

Research Progress on Warm-Mix and Odor-Reduction Technologies for CR/SBS Composite Modified Asphalt

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Abstract

SBS-modified asphalt has been widely used in the construction of high-grade highways because of its excellent high- and low-temperature performance, fatigue resistance, and durability. However, SBS-modified asphalt still suffers from problems such as relatively high cost and insufficient storage stability. Crumb rubber (CR)-modified asphalt can realize the resource utilization of solid waste and shows certain advantages in improving asphalt elasticity and high-temperature performance, but it also has shortcomings such as poor high-temperature storage stability, high construction viscosity, and susceptibility to phase separation. To simultaneously satisfy the requirements of pavement performance, storage stability, and resource utilization, CR/SBS composite modification has gradually become a research focus. Existing studies have shown that the composite modification of CR and SBS can significantly improve the high-temperature rutting resistance, low-temperature cracking resistance, and fatigue performance of asphalt and asphalt mixtures through the synergistic effects of rubber elasticity and polymer network structure. However, it also leads to problems such as increased system viscosity, elevated construction temperature, and increased emissions of volatile organic compounds (VOCs). Warm-mix technology can reduce energy consumption and emissions by lowering construction temperature, while odor-reduction technology can suppress the release of asphalt fumes and hazardous volatile substances at the source. This paper systematically reviews the domestic and international research status of CR/SBS composite modified asphalt, warm-mix technology, and asphalt odor-reduction technology, with emphasis on the performance enhancement mechanisms of multicomponent composite systems, VOC emission reduction pathways, and existing key issues. The prospects for the synergistic application of warm-mix additives and odor-reducing agents in CR/SBS composite modified systems are also discussed, with the aim of providing a reference for the development and engineering application of environmentally friendly, high-performance composite modified asphalt materials.

Keywords

CR/SBS Composite Modified Asphalt; Warm-Mix Technology; Odor-Reduction Technology; VOCs; Fume Emission Reduction.

1. Introduction

With the continuous increase in traffic loading and the increasing complexity of pavement service environments, conventional base asphalt has become increasingly unable to meet the comprehensive requirements of modern road engineering for high-temperature stability, low-temperature cracking resistance, durability, and fatigue resistance. Polymer modification and solid-waste-based modification are currently two important directions for the development of high-performance and sustainable asphalt materials. Among them, SBS-modified asphalt has been widely used in high-grade

pavements because of its excellent elastic recovery, good adaptability to high and low temperatures, and strong fatigue resistance[1]. However, SBS-modified asphalt still has problems such as insufficient storage stability, phase separation, and high cost, which to some extent limit its further application [2].

On the other hand, the use of waste tire CR for asphalt modification can not only improve some pavement properties of asphalt, but also realize the resource utilization of waste tires, with significant environmental and social benefits[3]. However, conventional CR-modified asphalt also faces problems such as poor high-temperature storage stability, high construction viscosity, and easy phase separation. To balance modification effectiveness and material stability, researchers have proposed the combined use of CR and SBS to improve asphalt properties through the swelling of rubber particles and the polymer network structure[4]. Studies have shown that the addition of SBS not only helps promote the degradation and fusion of CR in asphalt, thereby improving system uniformity and storage stability[5], but also forms a synergistic strengthening effect with CR, enabling the composite modified asphalt to possess good high-temperature deformation resistance, low-temperature cracking resistance, and fatigue durability[6].

Although CR/SBS composite modification has shown clear advantages in improving pavement performance, its engineering application still faces new problems. First, the viscosity of the system increases significantly after composite modification, usually requiring higher mixing and compaction temperatures, which increases energy consumption and may accelerate asphalt aging[7]. Second, the introduction of waste tire CR significantly increases VOC emissions during asphalt heating, and the fumes from rubber asphalt are more complex in composition, containing toxic and hazardous substances such as benzene-series compounds, sulfur-containing compounds, and polycyclic aromatic hydrocarbons, posing serious threats to construction workers' health and the environment[8-10]. Therefore, how to reduce construction temperature and suppress hazardous gas emissions while maintaining the pavement performance of composite modified asphalt has become an important issue in the research of sustainable road materials.

Warm-mix asphalt technology can lower the construction temperature of asphalt mixtures through foaming, viscosity reduction, or interfacial lubrication, effectively reducing energy consumption and emissions, and is an important technical route for low-carbon road construction[11]. Meanwhile, asphalt odor-reduction technology can reduce the release of irritating odors and hazardous volatile compounds through mechanisms such as adsorption, encapsulation, chemical reaction, or odor substitution[12]. In recent years, some studies have begun to introduce warm-mix and odor-reduction technologies into CR/SBS composite modified systems, in order to achieve high performance together with energy saving, emission reduction, and environmental protection.

