ISSN 1392-1320 MATERIALS SCIENCE (MEDŽIAGOTYRA). Vol. XX, No. X. 2026

Thermal-ultraviolet-humidness Coupling Aging Mechanisms of SBS Modified Asphalt Considering Actual Climatic Conditions

Xurong ZHANG [1], Yaya ZUO [1], Liyan JIN [2], Xinxin CAO [3] *

[1] *Sichuan Chuangao Engineering Technology Consulting Co., Ltd., No.90 Xiyiduan Erhuan Road, Chengdu, China, 610041*
[2] *Beijing Kuanmu Technology Co., Ltd., No.28 Hongyedong Road , Beijing, China, 100076*
[3] *School of Highway and Architecture, Shandong Transport Vocational College, No.7369 Bohai Road, Weifang, China, 261206*

http://doi.org/10.5755/j02.ms.40940

Received 24 March 2025; accepted 6 May 2025

Styrene-butadiene-styrene (SBS) modified asphalt is susceptible to aging due to the combined effects of environmental factors, including temperature, ultraviolet radiation, and humidness. However, existing studies primarily focus on single aging conditions, neglecting the synergistic effects of thermal, ultraviolet, and humidness factors on the aging properties of asphalt. Given the vast territory and significant environmental variations in China, this study selects five representative cities as subjects for research. The research utilizes the Rolling Thin Film Oven Test (RTFOT) in combination with a coupled aging chamber to simulate the aging process. This study analyzes the effects of varying temperature, duration of ultraviolet radiation exposure, and humidness conditions on the macroscopic performance of asphalt, specifically through ductility and softening point tests. Additionally, it elucidates the aging mechanisms of SBS modified asphalt using Fourier Transform Infrared Spectroscopy (FTIR) and fluorescence microscopy (FM). The results indicate that high humidness and temperature environments significantly accelerate the aging of asphalt, with temperature playing a dominant role in hastening the aging process of SBS-modified asphalt. Microscopic analysis reveals that the primary mechanisms of SBS degradation and oxidation reactions occur during the aging process. Notably, the change in the functional group index of SBS-modified asphalt under high humidness and temperature conditions is most pronounced. The decomposition of the SBS network crosslinking structure is most severe, resulting in the weakest fluorescence intensity.
Keywords: SBS modified asphalt, aging mechanisms, thermal, ultraviolet, humidity.

1. INTRODUCTION

Styrene-butadiene-styrene (SBS) modified asphalt is one of the most widely used materials in road construction in China, attributed to its advantageous performance characteristics at both elevated and reduced temperatures, as well as its durability. Additionally, it enhances driving comfort and contributes to the maintenance of road infrastructure [1 – 3]. SBS-modified asphalt pavements are exposed to prolonged environmental conditions, where they encounter a combination of various factors, including temperature fluctuations, ultraviolet radiation, and humidity. This exposure results in a significant degradation in the performance of SBS-modified asphalt, as evidenced by various forms of distress, including cracking and delamination on the pavement surface. Consequently, these issues negatively impact the overall service life of the asphalt pavement [4, 5]. Therefore, it is essential to clarify the aging mechanisms of SBS-modified asphalt when exposed to natural climatic conditions.

The aging processes of asphalt, both in the short term and long term, are modeled through the Rolling Thin Film Oven Test (RTFOT) and the Pressure Aging Vessel (PAV), respectively. Empirical studies have shown that asphalt undergoes hardening and an increase in butadiene levels due to varying degrees of thermal-oxidative aging [6 – 9]. Qin et al. 10 conducted a microscopic examination to assess the impact of thermal-oxidative aging on asphalt. Their findings revealed that this process leads to a transformation of asphalt components and polar functional groups into recombined structures. This transformation alters the original colloidal structure of the asphalt, leading to a deterioration of its properties. Sun et al. [11] utilized three ultraviolet lamps, each with a power output of 300 W, to simulate outdoor ultraviolet radiation. The vertical distance between the asphalt samples and the ultraviolet lamps was maintained at 30 cm, with a radiation area of 0.8 m^2. The measured intensity of ultraviolet radiation was 35 W/m^2. Liu et al. 12 initially conducted the Thin Film Oven Test (TFOT) to simulate the short-term aging of asphalt, subsequently using the aged asphalt from the TFOT for ultraviolet aging evaluation. The intensity of UV radiation was established at levels of 6 W/m^2, 7 W/m^2, 8 W/m^2, 9 W/m^2, and 10 W/m^2, with an exposure duration of 48 hours. Zeng et al. 13 conducted aging experiments at three distinct temperatures: 30 °C, 50 °C, and 70 °C, while ensuring consistent ultraviolet aging conditions. Their results indicated that temperature had a negligible effect on ultraviolet aging at 50 °C. However, under ultraviolet aging conditions at 70 °C, there was a significant increase in the aging index of asphalt, accompanied by considerable deterioration of SBS-modified asphalt. Li et al. 14 reported a decrease in the ductility of SBS-modified asphalt as aging time, temperature, and ultraviolet intensity increased,

* Corresponding author: X. Cao
E-mail: *caoxinxin@sdut.edu.cn*

particularly under the combined effects of heat and light. They also observed an increase in the concentrations of asphaltenes and aromatics in the material. Zhang et al. 15 investigated the aging effects of three distinct methodologies: Ultraviolet Radiation (UV), Pressure Aging Vessel (PAV), and Thin Film Oven Test (TFOT). Their findings indicated that both PAV aging and ultraviolet aging had more significant effects on the degradation of the SBS polymer. The existing literature primarily focuses on the various factors influencing asphalt aging, particularly in the contexts of ultraviolet aging, thermal aging, and thermal-ultraviolet aging, along with their interactions. It has been observed that the effects of complex aging processes are more pronounced than those resulting from singular aging mechanisms.

In regions with substantial precipitation, water molecules play a significant role in the aging process of asphalt [16, 17]. Water infiltration can accumulate within the asphalt mortar layer or the surface layer of the film, subsequently migrating inward through the asphalt film until it reaches the bonding interface between the asphalt and the aggregate 18. Due to the hydrophilic nature of the aggregate surface, the adhesive interaction between the aggregate and water molecules is significantly stronger than the adhesion between the aggregate and the asphalt film. As driving loads are continuously applied, detachment occurs between the asphalt film and the aggregate surface. Wei et al. 19 assert that the aging of asphalt pavement throughout its service life is influenced not only by high temperatures and ultraviolet radiation but also significantly by humidity, which warrants careful consideration. Liu et al. 20 demonstrated that immersing asphalt in water leads to several changes, including reduced adhesion, increased stiffness, and a higher concentration of oxygen-containing functional groups and polar components. Research indicates that the introduction of an aqueous solution to polymer-modified asphalt can compromise the colloidal integrity of the asphalt, accelerate its aging process, and ultimately reduce the lifespan of asphalt pavement [21, 22].

