, and wear. Non-destructive methods are commonly employed for pavement performance monitoring, falling into two categories: external evaluation methods and in-situ pavement sensors (Xue et al., 2014). By combining these two approaches, a more comprehensive and multi-faceted understanding of road surface conditions can be obtained.

(1) External evaluation methods
- Image-based techniques

Image processing technology quantifies road surface conditions through analysis of road surface images. This approach utilizes devices such as CCD cameras, unmanned aerial vehicle systems (UAVs) (Pan et al., 2018; Roberts et al., 2020), and 3D cameras (Ahmed et al., 2011; Mathavan et al., 2015). For instance, Zakeri et al. (2017) employed a quadcopter UAV to capture real-time road surface images. Peddinti and Kim (2022) efficiently monitored road surfaces in Korea using drones.

- Ground penetrating radar (GPR)

GPR offers high-precision, high-speed measurements with extensive coverage. The collected measurement data serves several critical purposes: predicting road density and layer thickness, monitoring subsurface anomalies, and evaluating the performance and longevity of the road infrastructure. Colagrande et al. (2020) used GPR to monitor specific road damage in Italian cities and successfully identified different types of road damage. Xie et al. (2021) conducted a full coverage scan of the airport road surface with GPR, and basing on complex signal analysis technology, it was found that the main diseases of the airport road surface were loose layers and small holes.

- Laser systems

Laser scanning employs laser beams for non-contact 3D measurements of road surfaces. It has been widely applied in road surface disease and deformation monitoring. Choi et al. (2016) developed a three-dimensional laser scanner based on the light cutting method to automatically measure the three-dimensional digital surface model of the road surface to monitor road cracks. Ferenčík et al. (2019) used laser profilometry for forest road monitoring, detecting cracks and potholes. Laser monitoring has the advantages of high accuracy, speed, and non-contact, but the approach was sensitive to numerous items on the road surface, including snow, ice, and fallen branches and leaves.

• Mobile on-board devices

Numerous researchers used innovative mobile vehicle devices based on smartphone sensor technology (Barri et al., 2020; Roberts et al., 2020) and black box for road surface monitoring. Chen et al. (2016) proposed a road surface monitoring system, denoted as CRSM, employing hardware modules strategically positioned on vehicles. These modules are equipped with low-end accelerometers and GPS devices, enabling the acquisition of vibration patterns, vehicle positions, and speeds. This setup proves instrumental in efficiently monitoring road potholes. Shtayat et al. (2022) used electric bicycles and private cars as test vehicles and collected vibration data using the "sensor log" smartphone application. They proposed a new technology for dynamic monitoring of road conditions based on vibration data and video recording. Meocci et al. (2021) utilized data collected from a black box inside the vehicle (equipped with a tri-axial gyroscope, inertial accelerometer, and GPS device) to achieve rapid and real-time monitoring of road surface diseases.

External evaluation methods are non-intrusive and provide efficient large-scale data collection methods. However, equipment is usually expensive, and these methods generally obtain the damage states of the road surface, which cannot reflect the stress and strain states inside the structure.

(2) In-situ pavement sensors

In-situ pavement sensors entail the installation of integrated sensors within the road structure to precisely gauge responses of road surface layers, including stress, strain, temperature, deflection, and more. This approach enables seamless, continuous monitoring of road conditions without disrupting traffic.

• Fiber optic sensing technology

Fiber optic sensors are widely embraced for their long-term stability, durability, corrosion resistance, electromagnetic interference immunity, affordability, and precision. These sensors can be classified into fiber grating sensors and fully distributed fiber optic sensors based on their operational principles (Wang, 2006). The former excels in precise local measurements like stress, strain, and temperature. The latter enables continuous monitoring across the entire length of the fiber, making it suitable for large-scale applications such as deformation monitoring.

Wang et al. (2014) developed enhanced industrial fiber optic sensors and deployed self-healing fiber optic sensing networks to comprehensively monitor road surfaces. Zhao et al. (2018) utilized embedded sensing optical fibers to collect and classify vibration signals from traffic vehicles, achieving an 89% accuracy in classification. Zhao et al. (2019) introduced a compression transmission system based on Brillouin optical time domain analysis (BOTDA) for assessing support conditions of concrete pavement slabs.

Although fiber optic technology has made remarkable progress in road surface monitoring, it still faces some challenges, such as the relatively high equipment cost of fiber optic sensing technology, and the need for professional knowledge for installation and maintenance. In addition, changes in environmental parameters may lead to signal complexity of fiber optic sensors, which is not conducive to analysis and interpretation.

• Embedded wireless sensor

One of the main limitations of traditional wired sensors is their deployment and maintenance. Installing a large number of wired sensors on the road is time-consuming and costly. Moreover, wire corrosion and damage can occur when embedded in concrete. As a solution, embedded wireless sensors are increasingly being used as substitutes for road monitoring systems. Wang et al. (2022e) proposed a method using embedded wireless sensors (SmartRock) for road damage monitoring. Wireless sensors serve as data collection nodes, capable of hosting traditional structural sensors for autonomous data collection and processing (Lynch and Loh, 2006).

It is worth mentioning that almost all sensors used for structural monitoring require external power supply. Maintenance or replacement of embedded sensor batteries, or the adoption of solar power technology, can incur high costs. This issue makes long-term continuous road surface monitoring very difficult, and many studies have found that using energy harvesting devices to convert mechanical energy into electrical energy is a good solution. Among various self-powered energy sources, piezoelectric transducers have been proven to be one of the most effective choices (Lajnef et al., 2011; Korhonen and Lankinen, 2014). Alavi et al. (2016b) designed a novel miniaturized spherical packaging system based on piezoelectric self-powered sensing technology.

5.2.1.2. Traffic flow monitoring. Traffic flow monitoring involves real-time tracking and analysis of vehicle positions and traffic conditions. This includes crucial information like vehicle speed, type, and weight. The current mainstream traffic flow monitoring technology is the weight-in-motion (WIM) system. This system utilizes various materials such as quartz crystals, ceramics, polymers, fiber optics, and strain gauges. Depending on the speed of the vehicles being monitored, WIM systems can be categorized into high-speed and low-speed systems. High-speed WIM systems are employed for comprehensive traffic data collection and flow management. Conversely, low-speed WIM systems are typically

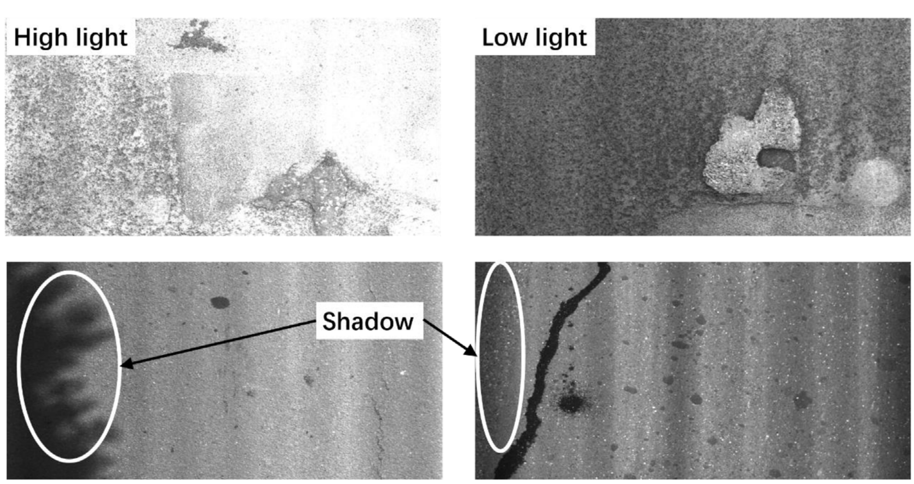


Fig. 85. Pavement surface images with different lights and shadows.

installed at toll booths, enabling law enforcement agencies to enforce fines for overweight vehicles.

The working mode of different types of WIM sensors is similar. They all convert the stress generated by the vehicle during movement into electrical response (Otto et al., 2017). The accuracy of these systems mainly depends on the traffic flow monitors used (such as piezoelectric sensors, bending plates, weighing sensors, and optical fibers) and the reliability of corresponding algorithms (Zhang et al., 2015).

5.2.1.3. The internet of things. Currently, the convergence of big data and internet of things (IoT) technologies is gradually taking shape, leading road surface monitoring towards real-time and highly efficient capabilities. Through the utilization of micro-electro-mechanical systems (MEMS) (Yang et al., 2015) and wireless sensor networks (Huang et al., 2017), various information related to road surface stress, strain, and vibration is captured. This enables the timely detection of abrupt road surface structural damages, along with the assessment and prediction of the condition and future trends of these structures. Micro-electro-mechanical sensors and associated system technologies are notable for their compact size, energy efficiency, and cost-effectiveness. In the study by Ye et al. (2020), acceleration sensing nodes based on MEMS technology were deployed for traffic flow monitoring. Wireless sensor networks, which establish connections among numerous distributed sensor nodes using wireless communication, enable comprehensive distributed monitoring. Bajwa et al. (2017) developed a wireless sensor network to classify vehicles and estimate axle loads. In a similar vein, Pei et al. (2009) employed the Mica2 Motes wireless sensor network to monitor road surface temperature and humidity, providing insights into traffic safety conditions.

5.2.2. Pavement intelligent detection

5.2.2.1. Pavement surface detection.

(1) Automatic data collection methods

In recent years, there are two main methods for pavement surface information collection: pavement digital images and three-dimensional (3D) cloud points. The form uses a line-scan digital camera or motion camera to obtain pavement surface images with a fixed step, while the latter uses a line or surface laser device to generate pavement surface cloud points. These image and cloud points are used for pavement surface distress detection and performance evaluation.

The most common and widely-used method is the digital image-based one, such as Cao et al. (2017) and Wang et al. (2017). This technology has two significant advantages in pavement surface information collection. One is its high collection efficiency, which can obtain pavement surface images with a speed of about 80 km/h. Another is its compatibility to many machine-learning algorithms, benefiting from the application of computer vision technologies on image processing. For example, many recent publications such as Tong et al. (2020b) and Ragnoli et al. (2018) has demonstrated the feasibility of using deep neural networks to detect and segment pavement surface distresses.

Unfortunately, such image-based information collection methods still face two challenges. The first one arises from the negative effect of road environments (Tong et al., 2022a), such as various real-world lighting and shadow conditions, which might make some important surface information not clear. For example, Fig. 85 shows that high light and shadow conditions make the surface crack and macro-texture partially invisible. This phenomenon hampers the accuracy and stability of intelligent pavement detection. Another problem is the inherent precision limitation of digital images. The resolution ratio of an image-based method basically depends on its pixel scale, which is 1–3 cm (Du et al., 2021a). Such resolution ratio can only represent pavement distress information. However, surface macro-texture information (0.05–5 cm in the lateral direction and 0.05–2 cm in the longitudinal direction) is important for pavement surface detection and performance evaluation (Tong et al., 2018).

Compared to image-based methods, 3D cloud points-based methods, such as handheld and vehicle-mounted 3D lasers such as Sengoz et al. (2012) and has the superiority of environmental stability. For example, many studies such as Chang et al. (2005) and Li et al. (2016) indicate that the precision of a laser device is robustness to various light and surface conditions. Thus, in the view of data stability, 3D clouds points-based methods exceed the image-based methods for pavement surface information collection. However, the forms of 3D cloud points-based methods are more complex than the form of digital images, such as *XYZ* coordinates and voxel grids. This problem leads to a fact that the combination of surface cloud points and advanced machine-learning methods is difficult and not common in pavement detection, even though some attempts have been done, see the next part.

