Engineering 32 (2024) 82–98

Contents lists available at ScienceDirect

Engineering

journal homepage: www.elsevier.com/locate/eng

Research
Civil Engineering—Review

A State-of-the-Art Review on the Functionality of Ultra-Thin Overlays Towards a Future Low Carbon Road Maintenance

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ARTICLE INFO

Article history:
Received 8 November 2022
Revised 25 January 2023
Accepted 21 March 2023
Available online 24 August 2023

Keywords:
Road maintenance
Ultra-thin overlay
Snow melting and deicing
Exhaust gas purification
Pavement cooling
Low-carbon

ABSTRACT

Highway maintenance mileage reached 5.25 million kilometers in China by 2021. Ultra-thin overlay is one of the most commonly used maintenance technologies, which can significantly enhance the economic and environmental benefits of pavements. To promote the low-carbon development of ultra-thin overlays, this paper mainly studied the mechanism and influencing factors of several ultra-thin overlay functions. Firstly, the skid resistance, noise reduction, rutting resistance, and crack resistance of ultra-thin overlays were evaluated. The results indicated that the high-quality aggregates improved the skid and rutting resistance of ultra-thin overlay by 5%–20%. The optimized gradations and modified binders reduced noise of ultra-thin overlay by 0.4–6.0 dB. The high viscosity modified binders improved the rutting resistance of ultra-thin overlay by about 10%–130%. Basalt fiber improved the cracking resistance of ultra-thin overlay by more than 20%. Due to the thinner thickness and better road performance, the performance-based engineering cost of ultra-thin overlay was reduced by about 30%–40% compared with conventional overlays. Secondly, several environmentally friendly functions of ultra-thin overlay were investigated, including snow melting and deicing, exhaust gas purification and pavement cooling. The lower thickness of ultra-thin overlay was conducive to the diffusion of chloride-based materials to the pavement surface. Therefore, the snow melting effect of self-ice-melting was better. In addition, the ultra-thin overlay mixture containing photocatalytic materials could decompose 20%–50% of the exhaust gas. The colored ultra-thin overlay was able to reduce the temperature of the pavement by up to 8.1 °C. The temperature difference between the upper and lower surfaces of the ultra-thin overlay containing thermal resistance materials could reach up to 12.8 °C. In addition, numerous typical global engineering applications of functional ultra-thin overlay were summarized. This review can help better understand the functionality of ultra-thin overlays and promote the realization of future multi-functional and low-carbon road maintenance.

1. Introduction

At present, many countries have multiple highway networks, and thus maintenance work has become increasingly important. By the end of 2021, the highway maintenance mileage reached 5.25 million kilometers in China, which accounted for 99.4% of the total highway mileage. The annual highway maintenance cost was 2.4 trillion CNY, accounting for 2.7% of the gross domestic product. With the continuous increase of the total mileage of highways, pavement maintenance has become the top priority of highway construction in recent years [1]. Preventive maintenance technology has been proven to enhance the functionality and reduce the maintenance costs of pavement, and thus exhibits high economic and environmental benefits [2]. Pavement maintenance measures typically include fog seal, slurry seal, gravel seal and fiber seal, micro-surfacing, and thin overlay and ultra-thin overlay [3–10]. In particular, the functions of ultra-thin overlays are more comprehensive compared to other pavement maintenance technologies [11]. Thus, it is generally used to improve the overall performance (including anti-skid, noise reduction, anti-rutting, and crack resistance, etc.) of pavement [12,13]. As a type of overlay, it can be used for both the maintenance of old pavement and construction of new pavement [14]. In addition, the ultra-thin overlay

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https://doi.org/10.1016/j.eng.2023.03.020
2095-8099/

also has environmental protection functions, such as pavement cooling and exhaust gas purification [15,16]. Therefore, it can be used for the construction of environmentally friendly pavement. The ultra-thin overlay is one of the most commonly used maintenance technologies due to its significant functional characteristics, including lower energy consumption, environmental pollution, and traffic disturbance and higher cost effectiveness [17]. It is also an effective maintenance technology for the low-carbon upgrading of rural roads. Life-cycle-cost analyses (LCCA) have been carried out on the ultra-thin overlay compared to conventional asphalt layers [18]. Results revealed lower agency and user costs at both high and low traffic conditions for ultra-thin overlays compared to conventional overlays. Within a total analysis period of 30 years, the results clearly supported the benefits of the ultra-thin overlay practice with respect to reduced initial costs, minimized traffic delays, and the ability to better handle heavy traffic [19]. Therefore, the research and further development of ultra-thin overlay technology will help to achieve the goals of carbon peaking and carbon neutrality for governments, thereby making a huge contribution to global climate governance.

Ultra-thin overlay technology originated in France and was initially mainly used to improve the evenness of pavements and increase anti-skid performance [20]. Following this, researchers in the United States and Europe conducted comprehensive research on ultra-thin overlay technology, allowing for the rapid development of ultra-thin overlays in recent decades [21]. The definition of ultra-thin overlay varies with the country and agencies. In China, the asphalt pavement with a (20 ± 5) mm compacted thickness is denoted as an ultra-thin overlay [11,22–24]. The thickness of ultra-thin overlays in France and several other European countries is usually 15–20 mm [11,25]. In some states (Texas, Michigan, and New York, etc.) of the United States, an ultra-thin overlay is often regarded as less than one inch (1 in = 0.0254 m; typically 3/4 inch, around 19 mm) in thickness [13,26]. The thickness of this overlay is less than half of the traditional wearing course, and thus it can quickly restore the pavement function and reduce the material and energy consumption [22]. Practice demonstrates that ultra-thin overlays can effectually enhance the skid resistance and anti-rutting performance of pavement [23,27,28]. Moreover, they can also improve crack resistance and noise reduction of pavement [29,30]. Despite their beneficial road functions, ultra-thin overlays are still associated with several technical defects that limit their application. Cedric et al. [31] reported that some ultra-thin overlays can be prone to shoving and raveling due to their lower thickness and higher porosity. Gardziejczyk [32] found that the surface pores of semi-open and open graded ultra-thin overlays are easily blocked, which can cause the rapid attenuation of noise reduction and drainage performance. Scholars have attempted to overcome the aforementioned limitations by improving the material properties and gradation designs of ultra-thin overlays. Research showed that the functional characteristics of ultra-thin overlays are markedly improved using high-performance materials [28,33]. Furthermore, due to the stability of the skeleton structure of ultra-thin overlays, the optimized grading design was conducive to improving the corresponding durability [22,34].

In addition to the basic road functions, researchers also added some functional materials to the ultra-thin overlay mixture. It made the ultra-thin overlay show environmentally friendly functions, such as snow melting, exhaust gas purification, and pavement cooling [14,35,36]. Increasing the amount of functional materials may enhance the environmental protection functions of ultra-thin overlays [37]. However, the addition of functional materials may adversely affect the road performance of ultra-thin overlay [35]. Therefore, the properties and amount of functional materials should be strictly controlled. The research and further development of ultra-thin overlay technology will help to achieve the goal of carbon peaking and carbon neutrality of the Chinese government, thereby making a huge contribution to global climate governance.

Based on the current research results of ultra-thin overlay technology, this paper systematically introduced the working mechanism and influence factors of the main functions of ultra-thin overlays. Several important global engineering applications of functional ultra-thin overlays were then summarized. This review points out the future research direction of ultra-thin overlays in pavement engineering. Fig. 1 illustrates the research content.

2. Skid resistance function of ultra-thin overlays

Skid resistance is one of the necessary functions of pavements. For pavement maintenance or new pavement construction, the ultra-thin overlay is always designed to ensure skid resistance [20]. Ultra-thin overlays are thinner than traditional asphalt mixture layers, and thus the grading of mixture needs to be specially designed. As shown in Fig. 2, researchers predominantly study

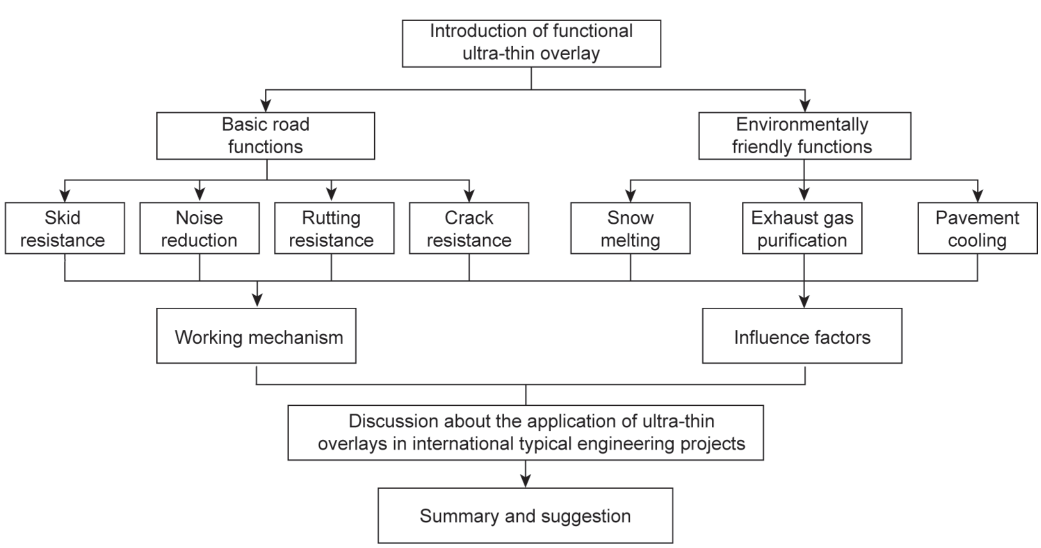

Fig. 1. Research content of functional ultra-thin overlays.

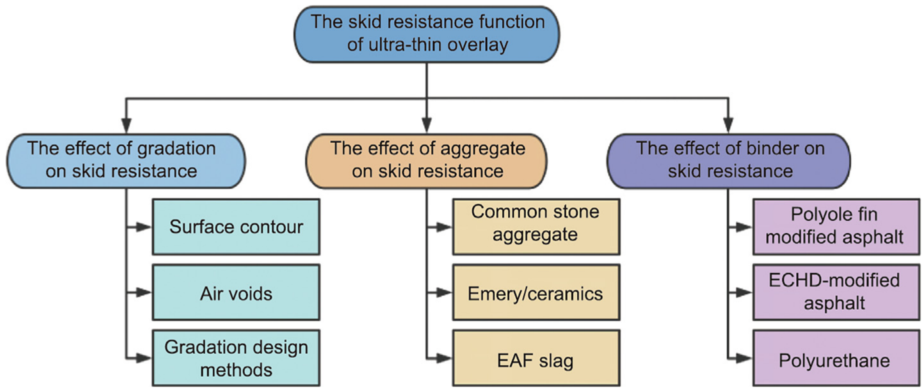

Fig. 2. Research content of the anti-skid function of ultra-thin overlays. EAF: electric arc furnace; ECHD: easy compaction and high-durability.

the anti-skid function of ultra-thin overlays in terms of three aspects: gradation, aggregate, and binder. The following sections present the influence mechanisms and effects of these factors on the skid resistance and discusses the key problems that limit the application of ultra-thin overlays.