In practical applications, the properties of asphalt are significantly influenced by environmental factors such as temperature, ultraviolet radiation, and humidity. These multifaceted conditions contribute to the degradation of asphalt characteristics to varying degrees. Therefore, it is essential to investigate the impact of various environmental factors on the aging of asphalt to enhance the effectiveness of practical applications [23, 24]. Researchers have utilized coupled aging test chambers to simulate the effects of environmental factors, including high temperature, humidity, ultraviolet radiation, and oxygen, on the aging process of asphalt [25 – 28].

Li et al. 29 found that the rheological properties of asphalt at low temperatures deteriorate more significantly under three-factor coupling aging conditions compared to two-factor or single-factor aging, leading to a reduction in crack resistance. Yang et al. 30 demonstrated that under thermal-oxidative conditions, the simultaneous effects of ultraviolet radiation and humidity lead to the formation of micro-cracks on the asphalt surface. Additionally, the interaction with humidity exacerbates the growth of these micro-cracks and accelerates the process of water-induced aging. Sun et al. 31 indicated that ultraviolet radiation can accelerate the aging process of asphalt. Specifically, daily exposure to ultraviolet radiation can increase the aging degree of matrix asphalt and modified asphalt by approximately 5 % and 1.5 %, respectively, compared to thermal-oxidative aging. Yuan et al. 32 showed that elevated temperatures increase the interaction with humidity, resulting in a significant reduction in the adhesion between asphalt and aggregate. This reduction subsequently leads to the spalling of asphalt from the exterior to the interior. Moreover, under the combined influence of ultraviolet light and humidity, both the oxidation and dissolution of asphalt occur simultaneously, further propagating cracks. The presence of these cracks allows water to infiltrate the asphalt, ultimately resulting in a decline in its performance.

In summary, the existing literature has thoroughly examined the effects of various environmental factors, including thermal-oxidative aging, ultraviolet aging, and humidness aging, on the properties of asphalt. However, the mechanisms driving changes in the macro properties and microstructure of asphalt subjected to aging from the combined influences of thermal-ultraviolet-humidness exposure remain insufficiently elucidated. Additionally, the synergistic interactions among various environmental factors within the multifactorial coupled aging process, along with their collective impact on asphalt properties, are not well understood. To address this gap, a multi-factor coupled aging test apparatus was utilized to simulate the environmental conditions characteristic of five distinct climatic regions: Lhasa, Harbin, Beijing, Shanghai, and Guangzhou. The study focused on the synergistic effects of temperature, ultraviolet radiation intensity, and humidness on the properties of asphalt materials. This was accomplished through the evaluation of densification and softening point, along with fluorescence microscopy, Fourier transform infrared spectroscopy, and various other microstructural characterization techniques. The objective of this research is to develop a theoretical framework for understanding the aging behavior of asphalt pavement under the combined effects of thermal-ultraviolet-humidness. Moreover, the findings have significant engineering implications for improving the performance and extending the lifespan of asphalt pavement.

2. MATERIALS AND METHODS

The SBS modified asphalt material analyzed in this research is supplied by Qilu Petrochemical Company, and its key parameters conform to the criteria outlined in the “Specifications for Construction of Highway Asphalt Pavements (JTG F40-2004)”. The primary characteristics of the SBS modified asphalt are detailed in Table 1.

The SYD-2806E asphalt softening point tester and the LYY-7D asphalt ductility tester were utilized to perform softening point and 5 °C ductility tests on asphalt, respectively, in order to characterize its performance at both high and low temperatures. Microstructural analysis was conducted using an LW100 FT/B fluorescence microscope at a magnification of 400×. The chemical functional groups of both aged and rejuvenated asphalt were examined using a Nicolet 5700 Fourier transform infrared (FTIR) spectrometer, which operated within a typical spectral wavenumber range of 400 – 4000 cm^{-1} and achieved a resolution of 0.4 cm^{-1}.

Table 1. Performance indicators of SBS-modified asphalt

Technical Indicators	Unit	Standards	Results
Penetration (25 °C, 100 g, 5 s)	mm	40 ~ 60	57
Softening point (ring and ball method)	°C	> 75	82.5
Ductility at 5°C	cm	> 20	61.4
Elastic recovery at 25 °C	%	≥ 75	92
Kinematic viscosity at 135 °C	Pa·S	< 3	2.710
Flash point (open cup)	°C	> 230	329
Solubility in trichloroethylene	%	>99	99.74
Density at 15 °C	g/cm^3	Actual measurement	1.033

First, each 35 g bitumen sample was aged for 85 minutes at 163 °C using the Rolling Thin Film Oven Test (RTFOT). This procedure was designed to simulate the thermal-oxidative aging process of bitumen. Following the initial phase of thermal-oxidative aging, the asphalt was placed in a coupling aging test chamber that allows for temperature regulation. Intermittent application of water was utilized to simulate the coupling aging effects on asphalt under conditions characterized by the interaction of thermal-ultraviolet-humidness. Various parameters were established in accordance with specific climatic conditions, ultimately facilitating the aging of asphalt under these diverse scenarios. For detailed conditions, please refer to Table 2 – Table 5, and the aging flowchart is presented in Fig. 1.

Table 2. Urban simulated rainfall

City	Total summer rainfall, mm	Average daily rainfall, mm
Beijing	6862.80	3.8
Guangzhou	17556.03	9.7
Shanghai	10671	5.9
Harbin	7430.4	4.1
Lhasa	6333.3	3.5

Table 3. Urban simulation temperature

City	Summer average temperature, °C	Simulated temperature, °C
Guangzhou	35 – 40	70
Shanghai	35 – 40	70
Beijing	30 – 35	65
Harbin	25 – 30	60
Lhasa	20 – 25	55

Table 4. Ultraviolet irradiation time

City	The average total solar radiation in summer, MJ/m^2	Ultraviolet radiation intensity, MJ/m^2	Ultraviolet duration, h
Beijing	1755.6 – 2048.2	95.095	110
Guangzhou	1254 – 1504.8	68.97	80
Shanghai	1254 – 1504.8	68.97	80
Harbin	1755.6 – 2048.2	95.095	110
Lhasa	2340.8 – 2672	125.32	145

Table 5. Combined aging conditions

City	Humidness, mm	Temperature, °C	Ultraviolet duration, h
Beijing	3.8	65	110
Guangzhou	9.7	70	80
Shanghai	5.9	70	80
Harbin	4.1	60	110
Lhasa	3.5	55	145