(2) Intelligent data processing methods

For the processing of pavement surface images, the main trend is to used deep neural networks to detect and segment pavement distresses (Guan et al., 2021; Zhu et al., 2022b), as well as reconstruct surface macro-texture. In the field of pavement inspection, distress detection is the process of classifying distress classes and locate them in an image, while distress segmentation is the process of assigning each pixel in an image into one of distress classes or background.

In recent years, attention-based deep networks, such as segmentation transformer (Tong et al., 2023) and CC-attention net (Tong et al., 2022a), have achieved state-of-the-art performance in pavement distress

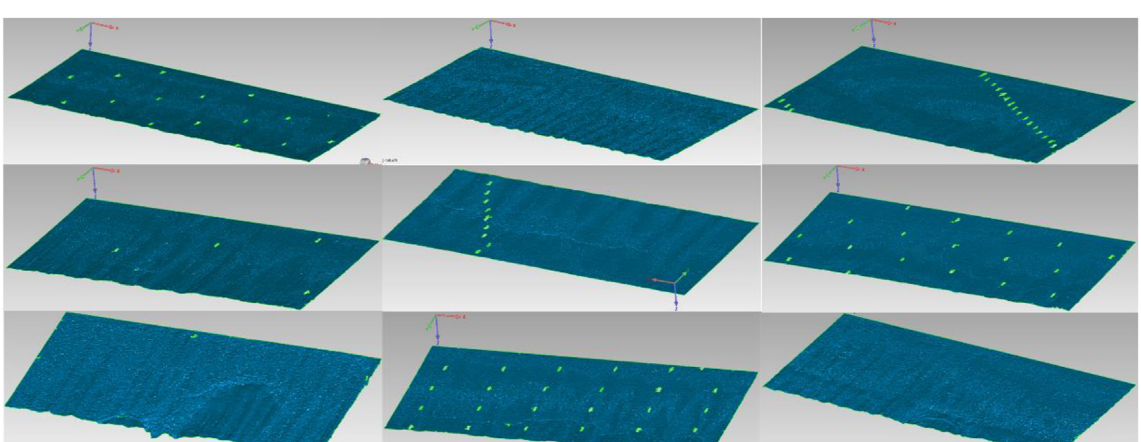


Fig. 86. Point omitting in 3D pavement surface data (Ma et al., 2021).

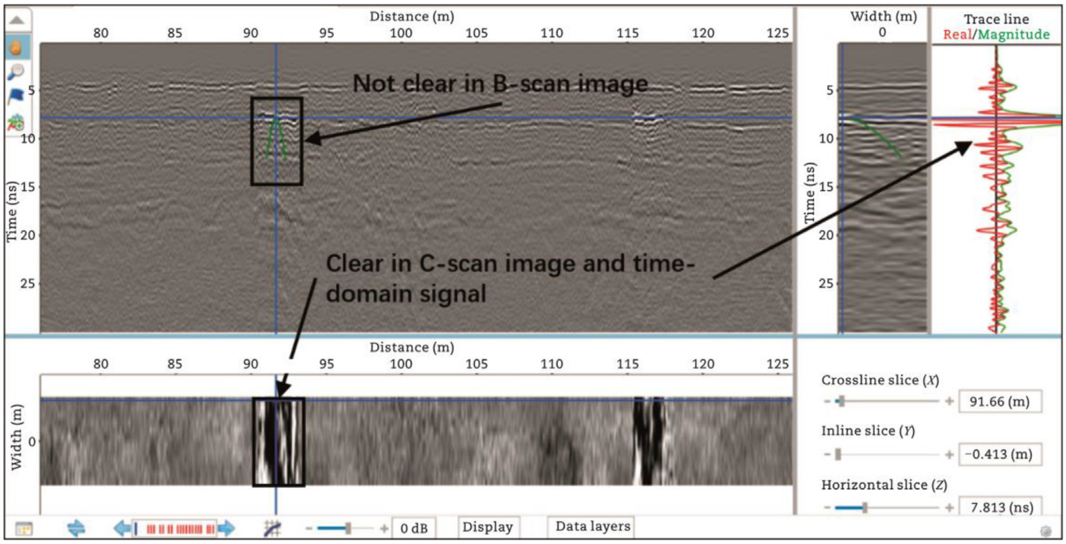


Fig. 87. Small object detection using B- and C-scan imaging.

detection and segmentation, even though the model stability is still significantly affected by road environment conditions owing to the limitation of image-based information collection methods. Further, several deep networks (Li et al., 2021a) have been proposed to map pavement surface images to macro-texture cloud points, but the accuracy and stability of these models are limited by the resolution ratio of pavement digital images.

Compared to the processing of pavement surface images, the advanced deep learning models are more complex and can be divided into five categories (Mahony et al., 2019). (i) The first category includes methods that extract descriptors from the 3D data and give these as input to the DNN. (ii) The approaches belonging to the second category exploit RGB-D 3D data (i.e., separate color and depth channels). (iii) Deep architectures designed to have direct access to the 3D data form the third category. (iv) The fourth category includes methods utilizing one or more 2D projections/views of the 3D object/scene captured from different viewpoints and use them to feed the employed deep model. (v) DL methods designed for data captured from hyperspectral cameras are included in the last category. In recent years, the studies mainly focus on the second and third category because of their relatively simple step, where a deep network can directly use the 3D data as inputs. Though achieving high accuracy and stability, these methods still face the problem of point omitting, such as the green areas in Fig. 86.

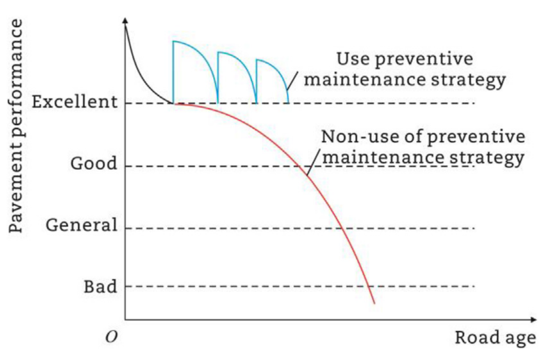


Fig. 88. Effect of multiple preventive and corrective maintenance on pavement performance.

5.2.2.2. Pavement structure detection.

(1) Automatic nondestructive testing methods

In recent years, ground-penetrating radars (GPRs), have achieved remarkable success in the data collection of pavement structure defects. GPR is a geophysical method that uses radar pulses to image the subsurface. It is a non-intrusive method of surveying the sub-surface to investigate underground utilities such as concrete, asphalt, metals, pipes, cables or masonry. A GPR transmitter and antenna emits electromagnetic

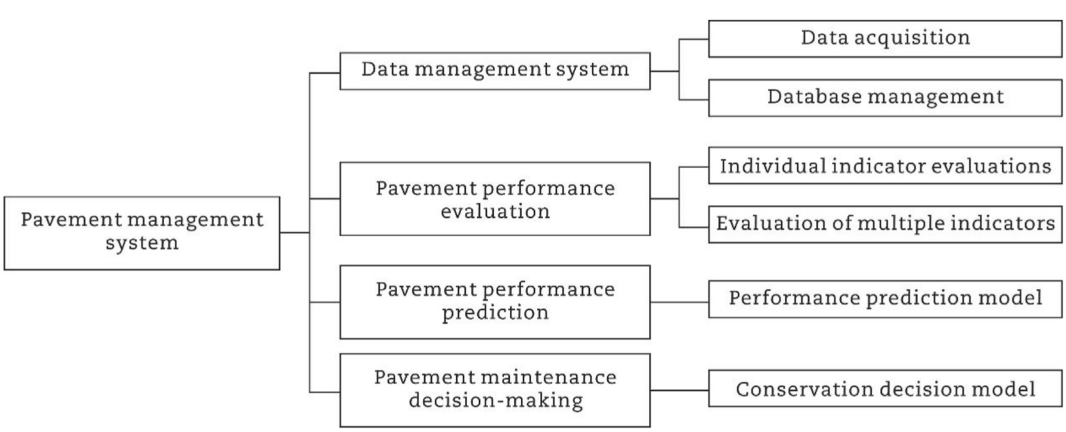


Fig. 89. Pavement management system.

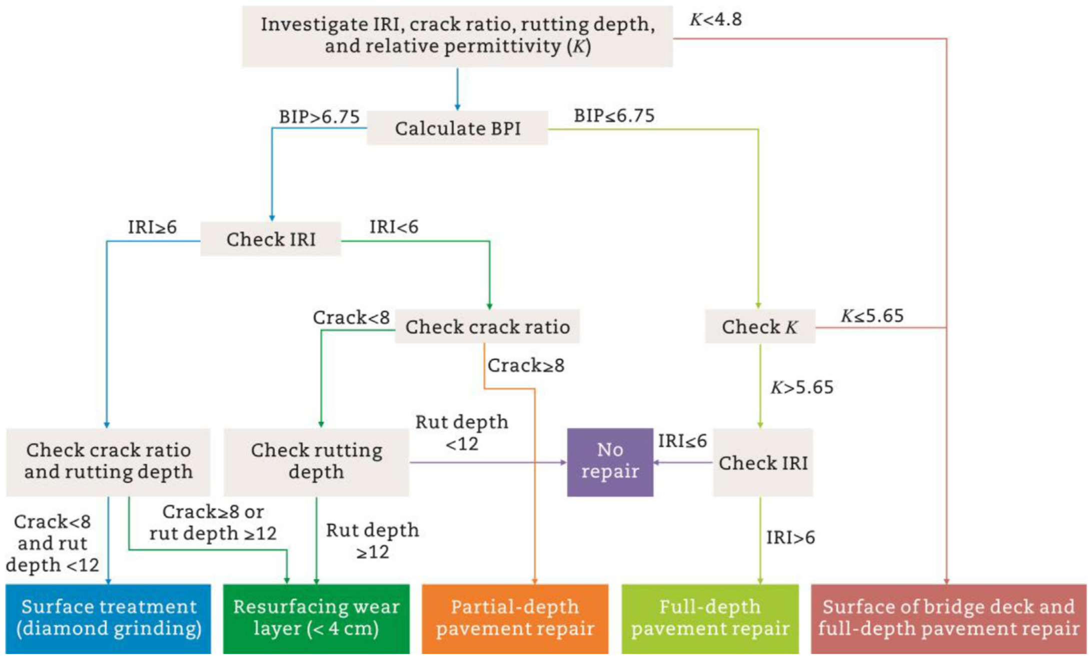


Fig. 90. Decision tree for maintenance of asphalt pavement systems.

energy in the range 10 MHz to 2.6 GHz into the ground (Srivastav et al., 2020). When the energy encounters a buried object or a boundary between materials having different permittivities, it may be reflected or refracted or scattered back to the surface. A receiving antenna can then record the variations in the return signal. Now, this technology has been widely used to detect pavement structure defects in expressway, airport pavements, urban roads.

In the form of GPR antenna, three are two types: air- and ground-coupled GPRs (Yang et al., 2022b, c). In general, the ground-coupled GPR has a higher precision than the air-coupled one thank to a distance approximate to 0 between the antenna and ground, which reduce the negative effect of air on the energy dissipation of GPR wave. However, an air-coupled GPR can work in a speed close to 80 km/h, while the speed of a ground-coupled GPR is less than 30 km/h.

In the form of GPR imaging, there are two categories: two- and three-dimensional GPRs. Individual lines of two-dimensional GPR data (a group of signals) represent a sectional (profile) view of the subsurface, while multiple lines of three-dimensional GPR data systematically collected over an area may be used to construct tomographic images. In the application of pavement detection, the three-dimensional data presents more information, especially for some small buried objects, such as the small crack in Fig. 87. The imaging of a single profile cannot represent the crack clear, while the effect of the crack is clear in the C-scan imaging.