2.1. The effect of gradation on skid resistance of ultra-thin overlay

The gradation is one of the main factors affecting the skid resistance of ultra-thin overlays. In order to determine the optimal gradation for the skid resistance of ultra-thin overlays, Hajj et al. [38] compared the anti-skid function of six overlay mixtures with different grading using dynamic friction tester (DFT) and three-wheel polishing device (TWPD). The results showed that coarser mixtures had a better anti-skid performance. The rough surface contour of coarse mixtures provides a high macro texture depth, which effectively enhances the grip force for vehicle tires and plays an important role in pavement anti-skidding [39].

Another study on porous ultra-thin asphalt overlay (PUAO) also proved this result [40]. The skid resistance of PUAOs was investigated by the one-third scale Model Mobile Load Simulator (MMLS3) accelerated abrasion test in this study. The result showed that compared with the dense ultra-thin asphalt overlay (DUAO), the PUAO showed better skid resistance. The mean texture depth (MTD) values of PUAO materials were 0.6–1.1 mm higher. And after 600 000 wear cycles, the standard friction number (FN; F60) values of DUAO were lower than those of PUAO. In addition, according to the research on skid resistance of PUAOs with air voids between 16% and 24%, it was found that within a certain range, the anti-skid performance of PUAOs gradually improved with the increase of porosity. This is because more air voids enriched the macro texture of the mixture. However, a critical value (around 20%) was determined for the positive effect of the macro texture on the anti-skid performance. More specifically, when the air voids reached the critical value, increasing the air void could not further enhance the skid resistance of the ultra-thin overlay.

In addition to increasing the air void, researchers also tried to improve the design methods of mixture gradation to optimize the stone skeleton of overlay mixture, so as to improve the anti-skid function of ultra-thin overlay. Son et al. [41] developed the stone matrix asphalt (SMA) ultra-thin overlay with a 4.75 mm nominal maximum aggregate size (NMAS). The Bailey method was used in mixture design. The results obtained from locked wheel friction test showed that 4.75 SMA exhibited slightly higher FN values than the control (12.5 SMA). Although the texture depth was 0.7–1.0 mm smaller, the voids filled with asphalt (VFA) of 4.75 SMA was about 2% lower than that of 12.5 SMA, resulting in a thinner asphalt film. This reduced the adverse effect of asphalt on the anti-skid function of overlay. In addition, the 4.75 SMA required extra sieving in the grading design, increasing the agency costs. However, the results from Fisher's least significant difference test indicated that this type of grading design enhanced the performance of the thinner ultra-thin overlays (e.g., skid resistance) compared to conventional overlays. Therefore, by comprehensively considering both the performance rating and cost analysis of the asphalt overlay, the engineering costs of 4.75 SMA ultra-thin overlays were about 30%–40% lower than those of the 12.5 SMA overlay.

A novel high-toughness ultra-thin friction course (HUFC) overlay was proposed by Yu et al. [22]. Its grading design was based on the improved coarse aggregate voids filling (CAVF) method. The friction coefficient and texture depth were mostly concentrated at 60–80 British pendulum number (BPN) and 0.9–1.1 mm, respectively. The HUFC mixtures with a thickness of just 1.0–1.5 cm exhibited a similar skid resistance to the conventional overlays. Based on the results of the pressure film and laser scanning, the grading design of HUFC made the coarse aggregate contact with each other to form a stable skeleton structure. It inhibited the aggregate spatial rotation under the tire load. Moreover, the fine-grained multi-gravel structure dispersed the stress concentration, thereby reducing the polishing of the mixture surface.

2.2. The effect of aggregate on skid resistance of ultra-thin overlay

The aggregate is the main contact medium of vehicle tires in the asphalt mixture [42]. The anti-skid function of ultra-thin overlay is closely related to the aggregate properties.

Beyene et al. [43] found that the limestone with a lower amount of acid-insoluble residue (about 5% by mass) was a poor choice for ultra-thin bonded wearing course (UTBWC). This limestone had a Moho's relative hardness value of 3, which was 50% lower than that of feldspar and quartz. The UTBWC samples with this limestone aggregate were polished by aggregate polishing equipment. The friction coefficient of the UTBWC was observed to be less than 0.25 after 100 000 revolutions, while that of the control sample was 0.3 or greater. Therefore, in order to improve the skid resistance, aggregates with higher acid-insoluble residue were recommended.

Moreover, Deng et al. [44] employed the emery as the aggregate to develop a polyurethane ultra-thin wearing course (PUTWC). MTD and BPN were used to evaluate the effect of the size and type of aggregate on anti-skid function. It was found that the BPN value of 2–3 mm emery PUTWC was about six higher than that of 1–3 mm, and the MTD values of 2–3 mm emery PUTWC were about

0.2 and 0.4 higher than those of 1–3 and 1–2 mm, respectively. This is because the emery with a larger particle size had an angular and approximately cubic shape, which optimized the surface structure of the ultra-thin overlay. Moreover, the ceramic was also added to the PUTWC, and the anti-skid function of the emery PUTWC exceeded that of the ceramic PUTWC. This is due to the rough surface of the 2–3 mm emery, which improved its friction coefficient. However, due to the smooth surface, the friction coefficient of the ceramics was reduced, resulting in a poor skid resistance performance. In addition, the molecular dynamics (MD) simulation method was used to calculate the interfacial interactions between the aggregate (emery or ceramic) and the polyurethane (PU) binder. The relative concentration distribution showed that there was a stronger interaction between emery and PU. This further indicated that the emery ultra-thin overlay had a better wear and skid resistance than the ceramic ultra-thin overlay.

Liapis and Likoydis [45] used electric arc furnace (EAF) slag as aggregates to prepare thin mixtures. The polished stone value (PSV) of EAF slag and andesite was determined as 64 and 56, respectively. As a result, the average skid resistance value (SRV) of EAF slag overlay was 55.3 after transit, which was about 5% higher than that of the natural andesite overlay. The macro structure depth of the EAF slag overlay was about 1.3 times of that of andesitic aggregate overlay after 30 or 41 months of transit. The skid resistance function of the ultra-thin overlay with EAF slag as the only aggregate component was enhanced greatly. This demonstrates the potential application of industrial waste residue to enhance the functionality of ultra-thin overlays.

2.3. The effect of binder on skid resistance of ultra-thin overlay

Research has revealed that the skid resistance is related to the compaction of ultra-thin overlays, with the binder identified as an important influencing factor of compaction. To delay the skid-resistance attenuation, multiple types of binders have been adopted to enhance the compaction effect of the ultra-thin overlay.

Previous research employed a modified ultra-thin wearing course mixture (M-UWM) using asphalt binder modified with a multi-chain polyolefin modifier. Results showed that the M-UWM had a larger texture depth compared to the unmodified ultra-thin wearing course mixtures (UWMs). The reduced texture depth proportion of the M-UWM was about 15% lower than that of the UWM after wheel loading. Moreover, the field texture depth test revealed the long-term skid resistance function of the M-UWM during road operations [28].

Besides, Guan et al. [46] designed a polyolefin and styrene–butadiene–styrene (SBS) modified asphalt (PSA) mixture. The molecular weight of polyolefin additive was 10 000–15 000 $g \cdot mol^{-1}$ and its melting point was 90–140 °C. The weight ratio of polyolefin to asphalt mixture was 0.35%. The PSA mixture was observed to have good anti-skid durability. This is because the polyolefin significantly increased the viscosity of asphalt at 60 °C but did not increase the viscosity at 135 °C. The viscosity of polyolefin is thus able to improve the compactness of the mixture and enhance its anti-stripping ability, consequently improving the anti-skid function of mixtures.

Ding et al. [24] studied the anti-skid function of ultra-thin overlay mixes with easy compaction and high-durability (ECHD). Modifiers and SBS modified asphalt were the main components of ECHD modified asphalt. Based on the improved sand-laying method and pendulum friction instrument, it was found that following 10 000 abrasions, the texture depth of matrix asphalt mixtures, SBS modified asphalt mixtures, and ECHD ultra-thin overlay mixes decreased by 31%, 29%, and 25%, and the pendulum value decreased by 20%, 18%, and 16%, respectively. The ECHD modifiers improved the compactness of the mixture, thus enhancing the skid resistance durability of the mixture.

Hong et al. [47] developed a PU/ultra-thin friction course (UFC). PU was used as the binder instead of asphalt. The results showed that the mean profile depth (MPD) values of the PU mixtures were about 1.05 times higher than those of the asphalt mixtures. After performing a polishing simulation for 300 min, the texture attenuation ratio of the PU mix was lower than that of the controlled asphalt mixtures. This is attributed to the excellent abrasive resistance and adhesion property of the PU binder [48]. In the future, additional high-performance binders will be used to enhance the anti-skid function of the ultra-thin overlay.

2.4. Summary and analysis

Table 1 [22,24,28,38,40,41,43–47] reports the summary and analysis of the factors influencing the anti-skid function of ultra-thin overlays. The current researches on gradation design mainly focused on increasing texture depth and optimizing skeleton structure. However, these two methods have the problems of critical value and cost increase, respectively. Compared with increasing the air voids, using the improved gradation design methods to optimize the skeleton structure has a wider research prospect. Limestone with a lower amount of acid-insoluble residue does has an insufficient Moho's relative hardness. This results in a sharp drop of the friction coefficient and a reduction in the skid resistance of ultra-thin overlays during operation. Due to the rougher surface, emery can better improve the anti-skid function of ultra-thin overlays compared to ceramic. Compared with the 1–2 and 1–3 mm emeries, the 2–3 mm emery can optimize the texture structure of ultra-thin overlays, thus improving the initial skid resistance. In addition, since EAF slag has a higher PSV than the andesitic aggregate, the average SRV of the EAF slag overlay is about 5% higher than the andesite overlay after 30 or 41 months of traffic. Binders with a higher 60 °C viscosity but lower 135 °C viscosity can ensure the adhesion function of binders and the compaction effect of mixtures. This enhances the initial skid resistance function and reduce the later anti-skid attenuation under the traffic load. But these high performance aggregates and binders may increase the material cost of the ultra-thin overlay. The use of industrial waste slag as an anti-skid aggregate for ultra-thin overlays not only ensures the skid resistance performance, but also solves the material cost problem [49]. The aforementioned studies can help to select environmentally friendly anti-skid aggregate for ultra-thin overlays.