Based on this, this paper reviews the research progress on CR/SBS composite modified asphalt, warm-mix technology, and odor-reduction technology, systematically summarizes the relevant studies, and analyzes the key scientific issues and development directions in the synergistic regulation of performance and emission reduction in multicomponent composite systems, so as to provide a theoretical reference for subsequent research and engineering application.

2. Research Progress on CR/SBS Composite Modified Asphalt

2.1 Basic Composition and Preparation Characteristics of Composite Modified Systems

CR/SBS composite modified asphalt usually uses base asphalt or SBS-modified asphalt as the matrix, with a certain proportion of waste tire CR incorporated, and compatibilizers, stabilizers, activators, or other functional additives added as needed, ultimately forming a multiphase composite system composed of swollen CR particles, an SBS polymer network, and a continuous asphalt phase. The core concept is to fully utilize the high elasticity and resource utilization advantages of CR, as well as the reinforcing effect of the SBS polymer network structure, so as to achieve performance complementarity among multiple components.

In terms of preparation process, CR/SBS composite modified asphalt generally undergoes heating, premixing, shearing, and development stages. Existing studies suggest that relatively high temperature and strong shear conditions are favorable for the sufficient swelling of CR and the uniform dispersion of SBS, thereby forming a relatively stable composite system[13,14]. However, excessively high preparation temperature or overly long preparation time may lead to asphalt oxidative aging and partial polymer degradation, and therefore a balance among process parameters is required.

Since there are complex interactions among CR and asphalt, SBS and asphalt, as well as CR and SBS, the preparation quality of the composite system is highly dependent on raw material properties and process control. To improve the compatibility between CR and the asphalt matrix, researchers usually subject CR to activation, desulfurization, micronization, or surface modification, and supplement it with compatibilizers and stabilizers to suppress phase separation during storage[15,16]. This indicates that CR/SBS composite modification is not a simple addition, but rather a complex evolution process involving swelling, degradation, adsorption, entanglement, and structural reconstruction.

2.2 Composite Modification Mechanism

The enhancement mechanism of CR/SBS composite modified asphalt is mainly reflected in two aspects: the absorption and swelling effect of CR on the light fractions of asphalt, and the formation of a continuous or semi-continuous polymer network structure by SBS in asphalt. Under high-temperature conditions, CR absorbs aromatic fractions and part of the saturates in asphalt and undergoes volumetric expansion, thereby improving system elasticity and increasing viscosity. Meanwhile, SBS undergoes phase separation and rearrangement in asphalt, forming a spatial network structure with elastic recovery capability, thereby improving the temperature susceptibility and deformation recovery capability of asphalt.

Studies have shown that the addition of SBS can promote the further dispersion and degradation of CR in asphalt, thereby improving the interfacial bonding ability between CR and the matrix[5]. At the same time, CR particles themselves can act as a filling phase or reinforcing phase in the SBS network, improving the balance between stiffness and flexibility of the system to some extent. The synergistic effect between CR and SBS allows the composite modified asphalt to have better resistance to flow deformation at high temperatures while maintaining good flexibility at low temperatures[6].

However, it should be noted that this system is still dominated by physical blending, accompanied by a certain degree of chemical reaction under some conditions[17]. Differences in raw material sources, particle size distribution, SBS type, and preparation process all significantly affect the phase structure and performance of the composite system. Therefore, the modification mechanism of CR/SBS composite modified asphalt shows clear condition dependence and multiscale characteristics.

2.3 Effects on Asphalt Rheological Properties

In terms of high-temperature performance, CR/SBS composite modification can usually significantly increase the complex modulus and reduce the phase angle of asphalt, thereby enhancing its high-temperature deformation resistance. Relevant studies have shown that although different modifier combinations may correspond to the same PG high-temperature grade, there are still obvious differences in actual rutting resistance[18-20]. This indicates that grade evaluation alone cannot fully reflect the high-temperature performance of composite modified asphalt, and comprehensive analysis with indicators such as MSCR and rutting factor is still necessary.

In terms of low-temperature performance, the introduction of CR helps improve the low-temperature creep ability and flexibility of SBS-modified asphalt, and slows down the embrittlement tendency of the material at low temperatures[21,22]. SBS improves the elasticity of the system, while CR increases the internal energy dissipation capacity to some extent, thereby suppressing crack initiation and propagation. The synergistic effect of the two can improve low-temperature cracking resistance,

but excessive CR dosage or nonuniform system dispersion may also lead to fluctuations in low-temperature performance.