Now, the GPR technology still faces two problems: signal scattering in heterogeneous conditions and complex data processing. The first problem arises from the fact that the heterogeneous pavement materials, such as asphalt mixture with asphalt and aggregates, always lead to energy dissipation and signal diffraction, which limits the detection depth and precision, respectively (Zhang et al., 2023a). Another problem means that the complex waveform interpretation process is required to explore the electrical properties of a buried object based on the collected reflected signals (Zhu et al., 2021). Therefore, intelligent data processing methods is required for GPR detection.

(2) Intelligent data processing methods

Intelligent GPR data processing methods can be grouped into two directions: image- and signal-based inversion methods. The first one combines GPR imaging with deep-leaning models to classify and detect pavement defects (Tong et al., 2017, 2020a; Travassos et al., 2018; Li et al., 2021b), which is the mostly common way for GPR data inversion, thanks to the compatibility of GPR images and deep neural networks. Unfortunately, such technology has two problem of Fresnel diffraction. Fresnel diffraction in high-frequency electromagnet wave is a phenomenon that a GPR wave diffracts when it propagates through an object whose shape is smaller than the first Fresnel diameter. This phenomenon

Table 11
Algorithms and their core ideas.

Arithmetic	Core idea
Clustering algorithm (Sandra and Sarkar, 2015; Rejani et al., 2021)	Numbering each object as a separate cluster by itself, then merge it with other objects and form a larger cluster based on the distance between them, terminating the clustering process when all the objects are in a single group or at any other point desired by the user
Genetic algorithm (Li et al., 2022l)	Computational modeling of biological evolutionary processes simulating the natural selection and genetics mechanisms of Darwinian biological evolution, searching for optimal solutions by simulating natural evolutionary processes
Water cycle algorithm (Naseri et al., 2022c)	Finding optimal solutions by inspiring the collective behavior of real-world rivers and streams flowing downhill to the sea
Coyote optimization algorithm (Naseri et al., 2022b)	Simulating the social behavior and interactions of dingo populations to study the feasible domain of the optimization problem and find the optimal solution
Particle swarm algorithm (Ahmed et al., 2019b)	Simulating bird behavior to find locally optimal solutions
Ant colony optimization algorithm (Terzi and Serin, 2014)	Determining the shortest path between messages using tracks where other ants have deposited hormones, inspired by simulating the behavior of real ants

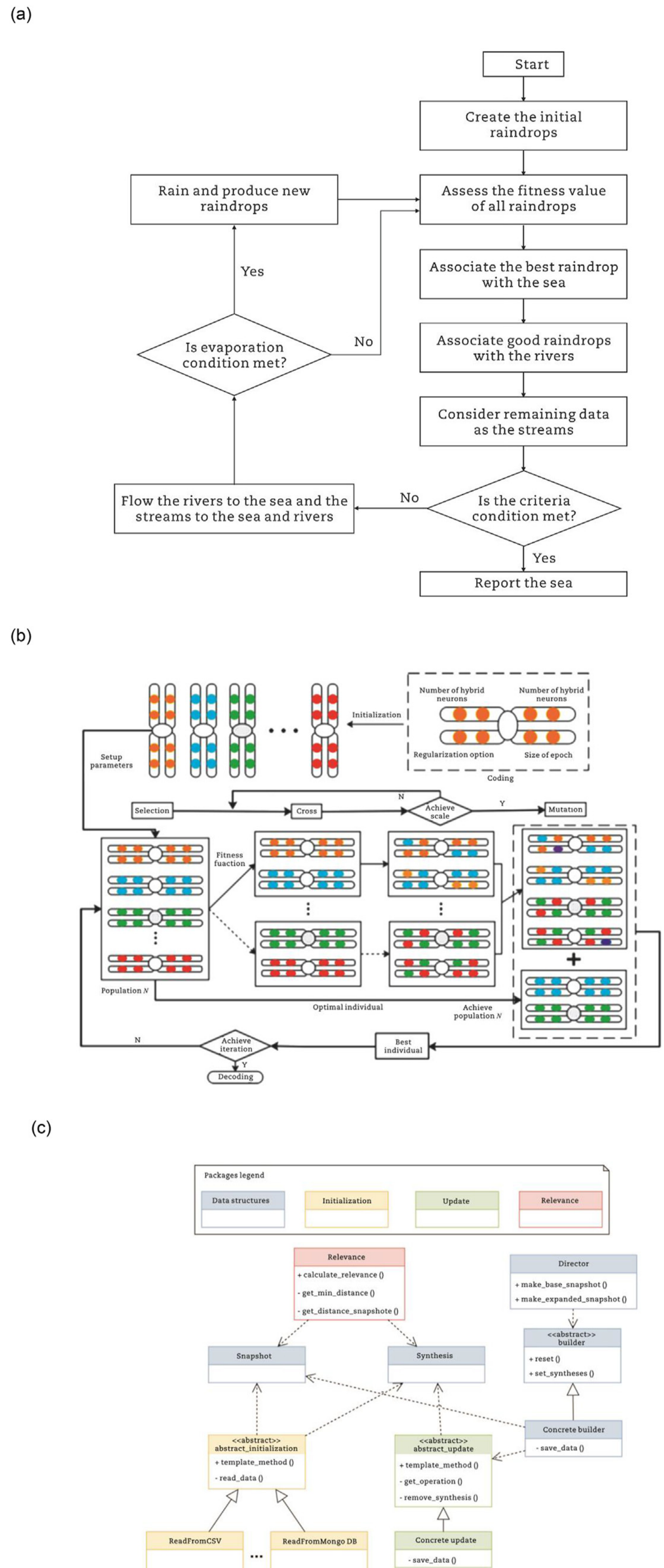


Fig. 91. Algorithmic structure. (a) Water cycle algorithm (Naseri et al., 2022c). (b) Genetic algorithm (Li et al., 2022g). (c) Clustering algorithm (Bianchini et al., 2023).

Table 12
Comparison of ANN and DL.

Discrepancy	ANN	DL
Data volume	Lesser	More
Feature processing	Manual handling	Auto-execution
Hardware requirement	Low equipment requirements	High equipment requirements
Application scenario	Broader	Broader
Problem-solving approach	Splitting and calculating the set to be solved	End-to-end
Data processing speed	Shjreng_50_fx31_bw.tif - arp	Relatively soon
Decision-making accuracy	High	High

makes the GPR imaging not represents the actual shape of a small object. With accurate GPR imaging, this approach cannot measure the shape of pavement defects, not mentioned to the three-dimension reconstruction of pavement defects.

Signal-based inversion methods, also known as full-waveform inversion (FWI), determines the optimal velocity model by minimizing the misfit between predicted and observed GPR waveforms (Tarantola, 1984; Virieux and Operto, 2009). Recent studies of deep learning have drawn attention to its potential application in FWI. One research direction is to build a direct inverse mapping from observations to pavement defects by training neural networks on paired data of seismic waveforms and velocity models (Tong et al., 2020c). This direction does not rely on solving the wave equation but instead treating FWI as a data-driven machine learning problem similar to that in image recognition or natural language processing. The accuracy and generalization of this approach, however, cannot be guaranteed without the partial differential equation constraint in FWI. Another research direction is to apply deep learning as an effective signal processing tool to improve the optimization process of conventional FWI. For example, several studies applied neural networks to extrapolate the missing low frequencies and help mitigate the cycle skipping problem (Ovcharenko et al., 2019; Sun and Demanet, 2020; Hu et al., 2021).

5.3. Advanced pavement performance evaluation and maintenance decision-making

5.3.1. Pavement maintenance decision-making

Road infrastructure, subjected to increasing traffic loads, experiences significant deterioration in asphalt pavement and its structural performance over time (Tong et al., 2022b; Yu et al., 2023a, 2023b). Appropriate maintenance practices can effectively prolong the service life of pavements (Liu et al., 2019b). Maintenance strategies are generally categorized into corrective maintenance (CM) and preventive maintenance (PM). CM is a widely employed approach (Montoya-Alcaraz et al., 2020), involving repairment when the pavement has already suffered considerable damage. In contrast, PM involves maintenance actions taken before significant pavement damage occurs, ensuring that pavement performance remains at an acceptable level (Li et al., 2022l). Fig. 88 depicts the degradation curve of pavement performance under different maintenance strategies (Yao et al., 2020). Compared to CM, PM mitigates the rate of performance deterioration, and concurrently offering

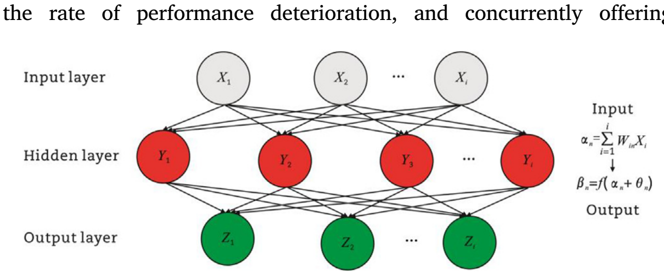


Fig. 92. Artificial neural network workflow.

potential cost savings in maintenance expenditures (Hafez et al., 2019).

Building upon the aforementioned practical demands, the concept of a pavement management system (PMS) was introduced in 1971 by the United States and Canada (Santos and Ferreira, 2013; Shon et al., 2022). In 1979, the US Army Corps of Engineers developed the PAVER pavement management system, which assigned pavement condition ratings based on the extent of pavement damage and introduced the pavement condition index (PCI) as a measure of pavement deterioration (Liu, 2003). In 1980, the Transport and Road Research Laboratory in the United Kingdom established the highway maintenance assessment and reporting technique (CHART). Canada launched the municipal pavement management system (MPMS) in 1987. Denmark established its own pavement management system in 1980, while in 1991, China established the comprehensive pavement management system (CPMS) for arterial highways. The primary modules of maintenance management systems are illustrated in Fig. 89 Within the decision framework of pavement management systems, optimization algorithms play a pivotal role in enabling efficient and high-quality decision-making (Consilvio et al., 2023). Presently, common decision-making methods can be categorized into three types: operations research methods, heuristic algorithms, and artificial intelligence methods (Han et al., 2021a). Over the years, numerous scholars have continuously refined and enhanced maintenance decision-making methods. This paper provides a comprehensive review of these decision-making approaches.

5.3.1.1. Decision-making methods based on operations research. Operations research involves the utilization of statistical and mathematical modeling methods to provide scientific foundations for decision-making by managerial personnel (Worm and van Harten, 1996). This is achieved by establishing single-objective or multi-objective linear programming models, specifying optimization objectives, constraints, and the feasible domain of decision variables, with the aim of solving maintenance decision optimization problems (Albuquerque and Núñez, 2010; Mahmood et al., 2018).

One of the most common methods is the decision tree approach (de Figueiredo et al., 2022), which involves the incorporation of a comprehensive assessment index for the technical condition of asphalt pavements (such as pavement quality index (PQI), and pavement condition index (PCI) (Chou, 2009), as shown in Fig. 90 (Lee et al., 2022). By combining specific data on pavement conditions, traffic loads, climatic environment, and construction quality, hierarchical weighting is assigned to these factors. Trigger values of evaluation indices are employed to classify distress levels, facilitating a comprehensive assessment of pavement inspection performance (Chen et al., 2015). Subsequently, the designated pavement sections are categorized into various types, including routine maintenance, preventive maintenance and repair, specialized maintenance, and emergency maintenance (Hoffman et al., 2022). This approach offers advantages such as easy data collection, simplicity of evaluation models, and well-defined sub-indicators (Lee et al., 2022). However, it also presents limitations including fuzzy boundary values, substantial discrepancies among various evaluation indices, and challenges in accurately defining maintenance types (Han et al., 2022a).