Considering the vast geographical diversity of China and the significant regional disparities in climatic conditions, this study aims to conduct a comprehensive examination of the aging behavior characteristics of SBS-modified asphalt. To facilitate this investigation, four cities with distinct climatic profiles were selected: Shanghai, which exemplifies the eastern coastal subtropical monsoon climate; Guangzhou, representing the southern tropical monsoon climate; Lhasa, indicative of the western plateau mountain climate; and Harbin, reflecting the northern cold temperate climate. Furthermore, Beijing, known for its relatively moderate climate, was designated as the control region for this analysis. Due to significant variations in seasonal characteristics, the climatic conditions of summer are primarily used as the experimental benchmark in this research. Building on previous studies, a multi-factor coupling aging experimental system was developed to accurately simulate the aging process of asphalt as influenced by natural environmental conditions. This system achieves this by regulating various environmental parameters, including temperature, humidity, and the duration of ultraviolet radiation exposure.

1. Assessment of precipitation conditions. This research utilized meteorological observation data obtained from the China Meteorological Data Network to compile and analyze summer precipitation data (from June to August) for Guangzhou, Shanghai, Beijing, Harbin, and Lhasa, covering the period from 2001 to 2020. The cumulative precipitation and mean daily precipitation for the summer season were calculated through statistical analysis. Comprehensive data is presented in Table 2.

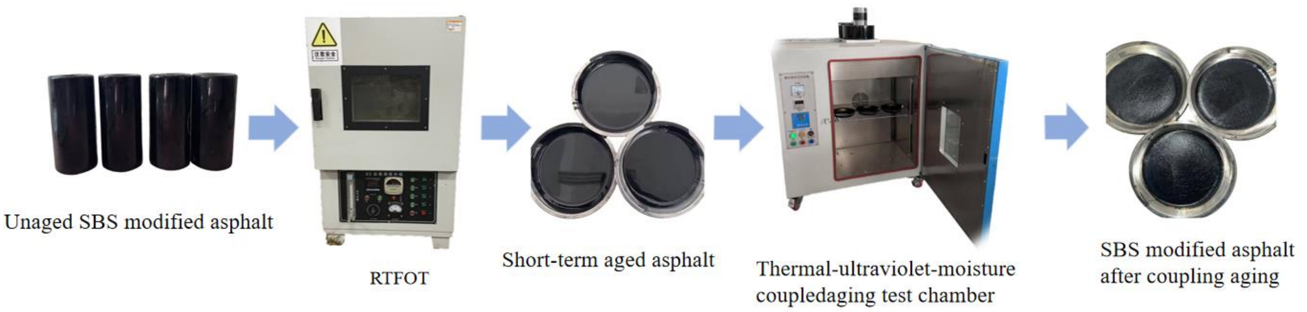


Fig. 1. Aging process flow chart

2. Assessment of thermal conditions. A statistical analysis was conducted on the maximum summer average temperatures of five representative cities – Guangzhou, Shanghai, Beijing, Harbin, and Lhasa – using data from the China Meteorological Data Network. Research conducted by both domestic and international scholars has revealed a significant disparity between the surface temperature of asphalt pavement and the ambient air temperature. It is generally observed that the surface temperature of asphalt pavement can exceed the ambient air temperature by approximately 30 °C. In light of this temperature differential, the present study designates 30 °C as the threshold for the experimental group to ensure that the experimental conditions accurately reflect real-world scenarios. Specific data is presented in Table 3.
3. Determination of ultraviolet conditions. An analysis of the survey data obtained from the China Meteorological Data Network was conducted to quantify the total solar radiation for five representative cities: Guangzhou, Shanghai, Beijing, Harbin, and Lhasa, during the summer season. A heat-light-water coupling aging test chamber has been constructed and is equipped with six integrated 40W ultraviolet lamps. In accordance with the principle of energy equivalence 32, the duration of the testing period is designed to simulate one year of exposure in a real-world environment, as established by Eq. 1. Specific data are detailed in Table 4.

$$T = \frac{Y}{3600X}, \quad (1)$$

where T is the indoor ultraviolet irradiation time, h; X is the irradiation intensity of the ultraviolet lamp, W/m²; Y is the average solar ultraviolet radiation intensity during summer, MJ/m².

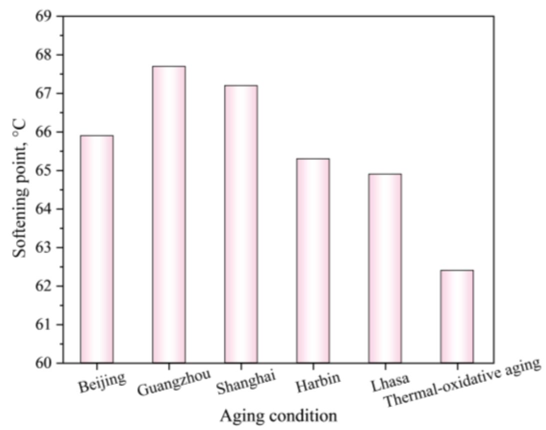
4. Determination of coupling aging conditions. Table 5 provides a comprehensive overview of aging temperature, ultraviolet radiation, and precipitation.

3. ROAD PERFORMANCE

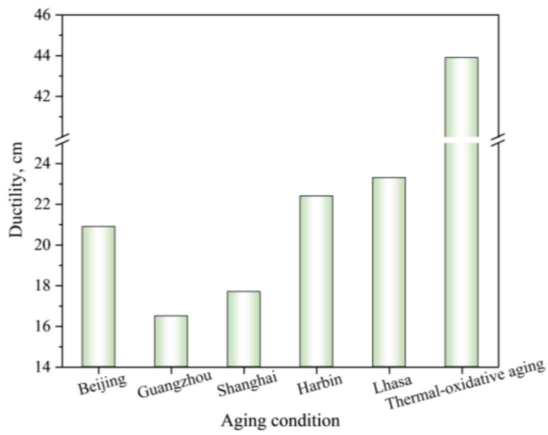
The softening point and ductility of SBS-modified asphalt were evaluated under different aging conditions, and the results are presented in Fig. 2.