3. Noise reduction function of ultra-thin overlays

Traffic noise is an important source of environmental noise pollution. With the development of the traffic industry, traffic noise pollution has become increasingly serious and road noise reduction technology is currently a hot issue. Tire–pavement noise is mainly due attributed to the tire vibration and tire air-pumping effect [50]. To improve the noise reduction function, researchers have studied the effect and mechanism of ultra-thin overlay noise reduction in terms of the gradation and material.

3.1. The effect of gradation on noise reduction of ultra-thin overlay

Numerous studies have investigated the noise reduction performance of ultra-thin overlays with different gradations.

Hong et al. [47] evaluated the noise reduction performance of PU/asphalt concrete (AC) and PU/open graded friction course (OGFC) ultra-thin overlays by the impedance tube method. The sound absorption coefficients of mixtures were calculated from

Table 1
Analysis of factors influencing the skid resistance function of ultra-thin overlays.

Influence factor	Measurement	Effect on skid resistance	Advantages	Disadvantages
Gradations	Selecting the coarse mixtures with a larger NMAS [38]	The DFT friction value increased by about 15%	The anti-skid function of ultra-thin overlay can be improved by increasing the texture depth and optimizing the skeleton structure	① When the air voids reached the critical value, increasing the texture depth cannot further enhance the anti-skid function of ultra-thin overlay ② In order to obtain the target aggregate grading, the ultra-thin overlay may increase the material cost in the gradation design
	Increasing air voids of mixtures [40]	F60 value increased by 36%–49%		
	Improving the gradation design methods [41]	FN value increased by about 5% after construction		
	Using the improved CAVF method in mix design [22]	For more than 70% of test values, the texture depth value and BPN values were at least 12.5% and 33.3% higher than the technical specifications respectively		
Aggregates	Using aggregates with higher amount of acid-insoluble residue [43]	The DFT friction value increased by about 20% at 100 000 revolutions	① By increasing the hard mineral content and friction coefficient of the aggregate and selecting the appropriate particle size range of the aggregate, the anti-skid function of ultra-thin overlay can be significantly improved ② The use of industrial waste residue in ultra-thin overlay is environmentally friendly	① The use of high-performance materials will increase the material cost of the mixture ② Industrial wastes may have adverse effects on other road functions of asphalt mixtures
	Adding emery with rough surface [44]	The MTD values of 2–3 mm emery PUTWC were about 33% and 13% higher than those of 1–2 and 1–3 mm respectively		
	Adding EAF slag with higher PSV [45]	SRV increased by about 5%		
Binders	Using multi-chain polyolefin modified asphalt [28]	M-UWM10 had a similar texture depth with UWM10, but the reduction in the texture depth ratio was lower	① These adhesives can ensure the adhesion function of binders and the compaction effect of the mixture, thereby improving the initial skid resistance performance and reducing the subsequent skid resistance attenuation under traffic load ② Some binders, such as the easy compaction modified asphalt and PU, can reduce the energy consumption of pavement construction and have excellent environmental benefits	① These binders may increase the material cost of mixture ② These binders may have adverse effects on other functions of asphalt mixtures
	Using polyolefin modified asphalt [46]	Texture depth values and the BPN values were 9.0%–81.8% and 17.8%–26.7% higher than the technical standard respectively		
	Using the easy compaction modified asphalt [24]	ECHD asphalt mixture had slight advantages over base asphalt mixture in terms of anti-skid		
	Using PU as binder [47]	polishing and the BPN increased by 15%–30% after polishing		

the measured incident and reflected sound energy. The results showed that the maximum absorption coefficient of PU/AC was only 43% at roughly 1270 Hz. However, the PU/OGFC exhibited maximum absorption coefficients of 86% at 1425 Hz. In addition, compared with PU/AC, PU/OGFC samples showed higher absorption coefficients in a wider frequency range, which meant better noise reduction performance. This is due to the abundant pore structures of OGFC mixtures, which can greatly reduce the air-pumping effect between the pavement and tire. Moreover, the noise could be transmitted in the interior of the pavement, which consumed part of the noise energy, hence reducing the intensity of the noise source and effectively controlling the tire–pavement noise [51]. The air-pumping effect and noise reduction mechanism of ultra-thin overlay are shown in Fig. 3 [50].

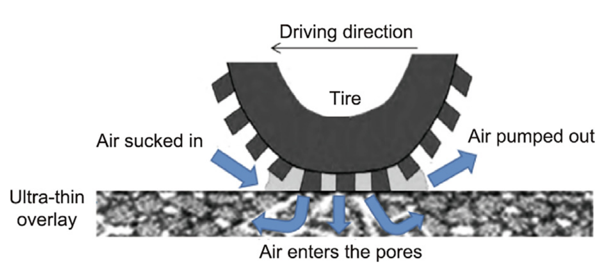

Fig. 3. Air-pumping effect and noise reduction mechanism of ultra-thin overlays [50].

Based on the statistical pass-by (SPB) method, Gardziejczyk [32] studied the noise level of very thin asphalt concrete (VTAC) and SMA. The void content of VTAC 8 was 12%–15%. Results indicated that compared with dense graded mixture, VTAC reduced the maximum sound level by about 6 dB due to the higher voids content. However, the maximum sound level of VTAC 8 increased about 10 dB at a frequency of 1000 Hz after three years. This may be attributed to the plugging of surface pores caused by the use of sand to remove black ice on porous roads. As a result, to extend the noise reduction function of porous ultra-thin overlays, special attention should be paid to road maintenance in winter. Cedric et al. [31] evaluated the acoustic properties of thin noise-reducing asphalt layers (TAL) with a void percentage of 11%–25% based on the SPB and close proximity method (CPX). Mixtures with a high void content showed the largest initial noise reduction (up to 6 dB(A); A-weighted decibel). However, based on the SPB and CPX measurements, the noise of the TAL layers increased by 0.02–0.14 and 0.05–0.20 dB(A) per month respectively in 2.5–3.0 years. This noise increase was related to raveling. In addition, TAL with a high void content exhibited a higher sensitivity to raveling. The simultaneous achievement of excellent durability and noise reduction performance proved to be difficult.

This conclusion agreed with Vaitkus et al. [52], who optimized the most common conventional AC mixtures and designed two types of Lithuanian stone and mastic asphalt mixtures. Due to the high sound absorption and MTD, the two ultra-thin overlay mixtures with improved gradation exhibited a better noise reduction performance compared to the dense graded mixture AC. However, after frost–thaw cycles, the particle mass loss of mixture with an NMAS of 8 mm was about twice that of the mixture with an NMAS of 5 mm. This indicated that a higher void content may reduce durability. Therefore, in areas prone to freeze–thaw cycles, it was recommended to use low-noise pavements with a voidage of 5%–8%.

Note that a larger void content does not necessarily result in a better noise reduction effect. Jiang et al. [40] evaluated the noise reduction of PUAO mixtures. When the air void increased from 15.8% to 24.4%, the peak value of the sound absorption coefficient of the PUAO mixture also increased, but the frequency corresponding to the peak value moved from 400 to 1250 Hz. Thus, in order to design an appropriate air void, the sound absorption coefficient and frequency characteristics of mixtures must be considered comprehensively, so as to realize better noise reduction.

The HUFC ultra-thin overlay has been proven to have a good noise reduction performance. The skeleton of the HUFC mixture is composed of aggregates with smaller particle sizes, and thus a richer pavement texture structure is formed, resulting in multiple reflections and the interference of noise and sound waves. Compared with AC-13 and SMA-13, the noise of HUFC-8 was reduced by 5.9 and 4.3 dB, respectively [22]. This shows that ultra-thin overlays can achieve noise reduction by optimizing the surface texture of mixtures through the grading design.

3.2. The effect of additives on noise reduction of ultra-thin overlay

In addition to the grading optimization, several additives are also used to improve the noise reduction function of ultra-thin overlays (Table 2 [33,53,54]). Research has revealed that both high viscosity modified asphalt and rubber particles are damping materials. These materials can store part of the vibration energy produced by automobile tires, with another part dissipated in the form of heat through the mutual displacement and viscous internal friction process in damping materials [55]. In addition, the noise reduction ultra-thin overlays, such as reacted and activated rubber modified gap-graded mixture (RAR-ThinGap) [53], asphalt rubber ultra-thin layer (ARUTL) [33], and ultra-thin full-AC (UFAC) [54], are high damping polymer composite materials. Therefore, they can effectively attenuate the impact and vibration of the tires by using the dispersion viscosity mechanism inside the damping materials, so as to reduce the tire–pavement noise [56]. Current research mainly focuses on environmentally friendly materials (rubber) and high viscosity modifiers. Additional road materials that can improve the noise reduction performance and should be the subject of future studies.

3.3. Summary and analysis

The change in mixture gradation leads to the change in micro pore characteristics (e.g., the number and size of pores), which will affect the peak sound absorption coefficient and sound absorption frequency of mixtures. It is necessary to optimize the gradation of ultra-thin overlay mixture and design a suitable void content based on the main frequency range of pavement noise. The porous ultra-thin overlay is generally a good choice for road noise reduction. The maximum sound absorption coefficient of the PU/OGFC ultra-thin overlay is twice that of the PU/AC ultra-thin overlay. Compared with dense-graded mixtures, VTAC with a void content of 12%–15% reduced the maximum sound level by approximately 6.0 dB. However, the unfavorable location of the road, improper maintenance methods, and the lack of system cleaning in winter will lead to the blockage of the pores of functional ultra-thin overlays. This may increase the maximum sound level of pavements by 0.7–10.0 dB. In addition, the high void fraction will lead to the poor durability of ultra-thin overlays, and the particle mass loss of mixtures will be doubled. The greater macrotexture depth formed by the special gradation design can ensure the noise reduction function of mixtures. Therefore, future research should focus on noise reduction ultra-thin overlays with an optimized surface texture and low void content. In addition, rubber additives can reduce the noise of the ultra-thin overlay by 0.4–5.0 dB. However, the addition of rubber also has some adverse effects on the basic road functions of ultra-thin overlays. Therefore, it is necessary to strictly control the amount of rubber. Table 3 [22,31–33,47,52,54] details the factors influencing the noise reduction function of the ultra-thin overlay.