5.3.1.2. Methodological algorithm based decision-making approach. The high-quality development of road traffic imposes greater demands on road maintenance management, leading road maintenance decision-making towards a more refined and accurate direction. The application of methodological algorithms plays a significant role in this context, as shown in Table 11, encompassing mainly clustering algorithms (Janstrup et al., 2019), genetic algorithms (Fwa et al., 1994; Hamdi et al., 2017), ant colony algorithms (Terzi and Serin, 2014), coyote optimization algorithms (Naseri et al., 2022a, b), particle swarm optimization algorithms (Ahmed et al., 2019a, b), water cycle algorithms (Naseri et al., 2022a, b), among others. As illustrated in Fig. 91, such algorithms

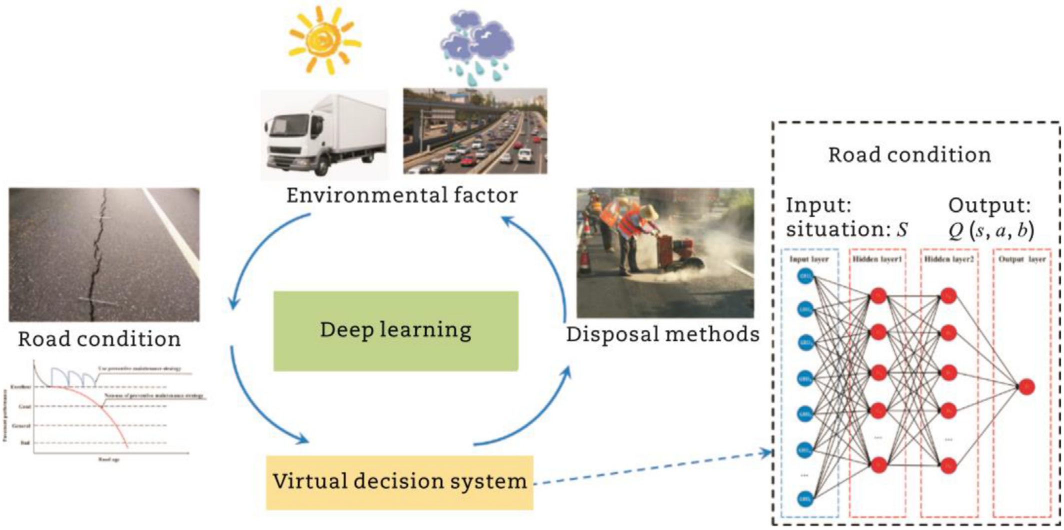


Fig. 93. Deep learning workflow.

typically aim for optimal planning with the objective of minimizing societal and economic impact while maximizing performance. Within constrained budgets and performance requirements, they seek to attain an optimal balance, often employed in the quest for optimal solutions to multi-objective problems.

In the pursuit of optimal road maintenance decision-making solutions, heuristic algorithms serve to simplify the complexity of decision problems, thereby identifying acceptable local optima. By emulating behaviors observed in nature, these algorithms offer advantages such as a reduced number of adjustable parameters, straightforward principles, and rapid convergence. However, heuristic algorithms possess inherent limitations, with a notable deficiency lying in their capacity to handle extensive datasets (Han et al., 2021a).

With the continuous optimization and refinement of various algorithms, their increased precision has essentially met the requirements of road maintenance decision-making. Furthermore, extant research in jreng_50_gr83_bw.tif - icates that the future trajectory of development lies in the integration of diverse algorithms, methods, and tools for road maintenance decision-making. The incorporation of techniques such as the water cycle optimized backpropagation neural network (Terzi and Serin, 2014), the utilization of random forest regression prediction algorithms to optimize the whale optimization algorithm (WOA) (Naseri et al., 2022c), and the amalgamation of local search techniques with genetic algorithms (Santos et al., 2019) have yielded models characterized by enhanced convergence rates and elevated accuracy.

5.3.1.3. Artificial intelligence based decision-making methods. The objective of artificial intelligence is to leverage the computational prowess of computers to emulate human cognition and generate responses akin to human reasoning, with the intention of assisting in the accomplishment of tasks (Saha et al., 2021; Wang et al., 2023a, b, c). Presently, AI-based analytical approaches are progressively finding application within road maintenance decision-making processes (Consilvio et al., 2023; Li et al., 2022g, l, m; Mahpour and El-Diraby, 2022).

AI-based analytical approaches necessitate the establishment of a comprehensive road data management repository by harnessing extensive road monitoring data (de Paula Vidal et al., 2022). Through a thorough exploration of interrelationships within the data, these approaches analyze and forecast the operational status of roads, subsequently formulating road maintenance decisions (Bukhsh et al., 2020).

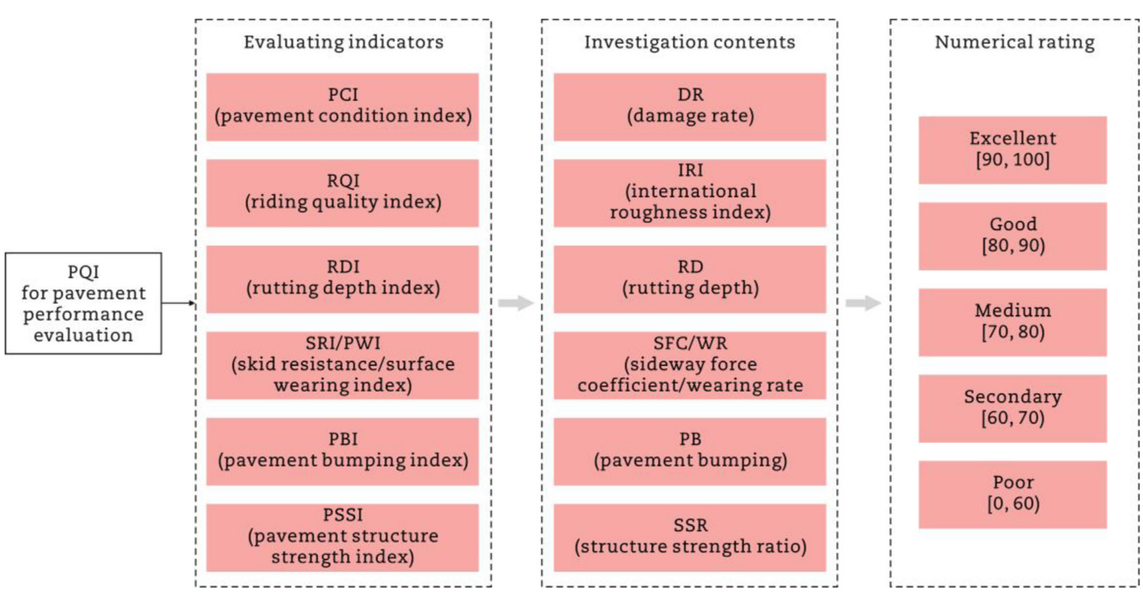


Fig. 94. Pavement performance evaluation system diagram.

Among these, artificial neural networks (ANN) and deep learning (DL) methods have garnered significant application, demonstrating expeditious, efficacious, and precise road maintenance decision-making capabilities. Notable distinctions between ANN and DL are elucidated in Table 12 (Han et al., 2021a; Li et al., 2022g, l, m; Morato et al., 2023; Xin et al., 2023).

ANN possesses the capability to unveil intricate interconnections among data, culminating in the derivation of more precise decision models (Li et al., 2022g, l, m). The architecture of ANN, depicted in Fig. 92, entails an adaptive learning process through continuous iterations triggered by the initial layer of data input. While ANN is adept at swiftly and accurately rendering decisions, models trained through this approach may inadequately account for the comprehensive lifecycle of roads (Yang et al., 2021b; Vyas et al., 2022). Additionally, the inputted feature values necessitate manual selection, rendering the established decision models less adaptable to other road contexts (Han et al., 2021a).

The DL model has the capacity to embed ANN and operations research algorithms within its architecture, thus synergistically integrating the precise analysis of road deterioration processes from operations research methodologies with the exceptional fitting capability of ANN (Han et al., 2021a). The structure of the DL model is illustrated in Fig. 93 DL has the ability to perform clustering operations on raw data (García-Segura et al., 2023), autonomously extracting feature values. Through continual training on data, deep learning can autonomously identify types of distress and make maintenance judgments (Zhang et al., 2022d; Ren et al., 2023). This approach facilitates integrated management of road distress diagnosis and maintenance decisions, offering a pathway towards unmanned, expeditious, and accurate assessment (García-Segura et al., 2023).

In conclusion, the three decision-making methods each possess their own merits and shortcomings. Among them, the direction for future intelligent asphalt pavement maintenance decision-making leans towards AI-based deep learning. This approach enables comprehensive and automated road management encompassing distress identification, pavement performance evaluation, and optimization of maintenance strategies. It achieves high-precision pavement maintenance decisions. However, the DL model necessitates a substantial database of detection and monitoring data for training samples. Therefore, the future of road maintenance management should establish a real-time monitoring data platform for roads to achieve intelligent and unmanned road maintenance decisions, better supporting and servicing the high-quality development of the road transportation sector.

5.3.2. *Pavement performance prediction*

As traffic loads and climatic conditions are applied to roads repetitively, the pavement performance deteriorates, resulting in poor ride comfort and a considerably high rate of traffic accidents. Pavement performance is defined as the overall appraisal of the serviceability history of a pavement (Sun, 2001). Pavement performance metrics include various indicators, such as pavement damage rate, smoothness, skid resistance, etc. (Guan et al., 2023). To maintain good performance and long service life of pavements, regular implementation of pavement maintenance measures is required. However, choosing the right timing for maintenance requires assessing and predicting pavement conditions. Therefore, transportation agencies worldwide have established different indexes to assess pavement performance, such as the present serviceability rating (PSR), the pavement condition index (PCI), and the pavement quality index (PQI), etc.

Introduced during the AASHO road trials, the PSR is one of the most widely used metrics. The PSR integrates pavement distresses, such as cracking, slope change, and surface rutting, with scoring results ranging from 0 to 4 (Hanandeh, 2022). However, with the expansion of the pavement network, PSI was no longer applicable due to the limitations of manual measurements. Developed by the U.S. Army Corps of Engineers, the PCI index is used to assess pavement performance. Compared to other pavement condition indicators, the PCI index is based on quantitative pavement condition indicators and considers a more comprehensive set of factors (Shahin, 2005). The calculation of PCI involves counting different distress types and their severity. The dimensions (length or area) of these distresses are considered in the severity assessment. In addition, each distress type is assigned a specific weighting factor. Subsequently, the corresponding points are deducted starting from 100 (ASTM, 2014). The PCI ranges from 100 to 0, where 100 means brand new pavement and 0 is the worst-case situation. Similar to the PCI index, China uses the PQI index to evaluate pavement utilization performance. As elaborated in the Highway Performance Assessment Standards (JTG 5210-2018), the PQI consists of different sub-indicators and their corresponding weighting coefficients, as shown in Eq. (5) (Ministry of Transport of the People's Republic of China, 2018). The different sub-indicators consider the various types of distress, the severity of the related kind of distress, smoothness, rutting, and skidding resistance, while road rating and road type determine the weighting factors. The score intervals of the PQI correspond to the grades of the pavement's performance in service, which are five grades, namely, excellent, good, medium, secondary, and poor. The evaluation process of pavement performance is shown in Fig. 94.

$$\begin{aligned}\mathrm{PQI} = {} & \omega_{\mathrm{PCI}}\mathrm{PCI} + \omega_{\mathrm{RQI}}\mathrm{RQI} + \omega_{\mathrm{RDI}}\mathrm{RDI} + \omega_{\mathrm{PBI}}\mathrm{PBI} + \omega_{\mathrm{PWI}}\mathrm{PWI} \\ & + \omega_{\mathrm{SRI}}\mathrm{SRI} + \omega_{\mathrm{PSSI}}\mathrm{PSSI}\end{aligned} \tag{5}$$

where PQI is pavement maintenance quality index, PCI is pavement surface condition index, RQI is pavement riding quality index, RDI is pavement rutting depth index, PBI is pavement bumping index, PWI is pavement surface wearing index, SRI is pavement skidding resistance index, PSSI is pavement structure strength index, ω_{PCI}, ω_{RQI}, ω_{RDI}, ω_{PBI}, ω_{PWI}, ω_{SRI}, ω_{PSSI} are all weighting coefficients.