The softening point and ductility of SBS-modified asphalt decreased by 24.36 % and 28.50 %, respectively, after undergoing thermal oxidation aging treatment. This indicates significant declines in both the high-temperature and low-temperature performance properties of the asphalt. Ren et al. [34] also confirmed that pure thermo-oxidation has a significant aging effect on asphalt. In comparison to single thermo-oxidative aging, asphalt subjected to the combined effects of thermal-ultraviolet-humidness three-factor coupling aging exhibited a more significant decline in performance. The observed variations in softening point and ductility across different samples indicate a ranking of aging severity in asphalt as follows: Guangzhou > Shanghai > Beijing > Harbin > Lhasa. The aging of asphalt is influenced by thermal oxidation, ultraviolet radiation, and humidity, correlating with variations in temperature and moisture levels, with thermal oxidation playing a critical role. This finding contrasts with the results of Zhang et al. [33] which indicates that ultraviolet light is the primary factor influencing the low-temperature performance of SBS-modified asphalt. This discrepancy may be attributed to the fact that humidity during the three-factor coupling aging process exacerbates the thermo-oxidative aging effect.

A comparative analysis reveals that Shanghai and Guangzhou exhibit similar climatic conditions concerning temperature and ultraviolet radiation. However, Guangzhou, designated as a rainy city, experiences greater degradation of asphalt compared to Shanghai. This finding suggests that humidity accelerates the aging of asphalt when exposed to the combined effects of thermal-ultraviolet-humidness. The climatic conditions, particularly temperature and humidity, in both Guangzhou and Shanghai are significantly higher than those in Beijing. Despite Beijing's elevated levels of ultraviolet (UV) exposure, the rate of asphalt aging in the city is comparatively lower than that in Guangzhou and Shanghai. This observation indicates that the combined effects of increased temperature and humidity have a more significant impact on asphalt degradation.



a



b

Fig. 2. Microscopic experimental equipment: a – softening point;b – ductility

Harbin and Beijing experience identical durations of ultraviolet irradiation; however, the 8.33 % higher temperatures in Beijing have resulted in a more pronounced asphalt aging reaction. This is evidenced by significant macro-performance disparities, with ductility and softening point differing by 6.69 % and 0.92 %, respectively. These findings indicate that temperature plays a primary role in the coupling effect. The temperature and humidity conditions in Beijing are 1.18 and 1.09 times greater than those in Lhasa, respectively, while Lhasa's ultraviolet radiation intensity is 1.32 times greater than that of Beijing. From a pavement performance perspective, the degree of aging in Beijing is significantly higher than that in Lhasa, with ductility reduced by 10.30 % and the softening point decreased by 1.54 %. This reaffirms that the coupling effect between temperature and humidity surpasses that of ultraviolet radiation, with temperature exerting the predominant influence.

4. FUNCTIONAL GROUPS

The results of the Fourier Transform Infrared (FTIR) analysis for Styrene-Butadiene-Styrene (SBS) modified asphalt, which has been subjected to aging conditions that include the simultaneous effects of heat, light, and moisture in various urban environments, are presented in Fig. 3 and Fig. 4.

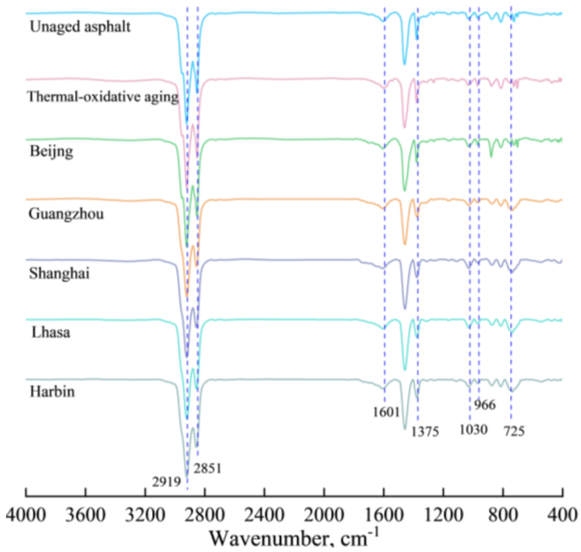


Fig. 3. Functional groups of aged asphalt

The analysis of the infrared spectrum indicated that the bitumen samples, which underwent various aging processes, displayed distinct absorption peaks at wavenumbers of 2919, 2851, 1601, 1375, 1030, 966, and 725 cm^{-1}. The prominent peaks at 2919 cm^{-1} and 2851 cm^{-1} are attributed to the asymmetric and symmetric stretching vibrational modes of the C-H bonds found in methylene groups. The absorption peak at 1601 cm^{-1} corresponds to the skeletal vibrations of the benzene ring. The absorption peak at 1601 cm^{-1} corresponds to the skeletal vibrations of the benzene ring. The absorption feature at 1375 cm^{-1} is associated with the symmetric bending vibrations of the methyl group, while the peak at 1030 cm^{-1} corresponds to the stretching vibrations of the sulfoxide functional group. Notably, the absorption at 966 cm^{-1} is attributed to the bending vibrations of the C=C bond in polybutadiene, whereas the peak at 725 cm^{-1} corresponds to the vibrational mode of methylene groups linked to the benzene ring in polystyrene.

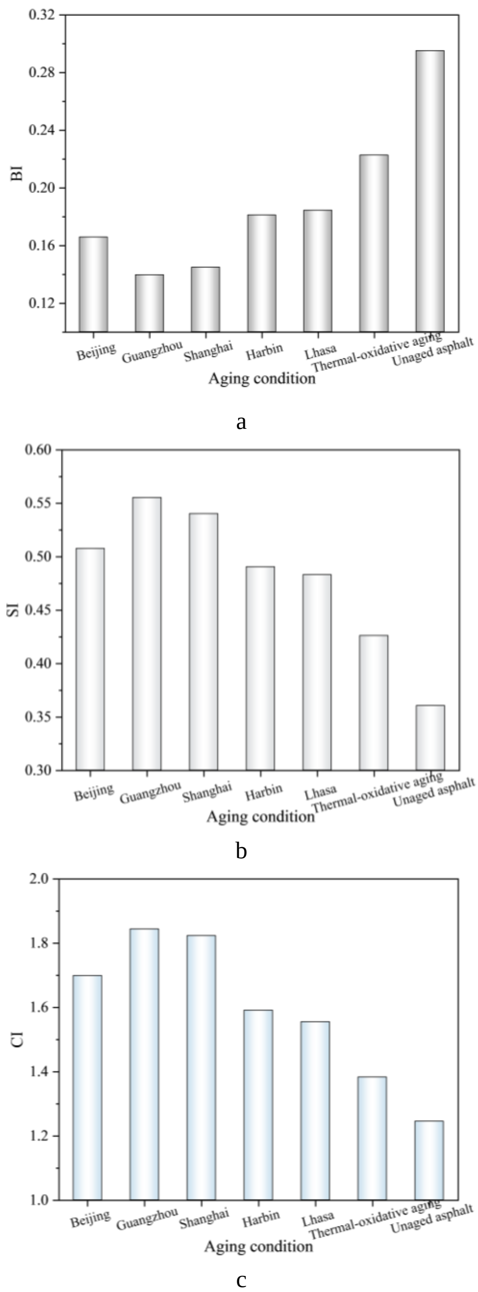


Fig. 4. BI, SI and CI under different aging conditions: a – BI after aging; b – SI after aging; c – CI after aging

