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Advances in Pavement Technology Types and Structural Systems for Orthotropic Steel Bridge Decks

Yunhai Li

Institute of Transportation Engineering, Chang'an University, Xi'an, China
2022901096@chd.edu.cn

Abstract. Orthotropic steel bridge deck pavement is a critical technology ensuring the durability of orthotropic steel bridge decks. This paper analyzes core characteristics of four mainstream systems and systematically reviews research advances and engineering practices in steel bridge deck pavement: Guss Asphalt Mixture, Epoxy Asphalt Mixture, Stone Mastic Asphalt, and Epoxy Resin System. Future work must address bottlenecks in quantifying extreme climate-heavy load coupled damage, mitigating stress concentrations, and assessing long-term performance of low-carbon materials. Integrating intelligent monitoring technologies will drive pavement systems toward high-toughness ultrathin configurations and full-lifecycle reliability upgrades. This contributes to green pavement development trends under carbon neutrality goals and provides theoretical support for enhancing long-term service capacity of major infrastructure.

Keywords: orthotropic steel bridge deck pavement, pavement types and structures, advancement of pavement systems, application status

1. Introduction

Orthotropic steel decks (OSDs) have become the mainstream choice for long-span bridge construction globally due to their superior mechanical properties and structural efficiency. With their widespread application, deck pavement systems face increasingly severe service environment challenges, significant disparities in material performance within the structure and stress concentrations at structural details, compounded by external continuously growing heavy traffic loads and frequent extreme climate events, collectively accelerate pavement layer deterioration. To address these complex service conditions, pavement material systems continue to diversify in international engineering practice and research, while pavement structural configurations exhibit a trend toward increasing variety. This necessitates engineers to select and design pavement solutions with enhanced compatibility based on specific bridge traffic load characteristics, geographic-climatic conditions, and structural detail requirements. Consequently, research on steel bridge deck pavement materials and systems possesses significant development potential.

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2. Types and characteristics of pavement technologies for orthotropic steel bridge decks

2.1. Technical characteristics of Guss Asphalt Mixture

Guss Asphalt mixture (GAM) typically comprises bitumen, modifiers (rock asphalt, lake asphalt, SBS modifier), and mineral aggregates including coarse aggregate, fine aggregate, and filler [1]. Fibers are occasionally incorporated to enhance high-temperature durability and other properties.

Guss Asphalt pavement technology originated in Germany. China adopted this technology later, introducing it from the mid-1990s to the early 2000s. It gained significant traction among industry professionals and has been increasingly applied to orthotropic steel bridge deck pavements. At suitable temperatures, the material flows naturally to form its structure. Consequently, Guss Asphalt mixture (GAM) requires no compaction equipment such as rollers during paving – only spreading and leveling by a paver [2]. This provides substantial advantages for construction in confined or load-restricted areas. The technology not only significantly shortens construction cycles and reduces costs but also delivers superior deformation compatibility and flexibility. Guss Asphalt mixture exhibits triple-high characteristics: elevated mixing temperature (220–260°C), high filler content (20%–30%), and high bitumen content (8%–10%). This results in near-zero internal voids and high density, conferring exceptional impermeability that effectively mitigates issues induced by low temperatures, aging, and corrosion. In Guss asphalt mixture, the asphalt mastic acts as the primary load-bearing component rather than the mechanically superior coarse aggregate. Consequently, GAM exhibits inherent limitations including low shear resistance and susceptibility to strength deficiencies and excessive deformation under elevated temperatures.

To enhance material performance and applicability, global researchers have conducted extensive studies: He et al [3]. incorporated varying proportions/lengths of glass fiber into GA, improving its fluidity while identifying optimal fiber types and dosages; Cao et al [4]. added RA and Sasobit to warm-mix gussasphalt, enhancing road performance; Lin [5] investigated critical sieve passing rates for GA-10, revealing that angular aggregates should be avoided and mix gradation optimized. Although current gussasphalt research approaches maturity in material modification—exhibiting coordinated compactness-self-fatigue resistance optimization—this study identifies limitations including the absence of multifactorial coupling models (climate-load-aging), leading to prevalent interlayer delamination and rutting in extreme climates. Future integration of digital twins and smart sensors will establish material-environment-damage dynamic feedback mechanisms, aligning with smart infrastructure O&M strategies.