Gathering comprehensive road condition data efficiently is pivotal in appropriately evaluating pavement performance. Many conventional data collection approaches rely on manual detection or the utilization of relatively less automated auxiliary equipment for data gathering. However, the manual detection method is time-consuming and laborious. With the rapid development of road construction, the demand for pavement management systems (PMS) for pavement performance evaluation is gradually increasing. Researchers and engineers have been committed to considering lower inspection costs and higher inspection accuracy within the scope of developing intelligent road infrastructure systems to realize accurate pavement performance predictions quickly. The following sections of this paper describe the assessment and prediction methods for some of the sub-indicators reflecting the pavement performance, with the pavement type restricted to asphalt pavements.

5.3.2.1. Prediction of pavement surface condition index. The PCI is an indicator to quantify the extent of pavement damage. The pavement damage rate (DR) is calculated based on different parameters according to the type of distress and its severity. Then the PCI value is calculated based on the DR to provide a direct decision-making basis for pavement maintenance, as shown in Eqs. (6) and (7).

$$\mathrm{PCI} = 100 - a_0\mathrm{DR}^{a_1} \tag{6}$$

$$\mathrm{DR} = 100 \times \frac{\sum_{i=1}^{i_0} w_i A_i}{A} \tag{7}$$

where for a_0, asphalt pavement is assigned as 10, while concrete pavement is assigned as 9; for a_1, asphalt pavement is set at 0.40, whereas for concrete pavement, it is 0.42; w_i represents the weight of damage for the ith type of pavement; A_i denotes the area of damage for the ith type of pavement (m^2); A represents the total surveyed area of pavement (m^2).

Advancements in image processing technology and artificial intelligence have led to the utilization of inspection vehicles equipped with high-definition cameras, laser scanners, rangefinders, and other instrumentation. This integration, coupled with deep learning algorithms, facilitates rapid, all-encompassing, and efficient data collection about road conditions. Researchers have acquired various pavement damage images through pavement detection equipment or online, then realized automatic pavement distress detection and classification based on the deep learning (DL) model (Fei et al., 2020; Majidifard et al., 2020; Zhang et al., 2022c). Llopis-Castelló et al. (2021) presented an automated 2D image-based pavement condition detection method that utilized cascaded convolutional neural networks to identify and classify distresses on multiple urban flexible pavements. The first model was used to identify pavement distresses, and the second was used to classify the detected distresses for subsequent quantification of the severity level to calculate the PCI to assess pavement performance. Model 1 achieved an $F1$ score of 0.9431 on the test set. The automated detection method only takes about three days for network-level monitoring of urban road conditions. In contrast, traditional manual detection takes at least four weeks for the same amount of work. Combining stereo vision and deep learning, the researchers identified pixel-level cracks and pothole damage on asphalt pavements (Guan et al., 2021). They achieved an $F1$ score of 0.8519 using an improved U-Net model. This model was developed based on a 3D pavement damage dataset generated by a multi-viewpoint stereo imaging system. The authors also proposed a highly accurate automated pothole volume measurement method based on segmentation maps to assess the severity of potholes. The calculated pothole volume can be used to calculate DR by post-processing algorithms to refine the application of predicting pavement performance.

Although various improved network models have achieved high accuracy in pavement distress identification, pure distress identification and extraction of morphological features of distresses have no practical significance in guiding maintenance decisions. The calculation of morphological features of pavement distress should be transformed into relevant indicators of pavement performance to guide pavement maintenance decisions. Li et al. (2022g), accurately identified crack damage types using the GA-CNN network. Linear crack dimensions (length and width) and reticulated crack characteristics (blockiness and area) were extracted by introducing external rectangles. Ellipse fitting was employed to capture parameters like mesh crack blockiness. The authors computed pavement the DR for each image by rating the severity of various crack types according to specifications. In field validation, the model demonstrated an average accuracy of 90.57% and an average DR index error of 0.094, underscoring its efficacy across diverse crack scenarios.

Most present pavement performance prediction approaches predominantly revolved around pavement cracks' classification and severity assessment, or involve quantification based on a solitary disease type. However, standards (Ministry of Transport of the People's Republic of China, 2018) have outlined 20 types of pavement distress for asphalt surfaces that necessitate the incorporation of a pavement damage severity index. Undoubtedly, as the diversity of distress types within a single image increase, the accuracy of neural network models diminishes, requiring more computational resources during training. Consequently, algorithms achieving recognition for multiple distress types, extracting corresponding features, and converting them into pavement performance indicators remain a subject of ongoing research and development.

5.3.2.2. Prediction of pavement smoothness. Pavement smoothness is the road surface variation in horizontal and vertical directions (Mahmoudzadeh et al., 2019). A well-maintained smooth pavement offers the public a comfortable driving experience and extends the road surface's lifespan (Ali et al., 2021; Liu et al., 2021c; Hettiarachchi et al., 2023). Consequently, transportation agencies worldwide established smoothness specifications to achieve smooth road surfaces. The riding quality index (RQI) is used in the specification (Ministry of Transport of the People's Republic of China, 2018) to evaluate the roughness of the road surface, as shown in Eq. (8).

$$\mathrm{RQI} = \frac{100}{1 + a_0 \mathrm{e}^{a_1 \mathrm{IRI}}} \tag{8}$$

where the IRI is the international roughness index, and a_0 and a_1 are empirical parameters.

Conventional inspection methods used physical or rolling straightedge measurements to measure pavement smoothness and calculated the associated straightedge index (SE). Because of its easy operation, the SE index is still widely used in site construction quality control. However, there are certain limitations due to its low efficiency in large-area detection. Therefore, an inertial profiler was developed to measure pavement smoothness more accurately and quickly. A profiler consists of an array of sensors and computing devices that enable profile data collection at high speeds, combined with a full-scale vehicle equipped with a rangefinder. The unevenness index can be calculated using the data derived from the profiler. The World Bank first introduced the international roughness index (IRI) (Sayers, 1986). It is calculated by the mathematical model of the quarter car model, which represents the change in the vertical movement of a single car tire due to changes in the road surface profile. Since the modern profiler can simultaneously measure the wheel track in the left and right directions without error. Based on the IRI represented by the single-wheel trajectory, the researchers proposed the half-vehicle roughness index (HRI) and the mean roughness index (MRI) (Sayers, 1989; Smith and Ram, 2016). The difference between HRI and MRI is that the former uses the point-by-point average of the contours of the left and right wheels as input to calculate IRI, while the latter calculates the IRI of the left and right wheel tracks and then takes the average. Some researchers have established roughness calculation methods based on different models, such as a quarter car model with 2 degrees of freedom (DoF), a passenger car model with 3 DoF, a truck model with 8 DoF, and a whole vehicle model (Capuruço et al., 2005; Kropáč and Múčka, 2009; Nouri et al., 2011). As the most widely accepted index for characterizing road surface roughness, IRI has been included in most countries' normative standards to reflect road surface roughness. However, there are differences in the representative road segment interval lengths and acceptable IRI thresholds selected by different countries when evaluating pavement smoothness (Hettiarachchi et al., 2023).

In addition to mathematical models based on mechanics theory and professional equipment measurements, some researchers used drones combined with visual algorithms to reconstruct 3D pavement images to detect multi-scale pavement performance (Guan et al., 2023). The radial profile data of different cross-section points of the lane were obtained

Table 13
Some models for predicting skid resistance.

Literature	Model	Input	Output	R^2
Zuniga-Garcia and Prozzi (2019)	MLP	Texture parameters	BPN, DFT, GN	0.8080
Kováč et al. (2021)	MLP	Texture parameters	BPN	0.8161
Zou et al. (2023)	ANN	Texture parameters	SFC	0.8500
Peng et al. (2020)	ANN	Texture parameters	DFT	0.7700
Zhan et al. (2021)	XGBoost	Texture parameters	BPN	0.8800
Hu et al. (2022)	Bayesian-LightGBM	Texture parameters	BPN	0.9283
Zhan et al. (2020)	Friction-ResNets	3D texture images	A GN interval class	0.9130
Yang et al. (2022a, b, c)	FrictionNet-V	3D texture images	A GN interval class	0.8256

from the 3D pavement surface image, and IRI was calculated after various filtering and interval sampling of the data. The findings indicated that an increase in filter size and sampling interval adversely affects the IRI value. Calculations taken at various lateral positions exhibited distinct spatial patterns, with IRI values being larger in the wheel path compared to those outside the wheel path. Furthermore, the author employed a fusion of machine learning (ML) and deep learning (DL) techniques to achieve functionalities such as lane marking positioning, rutting recognition and positioning, and regional deformation recognition. This approach provides valuable insights for the potential multi-functional integration in pavement performance applications.

5.3.2.3. Prediction of pavement skid resistance. Road traffic safety is closely related to pavement skid resistance (Dan et al., 2017). Insufficient skid resistance of pavement will likely induce traffic accidents, especially on rainy days. Therefore, regular monitoring of pavement skid resistance is of great significance to road traffic safety management. In Chinese specification, it was recommended to choose one of the mean profile depth (MPD) and the sideway force coefficient (SFC) to evaluate the skid resistance of the pavement (Ministry of Transport of the People's Republic of China, 2018). Road surface texture data is commonly acquired through laser scanning devices to calculate MPD. The determination of SFC values is accomplished by utilizing specialized detection vehicles. However, MPD does not always correlate well with friction coefficient (Yang et al., 2018). Aside from the SFC testing vehicle, on-site measurement of road surface skid resistance values can also be achieved using tools like british pendulum tester (BPT), dynamic friction tester (DFC), grip tester, and others. The distinction lies in their ability to provide continuous measurements. Researchers attempted to establish empirical relationships with skid resistance values from the perspectives of texture features and material properties. They achieved this by constructing models using techniques like multiple linear regression (MLR), machine learning (ML), and artificial neural networks (ANN) (Zuniga-Garcia and Prozzi, 2019; Peng et al., 2020; Hu et al., 2022). Their research work and some similar research summaries are listed in Table 13 Some scholars also incorporated input features such as power spectral density (PSD) and fractal dimension (FD), representing road surface texture, to predict skid resistance performance (Deng et al., 2021; Liu et al., 2021a, c). Although the proposed models exhibited promising correlations, they tended to maintain applicability only under specific conditions. Additionally, some researchers, leveraging DL techniques, utilized 3D texture images and corresponding skid resistance levels as datasets. These datasets were used to train CNN models, thereby achieving road surface skid resistance performance predictions (Zhan et al., 2020; Yang et al., 2022e). However, these models only considered the texture of the road surface. Friction involves the intricate contact characteristics between tires and the road surface under various conditions. It's a comprehensive attribute influenced by material parameters, texture features, load pressure, environmental factors, and other variables. Indeed, relying solely on texture features cannot comprehensively characterize road surface skid resistance. In other words, the skid resistance of road surfaces exhibits temporal and spatial variations. Hence, exploring non-contact feature parameters that can represent actual contact conditions for predicting road surface skid resistance is essential.

