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The effect of freeze-thaw cycles on durability properties of SBS-modified bitumen

Tengfei Nian [a], Ping Li [a,b,*], Xiying Wei [a], Penghui Wang [a], Huishan Li [a], Rui Guo [c]

[a] School of Civil Engineering, Lanzhou University of Technology, Lanzhou 730050, China
[b] Western Center of Disaster Mitigation in Civil Engineering of Ministry of Education, Lanzhou University of Technology, Lanzhou 730050, China
[c] School of Civil Engineering and Architecture, Shaanxi University of Technology, Hanzhong 723000, China

HIGHLIGHTS

- The relation between the rheological parameters of bitumen was analyzed during freeze-thaw cycles.
- The relation between %R and J_{nr} of SBS-modified bitumen after freeze-thaw cycles was discussed by the MSCR.
- Using the FTIR technology was analyzed the changes in the chemical composition of bitumens under freeze-thaw cycles.

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ABSTRACT

To study the high-temperature characteristics of bitumen under the influence of freeze-thaw cycles, the results of DSR tests of bitumen and SBS-modified bitumen after 0, 3, 6, 9, 12, 15, and 18 freeze-thaw cycles were investigated. First, based on the simplified model for the DSR tests, the relation between the rheological parameters of the bitumen was analyzed. Then, in combination with the MSCR tests of the SBS-modified bitumen after freeze-thaw cycles, the relation between %R and J_{nr} was discussed. Finally, FTIR was used to analyze the changes in the chemical composition of the bitumen under freeze-thaw cycles. The results showed that the incorporation of SBS modifiers can increase the elasticity of the bitumen significantly and slow the tendency of the bitumen's complex shear modulus to increase with the freeze-thaw cycles to a certain extent. The SBS modifiers also can reduce the bitumen's temperature sensitivity and improve its rutting resistance. After the freeze-thaw cycles, $G^*/\sin\delta$ decreased as temperature increased, and $G^*\sin\delta$ showed an exponential decay with increasing temperature. With an increase in the number of freeze-thaw cycles, $G^*\sin\delta$ of the bitumen and SBS-modified bitumen increased gradually, which indicated that the bitumen's fatigue resistance weakens gradually after freeze-thaw cycles. The %$R_{0.1}$ and %$R_{3.2}$ of SBS-modified bitumen showed a decreasing trend under different stress levels, and the $|\%R_{3.2} - \%R_{0.1}|$ increased, which indicates that bitumen's high temperature characteristics and temperature fatigue performance show an attenuating trend. The difference between the FTIR spectra of the SBS-modified bitumen fingerprint area after a freeze-thaw cycle was reflected largely in the significant increase in the 1700 cm^{-1} carbonyl group and 1031 cm^{-1} sulfoxide group peaks, while the two peaks at 967 cm^{-1} and 700 cm^{-1} were relatively stable. These results provide a theoretical basis and technical support for the design, material selection, popularization, and application of an SBS-modified bitumen mixture in roads in regions with seasonal freezing.

1. Introduction

Bitumen pavement has many advantages, including smoothness, riding comfort, low vibration and noise, and easy maintenance, and accordingly, all countries favor its use [1]. However, changes in bitumen's chemical composition and rheological properties play key roles in road performance. The selection of excellent bitumen can reduce the occurrence of a series of early-stage defects, including cracking, rutting, settlement, and spalling effectively [2,3]. In addition, because of atmospheric factors, (sunshine, temperature, rain, and snow), the environment, and traffic intensity, bitumen road's performance attenuates gradually, causing a variety of poor conditions in bitumen pavement, such as cracks, pits, potholes, and slush. These conditions shorten the service life

* Corresponding author at: School of Civil Engineering, Lanzhou University of Technology, Lanzhou 730050, China.

E-mail address: lzlgliping@126.com (P. Li).

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of bitumen pavements, increase their maintenance frequency and costs, and affect the smooth flow of traffic and transportation safety [4,5]. As the service environment affect bitumen pavement, its high-temperature rheological properties and temperature fatigue characteristics have a significant effect on the performance of the bitumen mixture used in pavement, especially in regions that are frozen seasonally.

Because of increasing traffic volume and loading, there are continuing efforts to improve bitumen's mechanical properties through the addition of polymers, to reduce potential rutting and fatigue cracking, increase cohesion, and decrease temperature susceptibility [6–8]. Styrene-butadiene-styrene (SBS) is a polymer that has both rubber elasticity and resin thermos plasticity, so it has good elasticity, high tensile strength, good low-temperature deformation properties, and other advantages. Thus, scholars from various countries have advocated its widespread use as a bitumen modifier.

It has been proven that when bitumen and SBS are blended and modified, this mixture can improve the elasticity and anti-permanent deformation ability of bitumen materials effectively and reduce their temperature-sensitivity; as a result, the engineering performance of the modified bitumen pavement shows obvious enhancement [9,10]. Using fluorescence microscopy technology, fluorescence micrographs of SBS modifiers with different contents have been compared and analyzed. It was found that the network structure of SBS-modified bitumen was the most significant when the SBS content was 5%, which indicated that this modification of bitumen produces the best effect [11]. However, it also has been found that the addition of SBS modifier sometimes is too large or too small to be beneficial to the bitumen's modification. Thus, understanding bitumen's durability properties has become one of the most challenging topics in pavement engineering, and many researchers have studied the effects of SBS modifications in improving bitumen's mechanical properties; however, few have studied their effects on bitumen's durability.