2.2. Technical characteristics of epoxy asphalt mixture

Epoxy asphalt mixture comprises base asphalt, epoxy resin, curing agent, aggregate, filler, and additives.

It forms through an irreversible curing reaction when epoxy resin is incorporated into asphalt. This unique thermoset compound binds with concrete to create epoxy asphalt mixture, delivering significantly enhanced properties: superior fatigue resistance, rutting resistance, high-temperature strength with deformation tolerance, and impermeability. Compared to conventional asphalt mixtures, it exhibits higher compressive strength, enhanced bond strength, extended fatigue life, chemical corrosion resistance, and reduced temperature sensitivity. Epoxy asphalt mixtures are classified by mixing temperature into two primary types: warm-mix epoxy asphalt (80–120°C), pioneered in the United States, and hot-mix epoxy asphalt (150–180°C), developed primarily in Japan. Unlike hot-mix types that rely on temperature for curing, warm-mix epoxy asphalt requires

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extended curing times at lower temperatures using low-temperature curing agents [6, 7]. When material costs, energy consumption, and environmental compliance requirements are considered, both methods demonstrate comparable overall costs. Amid growing emphasis on environmental protection, advancements in low-temperature curing agents and nano-modification technologies will narrow the performance gap between epoxy asphalt types, accelerating warm-mix technology development. However, strict construction procedures, complex equipment requirements, and costs 3–5 times higher than conventional asphalt restrict epoxy asphalt mixture application in concrete bridge decks and pavement engineering. Hot-mix epoxy asphalt mixture predominates in orthotropic steel bridge deck construction due to its inherent advantages.

Researchers globally enhance material properties through additive incorporation. In 2022, Zhao et al [8]. introduced graphene nanoplatelets (GNPs) into epoxy asphalt binders, demonstrating increased late-stage viscosity, reduced construction time, and improved mechanical stress distribution. That same year, Sun et al [9]. partially substituted petroleum-based components with bio-based materials, formulating PEMMA mixtures via MRA, which enhanced low-temperature performance. In 2023, Li [10] incorporated converted APDR (alkylphenol distillation residue), achieving dual benefits: resource recovery of petroleum industry waste and improved mechanical and thermal stability in pavement performance.

Epoxy asphalt mixture achieves performance leaps in orthotropic steel bridge deck pavements through its irreversible cross-linked networks. However, this irreversible curing demands error-free execution during construction, heightening interlayer weakening risks. Future research will integrate optical fiber sensing and molecular dynamics simulations to develop molecular-level selective depolymerization technology for enhanced recyclability.

2.3. Technical characteristics of stone mastic asphalt mixture

Stone Mastic Asphalt (SMA) comprises bituminous binder (6.0%–7.5%), aggregates including coarse aggregate (70%–80%) and fine aggregate (8%–12%), and filler (8%–12%) [11]. To enhance mixture performance and skeletal structure stability, lignin fibers or other fiber stabilizers are occasionally incorporated.

Stone Mastic Asphalt (SMA) features a dense stone-on-stone skeleton structure characterized by a "three-high-one-low" composition: high filler content, high bitumen content, high coarse aggregate content, and low fine aggregate content [12]. This material demonstrates superior performance properties including shear resistance, fatigue resistance, high-temperature rutting resistance, and low-temperature cracking resistance. The fundamental design principle involves gap-grading optimization to achieve direct stone-to-stone contact and interlocking among coarse aggregates, establishing a self-supporting skeletal framework that enhances overall deformation resistance. This structural configuration ensures maintained stability under elevated temperatures, thereby controlling rut formation. Owing to its non-continuous gradation, a pronounced surface texture depth is attained, thus enhancing the skid resistance of the pavement layer and ensuring traffic safety. Comprehensive consideration of material properties and extended service life indicates a lower cost for this material.

To enhance the material properties of Stone Mastic Asphalt (SMA), researchers globally have implemented modifications through improved asphalt performance, additive formulations, and incorporation of high-performance materials such as fibers. In 2020, Mohammed Babalghaith et al [13]. utilised waste from palm oil industry by substituting fine aggregates in SMA with palm oil clinker (POC). Mechanical testing revealed enhanced resilience modulus and improved rutting resistance in the resulting pavement. In 2021, Noura et al [14]. adopting a waste-recycling concept,

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modified SMA mixtures with truck tyre rubber powder (TRP). SMA-WP exhibited greater elasticity than SMA-DP, thereby effectively mitigating rutting. In 2023, Chen [15] examined SMA properties modified with four fibers, including granular wood fiber. Basalt fiber significantly enhanced both road performance and high-temperature stability of asphalt mixtures.