These two specific peaks may serve as a basis for evaluating the SBS modifier. Although there is variability in the intensity of the absorption peaks, their positions in terms of wavenumber demonstrate a high degree of stability. Due to the significant systematic error associated with measuring the carbonyl peak area, the butadiene index (BI), sulfoxide index (SI), and aromaticity index (CI) were calculated to assess the content and degree of aging of the SBS modifier. This methodology facilitates the analysis of the aging and regeneration mechanisms of asphalt, as outlined in Eq. 2, Eq. 3, and Eq. 4.

$$BI = \frac{A_{966}}{A_{1375}}; \quad (2)$$

$$SI = \frac{A_{1030}}{A_{1375}}; \quad (3)$$

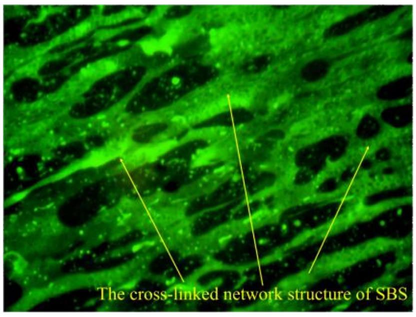
$$CI = \frac{A_{1600}}{A_{1375}}, \quad (4)$$

where A_{966}, A_{1030}, A_{1375}, and A_{1741} are the areas of the absorption peaks at 966 cm^{-1}, 1030 cm^{-1}, 1375 cm^{-1}, and 1741 cm^{-1}, respectively.

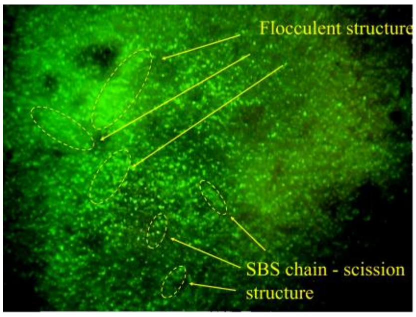
As illustrated in Fig. 4, the Butadiene Index (BI), Sulfoxide Index (SI), and Aromaticity Index (CI) of asphalt exhibit significant variations due to the aging process. This observation indicates that the concentrations of butadiene, sulfoxide, and aromatics in the asphalt have undergone substantial changes. The results indicate that the aging process is primarily characterized by the degradation of styrene-butadiene-styrene (SBS) and oxidative reactions. The intensified thermal-oxidative effects associated with hot oxygen aging catalyze extensive oxidation reactions, leading to the degradation of SBS. This process results in a 24.56 % decrease in the Butadiene Index (BI), an 18.18 % increase in the Sulfoxide Index (SI), and an 11.06 % increase in the Aromaticity Index (CI). Furthermore, the performance of asphalt on roadways is significantly affected by a reduction in both the softening point and ductility. Consequently, the overall performance of the asphalt is further compromised by the combined effects of thermal-ultraviolet-humidness. A comparison of the degree of aging across each group revealed that the indices recorded in Guangzhou exhibited the most significant changes. The Butadiene Index (BI) decreased by 37.31 %, while the Sulfoxide Index (SI) and the Aromaticity Index (CI) increased by 30.35 % and 33.35 %, respectively. In contrast, the indices observed in Lhasa showed the least variation, with the BI decreasing by 17.19 %, while the SI and CI increased by 13.39 % and 12.46 %, respectively. These variations in index changes underscore the substantial effects of aging attributable to temperature and humidness. The Butadiene Index (BI), Sulfoxide Index (SI), and Aromaticity Index (CI) in Guangzhou have shown a decline of 3.60 %, an increase of 2.78 %, and an increase of 1.14 %, respectively, compared to those in Shanghai. This observation indicates that the significantly higher humidness levels in Guangzhou, which are 1.64 times greater than those in Shanghai, play a critical role in accelerating the aging process. In contrast to Beijing, Harbin, and Lhasa, both Guangzhou and Shanghai exhibit more significant declines in the Butadiene Index (BI), accompanied by increases in the Sulfoxide Index (SI) and the Aromaticity Index (CI). This trend indicates that the coupling effect under high temperatures and humidness is more significant than in environments with high UV radiation exposure. Ma et al. [0] and Gong et al. [36] also confirmed the enhancing effect of the interaction between temperature and humidity on asphalt aging. However, their experiments only simulated the aging behavior of asphalt under the combined influence of thermal and humidity factors. The BI, SI, and CI values in Beijing decreased by 8.44 %, while the SI and CI values increased by 3.50 % and 6.76 %, respectively, compared to those in Harbin. This indicates that the additional humidness condition in Harbin (7.89 %) had a weaker enhancing effect on the coupling effect compared to the higher temperature condition in Beijing (8.33 %). In contrast, the BI, SI, and CI values in Harbin decreased by 1.82 %, increased by 1.53 %, and increased by 2.32 %, respectively, when compared to those in Lhasa. The lower BI gap confirms the aging effects of ultraviolet radiation, as Lhasa's UV intensity was 1.32 times greater than that of Harbin. However, the resulting aging effect remained limited. Collectively, these results demonstrate that high-temperature and high-humidity environments exhibit stronger coupling aging effects compared to high-UV environments. Specifically, elevated temperatures accelerate the formation of oxidative cross-linking chains in asphalt, while moisture exacerbates this process. This finding contrasts with the mechanism proposed by Sun et al. [31], which suggests that water mitigates aging through physical shielding and the inhibition of oxidation in both thermo-humidness coupling and thermal-ultraviolet-humidness coupling systems. The discrepancy may be attributed to variations in the thickness of the asphalt film used in the experiments.