4. Rutting resistance function of ultra-thin overlays

After an asphalt pavement is opened to traffic, rutting may occur under high temperature conditions or long-term repeated vehicle load [57]. Although the ultra-thin overlay is usually used as the wearing course, it should possess some rutting resistance. Considering the lower thickness of the ultra-thin overlay, scholars generally focus on improving its rutting resistance by optimizing the gradation and using high-performance materials.

Table 2
Influence of additives on the noise reduction function of ultra-thin overlays.

Ultra-thin overlay	High-performance additive	Additive content (%)	Test method	Noise reduction effect
RAR-ThinGap [53]	Crumb rubber	4.4[a]	Pass-by noise method	Decreasing the noise by 0.4–2.5 dB
ARUTL-13 [33]	AR	–	Indoor tire-rolling-down test	Decreasing the noise by 1.6 dB
UFAC [54]	Rubber	21.0[b]	Noise measurement inside motor vehicles	Decreasing the noise by about 5.0 dB

Additive content is calculated by the weight of asphalt mixture[a] or asphalt binder[b].
RAR-ThinGap: reacted and activated rubber modified gap-graded mixture; ARUTL: asphalt rubber ultra-thin layer; UFAC: ultra-thin full-AC; AR: asphalt rubber.

Table 3
Summary of factors influencing the noise reduction function of ultra-thin overlays.

Influence factor	Effect on noise reduction	Noise reduction measure and mechanism	Existing problem
Gradations	Maximum noise reduction value can reach 6.0 dB [22,31,32]	① Increase in voids content to reduce the tire air-pumping effect [47] ② Form greater texture depth to reflect and interfere the noise [22]	① Clogging of the pores will reduce the noise reduction function of ultra-thin overlay [32] ② High voids content may reduce the durability of ultra-thin overlays [52]
Additives	Noise can be reduced by 0.4–2.5 dB [33,54]	Increase the damping of ultra-thin overlay to reduce the impact and vibration noise of the tire	The anti-skid function of rubber modified asphalt mixtures may perform worse than that of SBS asphalt mixtures [54]

4.1. The effect of gradation on rutting resistance of ultra-thin overlay

The gradation type is reported to have a great impact on rutting resistance of ultra-thin overlay. Hajj et al. [38] compared the rutting resistance of six ultra-thin overlays with different gradations. Results from the Hamburg wheel tracking device (HWTD) showed that fine-graded mixtures started stripping and rutting almost immediately, while coarse-graded mixtures did not strip until about 10 000 cycles. Prior to the 15 000 cycles, the rutting depths of coarse-graded mixtures were less than 12.5 mm [38]. This is attributed to the formation of the close interlocking structure via the internal aggregates of the coarse ultra-thin overlay asphalt mixture after pavement compaction. This consequently increased the internal friction angle within the mixtures [58]. As a result, the anti-rutting function of coarse mixtures is generally much better than that of fine mixtures.

However, fine graded mixtures can also exhibit a good high temperature stability by gradation optimization. Son et al. [41] evaluated the rutting resistance function of 4.75 SMA, with a gradation design based on the Bailey method. The results from the wheel tracking test revealed that after 20 000 passes at 50 °C, the rutting depth of 4.75 SMA was only 0.2 mm deeper than that of 12.5 SMA. Therefore, although the NMAS was smaller, the 4.75 SMA did not show an obvious difference in rutting resistance compared to the coarser mixture. This is because the optimized gradation ensured the appropriate skeleton structure of mixture, thus ensuring the compactibility of the thinner overlay.

Cui et al. [34] evaluated the rutting resistance of ultra-thin wearing course (UTWC)-10, with a gradation design based on the CAVF method. Rutting test results showed that the dynamic stability value of UTWC-10 was 77.2% higher than that of OGFC-7 and 36.9% higher than that of NovaChip-B due to the better high-temperature stability of the former. This is attributed to the strengthening ability of this grading design method for the stone-to-stone skeleton of the ultra-thin overlay mixture, which increases the stability of the mixture more stable. This also provides new concepts for the gradation design method of ultra-thin overlays.

In addition to optimizing the grading design method, Jiang et al. [40] found that the increase in air voids had adverse effects on the anti-rutting function of mixtures. The dynamic stability value of PUAOs decreased by about 60% when the air voids changed from 15.8% to 24.4%. When the air voids exceeded 20%, the dynamic stability tended to decrease rapidly. As a result, in order to guarantee the anti-rutting function of ultra-thin overlays, the air voids content of the mixture should be less than 20%. In addition, due to the small thickness of ultra-thin overlays, the underlying structures also affect their performance evaluation. Previous work has demonstrated that a double-layer sample with PUAO as the upper layer and AC as the lower layer exhibited a better rutting resistance than PUAO single-layer samples of the same size.

4.2. The effect of high-performance materials on rutting resistance of ultra-thin overlay

In addition to optimizing the grading, the use of high-performance materials can also enhance the anti-rutting function of ultra-thin overlays [49].

High performance modified asphalts were usually used in ultra-thin overlays (Table 4 [59–61]). On the basis of SBS modified asphalt, Wang et al. [59] prepared SBS/ethylene-butylacrylate-glycidyl methacrylate terpolymer (PTW) high viscosity modified asphalt for ultra-thin overlay. The solubilizer, toughener PTW, and nano-ZnO were used as modifiers. Results from wheel tracking test indicated that the dynamic stability value of mixtures with SBS/PTW modified asphalt as binder reached 10 227 cycles·mm^{-1}, which was about 1.3 times that of SBS modified asphalt mixtures. This can be explained by the ability of the toughener and nano materials could improve the dispersion of polymer in asphalt, thereby enhancing the performance of asphalt at high temperature [62,63].

Table 4
Effect of different types of asphalt on rutting resistance of ultra-thin overlay.

Ultra-thin overlay	Asphalt type	Optimum asphalt content (%)	Dynamic stability (cycle·mm^{-1})
SMA-13 [59]	SBS modified asphalt	5.6	7 957
	SBS/PTW high-viscosity modified asphalt	5.9	10 227
SMA-10 [60]	SBS modified asphalt	6.8	5 045
	SBS/MCF modified asphalt	6.8	5 625
	High-content SBS/MCF composite-modified asphalt	6.8	6 774
SMA-10 [61]	SBS modified asphalt	6.8	5 045
	SBS/MCF modified asphalt	6.8	5 625
	SBS/MCF/SBR modified asphalt	6.8	11 455

MCF: micro carbon fiber; SBR: styrene–butadiene-rubber.

Zhao et al. [62] used SBS/micro carbon fiber (MCF) modified asphalts as the binder for ultra-thin overlay mixtures and investigated their high-temperature stability by rutting tests. The results showed that compared with 5.0%SBS modified asphalt mixtures, the dynamic stability values of 5.0%SBS + 0.8%MCF and 6.0%SBS + 0.8%MCF modified asphalt mixtures increased by about 10% and 20%, respectively. This indicates that increasing the content of MCF and SBS can effectively enhance the stability of ultra-thin overlay mixtures. SBS and MCF increased the viscosity and toughness of asphalt. The modified asphalt of 6.0%SBS + 0.8%MCF was suitable for ultra-thin overlay.

On the basis of SBS/MCF modified asphalt, Zhao et al. [63] prepared SBS/MCF/styrene–butadiene-rubber (SBR) modified asphalt by adding SBR as modifier. Results showed the dynamic stability of ultra-thin overlay mixture increased by about 130% after adding 0.8%MCF and 2.0%SBR. Due to the excellent high-temperature performance, 0.8%MCF + 5.0%SBS + 2.0%SBR composite modified asphalt greatly improved the anti-rutting function of ultra-thin overlays.

Moreover, the anti-rutting function of ultra-thin overlay is also related to the aggregate properties. Rahman et al. [64] studied the rutting resistance of 4.75 mm ultra-thin overlays by HWTD tests. Aggregates used in this study were from US-160 and K-25 (two projects in Kansas, USA). Results indicated that rutting performance of above mixtures was aggregate-type and source specific. Compared with US-160 mixes, most K-25 mixtures had difficulties in stripping, and the skeleton structure composed of granite aggregates from K-25 aggregate source helped to delay the stripping injection point by about 2000 wheel cycles. It is found that the granite aggregate is usually in the shape of a cube with many contact points and lines. Therefore, it is easier to form a stable interlocking aggregate structure, and it is more difficult to slide and change the tangential plane under repeated stress [65].

Several types of industrial solid wastes have also been employed to enhance the anti-rutting function of ultra-thin overlay mixtures. Wan et al. [66] used steel slag to replace all aggregates of permeable asphalt concrete (PAC), and investigated its high temperature rutting resistance by rutting tests. The dynamic stability of PAC-5 mixtures with steel slag as aggregates was 20% higher than that of mixtures with common stone aggregates. Furthermore, the mechanical strength of steel slag was higher, and could form a robust skeleton structure in the asphalt mixture. There was a strong adhesion between asphalt and steel slag, which improves made the high temperature stability of the ultra-thin overlay.

4.3. Summary and analysis

Coarser overlay mixture generally exhibits a better high temperature stability than the finer mixtures. However, by optimizing the grading design, the finer ultra-thin overlay mixture can also have a good rutting resistance. In addition, there is a linear negative correlation between air void and dynamic stability. Thus, in the grading design, the air void of ultra-thin overlay mixture should be controlled. In order to improve the rutting resistance, more optimized gradation design methods should be used for ultra-thin overlay mixture in the future.

Some high-performance modified asphalts, such as rubber modified asphalt and high viscosity modified asphalt, have been proven to be able to enhance the rutting resistance function of ultra-thin overlays due to their good deformation resistance. In addition, the rutting performance of ultra-thin overlay was aggregate-type and source specific. High performance aggregates, such as granite aggregates, can improve the rutting resistance. Industrial solid waste is also used to enhance the functions of ultra-thin overlay, which provides ideas for the design of low-cost environmentally friendly ultra-thin overlay. More high-performance binders and aggregate substitutes can be employed to enhance the anti-rutting function of ultra-thin overlay in the future.

The analysis of influencing factors on rutting resistance function of ultra-thin overlay is shown in Table 5 [33,34,40,41,54,59,62–64,66].

5. Crack resistance function of ultra-thin overlays

Cracks may occur in pavements due to factors such as temperature/humidity variations and vehicle loads [67]. Because of the thinner thickness, overlays are more likely to develop cracks. This may lead to early deterioration and shorten the service life of overlay. To improve the crack resistance function of ultra-thin overlays, the effect of gradation and materials of mixture on crack resistance has been the focus of numerous recent studies.