Maturity has been attained in China's steel bridge deck pavement technology employing Stone Mastic Asphalt (SMA), specifically in the domains of high-elasticity asphalt modification, fibre reinforcement, and composite structural design. Nevertheless, significant knowledge gaps persist concerning: extreme-environment adaptability, long-term heavy-load response mechanisms and intelligent maintenance systems. Consequently, multidisciplinary convergence of materials science, smart sensing, and structural mechanics is imperative to transition SMA pavement systems from short-term functionality to full life-cycle reliability.

3. Application status of pavement technology for orthotropic steel bridge decks

3.1. Application status of Guss Asphalt Mixture pavement system

Guss Asphalt concrete originated in Europe. In 1917, Germany pioneered research into cast asphalt concrete, initially applying it in building waterproofing construction. Its application later expanded to bridge deck paving, aiming to address issues of waterproofing and deformation compatibility on bridge decks. In 1929, Trinidad Lake Asphalt-modified cast asphalt concrete was first used in the deck paving of the Sudan Nile River Bridge. During the 1930s and 1940s, it became widely adopted on steel bridge decks. Validated through practical engineering applications, it gradually replaced SMA (Stone Mastic Asphalt) structures and was extensively used in the lower paving layer. Examples include the Forth Road Bridge (UK), the Humber Bridge (England), the Normandy Bridge (France), the Zoo Bridge (Germany), the High Coast Bridge (Sweden), the Oresund Bridge (Denmark-Sweden), the Rhine-Knie Bridge (Germany) [2]. Consequently, it has become a mainstream paving technology in Europe.

In 1956, Japan adopted German technical specifications for cast asphalt concrete paving [16]. To suit its rainy and earthquake-prone conditions, Japan adjusted the gradation and binder, enhancing high-temperature stability and skid resistance. Japan formulated and promulgated its own relevant technical specifications in 1961. By the 1970s, the technology was widely applied in major projects such as the Honshu-Shikoku Bridge Project, including the Ōnaruto Bridge (completed in 1985) and the Akashi Kaikyō Bridge (completed in 1998) [17]. These adaptations made the technology suitable for Japan's national context and led to significant advancements。

In the early 1990s, China introduced and directly applied the UK's Mastic Asphalt technology, which utilized a binder composed of TLA (Trinidad Lake Asphalt) and hard asphalt. During the localization process of the German technology, adjustments were made to the gradation and binder formulation, but the construction method showed little difference from GA. Representative projects include the Tsing Ma Bridge (Hong Kong SAR) and the Jiangyin Yangtze River Bridge. However, due to inadequate consideration of traffic volume and China's unique climatic conditions, varying degrees of damage emerged soon after operation commenced. In 1997, Taiwan, China, introduced Japan's modified paving scheme of "guss asphalt concrete in the lower layer + modified asphalt in the upper layer" for steel bridge decks [16]. Through localized research and improvement drawing on foreign practical experience, a cast asphalt concrete suitable for Taiwan's hot and rainy conditions was ultimately designed. This was applied on the Gao ping River Bridge and the Hsin-tong Bridge.

3.2. Application status of epoxy asphalt mixture pavement system

The development and application history of epoxy asphalt concrete is relatively brief. In the 1950s, Shell Oil Company heavily invested in researching and developing epoxy asphalt concrete with high strength and good temperature stability for use as a paving material on airport runways, aiming to address issues caused by aircraft fuel and high temperatures [18]. After resolving the compatibility issue between epoxy resin and asphalt, the United States first applied epoxy asphalt concrete to the orthotropic steel bridge deck paving of the San Mateo-Hayward Bridge in California in 1967. This pioneered the application of epoxy asphalt in global steel bridge deck paving.

In the 1970s, Japanese scholars such as Masakazu Hazama and Teruo Sugahara began research on epoxy asphalt concrete, focusing on mix design, modulus, and failure performance. By approximately the 1990s, research on epoxy asphalt concrete in Japan had matured considerably. Japan developed its own independent epoxy asphalt system. This system is characterized by a short curing period and higher cost compared to the US version. Epoxy asphalt gradually saw application in projects such as the Honshu-Shikoku Bridge Project. Subsequently, Japanese epoxy asphalt technology was introduced to China for application.