In terms of fatigue performance, existing studies based on time sweep and linear amplitude sweep (LAS) tests have indicated that CR/SBS composite modification can effectively extend the fatigue life of asphalt[23]. This is because the composite system has both strong elastic recovery ability and good stress dissipation capacity, making it less likely to undergo rapid damage accumulation under repeated loading. Pretreatment of CR by catalytic oxidation can further improve its reactivity and dispersion, thereby enhancing the overall rheological performance of the composite modified system[24].

2.4 Effects on Mixture Pavement Performance

At the asphalt mixture level, CR/SBS composite modified asphalt can usually significantly improve the high-temperature stability, low-temperature cracking resistance, and fatigue performance of mixtures. Relevant studies have pointed out that this system often performs better than base asphalt and single-modified systems in rutting tests, bending tests, and fatigue tests[25]. This is mainly attributed to the optimization of the viscoelastic characteristics of the asphalt binder after composite modification, enabling it to resist permanent deformation at high temperatures and delay crack development under low temperatures and repeated loading.

However, some studies have also found that there may be certain uncertainties in the moisture damage resistance of composite modified systems[17]. On the one hand, the presence of CR and SBS may increase asphalt film thickness and adhesion performance. On the other hand, if the system viscosity is too high, coating is nonuniform, or interfacial compatibility is insufficient, the aggregate coating quality and interfacial stability may be affected. Therefore, mixture performance depends not only on the binder itself, but is also closely related to temperature control, mixing uniformity, and interfacial regulation.

2.5 Current Problems in Research

Overall, CR/SBS composite modified asphalt has clear advantages in improving pavement performance and realizing the resource utilization of waste tires. Current studies mainly focus on performance characterization and mechanism analysis under conventional hot-mix conditions, whereas the influence mechanisms of CR swelling behavior, SBS phase structure evolution, and multiphase system stability under low-energy construction conditions such as warm-mix technology remain insufficiently studied. At the same time, insufficient attention has been paid to the coupling relationship among storage stability, construction viscosity, and fume emissions, which still creates practical obstacles for the engineering promotion of this system.

3. Research Progress on Warm-Mix Technology

3.1 Basic Principles and Classification of Warm-Mix Technology

The core of warm-mix asphalt technology is to reduce the mixing and compaction temperatures of asphalt mixtures, so as to achieve energy saving, emission reduction, and sustainable construction on the premise of minimizing performance loss or even partially improving pavement performance. According to the mode of action, warm-mix technology can be mainly divided into three categories: foaming technology, organic additive technology, and chemical additive technology [26,27].

Foaming technology introduces a small amount of water into hot asphalt, causing instantaneous vaporization and the formation of a large number of fine bubbles, thereby temporarily increasing asphalt volume, reducing apparent viscosity, and improving workability. Its advantages are a clear temperature-reduction effect and relatively strong equipment adaptability, but its action time is relatively short and it requires stricter construction process control.

Organic additive technology mainly uses materials such as low-melting-point synthetic waxes and fatty acid amides, which reduce asphalt viscosity through melting and lubrication at construction

temperatures and may form crystalline structures after cooling, thereby improving the high-temperature stability of mixtures[28]. Representative products of this type include Sasobit[29].

Chemical additive technology mainly relies on surfactants or interfacial modification components to reduce internal friction by improving the lubrication and adhesion state of the asphalt–aggregate system, allowing asphalt to achieve good coating and compaction even at relatively low temperatures[30]. Evotherm is one of the representative warm-mix additives of this type[31].

3.2 Application Characteristics of Typical Warm-Mix Additives

Sasobit and Evotherm are currently the two most widely used types of warm-mix additives, but their mechanisms and applicable scenarios are not the same. Sasobit is an organic wax warm-mix additive that can significantly reduce high-temperature construction viscosity and subsequently form a certain crystalline structure, thereby improving high-temperature deformation resistance[32]. However, excessive dosage may also reduce the low-temperature flexibility of asphalt, adversely affecting low-temperature cracking resistance.

Evotherm is a chemical warm-mix additive that mainly improves the coating and compaction performance of asphalt through interfacial lubrication and surface activity, and its effect on the intrinsic rheological properties of asphalt is relatively small[33,34]. For composite modified systems with complex compositions, Evotherm is often more favorable for balancing constructability and performance stability, which is also an important reason for its attention in studies on composite modified asphalt.