5. MICROSCOPIC FORM

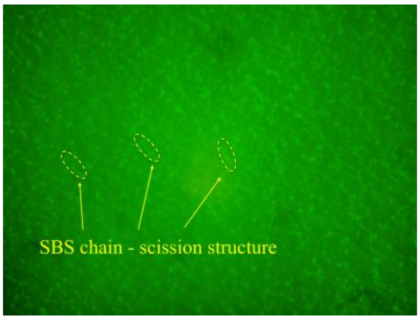
Fig. 5 illustrates the results of the FM test conducted on SBS-modified asphalt that has undergone aging due to the combined effects of heat, light, and moisture in various urban environments. As depicted in Fig.5 a, the SBS component in unaged asphalt demonstrates a distinctive cross-linked network structure. This structure is formed through the adsorption and subsequent sulfoxidation of asphalt, which facilitates the development of a network configuration. The presence of this network structure significantly enhances the fundamental properties of asphalt. In the context of thermal-oxidative aging (Fig. 5 b), the cross-linked structure of the SBS network experiences significant disintegration, transforming into a distinct flocculent and point-like morphology, accompanied by a loss of clarity in its outline. During the coupling aging process, the cross-linked structure of the SBS network within each group completely disperses into a disrupted, chain-like configuration. This transformation results in a reduction in volume and a corresponding decrease in fluorescence intensity. The findings indicate that the coupling aging process significantly impacts SBS, leading to the deterioration and degradation of numerous SBS units, as well as the disruption of the network structure. This observation correlates with the noted decline in macroeconomic performance. The primary factors contributing to the degradation of the asphalt SBS structure can be attributed to two main aspects. First, the degradation of lighter components, particularly the saturated and aromatic constituents, results in reduced compatibility at the asphalt-SBS interface. Second, the thermal-oxidative decomposition of the butadiene chain segment leads to the cleavage of molecular chains, a phenomenon corroborated by previous detection results of the butadiene index. Based on the volume size of fractured SBS chains, the degree of connectivity, and the fluorescence intensity shown in Fig. 5 c, d, e, f, and g, the degradation levels of each group are ranked as follows: Guangzhou > Shanghai > Beijing > Harbin > Lhasa. The reduced and more dispersed volume of fractured chain structures observed in Guangzhou and Shanghai suggests that significant chemical reactions are occurring within the asphalt matrix.



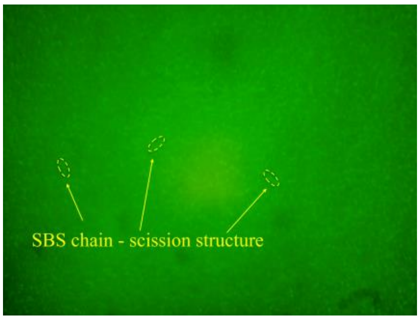
a



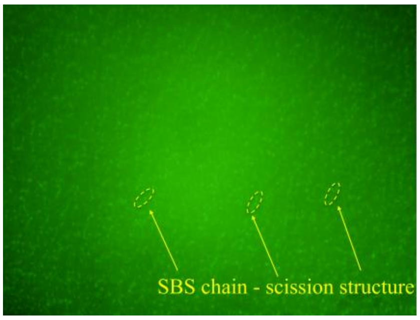
b



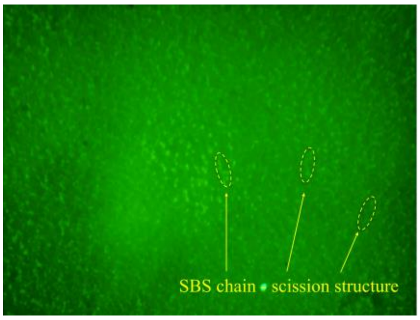
c



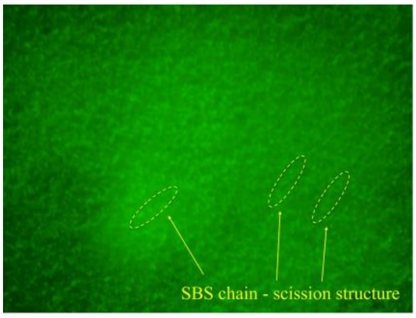
d



e



f



g

Fig. 5. SBS morphology and distribution after aging (400×): a – unaged asphalt; b – thermal-oxidative aged asphalt; c – Beijing; d – Guangzhou; e – Shanghai; f – Harbin; g – Lhasa

This observation supports the assertion that the interplay of humidness and temperature has a significant degrading impact on SBS materials. Compared to Guangzhou, the more intact structure of SBS chain scission observed in Shanghai suggests that higher humidness exacerbates SBS degradation. However, this finding contrasts with the results from asphalt immersion tests, which indicate that water does not significantly degrade the chemical structure of SBS [20]. This discrepancy may be attributed to the fact that the immersion tests were conducted at ambient temperature, resulting in a reduced temperature-coupling effect. Furthermore, when comparing Harbin to Beijing, the higher incidence of disrupted SBS chains in Beijing indicates that elevated temperatures have a more significant degrading effect on SBS than humidity. In contrast to the conclusion that ultraviolet (UV) light significantly degrades SBS under single aging conditions [15], the SBS chain scission structure observed in Lhasa demonstrates relatively tight connections between the scissions. This suggests that ultraviolet (UV) light has a diminished effect on the degradation of the network crosslinking structure of SBS under combined environmental conditions. This outcome may be attributed to the limited aging effects of ultraviolet (UV) light during the thermal-ultraviolet-humidity coupled aging process of asphalt.

6. CONCLUSIONS

This study utilized indoor simulations to replicate various urban climate conditions, with a particular emphasis on the interactions of thermal-ultraviolet-humidness within an aging environment. An analysis was conducted on the macroscopic properties and microstructural changes of

SBS-modified asphalt during the aging process. The investigation provided valuable insights into the aging mechanisms associated with SBS-modified asphalt, which was beneficial to the development of anti-aging technology of SBS modified asphalt. The key findings are summarized as follows:

1. Research indicates that thermal-ultraviolet-humidity significantly influences the aging process of SBS-modified asphalt, albeit to varying degrees. This aging process leads to a reduction in ductility and an increase in the softening point of the material. Notably, the overall performance of asphalt deteriorates primarily at elevated temperatures, highlighting the significance of temperature as a critical factor in asphalt aging. The aging process leads to the partial hardening of the asphalt's surface layer. When this hardening occurs alongside the formation of a water film on the surface, it mitigates the effects of ultraviolet radiation. Additionally, the presence of humidness has been observed to contribute to the accelerated aging of asphalt to some extent.
2. In the field of thermal-ultraviolet-humidness coupling aging, the aging characteristics of SBS-modified asphalt demonstrate significant regional disparities. The degree of aging is observed to decrease in the following sequence: high-temperature and humidness environment, medium temperature and humidness environment, benchmark climate environment, cold temperate continental climate environment, and plateau environments with strong ultraviolet exposure. This phenomenon is closely linked to the temperature and humidity conditions prevalent in different geographical regions. Notably, the effects of a hot-wet environment on asphalt aging are more pronounced than those of a dry environment with increased ultraviolet exposure. This finding further underscores the critical influence of temperature and humidity on the aging process of asphalt.
3. Fluorescence microscopy has shown that the microstructural characteristics of SBS-modified asphalt undergo significant changes during the aging process. In unaged asphalt, the SBS component exhibits a cross-linked network structure. However, with aging, this network progressively disintegrates, resulting in the emergence of a distinct flocculent and punctate morphology. The degradation of the SBS polymer is further exacerbated by the aging effects associated with hot-wet environments, as indicated by an increased disruption of its chain structure. These findings suggest that SBS is particularly susceptible to degradation under conditions of high temperature and humidity.
4. Analysis conducted using Fourier transform infrared spectroscopy indicated a decrease in the Butadiene Index, accompanied by an increase in both the Sulfoxide Index and the Aromaticity Index during the aging process. This finding suggests that the primary mechanisms driving aging are the degradation of styrene-butadiene-styrene (SBS) and oxidation reactions. The modification of the functional group index is particularly significant in environments characterized by high temperatures and humidity. Elevated temperatures accelerate the degradation of SBS and the oxidation of asphalt components. Furthermore, the presence of moisture exacerbates the deterioration of the asphalt structure through infiltration and dissolution processes. This observation underscores the synergistic effects of temperature and humidness on the aging of asphalt.

REFERENCES

1. **Durmaz, A.C., Morova, N.** Investigation of Performance Properties of Milled Carbon Fiber Reinforced Hot Mix Asphalt *Materials Science (Medžiagotyra)* 30 (1) 2024: pp. 87 – 95. https://doi.org/10.5755/j02.ms.34075
2. **Zhang, M., Yuan, D., Jiang, W.** Effects of TLA on Rheological, Aging, and Chemical Performance of SBS Modified Asphalt *Construction and Building Materials* 438 2024: pp. 137283. https://doi.org/10.1016/j.c0nbuildmat.2024.137283
3. **Cao, Z., Yu, J., Yi, J., Sun, G., Xu, S., Han, X.** Investigation of Road Performances of Rejuvenated Styrene-Butadiene-Styrene Modified Asphalt Mixture *Case Studies in Construction Materials* 18 2023: pp. e02181. https://doi.org/10.1016/j.cscm.2023.e02181
4. **Qin, Y., Meng, Y., Lei, J., Fu, T., Xu, R., Yang, X., Zhao, Q, Xi, C.** Study on the Microscopic Characteristics and Rheological Properties of Thermal-Oxidative Aged and Virgin-Old Recycled Asphalts *European Polymer Journal* 154 2021: pp. 110499. https://doi.org/10.1016/j.eurpolymj.2021.110499
5. **Zhang, Y., Sun, C., Xiao, P., Qian, P., Zhang, Y., Kang, A., Li, Y., Cao, Z.** Study on the Synergistic Regeneration Effect of Tall Oil and Crumb Rubber on Aged SBS Modified Asphalt *Construction and Building Materials* 444 2024: pp. 137870. https://doi.org/10.1016/j.conbuildmat.2024.137870
6. **Hu, J., Lu, J., Wang, L., Wang, G.** Quantitative characterization and analysis of asphalt aging resistance based on dielectric properties *Journal of Building Materials* 25 (9) 2022: pp. 945 – 952. https://doi.org/10.3969/j.issn.1007-9629.2022.09.009
7. **do Nascimento Camargo, I.G., Hofko, B., Mirwald, J., Grothe, H.** Effect of Thermal and Oxidative Aging on Asphalt Binders Rheology and Chemical Composition 13 (19) *Materials* 2020: pp. 4438. https://doi.org/10.3390/ma13194438
8. **Zhang, H., Yang, X., Lin, Y., Wu, C., Jiang, X., Chen, Z.** Comparative Investigation of Different Blends Ageing Behaviours for Short-Term Thermal Oxidation Ageing Mechanism of SBS-Modified Bitumen *Road Materials and Pavement Design* 24 (4) 2023: pp. 1088 – 1102. https://doi.org/10.1080/14680629.2022.2060126
9. **Li, X., Jian, C., Kang, S.** Thermal Oxidative Aging Mechanism of Crumb Rubber/SBS Composite Modified Asphalt *Construction and Building Materials* 75 2015: pp. 169 – 175. https://doi.org/10.1016/j.conbuildmat.2014.08.035
10. **Qin, Y., Meng, Y., Lei, J., Fu, T., Xu, R., Yang, X., Zhao, Q., Xi, C.** Study on the Microscopic Characteristics and Rheological Properties of Thermal-Oxidative Aged and Virgin-Old Recycled Asphalts *European Polymer Journal* 154 2021: pp. 110499. https://doi.org/10.1016/j.eurpolymj.2021.110499
11. **Sun, X., Peng, Q., Zhu, Y., Chen, Q., Yuan, J., Zhu, Y.** Effects of UV Aging on Physical Properties and Physicochemical Properties of ASA Polymer-Modified Asphalt *Advances in Materials Science and Engineering* 2022 (1) 2022: pp. 1157687. https://doi.org/10.1155/2022/1157687