Research on epoxy asphalt in China started relatively late, commencing in the 1990s. Initially, it was limited to incorporating coal tar for filling pavement cracks. The development of epoxy asphalt bridge deck paving technology in China, evolving from the introduction of foreign technology to independent innovation, can be broadly divided into three phases. The first phase (1990-2000) was a period of technology introduction and learning. In the early 1990s, numerous Chinese scholars initiated research on epoxy asphalt production technology. Among them, Southeast University and Tongji University began systematic research on epoxy asphalt and its technical applications in 1995. The epoxy asphalt used in engineering projects during this period was almost entirely imported.

The second phase (2000–2006) represented a localization breakthrough stage. Southeast University filed China’s first patent related to epoxy asphalt in 2003, marking the preliminary formation of domestic asphalt technology. A coexistence scenario emerged wherein imported and domestic epoxy asphalt were both utilized in China [19, 20].

The third phase (2006 to present) represents a period focused on large-scale application, innovation, and research into epoxy asphalt steel bridge deck paving technology for heavy-duty traffic. Following the completion of maintenance work on the Jiangyin Yangtze River Bridge, breakthroughs in domestic epoxy asphalt paving technology led to the gradual popularization of hot-mix epoxy asphalt technology. In 2007, domestically produced epoxy asphalt was first applied on a large scale in the deck paving of the Tianjin Fumin Bridge [19].

Domestic epoxy asphalt not only offers low cost, being only approximately 60% of that of imported materials, but also surpasses imported products in performance indicators. At this stage, China's epoxy asphalt technology has not only broken the foreign monopoly of the late 20th century but has also spurred the development and application of intelligent construction equipment, forming a complete industrial chain that has further enhanced comprehensive manufacturing capabilities. Having undergone rapid development, epoxy asphalt is now relatively mature.

3.3. Application status of stone mastic asphalt mixture pavement system

The development of SMA technology can be traced back to European asphalt paving systems. The technical accumulation of GA laid the foundation for the development of asphalt paving systems. In the 1960s, countries such as the United Kingdom and France began using mastic asphalt (MA) as a paving material for steel bridge decks, which faced issues such as high cost and insufficient high-temperature stability. Subsequently, German road workers adjusted the gradation, asphalt content, and additives of MA. This formed a 'skeleton-embedded structure' and gradually evolved into Stone Mastic Asphalt (SMA) technology, resulting in significantly improved rutting resistance.

In 1990, the United States dispatched a delegation composed of agencies such as the FHWA, the AASHTO, and the NAPA to Europe to investigate SMA paving technology. They identified the advantages of modified asphalt and SMA technology and ultimately decided to introduce this technology to the United States, laying the foundation for its subsequent promotion there. The following year, the United States began constructing SMA test sections on the surface layers of highways in 23 states to verify the applicability of European SMA technology under American climatic, traffic, and other environmental conditions. Through collecting and analyzing test road data, adjustments were specifically made to the coarse aggregate proportion and asphalt content. By introducing the technology, making localized improvements, and conducting systematic research, the United States not only provided crucial data and references for advancing the global development of SMA technology but its own successful practice also promoted the adoption of SMA technology in other countries.

China introduced SMA technology in the 1990s and successively initiated the construction of test roads in multiple locations across the country. In 1997, SMA was first applied on the Humen Bridge, marking the inception of steel bridge deck paving technology in China. After 2000, institutions such as CCCC Second Highway Consultants Co., Ltd. optimized the mix design of SMA and implemented it on the elevated bridge of National Highway 107 in Hubei Province. Engineering verification demonstrated that rutting resistance increased by over 30%. From 2010 to the present, China has undertaken large-scale technological innovations in SMA technology.

Research reveals that the application of SMA in steel bridge deck paving is undergoing a transition from a “leading role” to a “supporting role”. Its use in heavy-load long-span bridges is less than 10%, while epoxy asphalt and UHPC, which offer superior performance, are gradually becoming mainstream. In small and medium-span bridges, due to its cost advantage, SMA still occupies a significant share in temperature-stable regions. In the future, establishing grading selection guidelines, clarifying applicable and prohibited scenarios for SMA systems, incorporating life-cycle cost models into engineering decision-making, and further promoting its development are necessary.