Considering tire-road contact conditions, the presence of a certain thickness of water film within the tire-road gap significantly affects skid resistance performance. Due to its inability to be promptly expelled, sealed water creates a lift for the tire, reducing the effective contact area with the road surface. This results in a decrease in skid resistance performance (Nakajima et al., 2000). Hence, a critical scenario exists where under specific water film thickness and driving speed, the skid resistance provided by the road surface becomes zero. This phenomenon is known as hydroplaning. Researchers used finite element models (FEM) and fluid mechanics theories to construct tire-fluid-road models to simulate pavement skid resistance performance (Ma et al., 2022a, b, c, d; Tang et al., 2019). Their studies take various parameters such as different tire tread patterns, tire loads, water film thickness, road surface texture, slope, and driving speed as inputs. Skid resistance values of the pavement were the outputs, helping determine the relevant parameters that lead to hydroplaning. Researchers can offer more precise computational outcomes for predicting road surface skid resistance performance by utilizing three-dimensional road surface models reconstructed based on X-rays and considering the seepage process of porous structures.

Given the temporal and spatial variability of road surface skid resistance, skid resistance values exhibit seasonal variations in the short term while gradually attenuating in the long term (Mulry et al., 2012; Zhan et al., 2021). The former can be attributed to temperature fluctuations, while the latter is due to the repeated abrasion of aggregate caused by traffic loads, resulting in the smoothing of surface texture. Researchers designed asphalt mixture specimens using various types of coarse aggregates, binder-to-aggregate ratios, and gradation curves. They then employed an indoor accelerated wear device to study the deterioration characteristics of asphalt pavement skid resistance (Zhu et al., 2023). The performance of different types of coarse aggregates was represented by attributes such as hardness, polishing value, and crushing value. The authors used exponential and logarithmic models to predict the road surface's mean texture depth (MTD) and British pendulum number (BPN). These predictions served as evaluation metrics for skid resistance performance. The proposed prediction models have been effectively validated, offering optimized designs for the long-term skid resistance performance of asphalt pavement. Moreover, they provided a scientific foundation for predicting maintenance timing.

Skid resistance can, to a certain extent, reflect road surface usability. However, models based solely on the correlation between road surface texture feature parameters and skid resistance values have limitations. In addition to the adhesive and hysteresis components generated by the interaction between rubber and road surface texture, it's essential to consider the skid resistance mechanism under various conditions, such as lubricating mediums, different temperature scenarios, and driving speeds. This is essential for constructing a more comprehensive model. Finite element numerical simulation systems show promising development prospects. In the future, there should be a focus on establishing more accurate tire-fluid-road surface contact models. Additionally, enhancing the mechanical theoretical framework to achieve coupled analysis will improve the prediction accuracy of skid resistance performance.

5.3.2.4. Prediction of rutting

Rutting is characterized as the longitudinal strip-like depressions formed on the wheel path of the pavement due to repeated tire compaction and deformation after traffic loads (Cui et al., 2009). The formation of rut will further cause cracks and looseness on the road surface, reduce driving comfort, and seriously affect driving safety. Therefore, pavement rutting is a vital detection index reflecting the pavement performance. The pavement rutting depth index (RDI) is used in the specification to evaluate road rutting, as shown in Eq. (9) (Ministry of Transport of the People’s Republic of China, 2018).

$$\mathrm{RDI} = \begin{cases} 100 - a_0\,\mathrm{RD} & \mathrm{RD} \le \mathrm{RD_a} \\ 90 - a_1(\mathrm{RD} - \mathrm{RD_a}) & \mathrm{RD_a} < \mathrm{RD} \le \mathrm{RD_b} \\ 0 & \mathrm{RD} > \mathrm{RD_b} \end{cases} \tag{9}$$

where RD is rutting depth, $\mathrm{RD_a}$ and $\mathrm{RD_b}$ are empirical parameters.

Traditional manual rut detection primarily relies on measurements using rulers and levels. However, these methods were characterized by low efficiency and can disrupt regular traffic flow. The most widely used pavement rutting detection technology is point laser technology and line laser technology. Obtain cross-section elevation data at specific intervals through laser sensors to fit the road cross-section curve (Li et al., 2013;

Urano et al., 2019). Point laser technology demands at least 13-point lasers for accurate detection. The precision of detection improves with a higher number of lasers. However, due to the driver's operation, the detection vehicle drift during the driving process, which cause errors in calculating the rutting depth index. The more serious the deviation, the greater the calculation error (Hui et al., 2018). The width of the laser beam should be increased appropriately to cover a wider area or use a correction algorithm to correct the drift. Unlike multi-point laser, line laser technology provides higher precision. However, complications arise from road texture, lane markings, and other interference, resulting in intricate image backgrounds that undermine the accuracy of laser line extraction. Researchers have successfully employed a non-negative feature and peak continuity-based method to address such issues for extracting rut laser lines from complex road backgrounds (Hong et al., 2018). This technique ensures rapid and accurate extraction of rut laser lines in challenging road scenarios. Nevertheless, the existing detection technology does not consider the influence of superimposed pavement diseases on the calculation of rut depth. To solve this problem, the researchers identified and located the distress type based on the improved DeeplabV3+ model, achieving an accuracy rate of 81.63% (Wang et al., 2023a, 2023b, 2023c). Subsequently, the correction rule of Lagrangian interpolation was used to correct the abnormal rutting. Experimental results showed that this correction method can restore the natural rut cross-section curve, thus fixing the RDI value.

5.3.2.5. *Other studies on pavement performance*

Pavement deflection is an important parameter to evaluate the strength of pavement structure in asphalt pavement (Gao et al., 2023). Research has found that it is not comprehensive to evaluate pavement performance only by pavement surface indexes, such as cracks, smoothness, rutting, etc. (Zihan et al., 2019). While a clear correlation between pavement deflection and the pavement surface index might not be evident, considering the holistic nature of maintenance decision-making, it's prudent to encompass pavement deflection and other structural indicators within the comprehensive pavement performance evaluation. This inclusion enhances the quality of decision-making for more effective maintenance strategies. The latest pavement deflection detection method is the traffic speed deflectometer (TSD) method. Compared with the traditional Beckman beam (BB) method and the falling weight deflectometer (FWD) method, the TSD can quickly collect road structure state data at the road network level. This method shows obvious potential and advantages in applying PMS. Even though there are differences in the load arrangement and the measured deflection values of the TSD and the FWD, many studies have shown that the deflection values measured by the two devices have a significant correlation (Katicha et al., 2017; Manoharan et al., 2018; Shrestha et al., 2018). The BB test results are still the benchmark in China's current specification (Ministry of Transport of the People’s Republic of China, 2018). While evaluating pavement performance using the TSD, it becomes imperative to translate the test outcomes into values compatible with the BB test. Subsequently, these values are utilized for assessment through the pavement structure strength index (PSSI), which is expressed in Eqs. (10) and (11).

$$\mathrm{PSSI} = \frac{100}{1 + a_0 \mathrm{e}^{a_1 \mathrm{SSR}}} \tag{10}$$

$$\mathrm{SSR} = \frac{l_\mathrm{R}}{l_0} \tag{11}$$

where SSR is pavement structure strength ratio, l_R is the allowable deflection value of pavement, l_0 *is* the representative deflection value measured on the pavement.

High-speed non-destructive testing equipment with many advantages has become a new direction for future pavement performance testing development. By employing big data technology, it is essential to establish a road network-level database that integrates historical data. This fusion enables predicting future pavement performance at a specific time node. Researchers transformed historical pavement performance characteristic parameters acquired through high-speed non-destructive testing equipment into a time-series dataset (Li et al., 2022m). They then employed an improved gated recurrent neural network (GRU) for training purposes, facilitating pavement performance prediction at the next time node. In the example verification, the data of the first six years were used as input to train the neural network to predict the PQI and the corresponding sub-indices in the next year. The results showed a good correlation with an R^2 value of 0.67. This shows the great potential of the time-series feature model in predicting road performance and highlights the importance of establishing a road network-level database.

5.3.3. *Pavement performance evaluation*

Under the combined effect of traffic loads and environmental forces, the service performance of road pavements will show different degrees of decline. In order to ensure that the pavement has good serviceability, regular pavement maintenance and repair is required. Accurate assessment of the technical condition of pavements is a necessary prerequisite for pavement maintenance and repair. Pavement technical condition assessment refers to the collection of pavement service condition data to accurately assess the pavement service performance (Babashamsi et al., 2016), based on the assessment results to grasp the pavement performance condition and the road network service level, and to identify the road sections in need of maintenance and repair measures for which the appropriate maintenance and repair strategies are selected. Pavement technical condition assessment is the basis for pavement maintenance and road economic analysis, and is an important part of the pavement management system (Miah et al., 2020; Cano-Ortiz et al., 2022).

5.3.3.1. Factors of the technical condition of pavements. The factors affecting the technical condition of pavements are numerous and the relationships are relatively complex, with the vast majority of them having a high degree of uncertainty. Based on the multifaceted and complex characteristics of pavement technical condition, the main influencing factors of the technical condition of pavements can be summarized as follows. (1) Pavement type (Liu and Han, 2018; Fang et al., 2019; Chen et al., 2023b). It mainly includes two types of pavement base layer type and surface layer type. Different base layer types have different mechanical properties and stability, and the thickness of the base layer directly affects the strength and bearing capacity of the pavement. Thicker base layer can disperse and bear the vehicle load, reducing the impact of the surface layer; reasonable thickness of the base layer can also provide a certain cushioning effect to reduce the pavement damage caused by deformation of the foundation. The quality and performance of the surface layer directly determines the comfort, durability and safety of the pavement. The right choice of surface layer can provide sufficient friction, skid resistance and wear resistance to cope with challenges such as vehicle loads and climate change. (2) Climatic conditions (Llopis-Castelló et al., 2020; Maadani et al., 2021; Chen et al., 2023b). Road pavement during operation will be subjected to solar radiation, high temperature sun exposure, low temperature freezing, freezing and thawing cycle, dry and wet cycle, rain, snow and frost, and other different environmental forces, very easy to pavement damage phenomenon, in which the humidity mainly affects the stability of the road base and pavement material service durability, and temperature directly affects the performance of pavement material decay situation. (3) Traffic flow and traffic load (Assogba et al., 2020; Mshali and Steyn, 2022; Chen et al., 2023b). The direct cause of road pavement damage is the increase in the number of vehicle axle loads. The damage to pavement performance is exacerbated by both elevated road traffic volumes and increased traffic loads. (4) Age of roads (Sirin et al., 2018; Cong et al., 2019; Saleh et al., 2020). The increase in road age will inevitably affect the pavement deterioration condition. From construction to operation and maintenance stage of the highway, the road surface settlement is increasing, the asphalt pavement material gradually aging, the overall stiffness of the pavement is reduced, and ultimately cause time-sensitive fatigue damage phenomenon. (5) Construction and operation management (Santos et al., 2017; Ragnoli et al., 2018; Han et al., 2022b). Factors such as the quality of highway construction, pavement drainage facilities, maintenance level and operation also directly or indirectly affect the pavement technical condition.

5.3.3.2. Assessment index system of the technical condition of pavements. The research on the assessment index system of pavement technical condition is relatively early (Marcelino et al., 2018). And developed countries such as Europe, the United States and Japan have promulgated a series of standard systems on the assessment of the technical condition of pavement in the early years, including pavement abrasion, fatigue damage, water permeability, skid resistance, etc., as well as the pavement chromaticity, the strength of the ice film adhering to the ice film, the value of the reduction in the temperature of the pavement, the value of the reduction in the vibration of the pavement and other assessment indexes.