5.1. The effect of gradation on crack resistance of ultra-thin overlay

The gradation has a great impact on the crack resistance function of ultra-thin overlays. Garcia-Gil et al. [68] compared the crack resistance of seven different graded thin overlay mixtures by the Fénix test. The results showed that the NMAS and fine fraction content affect the crack performance of mixtures. The toughness of the mixture with lower content of fine aggregate and smaller NMAS was further improved. It was concluded that compared to the NMAS, the fine fraction content had a greater impact on the ductility of the overlay mixture. Therefore, in the design of thin overlays, special attention should be paid to the fine fraction content to improve the crack resistance.

In order to save aggregate and asphalt, Budiarto et al. [69] designed ultra-thin surface hot mix asphalt mixture (UTSHMA) with a thickness of 12–15 mm and evaluated its crack resistance. The results from indirect tensile strength (ITS) test showed that the value of ITS of UTSHMA was 118 kPa larger than that of conventional asphalt concrete-wearing course (AC-WC). This was because the coarse graded UTSHMA had a higher optimum asphalt content, which made the mixture more elastic, thus improving the crack resistance.

In addition to influencing the optimum asphalt content, the gradation of the ultra-thin overlay mixture can also affect the crack resistance via the tack coat application rate. Usually, before paving the ultra-thin overlay, it is necessary to spray tack coat emulsion to ensure a strong bond between thin overlay and lower pavement [70]. Ahmed et al. [29] measured the fracture energies of a field core by the fracture test. Results indicated that with the increase of the tack coat application rate, the gap-graded thin-bonded overlay (TBO) mixtures showed a better fracture resistance. However, the dense-graded mixtures were limited by the tack coat emulsion application, and its crack resistance was reduced after exceeding the limit. The tack coat application rate of the gap-graded mixture was 0.90 $L{\cdot}m^{-2}$, while that of the dense-graded mixture was only 0.67 $L{\cdot}m^{-2}$. This indicated that the optimum tack coat application rate changed with the gradation type of TBO mixtures, thus affecting the crack resistance of different graded mixtures. However, the samples used in the study were only from seven field sections. In the future, additional ultra-thin overlays with different gradations should be studied in order to expand the current research.

5.2. The effect of high-performance materials on crack resistance of ultra-thin overlay

At present, the polymer modified asphalt (PMA) is typically used in ultra-thin overlay normally due to its higher performance [71]. Garcia-Gil et al. [68] investigated the effect of two types of asphalt on the crack resistance of ultra-thin overlays at different temperatures. Results from the Fénix test showed that compared to polymer modified binder (PMB) 45/80–65 asphalt, conventional B 35/50 asphalt improved the stiffness of mixtures within the whole test temperature range. When the test temperature was 5 °C, the TSI values of B 35/50 mixtures were about 600 $kN{\cdot}mm^{-1}$ larger than those of PMB 45/80–65 mixtures. In addition, PMB mixtures exhibited a better ductility due to the higher deformability of the binder. Therefore, mixtures manufactured with PMB 45/80–65 demonstrated a better crack resistance. However, as the temperature decreased, the difference between all mixtures was reduced due to the hardening process of the asphalt binder. Therefore, future research can further develop PMA with a lower temperature sensitivity.

Table 5
Summary of factors influencing the rutting resistance function of ultra-thin overlays.

Influence factor	Effect on rutting resistance	Rutting resistance measurement and mechanism	Existing problem
Gradations	The dynamic stability can be increased by up to about 80% [34]	The optimized gradation design method can enhance the stone–stone skeleton of the ultra-thin overburden mixture, thus providing a more stable internal structure of the mixture [34,41]	High void content may have an adverse effect on anti-rutting function of ultra-thin overlay [40]
Binders	The dynamic stability can be increased by about 10%–100% [33,54]	By modifying the asphalt, the toughness and viscosity of the asphalt are increased, thus enhancing the anti-rutting function of mixture [59,62,63]	The additives used in modified asphalt may increase the material cost of the mixtures
Aggregates	The dynamic stability can be increased by about 20% [66]	① The cube shape of aggregate can provide a good interlocking aggregate structures [64] ② Aggregate and binder have better adhesion [66]	The impact of industrial solid wastes on other road performance of ultra-thin overlay is not clear

Several scholars have attempted to add high-performance materials to mixtures to improve the crack resistance of ultra-thin overlays. Chen et al. [33] designed a reacted and activated rubber (RAR) modified gap-graded ultra-thin mixture denoted as RAR-ThinGap. The RAR particles include 62% fine crumb rubber, 22% soft asphalt binder, and 16% fillers by mass. The results showed that the fracture energy of the RAR-ThinGap was more than five times that of the control samples due to the high viscosity of the RAR modified binder. Moreover, the post-crack behavior of the RAR-ThinGap greatly improved. Moreover, the fatigue life of the RAR mixture was more than 50 times that of the traditional mixture due to the good elasticity of rubber. This provides a greater understanding of the role of RAR in the crack resistance of ultra-thin overlay mixtures.

Mogawer et al. [72] examined the effect of asphalt rubber (AR) on the ultra-thin lift overlay (ULO). AR binders were prepared by blending the virgin binder with ground tire rubber (GTR) using a wet process. The mixtures manufactured with AR or PMA modified binder exhibited a similar low-temperature crack resistance. However, compared with the PMA binder, the AR binder showed a poor performance in the mixture fatigue crack resistance and reflective crack resistance. In addition, the AR binder with smaller AR particles performed better in reflective cracking tests and worse in fatigue tests compared to the AR binder with larger AR particles. Therefore, in order to enhance the crack resistance of ultra-thin overlays, there is a need to control the size of the GTR and choose modified materials with a higher performance.

In addition to rubber, Lou et al. [73] studied the effect of basalt fiber (BF) content and length on the crack resistance of the UTWC. The results showed that adding 0.2% 3 mm BF into the UTWC mixture increased the fracture energy by 21.0% and the flexural index by 54.2%. This is because the BF formed a three-dimensional network, which dispersed part of the stress inside the mixture and reduced the relative movement of aggregates, thus limiting the development of cracks. However, an excessive BF content and length had a negative influence on the dispersion of the BF in the mixture. Therefore, an appropriate BF length and content should be selected according to the type of ultra-thin overlay mixture.

5.3. Summary and analysis

To sum up, the impacts of gradation on crack resistance of ultra-thin overlay are mainly reflected in four aspects: fine aggregate content, NMAS, optimum asphalt content, and tack coat application rate. However, these results are limited to the ultra-thin overlay with a specific gradation. Future research should systematically study the influence of the above four aspects on the crack resistance of other graded ultra-thin overlays. Moreover, the application of PMA binders can improve the crack resistance of ultra-thin overlays. Several environmentally friendly materials, such as rubber, were added into ultra-thin overlay mixture. The influence of these materials on the mixture needs to be further studied. Fibers have been proved to have an excellent crack resistance, and additional types of fibers can be used in ultra-thin overlays in the future. Table 6 [29,33,68,69,72,73] compares the influence of high-performance materials and gradation on the crack resistance function of ultra-thin overlays.

6. Snow melting and deicing function of ultra-thin overlay

6.1. Snow melting and deicing mechanism of ultra-thin overlay

To reduce the snow on pavement in winter, mechanical approaches, abrasives and salt application are usually employed. However, such methods will adversely affect the natural environment and transport infrastructure [74]. At present, the environmentally friendly deicing and snow removal technologies for pavements typically include self-stress flexible technology, low freezing point technology and energy conversion technology [75–77]. Among them, low freezing point technology and energy conversion technology are ideal choices for self-ice-melting ultra-thin overlays.

When it was raining or snowing, the principal ingredients (most of them are chloride-based materials) of deicing agent in the self-ice-melting ultra-thin overlay can be released to form the antifreeze solution. The antifreeze solution forms an isolation layer between the ice and pavement surface, which can effectively delay the ice and snow formation on the pavement [78]. In addition, the NMAS of the ultra-thin overlay mixture is generally no more than 10 mm and results in a lower thickness compared to conventional overlays. This makes it more conducive to the diffusion of chloride-based materials to pavement surfaces. Therefore, the snow melting effect of ultra-thin overlays is better than that of conventional overlays [11]. Fig. 4 [79] presents the snow melting mechanism of self-ice-melting ultra-thin overlays.

In addition to the aforementioned low freezing point technology, energy conversion technology has also been used to enhance the snow melting function of ultra-thin overlay in recent years.

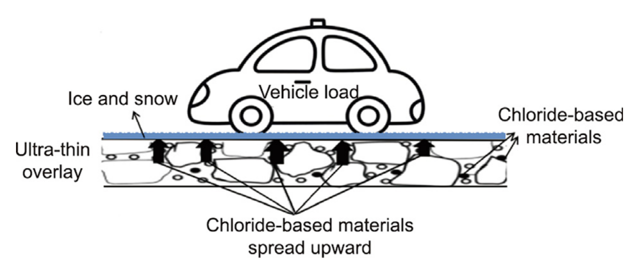

Fig. 4. Snow melting mechanism of a self-ice-melting ultra-thin overlay [79].

Table 6
Comparison of influence factors on crack resistance function of ultra-thin overlay.

Influence factor	Crack resistance measure and mechanism	Existing problem
Gradations	① Improve the toughness of the mixture by reducing the NMAS and the content of fine aggregate [68] ② Optimize the gradation to improve the optimum asphalt content of mixtures, so as to enhance the elasticity of mixtures [69] ③ Change the tack coat application rate of the adhesive layer by changing the gradation of mixture, thus affecting the crack resistance [29]	Current research is limited to the ultra-thin overlay with some specific gradations
High-performance materials	① Use PMA modified asphalt with a high deformation ability to improve the ductility value of the mixture [68] ② Use RAR to modify asphalt to improve the viscosity of binder [33] ③ Use BF to disperse the stress inside the mixture [73]	① With the decrease of temperature, the hardening process of PMA modified asphalt may occur, which will reduce the anti-crack function of mixtures [68] ② Rubber may exert a negative influence on the crack resistance of ultra-thin overlay mixtures [72]

Wan et al. [35] investigated the effect of steel fiber and steel slag on the snow melting function of ultra-thin wearing course. The steel fiber increased the thermal diffusivity and thermal conductivity of the mixture, thus improving the induction heating efficiency of the overlay. Ice-melting tests showed that the ice-melting speed of the mixture containing 3% steel fiber was more than twice that of the mixture containing 1% steel fiber. Moreover, as the steel slag generated heat in the alternating magnetic field, its negative effect on thermal diffusivity and conductivity was restrained, and thus the ice melting time was shortened. To ensure the road performance of the ultra-thin wearing course, the amount of steel fiber in the mixture should not exceed 2%. In addition, the optimum heating depth of the ultra-thin wearing course was determined as 20–28 mm. Therefore, the thickness of the overlay was recommended to be 20–25 mm. Li et al. [15] designed a conductive ultra-thin anti-skid wearing course (CUAWC) and evaluated its snow melting performance. The conductive functional layer was made of epoxy resin glue, carbon fiber, and graphite. Following the addition of graphite, carbon fiber and other conductive materials, the electric resistance of the mixture was significantly reduced and the asphalt pavement had the ability of electrical–thermal transformation. The mass percolation thresholds of carbon fiber and graphite in mixtures were 4% and 25%, respectively. These studies provide insight into the development of snow melting ultra-thin overlays.