3.3 Effects of Warm-Mix Technology on Asphalt and Mixture Performance

A large number of studies have shown that warm-mix technology can reduce the mixing and compaction temperatures of mixtures by approximately 30–40 °C, thereby significantly reducing fuel consumption and lowering CO₂ and other harmful emissions[35-37]. From the construction perspective, warm-mix technology can improve adaptability to low-temperature-season construction, extend transport distance and the construction time window, and has clear advantages for project organization[38].

In terms of performance, different warm-mix technologies have different effects. Organic wax warm-mix additives represented by Sasobit usually help improve high-temperature rutting resistance, but may also weaken low-temperature cracking resistance[39]. In contrast, chemical warm-mix additives represented by Evotherm have relatively little effect on the original properties of asphalt and may improve the moisture damage resistance of mixtures to some extent[40-42]. Therefore, there is no absolute superiority among different warm-mix technologies; the key lies in matching them with specific asphalt systems and engineering demands.

3.4 Applicability of Warm-Mix Technology in CR/SBS Composite Systems

For multiphase complex systems such as CR/SBS composite modified asphalt, the application of warm-mix technology is much more complicated than that in conventional asphalt. On the one hand, warm-mix additives can alleviate the problem of high construction temperature in composite modified systems through viscosity reduction and improved lubrication. On the other hand, the reduction in construction temperature may also affect the swelling degree of CR, the dispersion state of SBS, and the compatibility among multiple components[43]. This means that although warm-mix technology can improve constructability, it may also change the microstructural evolution path of the composite system.

Therefore, the applicability of warm-mix technology in CR/SBS composite modified asphalt needs to be evaluated from multiple aspects, rather than merely taking viscosity reduction or compaction temperature decrease as evaluation criteria.

4. Research Progress on Asphalt Fumes and Odor-Reduction Technology

4.1 Hazards of Asphalt Fumes and VOCs

Asphalt materials release a large amount of fumes and volatile organic compounds during high-temperature mixing, paving, and compaction. In particular, for CR-modified asphalt and rubber composite modified asphalt, because waste tire components with complex origins are introduced into the system, the emitted components are usually more complex and their concentrations are higher. These volatiles include benzene-series compounds, sulfur-containing compounds, aldehydes and ketones, and polycyclic aromatic hydrocarbons, which pose potential threats to construction workers' health, surrounding air quality, and the ecological environment.

Existing toxicological studies have indicated that asphalt fumes can irritate the skin and respiratory mucosa, and may induce cellular damage and even gene mutation under long-term exposure conditions[44,45]. Among them, 2–6 ring polycyclic aromatic hydrocarbons in petroleum asphalt fumes are generally considered to have relatively high health risks[46]. In CR-modified systems, the emission of characteristic pollutants such as benzothiazole has also received extensive attention[47,48]. Therefore, the control of fumes and VOCs has become an important component of research on sustainable asphalt materials.

4.2 Detection Methods for Asphalt Fumes

At present, asphalt fume detection methods mainly include gravimetric methods and instrumental analysis methods. Gravimetric methods usually evaluate fume generation by measuring mass change before and after heating or by collecting and weighing particulate matter. These methods are simple and low-cost, but are relatively sensitive to environmental conditions and operating procedures[49]. For the identification and quantitative analysis of complex fume components, instrumental analysis techniques are more commonly used.

Common instrumental analysis methods include ultraviolet-visible spectrophotometry (UV), gas chromatography-mass spectrometry (GC-MS), and portable VOC detectors [50-53]. In recent years, coupled techniques such as PY-GC-MS, TD-GC-MS, HS-GC-MS, and TG-MS have been widely used in asphalt fume research[54-57]. These methods can analyze fume release behavior, composition, and thermal cracking pathways from different perspectives, providing important support for the mechanistic study of odor-reduction technology. In addition, Odor-Reducing Asphalt Concrete (GB/T 43882-2024) has incorporated multiparameter gas detectors into the laboratory evaluation of fume emission grades, which also indicates that asphalt fume evaluation is gradually moving toward standardization and engineering application.

4.3 Main Types of Odor-Reduction Technology

Asphalt fume treatment technologies can generally be divided into external treatment and internal treatment. External treatment mainly collects and purifies fumes after generation, including combustion, condensation, adsorption, and electrostatic capture. Internal treatment refers to the addition of functional components into asphalt materials to reduce the generation of fumes and odors at the source. Since internal treatment is more suitable for field road applications and is more consistent with the development direction of material-based sustainability, recent studies have focused more on the internal regulation effect of odor-reducing agents[58].