After years of use and experience, China has also gradually formed a systematic standard system of pavement assessment methods, "Highway Technical Condition Assessment Standards". This standard divides the road surface performance assessment into single index assessment and comprehensive index assessment. Cement concrete pavement performance assessment includes pavement damage, smoothness and skid resistance three technical content, while asphalt pavement performance assessment includes pavement damage, flatness, rutting, skid resistance and structural strength five technical content, detailed to specific evaluation items are asphalt pavement damage, flatness, rut depth, skid resistance and bending five content, the corresponding assessment indexes are pavement condition index (PCI), riding quality index (RQI), rutting depth index (RDI), skidding resistance index (SRI) and pavement structural strength index (PSSI). The pavement quality index (PQI), which finally represents the comprehensive performance of the road surface, is calculated by the above five assessment indexes after converting and assigning weights (Gong et al., 2021).Through the research of Dong et al. (2023), it was found that the statistical indexes of pavement performance assessment have some similarity in the specifications of each country, and there is correlation between the specifications of each country, and the conversion of the index values of pavement condition assessment under different standards needs to be further researched.

5.3.3.3. Assessment model of the technical condition of pavements. In 1960, Carey Jr. and Irick (1960) proposed the concept of present serviceability-use performance, and established the world's earliest pavement performance assessment model PSI (present serviceability index) based on nearly 10 years of experimental observation data of roads by AASHO. Subsequently, many countries and organizations in the world have established their own pavement performance assessment models on the basis of PSI model. With the development of basic theories and the deepening of scholars' research, a variety of mainstream pavement performance assessment models have been formed, which are summarized into the following categories. (1) System analysis method. The main methods in the system analysis method are analytic hierarchy process and fuzzy mathematics. Analytic hierarchy process has the advantage of ordering and clarifying complex problems; while fuzzy mathematics creates specific affiliation function by using fuzzy theory according to the phenomenon of some fuzzy things in the system itself, and improves it according to the actual situation and experts' experience to form the pavement performance assessment model. Ma et al. (2021) proposed a preventive maintenance assessment model for asphalt pavements based on hierarchical variable-weight unconfirmed theory, which integrates three aspects of pavement performance, technical assessment, and economic assessment, and includes nine pavement assessment indexes, such as rutting condition of the pavement, highway grade, and cost-effectiveness, etc., and verified the practicability and validity of the model through examples. Fan and Wu (2002) established a survey form based on the improved hierarchical analysis method, quantified the experience of relevant experts in Liaoning Province, and obtained the weight values of pavement performance indicators reflecting the current situation of highway pavement performance and maintenance needs in Liaoning Province. When analyzing the reliability of asphalt pavement structure, Liu et al. (2018a, b) incorporated the fuzzy mathematical theory into the reliability analysis in order to be more in line with the actual working conditions of the pavement. The failure affiliation function of asphalt pavement structure is given, and the road surface bending settlement value is taken as the control index, so as to derive the fuzzy reliability calculation mode of asphalt pavement structure, and the relevant verification is carried out by combining the secondary asphalt road section in Xixian New Area. (2) Gray theory method. Gray system is a relatively scientific and accurate assessment method, which simplifies the complex problems in the assessment index and clarifies the fuzzy information. At present, there are three main methods applied to the assessment of pavement performance: grey clustering method, grey correlation evaluation method and grey closeness analysis method. Based on the detection and analysis of the pavement damage condition, bearing capacity, smoothness and anti-skid performance of the old road. Yu et al. (2017) proposed and demonstrated an evaluation method for micro-pavement treatment of asphalt pavement based on grey system model and grey relational degree theory. The proposed method verifies that micro-pavement treatment is a valuable assessment system and can be successfully applied to other pavement maintenance treatment. (3) Artificial intelligence method. Neural network and genetic algorithm are the two most important branches of artificial intelligence, they are realized by simulating some biological phenomena, both of them have very outstanding excellent characteristics, can accurately solve some problems that cannot be solved by other methods, and are widely used in the evaluation of pavement performance. Wang et al. (2017) applied the hybrid genetic neural network algorithm to analyze and evaluate the performance of expressway asphalt pavement, and further optimized the decision-making of improving the performance of expressway asphalt pavement. He et al. (2018) proposed a BP-based pavement performance assessment and prediction model, which was analyzed by the characteristics of artificial neural network to evaluate the pavement performance and applied, which is of great practical significance to reduce the cost of asphalt pavement maintenance and improve the pavement performance. Bosurgi et al. (2019) investigated the effect of regulating different features of the network architecture on the quality of pavement structure performance evaluation to maximize the final quality and thus maximize the benefits. (4) Combinatorial model method. Different pavement technical condition assessment models have different characteristics, and there is a complementary relationship among some models, so some scholars have taken advantage of their strengths and established a variety of combination models applied to pavement technical condition evaluation.

5.3.3.4. Existing limitations and research directions for assessment of the technical condition of pavements. A large number of previous experimental studies have shown that scholars have carried out a lot of researches on the assessment of pavement technical condition, and have made progress in the assessment index system and assessment model. However, there are still some limitations about the evaluation of pavement technical condition. The comprehensive assessment model of pavement condition generally adopts the assessment method recommended by the specification, but the pavement structure strength index is not considered in the comprehensive assessment in the specification, and the use does not vary from place to place, but only determines the weight according to the highway grade. The system analysis method is highly influenced by subjective factors. There is no basis for the selection of classification parameters for the gray clustering method, and its weighting function needs to be determined by experience, which is also more subjective in the aggregate. The analytic hierarchy process adopts the expert scoring system, which is influenced by human factors and leads to a lack of objectivity. In addition, some of the assessment models established by scholars are too theoretical and complex and do not utilize practical engineering applications. In view of the above problems, the future research direction of the pavement technical condition can be: (1) establishing a more efficient, objective and independent pavement technical condition assessment model; (2) choosing different weights for the comprehensive assessment of pavement condition taking into account the different road operating conditions; and (3) optimizing and simplify the assessment model on the basis of ensuring the accuracy of the assessment model results.

6. Conclusions

The selection of road materials, structures, equipment, and detection techniques holds paramount significance for the high-quality development of road engineering. This article synthesizes the latest research findings in advanced road materials, structures, equipment, and detection technologies, categorizing them into four classes: advanced road materials, advanced road structures and performance evaluation, advanced road construction equipment and techniques, and advanced road detection and assessment technologies. The paper analyzes the global and domestic research progress, hot topics, challenges, and existing issues while providing an outlook on future development trends. Moving forward, Journal of Road Engineering will continue monitoring the latest research advancements, serving as a reference for experts, scholars, and engineers, thereby advancing the development of advanced road materials, structures, equipment, and detection technologies.

Declaration of competing interest

Aimin Sha is an editor-in-chief of Journal of Road Engineering. Yue Huang is a contributing editor of Journal of Road Engineering. Augusto Cannone Falchetto, Mingjing Fang, Zhenqiang Han, Wei Jiang, Quantao Liu, Guoyang Lu, Chaohui Wang, Di Wang, Haopeng Wang, Chengwei Xing, Huanan Yu, and You Zhan are young academic editors of Journal of Road Engineering. They are not involved in the editorial review or the decision to publish this article. Editorial Office of Journal of Road Engineering strictly operated a double-blind review process for this article, which was handled by scholars who were not involved in the writing, revising, nor editing work. All authors declare that there are no competing interests.

Acknowledgments

The authors would like to acknowledge the financial support from the European Union's Horizon 2020 Research and Innovation Program under the Marie Skłodowska-Curie grant agreement No. 101024139, the RILEM technical committee TC 279 WMR (valorisation of waste and secondary materials for roads), RILEM technical committee TC-264 RAP (asphalt pavement recycling), the Swiss National Science Foundation (SNF) grant 205121_178991/1 for the project titled "Urban Mining for Low Noise Urban Roads and Optimized Design of Street Canyons", National Natural Science Foundation of China (No. 51808462, 51978547, 52005048, 52108394, 52178414, 52208420, 52278448, 52308447, 52378429), China Postdoctoral Science Foundation (No. 2023M730356), National Key R&D Program of China (No. 2021YFB2601302), Natural Science Basic Research Program of Shaanxi (Program No. 2023-JC-QN-0472), Postdoctoral Science Foundation of Anhui Province (2022B627), Shaanxi Provincial Science and Technology Department (No. 2022 PT-30), Key Technological Special Project of Xinxiang City (No. 22ZD013) and Key Laboratory of Intelligent Manufacturing of Construction Machinery (No. IMCM2021KF02), the Applied Basic Research Project of Sichuan Science and Technology Department (Free Exploration Type) (Grant No. 2020YJ0039), Key R&D Support Plan of Chengdu Science and Technology Project-Technology Innovation R&D Project (Grant No. 2019-YF05-00002-SN), and the China Postdoctoral Science Foundation (Grant No. 2018M643520). The authors would also like to acknowledge some post-doctoral researchers, PhD candidates, and post-graduate students, who have helped with the data collection, data analysis, literature review, as well as the writing and revising of this paper. Their names are listed in alphabetical order of their institutions, or in alphabetical order of their last names within the same institution. Beijing University of Technology: Guanyu Gong, Zhengyang Ren; Chang'an University: Yilin Dong, Hao Fu, Pengfei Li, Xianwu Ling, Bokai Liu, Xinyu Yan, Kun Yang, Dongdong Yuan; Changsha University of Science & Technology: Jingguo Ge, Zhiyu Yang; Harbin Institute of Technology: Shuang Liu; Hunan University: Yao Luo; South China University of Technology: Zengyao Lin; Southeast University: Jia Sun; Southwest Jiaotong University: Yuchen Li; Yukun Li, Tongji University: Huiyi Ouyang, Yuhang Si; Wuhan University of Technology: Pei Wan.

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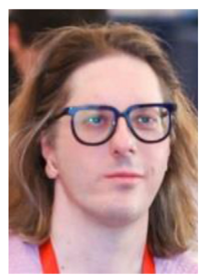
Dr. Maria Chiara Cavalli is currently an assistant professor at KTH Royal Institute of Technology. She focuses on designing bio-based sustainable materials in pavement engineering.

Dr. De Chen is currently an associate professor and master's supervisor of Southwest Jiaotong University. He graduated from Chang'an University, and had studied at the University of Wisconsin-Madison. He is a national railway youth post expert, a core member of the Railway Engineering Course Group Virtual Teaching and Research Room of the First National Virtual Teaching and Research Room, a member of the youth science and technology innovation research team of environmental system simulation and big data analysis in Sichuan Province, and a leader of the youth innovation research team of Green Development and Engineering Innovation. He has been selected as Southwest Jiaotong University's esteemed Young Eagle Program and Green Seedling Program. He was named the second Young Pioneers. Also, he is a provincial quality (first-class) course lecturer. At present, he is engaged in the teaching and research of road and railway engineering in the School of Civil Engineering, Southwest Jiaotong University. He has published more than 30 high-level academic papers. Also, he has been authorized more than 20 national patents.

Dr. Qian Chen is currently a lecturer and master supervisor of Chang'an University. He is the Young Key Talents Program of Chang'an Scholars. His research focuses on green functional pavement materials and high-performance road maintenance materials.

Dr. Yu Chen is currently a professor at Chang'an University. He focuses on pavement structure design and pavement material performance evaluation.



Dr. Augusto Cannone Falchetto is currently an assistant professor at Aalto University, Finland. His research focuses on infrastructure materials and pavement engineering and combines experimental research, advanced analysis and modelling. He has made outstanding contributions to the field throughout his career, which is evident in his widely published and cited work. As an active RILEM member, he has been involved in several technical committees and contributed to state-of-the-art reports, technical papers and recommendations. Based on the sound application of scientific principles, his research has developed solid practical relevance and attracted recognition through numerous awards, such as the prestigious Robert L'Hermite.

Dr. Mingjing Fang is currently serving as the associate professor in the School of Civil Engineering and Architecture of Wuhan University of Technology. His research interests are in pavement and alignment of road & railway engineering, including paving engineering, subgrade improvement, high-performance construction material, asphalt-based trackbed, and intelligent construction.

Dr. Hairong Gu is a professor and doctoral supervisor of Chang'an University. His research focuses on road construction machine and technology.