Thus, these durability properties were studied [5] at high temperature for two bitumen modified differently: SBS as an elastomer and EVA as a plastomer. Various amounts of polymer were used, ranging from 3% to 9%. The results showed that SBS-modified bitumen has lower viscosity and temperature sensitivity than does EVA-modified bitumen and is more resistant to cracking and rutting. Some studies [12,13] have investigated the effects of common laboratory short- and long-term aging methods on bitumen's rheological properties and compared them to the effects of durability. The hardening of bitumen largely was caused by oxidation, volatilization of light components, and the selective adsorption or absorption of components in bitumen by aggregates; further, it was believed that the oxidation occurred throughout the bitumen's life.

The Dynamic Shear Rheometer (DSR) test technique was used to evaluate the dynamic shear modulus and phase angle changes of short- and long-term aged bitumen, which indicated that the dynamic shear modulus and phase angle of bitumen can be used to evaluate the viscosity of aged and unaged bitumen and predict their ability to resist rutting and fatigue cracking. The dynamic shear modulus and phase angle exhibit a linear variation with aging times [14].

In summary, it can be seen that scholars worldwide have begun to pay more attention to the effect of bitumen's durability properties on bitumen pavement's performance. However, studies of bitumen's properties after freeze-thaw cycles has received less attention.

To characterize the properties of a bitumen related to bitumen mixture rutting, the Superpave Performance Grade System uses a high-temperature grade that is determined based on the complex shear modulus ($|G^*|$) and phase angle (δ) parameter ($|G^*|/\sin\delta$) as measured by a DSR test. As more and more modified bitumen is used in the pavement, the existing specifications used to grade bitumen, i.e., the AASHTO M320, have shown some inadequacies [15]. Accordingly, the U.S. federal government has proposed a method to evaluate the high-temperature properties of modified bitumen based on PG classification: The Multiple Stress Creep Recovery (MSCR) test that characterizes bitumen's high-temperature performance by testing the creep and recovery properties of modified bitumen. Several studies [15–17] have indicated that the MSCR is a performance-related test that has a good correlation with bitumen mixtures' rutting performance. MSCR also is a simple and fast test that can be performed in a standard DSR machine.

With the development of science and technology, higher requirements for the methods of characterizing bitumen also have been put forward. Because of bitumen's structure and properties, it is difficult to characterize with a purely material test. Fourier transform infrared spectroscopy (FTIR) is a test method used widely that has attracted many scholars' attention [18–20]. Research has shown that [21], by using FTIR, bitumen can be classified into natural, coal tar pitch, and petroleum bitumen. These three kinds of common bitumen's absorption peaks are 2920 cm^{-1}, 1600 cm^{-1}, 1460 cm^{-1}, 1380 cm^{-1}, and 910 cm^{-1}, respectively. By comparing the peak areas of the oxygen-containing functional groups in the 1800–600 cm^{-1} range of the infrared spectra before and after aging different bitumens, their infrared spectra differ after aging, as the sulfoxide group of bitumen with a higher sulfur content and the peak of the carbonyl group increased obviously after aging [13,19].

On the other hand, among the different climatic agents, the presence of moisture in bitumen mixtures is one of the major contributors to pavement degradation and the effects of freeze-thaw cycles and prolonged warm periods accelerate this deterioration [22–24]. When water freezes, the presence of moisture can damage the bitumen mixture by the expansion of water [25]. The effect of freeze-thaw cycles also leads to the loss of aggregate-binder adhesion [26], and bitumen becomes hard and brittle under freeze-thaw cycles, which are among the causes of bitumen pavement cracking [27].

Bitumen's rheological properties after freeze-thaw cycles were evaluated using the Bending Beam Rheometer (BBR) test [23,28], and the results indicated that the climatic and traffic load characteristics of regions frozen seasonally were factors that affect the deterioration in bitumen mixture's pavement performance. Therefore, because of the great differences in climates in different regions, the anti-fatigue and cracking properties of bitumen mixtures require further study.

In summary, research on the chemical groups of bitumen, rheological properties, and pavement performance has focused largely on the analysis and evaluation of physical and chemical changes, the rheological parameters of bitumen or modified bitumen after short- and long-term aging, or the introduction of various modern testing technologies to detect and characterize the bitumen's material structure and performance. In addition, with a change in the typical climatic environment (i.e., times of freeze-thaw cycles), research about the performance of bitumen and bitumen mixtures has concentrated primarily on the evaluation of the attenuation law with the changes in the times of freeze-thaw cycles. However, there are few studies of the changes in chemical composition, rheological property parameters of bitumen after freeze-thaw cycles. Therefore, this research addressed the durability properties of bitumen and SBS-modified bitumen after freeze-thaw cycles (Fig. 1).