4. Development of orthotropic steel bridge deck pavement systems

4.1. Single-layer pavement structures

Single-layer structures primarily include single-layer Stone Mastic Asphalt Mixture (SMAM) and single-layer GA Mixture (GAM). Both single-layer paving systems originated in Germany. Single-layer SMAM has been applied in European regions such as the United Kingdom, Denmark, France, and Sweden. Single-layer GAM was initially used for building waterproofing structures in Germany and was later applied to steel bridge deck paving. The Forth Road Bridge in the UK employed a 38mm GAM structure, the Humber Bridge in England used a 37mm GAM structure.

Research and application of single-layer paving systems in China, such as single-layer SMAM and single-layer GAM, primarily occurred before 2000. The Humen Bridge, opened to traffic in 1997, employed single-layer SMAM. Within one year of operation, rutting and shoving distress appeared, and it was replaced with a double-layer paving system in 1998.

The single-layer paving structure serves as a compromise solution under specific historical conditions, with core advantages of light weight, cost efficiency, and construction expediency. It is suitable for temperature-controlled, light-load small-to-medium bridges and temporary projects. However, constrained by low structural stiffness, high fatigue sensitivity, and weak environmental adaptability, it struggles to accommodate China’s current high-temperature, heavy-load traffic environments. Economically, despite low initial investment costs, its frequent maintenance requirements elevate 30-year lifecycle costs by 30% compared to epoxy systems, necessitating whole-life-cycle assessment before deployment. Presently, the maturity and cost reduction of double-layer paving systems have diminished the competitiveness of single-layer systems, rendering them nearly obsolete in engineering practice. Nevertheless, with declining costs of domestically produced UHPC and the proliferation of intelligent construction equipment, future high-performance single-layer paving will demonstrate potential in areas such as "lightweight new bridge construction" and "life extension of aging bridges.

4.2. Double-layer pavement systems

Paving structures have evolved from initial single-layer systems to contemporary double-layer paving systems and multi-layer composite structural systems. Current new steel bridge deck paving projects and maintenance/renovation projects universally adopt multi-layer paving systems. These achieve functional complementarity and performance synergy through stratified design, exhibiting advantages in durability, fatigue resistance, and environmental adaptability unattainable by single-layer systems. In double-layer paving systems: The lower paving layer serves as the structural load-bearing stratum, primarily transferring loads and accommodating steel deck deformations. It typically employs materials with high deformation capacity, such as gussasphalt concrete and high-elasticity modified asphalt mixtures. The upper paving layer functions as the surface operational stratum, directly enduring traffic wear while providing skid-resistant, smooth driving surfaces. Materials like stone mastic asphalt (SMA) or modified asphalt concrete (AC) with balanced durability and high modulus are commonly used for rutting resistance. Current homogeneous double-layer structures primarily include double-layer SMAM and double-layer EAM, while heterogeneous double-layer systems mainly comprise GAM+SMAM, GAM+EAM, and ERS.

4.2.1. Homogeneous double-layer structures

4.2.1.1. Double-layer SMAM pavement systems

As a paving layer, the double-layer SMAM structure exhibits poor high-temperature resistance and fails to adapt to steel bridge decks under extreme summer temperatures, thus frequently manifesting distresses such as rutting and shoving. The first major repair typically occurs five to six years after opening to traffic. Steel bridge decks constructed in the 1990s, typically thin at approximately 12mm, were a primary contributor to these distresses. Current newly built bridge decks feature increased thickness, partially mitigating distress issues. Its lower construction cost moderately expands application scopes. The Humen Bridge (China, 1998) initially employed a "30mm SMA-13 + 30mm SMA-10" paving structure. Due to severe distresses caused by inadequate high-temperature stability, it was later replaced with a double-layer epoxy asphalt concrete structure. During the construction of the Baishazhou Yangtze River Bridge (2000), a paving structure of "45mm SMA-13 + 35mm SMA-10" was adopted. Six years later, a major repair increased paving layer thickness to "50mm SMA-13 + 40mm SMA-10". For the Junshan Yangtze River Bridge (2001), the initial paving structure "40mm SMA-13 + 35mm SMA-10" was used. After five years, major repairs implemented a "rubber-modified epoxy mortar + double-layer SMA" paving system. In the Xiling

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Yangtze River Bridge (2011), the structure "25mm SMA-10 + 35mm SMA-10" was employed during construction. Five years later, major repairs replaced it with a resin-asphalt composite system.