According to the mechanism of action, internal odor-reduction technologies can be broadly classified into adsorption type, shielding type, and reactive type. Adsorption-type odor-reducing agents mainly include activated carbon, zeolite, molecular sieves, porous minerals, and expandable graphite, which reduce the escape of volatile components through physical adsorption and pore retention. Shielding-type odor-reducing agents mainly slow down the mass transfer of volatile components by constructing diffusion barriers. Reactive odor-reducing agents can chemically react with characteristic odor molecules or active components, thereby reducing the concentration of harmful substances[59-61].

Although adsorption-type and shielding-type odor-reducing agents have wide sources, low raw material costs, and relatively clear action pathways, they often require high dosages and are difficult to disperse in asphalt, which can easily cause adverse effects on low-temperature performance and rheological properties[62]. In contrast, reactive or substitutive odor-reducing agents have greater potential for balancing odor-reduction effectiveness and material performance stability.

5. Research on the Synergistic Application of Warm-Mix and Odor-Reduction Technologies

5.1 Necessity of Synergistic Application

For CR/SBS composite modified asphalt, high construction temperature and severe fume pollution often occur simultaneously. The use of warm-mix technology alone can reduce some VOC emissions by lowering construction temperature, but its control over characteristic hazardous components is limited. In contrast, the use of odor-reducing agents alone can reduce odor and the concentration of some pollutants, but if the construction temperature remains high, the emission reduction effect will also be limited. Therefore, combining warm-mix technology with odor-reduction technology to achieve both temperature reduction and fume suppression is a reasonable route for solving the secondary pollution problem of CR/SBS composite modified asphalt.

5.2 Analysis of Synergistic Emission Reduction Mechanisms

The emission reduction effect of warm-mix technology is mainly reflected at the temperature-control level. Since the release of many VOCs and harmful gases increases rapidly with temperature, lowering the mixing and paving temperatures can directly reduce the source strength of volatilization[63]. For example, at lower construction temperatures, the release of some aliphatic hydrocarbons, aromatic hydrocarbons, and sulfur-containing compounds in rubber asphalt decreases. Odor-reduction technology, in contrast, focuses more on component control and reaction inhibition. Reactive odor-reducing agents can chemically react with some odor molecules or active precursors, reducing their formation probability; adsorption-type odor-reducing agents can reduce volatilization pathways and escape rates. If the two are used synergistically, warm-mix technology reduces the total emission level, while odor-reducing agents further suppress key hazardous components. In theory, this can achieve a better emission reduction effect.

It should be noted that the addition of warm-mix additives and odor-reducing agents does not necessarily produce only positive effects. Warm-mix additives may alter the swelling kinetics of CR and the phase distribution of SBS polymers, while odor-reducing agents may affect the migration, adsorption, and reaction balance of some light fractions. If the compatibility among multiple additives is poor or their effects are antagonistic, not only may their respective emission reduction effects be weakened, but negative effects such as reduced storage stability, fluctuations in rheological properties, or deterioration in long-term durability may also occur.

Therefore, the synergistic application of warm-mix and odor-reduction technologies should not remain only at the level of apparent effects such as temperature reduction and odor reduction, but should also comprehensively examine their effects on viscosity, storage stability, high and low temperature performance, fatigue performance, aging resistance, and mixture pavement performance. Only when balance is achieved in performance, construction, and environmental protection can the relevant technologies have real engineering value.

6. Summary

(1) CR/SBS composite modified asphalt significantly improves pavement performance and realizes the resource utilization of waste tires through the synergistic effect of CR and SBS, making it an important direction for the sustainable development of road materials. However, this system also faces prominent problems such as high construction temperature and severe fume emissions.

(2) Warm-mix technology can reduce construction temperature and decrease energy consumption and some VOC emissions through mechanisms such as viscosity reduction, foaming, or interfacial lubrication; odor-reduction technology can reduce asphalt fumes and the release of hazardous components through adsorption, isolation, or chemical reaction. The introduction of warm-mix and odor-reduction technologies into CR/SBS composite modified systems is expected to achieve the synergistic goals of high performance, low energy consumption, and low emissions.

(3) At present, studies on the interaction mechanisms of multicomponent systems, the synergistic regulation mechanism of performance and emissions, and long-term service stability are still insufficient. Future work should be systematically carried out in terms of multiscale structural characterization, construction of comprehensive evaluation systems, long-term durability research, and development of efficient sustainable additives, so as to promote the engineering application and development of warm-mix odor-reduced CR/SBS composite modified asphalt.

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