6.2. Recent developments on snow melting and deicing function of self-ice-melting ultra-thin overlay with chloride-based materials

The salt concentration of the antifreeze solution between the ice and the self-ice-melting ultra-thin overlay affects the snow melting and deicing function of the pavement. The conductivity of the solution is typically employed as the evaluation index to characterize the salt concentration of the solution. Therefore, the snow melting and deicing performance of the self-ice-melting ultra-thin overlay can be indirectly evaluated by the conductivity of the solution [80]. Dou [81] found that the electrical conductivity of the soaking solution of the self-ice-melting ultra-thin overlay increased with the amount of salt applied. The improvement in the electrical conductivity of the soaking solution was more obvious when the amount of chloride-based material was more than 45%. Moreover, the conductivity of the soaking solution of the mixture with a salt content of 60% was about 0.59 $\mu S \cdot m^{-1}$, which was 43.9% larger than that of the mixture with a salt content of 45% [81]. This shows that the salt content exerted a great impact on ice melting function of ultra-thin overlay.

Additional research found that when the soaking time was 240 min, the conductivity of the ultra-thin overlay mixture at 60 °C was about 1.1 μS, which was 0.7 μS larger than that of the mixture at 25 °C. Furthermore, the conductivities were 0.4 and 0.6 μS for the sample with 3000 and 4000 mL water added, respectively. The porosity of the self-ice-melting ultra-thin overlay was observed to have little effect on the soaking solution conductivity. Finally, the order of the grey entropy correlation degree between each influencing factor and the electrical conductivity of the soaking solution of the self-ice-melting ultra-thin overlay was as follows: salt amount > temperature > amount of water added > porosity [82]. This further showed that the salt content was the most significant factor affecting the snow melting function of ultra-thin overlays.

However, the addition of salt may have an adverse impact on the basic road performance of ultra-thin overlays. The high-temperature stability, moisture susceptibility, and cracking resistance of mixes is reported to degrade with the increase of the content of antifreeze additives [83]. In addition, the particle size of the antifreeze filler also exerts great effects on the road performance of asphalt mixtures. Mixtures with smaller particles of antifreeze filler typically present a better rutting resistance and water stability [80].

In summary, the salt content is the most significant factor affecting the ice melting function and the basic road performance of ultra-thin overlays. It is also necessary to select the particle size of antifreeze additives according to the actual application. When the pavement is at an extremely low temperature, the dissolution rate of the salt slows down markedly, and the snow melting effect of the ultra-thin overlay mixture is not obvious. Other effective measures should be taken to remove the ice and snow to eliminate the potential safety hazards in a timely manner [84,85]. Future research can further study the application of other high-efficiency snow melting agents in ultra-thin overlays.

7. Exhaust gas purification function of ultra-thin overlay

7.1. Exhaust gas purification mechanism of ultra-thin overlay

Pavement exhaust gas purification technology is mainly adopted through the use of reusable catalytic materials on the road surface to reduce the harmful gases in the environment [86]. At present, photocatalytic technology is widely employed for pavement exhaust gas purification. TiO_2 nanoparticles have an excellent photocatalytic activity, chemical stability, and recyclability, which make them suitable materials for pavement exhaust gas purification [87–89]. It was found that under the action of sunlight, the TiO_2 nanoparticles on the surface of the pavement can cause carbonic oxide (CO), hydrocarbons (HC), and nitrogen oxygen (NO_x) in automobile tail gas react with oxygen and generate water (H_2O), carbon dioxide (CO_2), and nitrate, which are harmless to human health and the environment [90]. Fig. 5 presents the principle of pavement exhaust gas purification.

7.2. Recent developments on exhaust gas purification function of ultra-thin overlay

At present, the application ways of TiO_2 in asphalt mixtures generally includes the blending and spraying methods [91,92]. However, due to the larger thickness of conventional overlays, TiO_2 mixed in the mixture was largely wrapped. This greatly affects the photocatalytic effect of TiO_2 [11]. In addition, the thicker overlays greatly increase the consumption of TiO_2. In order to overcome this problem, Li [16] combined photocatalytic technology with ultra-thin overlay technology. Nano-TiO_2 was added into the asphalt mixtures to prepare a photocatalytic ultra-thin overlay with a thickness of 15–25 mm. The degradation effect of TiO_2 on exhaust pollutants (CO, HC, and NO) was investigated by the self-designed exhaust gas decomposition test equipment. In the test, the irradiance of the ultraviolet lamp was 25.0 $W \cdot m^{-2}$. The results showed that the degradation effect was enhanced with the increase of nano-TiO_2 content (within limits). When the content of nano-TiO_2 was 60% (proportion of the mineral powder mass), the cumulative decomposition rates of NO, HC, and CO after 90 min were about 50%, 23%, and 28%, respectively. The mixture with a larger amount of TiO_2 exhibited a serious decline in the rutting resistance and water stability. The optimal amount of nano-TiO_2 in ultra-thin overlay asphalt mixtures was recommended as 60% of the amount of mineral powder [16].

Wang et al. [93] added nano-TiO_2 to emulsified asphalt to prepare a photocatalytic coating. Through the independently-developed exhaust gas degradation test device, the exhaust gas degradation effects of the OGFC-10 asphalt mixture with photocatalytic coating were evaluated. The irradiance of the ultraviolet lamp was set as 26.7 $W \cdot m^{-2}$. When the nano-TiO_2 content and spraying

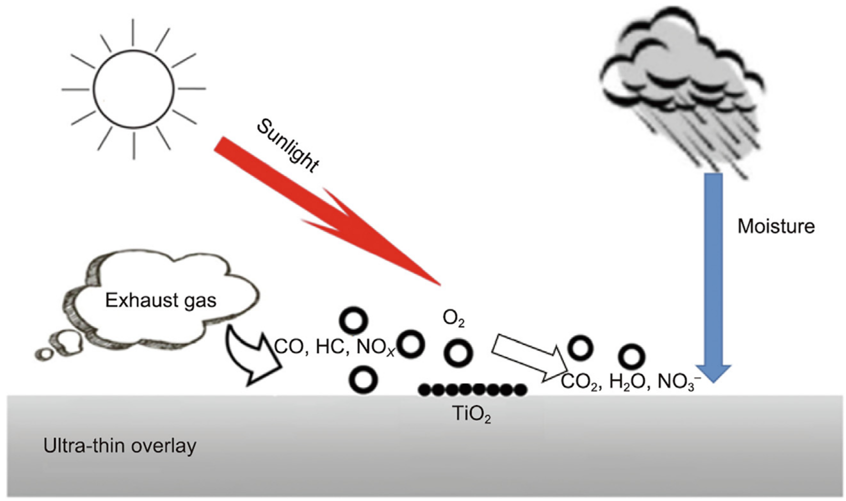

Fig. 5. Principle of pavement exhaust gas purification.

amount of the coating were lower than 8% and 333.3 g·m^{-2}, respectively, the cumulative degradation rate of the exhaust gas increased with the nano-TiO_2 content and spraying amount. After 90 minutes of testing, the cumulative decomposition rates of NO, HC, and CO peaked at about 25%, 40%, and 30%, respectively. When the nano-TiO_2 and spraying amounts exceeded this range, the degradation effect of this ultra-thin overlay on the exhaust gas was not dramatically enhanced due to the limited effective amount of nano-TiO_2 particles in contact with the exhaust fumes per unit area. To ensure the anti-skid function of the pavement, the coating-spraying amount should be limited to less than 550 g·m^{-2}. Moreover, Wu et al. [94] found that agglomeration occurred easily at excessive amounts of nano-TiO_2, which reduced the exhaust degradation efficiency of ultra-thin overlays.

In summary, the application methods of TiO_2 in ultra-thin overlay mixtures mainly include blending method and spraying method. Photocatalytic ultra-thin overlay prepared by both methods can effectively decompose about 20%–50% of pollutants such as CO, HC, and NO in tail gas. The tail gas degradation effect of photocatalysis ultra-thin overlay can be improved by increasing the amount of nano-TiO_2 and the spraying amount of photocatalysis coating. However, in order to improve the tail gas decomposition efficiency and ensure the road performance of photocatalytic ultra-thin overlay, the amount of nano-TiO_2 in ultra-thin overlay mixture should not exceed 60% of the amount of mineral powder. Without considering the engineering loss, the optimum coating spraying amount is 333.3 g·m^{-2}. More kinds of exhaust degradation materials should be developed for ultra-thin overlay in future research. In addition, how to ensure long-term performance of exhaust degradation materials in ultra-thin overlay mixture remains to be further studied.

8. Pavement cooling function of ultra-thin overlay

Asphalt material is sensitive to temperature, and thus the asphalt pavement will heat up rapidly after the sun irradiation, and high temperatures will cause pavement diseases [95]. In addition, the heat absorbed by pavements will also increase the temperature of urban environments, which will cause the heat island effect [96]. To solve the above problems, numerous scholars have proposed cool pavement technology, which reflects, blocks, or absorbs heat via special materials, so as to suppress the rise of the pavement temperature and reduce pavement diseases [11]. At present, cool pavement technologies mainly include pavement heat reflection technology [97], phase change temperature regulation technology [98], thermal resistance pavement technology [99], and water retaining and cooling pavement technology [100]. The technologies applied to ultra-thin overlays are generally pavement heat reflection technology and pavement thermal resistance technology.

8.1. Recent developments on pavement cooling function of heat reflective ultra-thin overlay

In recent years, the heat reflective overlay with a strong cooling effect has been widely used in asphalt pavements [101]. By adding pigments into asphalt mixture, the color of the pavement layer changes. This improves the solar radiation reflectivity of pavements, and subsequently reduces the heat absorbed [97]. For example, Santamouris [100] found that the total reflectance of the pavement coating with white pigments can reach 80%, which reduced the pavement temperature by 12 °C compared to ordinary pavements.