4.2.1.2. Double-layer EAM pavement system

The double-layer EAM structure exhibits strong high-temperature stability but inferior low-temperature performance, particularly insufficient low-temperature crack resistance. In practical applications, it primarily develops distresses including blistering, potholes, and cracking. The first major repair typically occurs six to nine years after opening. San-Mateo-Hayward Bridge (USA, 1967) adopted "25mm EAM + 25mm EAM", underwent major repairs after 5 years of operation; San Diego–Coronado Bridge (USA, 1969) employed "10mm steel plate + 25mm EAM + 25mm EAM", developed controlled cracking after 13 years; MacKay Bridge (Australia, 1970) implemented "13mm steel plate + 50mm EAM", exhibited cracking after 5 years; Rio-Niteroi Bridge (Brazil, 1974) used "9.5mm steel plate + 60mm EAM", experienced cracking issues after 2 years of operation; Lions Gate Bridge (Canada, 1975) applied "12mm steel plate + 25mm EAM + 10mm EAM", remained in good condition with minor distresses after 11 years.

Due to satisfactory performance in practical applications, most steel bridges in China have adopted this paving structure. The Humen Bridge has undergone three major repairs since completion. Post-2008 cracking and rutting distresses strongly correlated with heavy/overloaded traffic. After 2010, a "35mm EA-10 + 35mm EA-10" structure was implemented. Jiujiang Yangtze River Bridge (2013) adopted "16mm steel plate + 30mm EAM + 25mm EAM". Cracking constitutes the most severe distress in double-layer EAM systems, accelerating other distresses and substantially reducing service life. Enhancing crack resistance in double-layer EAM will significantly extend service cycles and expand application scenarios.

4.2.2. Heterogeneous double-layer structures

Different materials exhibit distinct positional suitability in steel bridge deck paving systems. SMA demonstrates superior surface deformation resistance, surface performance, load-bearing capacity, impermeability, and durability, resulting in extended service life. It is suitable as the upper paving layer to maximize traffic functionality, and can also serve in lower layers; GA offers favorable crack resistance with excellent deformation and recovery capabilities, making it applicable as the lower paving layer to leverage waterproofing and steel deck deformation coordination; EA excels in crack resistance, durability, impermeability, exhibiting strong comprehensive performance. It functions effectively in both upper and lower paving layers. Based on these characteristics, primary heterogeneous double-layer structures include: “Upper SMAM + Lower GAM”, “Upper AC + Lower GAM”, “Upper EAM + Lower GAM”.

4.2.2.1. Upper SMAM + lower GAM

In this paving system, SMAM's superior high-temperature stability complements GAM's strong deformation capability but poor high-temperature performance, maximizing both materials' advantages while ensuring adaptability in high-temperature conditions. Primary distresses involve cracking, with shorter maintenance cycles (major repairs required within 5–8 years). High Coast Bridge (Sweden, 1997) adopted "22mm GAM + 35mm SMAM"; Oresund Bridge (Denmark-Sweden, 2000) implemented this paving structure.

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Since its inaugural application on the Shengli Yellow River Bridge (Shandong, 2003) using "12mm steel plate + 35mm GA-10 + 35mm SMA-10" as the paving structure, this system has been extensively adopted in domestic Chinese engineering projects. Liuzhou Baisha Bridge (2018) implemented "35mm GA-10 + 35mm SMA-10"; Hong Kong-Zhuhai-Macao Bridge (2018) applied "35mm GA-10 + 45mm SMA-13".

This paving structure was originally designed to integrate GA's deformation adaptability with SMA's high-temperature stability, exhibiting better applicability than double-layer SMAM. However, its limitations have become increasingly pronounced amid bridge engineering trends toward long-span structures and heavy-load traffic. Analysis of over 20 Chinese bridges using this system in early stages reveals most were located in non-high-temperature regions with minor distresses. In contrast, steel bridge deck pavements in southern high-temperature zones and heavy-load corridors (e.g., ports) exhibit distress rates exceeding 60%, with severe structural defects, interlayer bonding failures, fatigue durability issues, and frequent maintenance demands. The "Upper SMAM + Lower GAM" system remains an economically practical choice for small-to-medium-span bridges with light-to-moderate traffic. Nevertheless, its short maintenance cycles and high recoating costs post-milling are drawbacks. Comparatively, epoxy resin systems, though higher in initial cost, offer more significant long-term economic benefits due to design lifespans exceeding 15 years. Constraints on its adoption in heavy-load particularly thermal stability and fatigue durability weaknesses, can be mitigated through integrated material-structure innovations and whole-life-cycle cost model optimization.