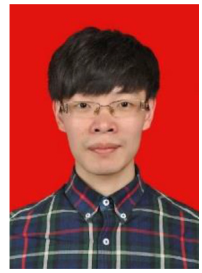
Dr. Zhenqiang Han is currently a lecturer and master supervisor of Chang'an University. His research focuses on numerical simulation, accelerated pavement testing, and integrated design of road engineering materials and structure. He is selected into the Young Talent Program of Association for Science and Technology in Xi'an of China, and serves as the principal investigator for the projects of National Natural Science Foundation of China, and National Key R&D Program of China.

Mr. Zijian He is currently a PhD student at The Hong Kong Polytechnic University. His research mainly focuses on pavement materials.

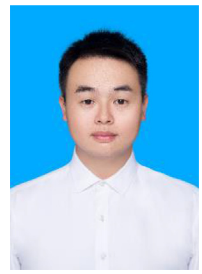
Dr. Jing Hu is currently an associate professor and doctoral supervisor of Southeast University. His research focuses on high performance materials and intelligent detection of pavement.

Dr. Yue Huang is currently an associate professor at the Institute for Transport Studies (ITS), University of Leeds, UK. After completing his PhD at Newcastle University in 2007, Dr. Huang started his career as a research engineer at Scott Wilson (now AECOM) until 2011. His previous employments include the University of Nottingham where he worked as a research fellow in 2011–2012. Before he joined ITS, Dr. Huang was a senior lecturer at Liverpool John Moores University between 2012 and 2018. He has been involved in winning and delivering a number of research projects in the UK, EU and overseas since 2004. Dr. Huang has a number of highly cited publications in reputable international journals. He has 10 years of experiences in teaching undergraduate and postgraduate courses, module/programme (including MOOC) development, and PhD supervision. Dr. Huang is a chartered engineer (CEng) and a fellow of the Higher Education Academy (FHEA).

Dr. Wei Jiang is currently a professor of pavement engineering at the School of Highway, Chang'an University. His research has focused on the theories and methods of green pavement materials and structures, green energy transformation of pavements. Dr. Jiang led over 14 national and provincial projects, including the National Science Fund for Excellent Young Scientists, National Key R&D Program of China, the National Natural Science Foundation of China, the Fok Ying-Tong Education Foundation for Young Teachers in the Higher Education Institutions of China, etc.



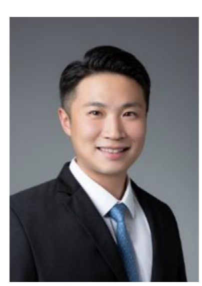
Dr. Xuan Li is currently a lecturer of Chang'an University and a postdoctoral fellow of Zhejiang Prulde Electric Appliance Co., Ltd. His research focuses on hot in-place recycling technology and equipment for asphalt pavement.



Dr. Chaochao Liu is currently a lecturer and master supervisor of Changsha University of Science & Technology. He is selected as Huxiang Youth Science and Technology Innovation Talents. His research interests include materials and structure for civil engineering, engineering mechanics, and green and smart maintenance of asphalt pavement in service.

Dr. Pengfei Liu is the junior professor (W1) in modeling and design of functionalized pavement materials at the Institute of Highway Engineering, RWTH Aachen University, Germany. Dr. Liu received his doctoral degree from RWTH Aachen University in 2017. His main research area is multiscale modelling and characterization of pavement materials. He has published more than 130 SCI papers as well as 4 books. He serves as an academic editor for 5 technical journals and a reviewer for 63 SCI journals. Dr. Liu has been recognized with 2017 Excellent Self-funded Student Scholarship of the Ministry of Education P. R. China. He won the RWTH Aachen-Tsinghua Senior Research Fellowships in 2019. And he received the Outstanding Associate Member Award from the Academy of Pavement Science and Engineering (APSE) in 2022. In 2023, he was awarded the title of “Excellent Early Career Scientist from Germany” by the Sino-German Center for Research Promotion (SGC).

Dr. Quantao Liu is currently a professor at the State Key Laboratory of Silicate Materials for Architectures, Wuhan University of Technology. His research interests focus on self-healing asphalt mixtures and asphalt anti-aging technology.



Dr. Guoyang Lu is currently an assistant professor at the Department of Architecture and Civil Engineering, City University of Hong Kong. His research interests mainly include intelligent transportation infrastructural materials and technologies, simulation of pavement structures and materials, and nondestructive evaluation of transportation infrastructure.

Dr. Yuan Ma is currently an assistant researcher at the School of Transportation, Southeast University. His major research areas are digital road engineering and digital twin technology.

Dr. Lily Poulikakos received her BS in architectural engineering from the University of Colorado, Boulder, USA, MS in civil engineering from University of Illinois, USA, and PhD in civil engineering from ETH, Zurich, Switzerland. She is currently a senior scientist at Empa, Swiss Federal Laboratories for Materials Science and Technology. Her research focus is on using multi scale characterization methods to study innovative bituminous materials chemically and mechanically with a focus on low noise pavements and the use of waste and marginal materials for roads. Dr. Poulikakos is a leading member of several RILEM technical committees. She is the author of over 140 publications in peer reviewed journals and editor of Elsevier journal Construction and Building Materials (CBM).

Dr. Jinsong Qian is currently a professor of Tongji University. His research focuses on intelligent construction and maintenance technologies for highway and airfield.

Dr. Aimin Sha is the professor of highway engineering at the School of Highway, Chang'an University. He is the vice chairman of China Highway & Transportation Society (CHTS). Prof. Sha focuses on road materials, pavement design theory, construction quality control, eco-friendly pavements, sustainable transportation and smart pavements. His researches were supported by NSFC, "973" Program, National Key R&D Program of China, etc. He was awarded by the second prize of the National Scientific and Technological Progress Award in 2009 and 2013, respectively.

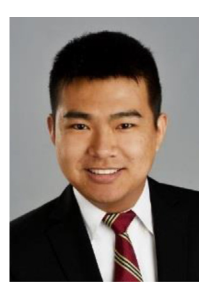
Dr. Liyan Shan is currently a professor and doctoral supervisor of Harbin Institute of Technology. She is also a national level young talent. Her research focuses on rheology of asphalt materials, genome of road materials, in-situ characterization technology of road materials, resource utilization of solid waste on road surface, road protection and repair technology.

Dr. Zheng Tong received his PhD degree from the Université de Technologie de Compiègne, France in 2022. Since then, he has been an associated professor with School of Transportation, Southeast University, China. His research interests include Dempster-Shafer theory, ground penetrating radar, nondestructive testing, and deep learning applied to pavement engineering inspection.

Dr. B. Shane Underwood is a professor in the Department of Civil, Construction, and Environmental Engineering at North Carolina State University. Dr. Underwood's research and education program focuses on materials and their interaction with society and the natural and built environments. This program pursues research, education, and service activities that evaluate, inform, and shape the science of these interactions, particularly how material decisions influence the use, function, and impact of civil infrastructure.

Dr. Chao Wang is a professor of the College of Metropolitan Transportation in Beijing University of Technology. His research topic is mainly focused on the performance modeling of asphalt pavement.

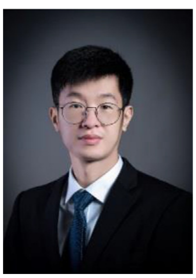
Dr. Chaohui Wang is currently a professor and doctoral supervisor of Chang'an University, as well as the leader of Key Scientific and Technological Innovation Teams in Shaanxi Province. He is selected as the world's top 2% scientists 2022, and the Young and Middle-aged Scientific and Technological Leading Talent of the Ministry of Transport. His research focuses on green functional pavement materials, intelligent power generation pavement technology, high-performance road maintenance materials, high value utilization technology of solid waste resources.



Dr. Di Wang is currently a post-doc researcher at Aalto University, Finland. He was appointed as an assistant professor and Canadian Research Chair Tier 2 in Cold Region Roads at the University of Ottawa, Canada. His research interests focused on the sustainable materials and structure of asphalt roads, and cold region roads.

Dr. Haopeng Wang is currently a lecturer in structural engineering materials in the Department of Civil and Environmental Engineering at the University of Liverpool. He received his PhD degree from Delft University of Technology in September 2021. From 2021 to 2023, he worked as a Marie Sklodowska-Curie Individual Fellow sponsored by EU's Horizon 2020 at the University of Nottingham. His research interests include multi-physics modelling of pavement materials and structures, polymer physics and chemistry, micromechanics of infrastructure materials, damage mechanisms in asphalt mixture (fracture, fatigue and healing), and sustainable pavement materials and technologies. He has an internationally recognized track record of publications in the fields of sustainable asphalt materials and engineering mechanics.

Dr. Xuebin Wang is a lecturer of Chang'an University. His research focuses on asphalt-pavement milling and rock cutting mechanism, unmanned and intelligent of construction machine.



Dr. Chengwei Xing is a lecture of Chang'an University. His research areas include bitumen aging and reclamation of recycled bitumen pavement. He is selected into the Young Talent Program of Association for Science and Technology in Shaanxi of China, and serves as the principal investigator for the project of National Natural Science Foundation of China.

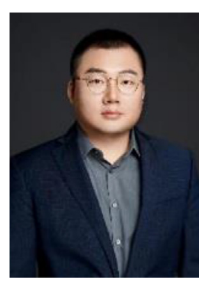
Dr. Xinxin Xu is a lecture of Chang'an University. Her research focuses on the mechanism of heat transfer in road surfaces during hot in-place recycling technology and equipment.

Dr. Min Ye is a professor and doctoral supervisor of Chang'an University, dean of School of Construction Machinery, director of the China Construction Machinery Society and the China Construction Machinery Industry Association, the chairman of the Hydraulic Technology Branch, the vice chairman of Transportation Equipment Branch of CHTS, the leader of Youth Innovation Team of Shaanxi University, and Young and Middle-aged Leading Talents in Scientific and Technological Innovation in Shaanxi Province. His research focuses on battery management system, battery state estimation, and vehicle power optimization control.

Dr. Huanan Yu is a professor and doctoral supervisor of Changsha University of Science & Technology. His research focuses on the design and characterization of pavement material, pavement construction quality intelligent monitor and compaction, funcational pavement.

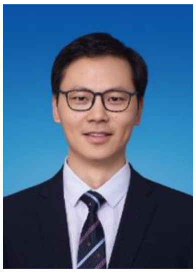
Dr. Huayang Yu is currently an associate professor and doctoral supervisor of South China University of Technology. His research focuses on sustainable and intelligent pavement structure and material.

Dr. Zhe Zeng is a postdoctoral research scholar in the Department of Civil, Construction, and Environmental Engineering at North Carolina State University. His research focuses on characterizing damage mechanisms and predicting the behavior of asphalt materials and pavements. Building upon this foundation, he extends his work to include material modification, improvements in pavement design, and the development of performance models.



Dr. You Zhan is an associate professor in the School of Civil Engineering at Southwest Jiaotong University. His main research interests include pavement skid resistance and road traffic safety, intelligent detection and evaluation of pavement service performance, intelligent maintenance management and decision-making of road infrastructure, and functional pavements.

Mr. Fan Zhang is currently a doctoral researcher at the Department of Civil Engineering at Aalto University, Finland. His research interests focused on the sustainable road maintenance methods, multiple recycing of asphalt materials, and solid waste applications in road engineering.



Dr. Henglong Zhang is a professor of College of Civil Engineering at Hunan University. His research interests include research and development and application of new pavement materials, durability theory and technology of pavement materials, and recycling technology of waste pavement materials.

Dr. Wenfeng Zhu is currently a lecturer of Chang'an University, postdoctoral fellow of Wuhu Hit Robot Technology Research Institute Co., Ltd. His research focuses on hydraulic transmission and control, and hydraulic robotics.