Synnefa et al. [102] compared the optical and thermal properties of six asphalt thin layers with different colors. The solar reflectance of the colored asphalt thin layers was 6.75 (red or green layer) to 13.75 times (off-white layer) that of the ordinary black layer. The daily average temperature of the colored thin layers was 3.1 (red layer) to 7.7 °C (off-white layer) lower than that of the ordinary black layer. This indicates that the temperature-reduction performance of the heat reflective overlay is closely related to the color of pigments in the mixture. The light-colored overlays exhibit a better cooling function.

In addition to light-colored pigments, near-infrared pigments have also recently been employed in heat reflective ultra-thin overlays. Xie et al. [103] added iron-oxide red, which is a near-infrared pigment, to the epoxy resin material to make a high reflectivity coating. It was found that the near-infrared reflectance of iron-oxide red could reach 60%. Based on this, Li et al. [14] developed a color ultra-thin overlay. Iron-oxide red was used as the filler and SBS modified emulsified asphalt with transparent waterborne epoxy resin (WER) was used as the binder. Iron-oxide red exhibited a strong ability to reflect sunlight and reduced the temperature of the ultra-thin overlay sample at a depth of −1.0 cm by 3.5 °C. Moreover, as the WER was transparent, there were less endothermic functional groups in the WER compared to those in asphalt. Thus, the WER reduced the mixture temperature by 1–2 °C alone and the colored ultra-thin overlay with two materials reduced the temperature by up to 8.1 °C. Compared to the light color pigments, the visible reflectance of near-infrared pigments for this pavement was much lower, and thus problems such as pavement glare could be avoided [95]. However, the addition of iron-oxide red was unfavorable to the wearing resistance of ultra-thin overlay [104]. Thus, its dosage should be controlled. This provides a direction for the selection of pavement pigments used in heat reflective ultra-thin overlays. Fig. 6 [105] depicts the cooling mechanism of thermal reflection ultra-thin overlays.

8.2. Recent developments on pavement cooling function of thermal resistance ultra-thin overlay

Thermal resistance aggregates with lower thermal conductivity are often used to prepare thermal resistance ultra-thin overlays. The type and amount of thermal resistance aggregates exert important influencing factors on the cooling performance of thermal resistance ultra-thin overlays.

Wang [106] measured the temperature of surface aggregate classification (SAC)-10 mixes with different ceramics contents. In this study, ceramics were used to replace aggregates with equal volume. The temperature difference between the upper and lower surfaces of SAC-10 increased with the ceramics content. When the ceramics amount was 80%, the temperature difference reached 12.8 °C. This is because the ceramics reduced the thermal conductivity of the pavement, thereby preventing heat from being transferred to the interior of the pavement. However, considering the road performance of ultra-thin overlays, it was recommended to replace 40%–60% (volume) of aggregates with ceramics.

Zou et al. [107] investigated the effect of ceramsite on the temperature of different layers of ultra-thin overlay mixtures. Under the same light conditions, the temperature of SMA-10 mixture with ceramsite was significantly lower than that of SMA-10 without ceramsite in each layer. When 40% of aggregates were replaced with ceramsite, the temperature difference between the 2 and 8 cm depths of the mixture reached 8 °C. In addition, the thermal conductivity of the ultra-thin overlay with ceramsite was obviously lower than that of the ultra-thin overlay without ceramsite. The optimum content of ceramsite for the ultra-thin overlay was 40% of the aggregate volume.

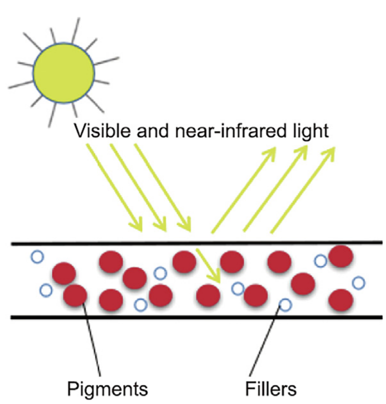

Fig. 6. Temperature-reduction mechanism of heat reflective ultra-thin overlay [105].

Table 7 [106,107] reports the different thermal resistance of ultra-thin overlays and their cooling effect.

8.3. Summary and analysis

In summary, both the heat reflective ultra-thin overlay and the thermal resistance ultra-thin overlay have been proven to have an excellent pavement cooling effect. Due to the high near-infrared reflectance, iron-oxide red reduces the maximum temperature of ultra-thin overlay mixtures by 3.5 °C, while WER binder helps to reduce the maximum temperature of the iron-oxide red ultra-thin overlay by 8.1 °C. By reducing the thermal conductivity of ultra-thin overlay mixture, the thermal resistance material can make the temperature difference between the upper and lower surfaces of the mixture reach 12.8 °C. However, in order to ensure the pavement performance of the ultra-thin overlay, the amount of pigment and thermal resistance material should not be too large. In future research, more types of pigments and heat-resistant materials should be applied to ultra-thin overlays. Moreover, further work is required to overcome the impacts of the cooling materials on road performance of ultra-thin overlays.

9. Application and analysis of functional ultra-thin overlays in typical engineering projects

Due to their excellent functionality and economic benefits, ultra-thin overlays are widely used in pavement engineering projects around the world. To promote the application of ultra-thin overlay in engineering, several typical global projects were investigated. The type and application effects of these ultra-thin overlays are shown in Table 8 [12,13,26,29,33,108–119].

Based on the information shown in Table 8, we can obtain the following findings.

(1) There are significant differences in the types and application functions of ultra-thin overlays in different countries. NovaChip is the most used ultra-thin overlay in China. It is mainly used to restore the anti-skid function and noise reduction function of pavements. In addition, some ultra-thin overlays, such as ultra-thin pavement (U-PAVE) and high-workability ultra-thin asphalt overlay (HWU), are also used to enhance the crack resistance and anti-rutting function of pavements in China. Similarly, ultra-thin overlays in other countries are also typically used to improve anti-skid and noise reduction functions. However, the types of ultra-thin overlays are quite different, such as Lärmoptimierter asphalt Deckschicht (LOA 5 D) in Germany and New Jersey

Table 7
Cooling effect of thermal resistance ultra-thin overlays.

Thermal resistance material	Ultra-thin overlay	Amount of thermal resistance materials (%)	Temperature difference (°C)	Position of temperature measurement
Ceramics [106]	SAC-10	0	3.5	Upper and lower surfaces of asphalt mixtures
		20	8.5	
		40	11.2	
		60	12.1	
		80	12.8	
Ceramsite [107]	SMA-10	0	5.6	At 2 and 8 cm from the upper surface
		20	7.6	
		40	8.0	
		70	4.5	

Table 8
Important engineering applications of ultra-thin overlay around the world.

Engineering project	Ultra-thin overlay type	Coarse aggregate type	Binder	Binder content (%)	Thickness (mm)	Function	Country	Completion year
Guangzhou–Shenzhen Expressway in Guangdong Province [108]	NovaChip-Type B	Granite	NovaBinder	5.0	20	Skid resistance, noise reduction	China	2009
Beijing–Hong Kong–Macao Expressway in Hunan Province [109]	UFC-10	Basalt	SBS modified asphalt	4.8	23	Skid resistance	China	2011
Lianyungang–Horgos Expressway in Henan Province [110]	NovaChip-Type B	Basalt	High-viscosity modified asphalt	4.2	20	Skid resistance, noise reduction, rutting resistance	China	2013
Nanning–Youyiguan Expressway in Guangxi Province [111]	OGFC-8	Dacite	SBS modified asphalt	4.2	20	Skid resistance	China	2014
Xinyi River Bridge in Jiangsu Province [112]	U-PAVE10	Basalt	Polyolefin and SBS composite modified asphalt	5.1	25	Skid resistance, rutting resistance, crack resistance	China	2016
G25 Changchun–Shenzhen Expressway in Guangdong Province [113]	NovaChip-Type C	Basalt	SBS modified asphalt	4.8	20	Skid resistance, noise reduction	China	2016
The artificial island passage in the Hong Kong–Zhuhai–Macao Bridge [114]	UFC-8	Diabase	High viscosity and high elasticity modified asphalt	7.0	20	Skid resistance, noise reduction, crack resistance	China	2018
A first grade highway in Suzhou City, Jiangsu Province [115]	HWU-10	Basalt	High-strength asphalt	6.0	25	Skid resistance, rutting resistance	China	2020
Kennedydamm in Düsseldorf [116]	LOA 5 D	Diabase	GTR modified asphalt	6.5	20–25	Noise reduction	Germany	2007
The regional road N19 Turnhout–Kasterlee [117]	TAL	Diabase	Paving grade asphalt 50/70	5.6	30	Noise reduction	Belgium	2012
Poznanska street in Wolsztyn [118]	BBTM #0/8	–	PMB 45/80–65	5.2	–	Noise reduction	Poland	2011
Rokycanska street in Praha [118]	BBTM #0/8	–	PMB 45/80–55	5.3	–	Noise reduction	Czech Republic	2013
I-195 interstate road in New Jersey [119]	NJ MOGFC	–	PMA	6.8	19	Skid resistance, noise reduction	The United States	2001
US-160 in Kansas [26]	SM-4.75A	Limestone	PG 64–22 asphalt	7.0	19	Skid resistance	The United States	2009
State Road 3 in Indiana [29]	Gap-graded TBO	–	PG 70–28 asphalt	–	19	Rutting resistance, crack resistance	The United States	2009
US-271 in Texas [13]	TOM	SAC A Grade 5 rock	PG 76–22 asphalt	7.2	19	Skid resistance, noise reduction, crack resistance	The United States	2014
Loop 338 Odessa District in Texas [13]	F-PFC	SAC A Grade 5 rock	PG 76–22 asphalt	6.5	19	Skid resistance, noise reduction	The United States	2014
I-80 in Nebraska [12]	SLX (25 mm-thick asphalt mixtures)	–	PG 64–34 asphalt	5.5	25	Rutting resistance, crack resistance	The United States	2014
A road project located in Michigan [33]	RAR-ThinGap	Crushed stone from local area	RAR modified asphalt	6.6	25	Noise reduction	The United States	2018

PG: performance grade; TOM: thin overlay mixtures; F-PFC: fine permeable friction course; SAC: surface aggregate classification; U-PAVE: ultra-thin pavement; HWU: high-workability ultra-thin asphalt overlay; LOA 5 D: Lärmoptimierter asphalt Deckschicht; BBTM: BétonBitumineux TrèsMince; NJ MOGFC: New Jersey modified asphalt binder OGFC; SM-4.75A: asphalt mixture with a 4.75 mm NMAS and a fine gradation.

modified asphalt binder OGFC (NJ MOGFC) in the United States. In addition, numerous ultra-thin overlays in developed countries are adopted to reduce pavement noise, such as TAL in Belgium and RAR-ThinGap in the United States. In general, the differences can be attributed to the late development of thin overlays in China. Moreover, ultra-thin overlay are typically used in China to restore the basic pavement functions of highways under heavy traffic conditions. Therefore, a large number of NovaChip overlays with excellent basic pavement functions have been introduced [22]. However, the development of ultra-thin overlays in some developed countries is more advanced, resulting in a greater amount of experience. The traffic volume and restricted speed of many projects are lower, and the surrounding population is dense. Therefore, more types of ultra-thin overlays have been developed to improve a specific function (such as noise reduction) of pavements and to reduce the adverse impact of vehicle traffic on surrounding residents [120]. Therefore, for highways under heavy traffic conditions, NovaChip, LOA 5 D, and NJ MOGFC are good choices to restore the skid resistance and noise reduction functions of pavements. In addition, U-PAVE10 and HWU can improve the crack resistance and rutting resistance of highway pavements. For roads with low traffic volumes and dense surrounding population, TAL and RAR ThinGap can be selected to reduce the adverse impact of road noise on surrounding residents. In addition, the new functions of ultra-thin overlay, including snow melting and deicing, exhaust gas purification, and pavement cooling, have not been applied to engineering due to insufficient research.