12. **Liu, H., Zhang, Z., Tian, Z., Lu, C.** Exploration for UV Aging Characteristics of Asphalt Binders Based on Response Surface Methodology: Insights from the UV Aging Influencing Factors and Their Interactions *Construction and Building Materials* 347 2022: pp. 128460. https://doi.org/10.1016/j.conbuildmat.2022.128460
13. **Zeng, W., Wu, S., Wen, J., Chen, Z.** The Temperature Effects in Aging Index of Asphalt During UV Aging Process *Construction and Building Materials* 93 2015: pp. 1125 – 1131. https://doi.org/10.1016/j.conbuildmat.2015.05.022
14. **Li, L., Guo, Z., Ran, L., Zhang, J.** Study on Low-temperature Cracking Performance of Asphalt under Heat and Light Together Conditions *Materials* 13 (7) 2020: pp. 1541. https://doi.org/10.3390/ma13071541
15. **Zhang, D., Zhang, H., Shi, C.** Investigation of Aging Performance of SBS Modified Asphalt with Various Aging Methods *Construction and Building Materials* 145 2017: pp. 445 – 451. https://doi.org/10.1016/j.conbuildmat.2017.04.055
16. **Baek, C., Underwood, B.S., Kim, Y.R.** Effects of Oxidative Aging on Asphalt Mixture Properties *Transportation Research Record* 2296 (1) 2012: pp. 77 – 85. https://doi.org/10.3141/2296-08
17. **Nabizadeh, H., Naderi, B., Tabatabaee, N.** Effects of Moisture on Warm Mix Asphalt Containing Sasobit *Scientia Iranica* 24 (4) 2017: pp. 1866 – 1873. https://doi.org/10.24200/sci.2017.4277
18. **Arabani, M., Hamedi, G.H.** Using the Surface Free Energy Method to Evaluate the Effects of Liquid Antistrip Additives on Moisture Sensitivity in Hot Mix Asphalt *International Journal of Pavement Engineering* 15 (1) 2014: pp. 66 – 78. https://doi.org/10.1080/10298436.2013.778410
19. **Wei, H., Bai, X., Qian, G., Wang, F., Li, Z., Jin, J., Zhang, Y.** Aging Mechanism and Properties of SBS Modified Bitumen under Complex Environmental Conditions *Materials* 12 (7) 2019: pp. 1189. https://doi.org/10.3390/ma12071189
20. **Liu, X., Sha, A., Li, C., Zhang, Z., Li, H.** Influence of Water on Warm-Modified Asphalt: Views from Adhesion, Morphology and Chemical Characteristics *Construction and Building Materials* 264 2020: pp. 120159. https://doi.org/10.1016/j.conbuildmat.2020.120159
21. **Ma, T., Huang, X., Mahmoud, E., Garibaldy, E.** Effect of Moisture on the Aging Behavior of Asphalt Binder *International Journal of Minerals, Metallurgy, and Materials* 18 (4) 2011: pp. 460 – 466. https://doi.org/10.1007/s12613-011-0463-4
22. **Luo, X., Xie, K., Zhao, S., Yao, Q., Qin, Y.** Study of the Molecular Components and Rheological Properties of Asphalt after Long-term Aging under the Action of Moisture *Sustainability* 14 (15) 2022: pp. 9080. https://doi.org/10.3390/su14159080
23. **Li, R., Wang, Y., Zhu, W., Chen, Y., Yue, J.** Research on the Rheological Performance of Fast-Melting SBS-Modified Asphalt under Complex Environmental Factors *Coatings* 14 (10) 2024: pp. 1241. https://doi.org/10.3390/coatings14101241
24. **Sun, G., Li, B., Sun, D., Yu, F., Hu, M.** Chemo-rheological and Morphology Evolution of Polymer Modified Bitumens under Thermal Oxidative and All-weather Aging *Fuel* 285 2021: pp. 118989. https://doi.org/10.1016/j.fuel.2020.118989
25. **Li, Q., Zeng, X., Wang, J., Luo, S., Meng, Y., Gao, L., Wang, X.** Aging Performance of High Viscosity Modified Asphalt under Complex Heat-Light-Water Coupled Conditions *Construction and Building Materials* 325 2022: pp. 126314. https://doi.org/10.1016/j.conbuildmat.2022.126314
26. **Wang, K., Cheng, X., Zhu, Y., Li,H.** Study on Performance Deterioration Regularity of Hot Regenerated Asphalt Mixture under Multiple Aging Factors *Construction and Building Materials* 369 2023: pp. 130568. https://doi.org/10.1016/j.conbuildmat.2023.130568
27. **Guan, M., Guo, M., Liu, X., Du, X., Tan, Y.** Effect of Multifactor Coupling Aging on Rheological Properties of Asphalt Binders and Correlations Between Various Rheological Indexes *Journal of Materials in Civil Engineering* 36 (5) 2024: pp. 04024088. https://doi.org/10.1061/JMCEE7.MTENG-17116
28. **Wang, H., Feng, Z., Zhou, B., Yu, J.** A Study on Photo-Thermal Coupled Aging Kinetics of Bitumen *Journal of Testing and Evaluation* 40 (5) 2012: pp. 1 – 4. https://doi.org/10.1520/JTE20120065
29. **Li, Y., Li, H., Nie, S., Wu, S., Liu, Q., Li, C., Shu, B., Li, C., Song, W., Zou, Y., Pang, L.** Negative Impacts of Environmental Factors (UV Radiation, Water and Different Solutions) on Bitumen and its Mechanism *Construction and Building Materials* 265 2020: pp. 120288. https://doi.org/10.1016/j.conbuildmat.2020.120288
30. **Yang, B., Li, H., Sun, Y., Zhang, H., Liu, J., Yang, J., Zhang, X.** Chemo-rheological, Mechanical, Morphology Evolution and Environmental Impact of Aged Asphalt Binder Coupling Thermal Oxidation, Ultraviolet Radiation and Water *Journal of Cleaner Production* 388 2023: pp. 135866. https://doi.org/10.1016/j.jclepro.2023.135866
31. **Sun, Y., Hui, L., Yang, B., Han, Y., Zou, Z.** Investigation on Rheological Properties and Aging Mechanism of Asphalt under Multiple Environmental Conditions *Construction and Building Materials* 443 2024: pp. 137713. https://doi.org/10.1016/j.conbuildmat.2024.137713
32. **Yuan, J., Li, H., Li, T., Huang, J., Sun, W.** Evolution of Asphalt Performance under the Coupled Aging of Ultraviolet, High Temperature and Water *Case Studies in Construction Materials* 20 2024: pp. e03220. https://doi.org/10.1016/j.cscm.2024.e03220
33. **Zhang, S., Cui, Y., Du, C., Liu, L., Chen, Q.** Low-Temperature Performance and Micro-structure of Warm Mix Recycled Composite Aged Asphalt *Construction and Building Materials* 440 2024: pp. 137443. https://doi.org/10.1016/j.conbuildmat.2024.137443
34. **Ren, J., Zhang, X., Peng, C., Wang, Y., Wang, Y., Zhao, H., Xu, X., Xia, L., Wang, C., Li, G., Zhao, Z., Chen, J., Wang, J.** Short-term Aging Characteristics and Mechanisms of SBS-modified Bio-asphalt Binder Considering Time-dependent Effect *Construction and Building Materials* 352 2022: pp. 129048. https://doi.org/10.1016/j.conbuildmat.2022.129048
35. **Ma, X., Zhang, C., Li, R., Zheng, L., Xu, J.** Effect of Temperature and Humidity Environment on the Microstructure and Physicochemical Properties of SBS Modified Asphalt *Case Studies in Construction Materials* 22 2025: pp. e04192. https://doi.org/10.1016/j.cscm.2024.e04192
36. **Gong, Y., Xu, J., Chang, R., Yan, E.** Effect of Water Diffusion and Thermal Coupling Condition on SBS Modified Asphalts' Surface Micro Properties *Construction and Building Materials* 273 2021: pp. 121758. https://doi.org/10.1016/j.conbuildmat.2020.121758