4.2.2.2. Upper AC + lower GAM

The development of this paving structure originated with Japan's introduction of European GAM technology, which was refined to form a paving system. It was applied to over 40% of major bridges in Japan, including the Akashi Strait Bridge and Tatara Bridge. Hong Kong subsequently adopted and adapted this technology, which later spread to mainland China for extensive implementation. The Nanjing Fourth Yangtze River Bridge employed this system. This structure closely resembles "Upper SMAM + Lower GAM", with the upper SMAM layer exhibiting significantly superior performance to AC, particularly in high-temperature zones. Consequently, under identical engineering conditions, China more frequently selects the "Upper SMAM + Lower GAM" configuration. Akashi Strait Bridge (Japan, 1998) employed "35mm GAM + 30mm AC" configuration, it maintained good condition after 10 years under proper maintenance; Nanjing Fourth Yangtze River Bridge (China, 2012) applied "14mm steel plate + 40mm GA-13 + 35mm AC-13" configuration.

This paving system represents a technical product specific to a developmental phase in the history of steel bridge deck paving systems. Objective evaluation of its value requires consideration within frameworks of full lifecycle performance and regional environmental adaptability. Future evolution of such systems will prioritize high-performance characteristics (e.g., UHPC) and intelligent functionalities. Should the "GAM+AC" system achieve innovations in interlayer bonding and thermal stability, it may persist as a component within the spectrum of multi-layer paving technologies. Otherwise, it will be progressively phased out by higher-performance alternatives.

4.2.2.3. Upper EAM + lower GAM

The upper EAM layer exhibits superior rutting resistance, while the lower GAM layer demonstrates high deformation compatibility with steel bridge decks. This two-layer configuration constitutes an

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effective composite system.

In 2006, Huang Wei et al. conducted a comparative study during major repairs on the Jiangyin Bridge (3 years post-opening), evaluating double-layer epoxy asphalt pavements of varying thicknesses and "Guss Asphalt Mixture + Epoxy Asphalt Mixture" structures. Assessments covered rutting performance, fatigue life, and low-temperature properties. Results indicated that double-layer epoxy asphalt outperformed alternatives in rut resistance, interlayer bond strength, and composite beam fatigue life. Although the "GAM+EAM" repair solution showed good low-temperature crack resistance, its durability was inadequate. Consequently, the Jiangyin Bridge repair adopted a 60mm double-layer epoxy asphalt mixture structure. Jiangyin Yangtze River Bridge (2009) used "12 mm steel plate + 25 mm GA-10 + 25 mm EA-10"; Taizhou Yangtze River Highway Bridge (2012) applied "35 mm GA-10 + 25 mm EA-10".

When comparing double-layer epoxy asphalt pavement and the "Guss Asphalt Mixture + Epoxy Asphalt Mixture" structure, he latter incurs higher costs due to requiring an additional set of specialized construction equipment. Analysis comprehensive cost, which encompass both material expenses and construction machinery for distinct paving layers, indicating that double-layer epoxy asphalt holds relative advantages under conditions of comparable performance metrics. Consequently, industrial adoption of the "GAM+EAM" system is declining.

5. Conclusion

Pavement for orthotropic steel bridge decks, as a core technology ensuring bridge safety and durability, directly governs structural safety and whole-life economics. This review examines the mechanical properties of mainstream paving materials (epoxy asphalt, guss asphalt, SMA, etc.) and the research/ application status of paving systems, revealing core failure mechanisms including fatigue cracking, delamination, and deformation. Future development necessitates: material performance optimization focusing on novel composites exhibiting high toughness, superior temperature stability, and strong aging resistance; structural system innovation emphasizing breakthroughs in high-performance bonding layer materials and interface treatment technologies to enhance interlayer bonding, alongside implementing gradient modulus matching designs to optimize interlayer stress distribution/transfer and mitigate failure risks; refined construction requiring precise control of key process parameters throughout construction stages and application of intelligent technologies to ensure high homogeneity of construction quality, thereby comprehensively enhancing the long-term service performance of paving layers.

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