(2) In terms of the coarse aggregate type, more than 60% of ultra-thin overlay projects adopt basalt as the coarse aggregate in China. However, diabase is more widely used in ultra-thin overlays in other countries. Research showed that aggregates with a low cost and good performance are typically selected for ultra-thin overlay projects. Basalt and diabase have the advantages of wear resistance, strong compressive strength, and good asphalt adhesion. This ensures the durability and strength of the skeleton structure of ultra-thin overlays [121]. Therefore, basalt and diabase are good aggregate choices for ultra-thin overlays. As granite is an acidic stone, its adhesion to asphalt is poor. In addition, the polishing resistance of limestone is low. Thus, granite and limestone should be avoided as coarse aggregates for ultra-thin overlays [43].

(3) In practical projects, high-performance modified asphalts are the predominant binders of ultra-thin overlay mixtures. Among them, SBS modified asphalt is the most common binder in the projects in China. In the United States, asphalt with a high performance grade (PG) is usually used to prepare ultra-thin overlays. Several special modified asphalts, such as GTR modified asphalt and RAR modified asphalt, have a damping effect, which can significantly improve the noise reduction function of ultra-thin overlays [33]. In addition, for the aforementioned projects, the asphalt contents of the mixture range from 4.2% to 7.2%. Among them, projects with an asphalt content below 5.4% in China account for about 3/4 of the total, while asphalt contents in other countries exceed 5.4%. This is mainly due to the different types of ultra-thin overlays applied. According to engineering experience, mixtures with a higher asphalt content are generally more durable. For example, the very thin overlay (VTO) in Texas, USA required a minimum asphalt content of 6.0%, which is much higher than that of conventional 50 mm dense mixtures (4%–5%) [13]. In order to a ensure good stability, crack resistance and raveling resistance for the majority of VTO mixtures, the target asphalt content should range from 6.5% to 7.5%.

(4) The overlay thickness of more than 2/3 of these ultra-thin overlay projects ranges within 20–25 mm. Among them, the thickness of all ultra-thin overlays in China is 20–25 mm, while that of most ultra-thin overlays in the United States is around 19 mm (3/4 in). The thickness of overlay mixtures mainly depends on the NMAS of the coarse aggregate, the original pavement conditions and the construction conditions. In China, ultra-thin overlays are mainly used to overcome pavement problems such as the low texture depth and large rutting depth caused by heavy traffic [111]. Therefore, coarse aggregates with larger NMAS values are selected to enhance the skid resistance and rutting resistance of overlays. Thus, the design thickness range of ultra-thin overlay mixtures typically ranges within 20–25 mm. However, due to the lower traffic volume of test pavements in several countries, the rutting of pavements is minimal. Most pavements do not need to be milled or the milling depth is small. Therefore, coarse aggregates with smaller NMAS values are generally selected in these countries. Moreover, coarse aggregates with a smaller particle size can enter the original pavement texture and increase the viscosity between pavement layers. Thus, the thickness range of ultra-thin overlays in some countries is typically 15–20 mm. In general, for heavy traffic highways with a large anti-sliding performance attenuation and serious rutting, ultra-thin overlays with a large aggregate size should be used, with a design thickness of 20–25 mm. For pavements with minimal rutting and a small milling thickness, ultra-thin overlays with a small aggregate size can be used, with a design thickness of 15–20 mm. In addition, the thinning of ultra-thin overlays induces great difficulties to the construction, particularly the control of construction temperature. Research reveals that the paving cooling speed of 25 mm ultra-thin overlay is twice that of the 38 mm overlay [122]. Therefore, the design thickness of overlays should not be too low otherwise it will complicate the pavement compaction, resulting in interlayer stripping or raveling. Similarly, thinner ultra-thin overlays should not be constructed in low temperature environments.

10. Conclusions and further research

10.1. Conclusions

The ultra-thin overlay is a preventive maintenance technology that can improve the economic and environmental benefits of pavements. By designing the grading and constituent materials of the mixture, the ultra-thin overlay can achieve multiple pavement functions. At present, research on the functions of ultra-thin overlays are still at the beginning stage, and there is still a long way to go to give full play to the functionality of ultra-thin overlays. According to the review of current studies, the following points can be concluded.

(1) The effect of gradation design on skid resistance is mainly reflected in the increasing texture depth and optimizing skeleton structure. However, these two methods are associated with having a critical value and cost increases, respectively. High-performance binders are generally used for ultra-thin overlay, which can ensure the adhesion function of the binder and the compaction effect of mixtures. Eco-friendly aggregate materials, such as EAF slag, can improve the skid resistance of overlay mixtures by 5% because of their good physical properties.

(2) The change of mixture gradation leads to differences in pore characteristics, which affect the peak sound absorption coefficient and sound absorption frequency of mixtures. The formation of larger texture depths through special gradation designs is also a good way to ensure the noise reduction function of ultra-thin overlays. At present, the additives used in the noise reduction function of ultra-thin overlay are mainly environmentally friendly materials (rubber) and high viscosity modifiers. The use of these materials provides further ideas for the design of environment-friendly ultra-thin overlays.

(3) By optimizing the grading design, finer ultra-thin overlay mixtures can also present good rutting resistance. In addition, there is a linear negative correlation between the air void and dynamic stability, and thus the air void of ultra-thin overlay mixtures should be controlled in the grading design. Some high-performance binders, such as SBS/PTW and SBS/MCF/SBR modified asphalt, have been proven to improve the anti-rutting function of ultra-thin overlay mixtures due to their good deformation resistance. Industrial solid waste can also promote the anti-rutting function of ultra-thin overlays, which is beneficial to the development of environmentally friendly ultra-thin overlays.

(4) The crack resistance function of mixtures with a lower con tent of fine aggregates and smaller NMAS has been improved. The gradation type of the ultra-thin overlay also affects the optimum asphalt content and tack coat application rate of mixtures. Within a certain range, a higher asphalt content and tack coat application rate may improve the crack resistance function of ultra-thin overlays. The application of PMA binders improved the crack resistance of ultra-thin overlays. However, as the temperature decreases, the performance of the PMA mixture may decline. The BF helps to restrain the extension of cracks. However, the larger lengths and contents of BF have negative effects on its dispersion.

(5) Ultra-thin overlays with a snowmelt function generally adopt the low freezing point technology. The salt content is the primary factor affecting the snowmelt function of self-ice-melting ultra-thin overlays. The snowmelt and deicing function of ultra-

thin overlays is enhanced with the increase of the deicing agent content. Considering other pavement functions of ultra-thin overlays, the deicing agent content should not be too high.

(6) Photocatalysis technology is the main technology used for the gas purification function of ultra-thin overlays. The exhaust gas purification function employs a photocatalyst (typically nano-TiO_2) to induce a reaction between automobile exhaust gas and oxygen in the sun to produce harmless substances. The degradation effect is enhanced as the nano-TiO_2 content increases within a certain range. Excessive photocatalyst amounts will reduce the gas purification function and affect the basic road functions of ultra-thin overlay mixtures.

(7) Ultra-thin overlays with the pavement cooling function can be divided into two types: heat reflection ultra-thin overlays and thermal resistance ultra-thin overlays. The main pigment of heat reflection ultra-thin overlays is iron-oxide red, while the dominant thermal resistance materials of thermal resistance ultra-thin overlays are ceramics and ceramsite. The optimum content of ceramics is 40%–60% of the aggregate volume.

(8) Considering global ultra-thin overlay physical engineering applications, the use of high-performance aggregates and asphalt binders, and an appropriate grading type are the basic requirements for realizing the ultra-thin overlay function. In addition, due to the different application functions and construction conditions of ultra-thin overlays around the world, the thickness of ultra-thin overlays in China is typically 20–25 mm, while that in the United States is usually 19 mm. In the future, with the development of ultra-thin overlay technology, ultra-thin overlays will develop towards a lower thickness and more environmentally friendly functions.

10.2. Further research

(1) The thickness of ultra-thin overlay mixtures is lower than that of common pavement layers, and the coarse aggregate of the ultra-thin overlay usually accounts for a larger proportion of the aggregate in mixtures. Thus, it is difficult for asphalt binders to restrict the coarse aggregates of ultra-thin overlay asphalt mixtures. Common road asphalt cannot play an effective adhesion role in ultra-thin overlay asphalt mixtures, thus having an impact on the road functions of ultra-thin overlays. Therefore, more high-performance modified asphalt needs to be developed to enhance the adhesion properties between binders and aggregates.

(2) On the one hand, a reduction in the NMAS of ultra-thin over lay mixtures is required, while on the other hand, the ultra-thin overlays are should have a coarser gradation to ensure a better skid resistance, noise reduction, and anti-rutting performance. These requirements are contradictory. In addition, compared with dense-graded ultra-thin overlays, some open-graded or semi-open graded ultra-thin overlays are easier to crack. Therefore, it is necessary to specifically design the gradation of ultra-thin overlay asphalt mixtures.

(3) At present, in order to ensure the road performance of ultra-thin overlays, the development of ultra-thin overlays with new functions has become a research hotspot.

Acknowledgments

This study was supported by the National Key Research and Development Program of China (2022YFE0137300), the National Natural Science Foundation of China (52078018), and the German Research Foundation (SFB/TRR 339 and 453596084).

Compliance with ethics guidelines

Meng Guo, Rui Zhang, Xiuli Du, and Pengfei Liu declare that they have no conflict of interest or financial conflicts to disclose.

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