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Connections between chemical composition and rheology of aged base asphalt binders during repeated freeze-thaw cycles

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HIGHLIGHTS

- A self-assembled device was used to make FT-IR test samples under damage conditions.
- A quantitative analysis using FT-IR was put forward to calculate asphalt binder functional groups.
- The variety rule of the rheological index of asphalt binder was explored.
- The relationship between the rheological indexes and contents of functional groups were established.

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ABSTRACT

The chemical composition and rheological properties of asphalt binder play a key role in the performance of the asphalt pavement. However, pavement diseases (cracks, pitted surface, potholes and slurry) caused by the degradation of pavement performance have shortened the service life of the asphalt pavement and increased maintenance and repair costs, seriously affected the smooth flow of traffic and traffic safety. In this study, the sum of the different absorption peak areas of the asphalt binder spectroscopy was selected as a reference. Fourier Transform Infrared Spectroscopy (FT-IR) quantitative analysis was carried out on the Rolling Thin Film Oven (RTFO) test with different aging cycles and Pressure Aging Vessel (PAV) test of the asphalt binder after aging. Based on the above analysis, the author tries to establish a reliable FT-IR quantitative analysis method. An FT-IR specimen which could be subjected to multiple freeze-thaw cycles could be prepared by the self-designed test sample preparation device. By carrying out the freeze-thaw cycle aging test of asphalt binder for 0, 3, 6, 9, 12, 15 and 18 times, combining FT-IR and Dynamic Shear Rheological (DSR) testing techniques, the author explored the relationship between chemical composition and rheological performance parameters of asphalt binder in cold region, which were based on the Levenberg-Macquarie method and test data of universal global optimization algorithm regression analysis. The results show that FT-IR can not only qualitatively analyze and study the structure and chemical composition of asphalt binder before and after aging on a micro level, but also quantitatively represent the changes of characteristic functional groups before and after aging of asphalt binder. It is feasible to calculate the absorption peak area for FT-IR quantitative analysis using the tangent at the lowest point on both sides of the spectral absorption peak as the calibration baseline. It is recommended to use the range of 2000–650 cm^{-1} absorption peak area sum as a benchmark for FT-IR quantitative analysis. The complex shear modulus of the asphalt binder shows a linear growth with the increase of freeze-thaw cycles, and phase angle of asphalt binder also shows a linear growth with the increase of $\ln T$. There is a multivariate linear relationship between the rheological index and chemical functional groups after the aging freeze-thaw cycle.

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1. Introduction

Asphalt pavement is of great importance and favored by all countries, based on its advantages of smooth-ride, small vibration, low noise and easy maintenance [1]. However, as a result of the influence of atmosphere, temperature, sunlight, rain and snow, the environment and traffic intensity, the pavement performance degrades gradually, leading to pavement distress such as cracks, pitted surface, potholes and slurry. Therefore, the service life of the asphalt pavement has been shortened, the maintenance frequency and the maintenance costs have increased, even the smooth flow of traffic and traffic safety have been seriously affected [2–4].

The chemical composition and rheological properties of asphalt binder play a key role in the performance of the asphalt pavement, which has been a hot issue about the study of road construction materials for domestic and international [5,6]. During the process of refining, storage, transportation, paving and using, asphalt has been influenced by high- and low-temperature, water damage and ultraviolet radiation and other factors, leading to changes of its chemical composition, physical properties and rheological properties changed, which has caused different degree of aging of asphalt binder, namely "hardening" [7–9]. The Strategic Highway Research Program (SHRP) proposes that there are long and short-term aging of asphalt binders. And it is very effective to simulate the short-term aging of asphalt binders during the mixing and paving process with a RTFO. At present, pressure aging container test (PAV) has been adopted in many countries to study long-term aging asphalt binders [10–13]. Mallick et al. [14,15] compared the effect of RTFO aging of asphalt binders and short-term oven aging of asphalt mixtures using gel-permeation chromatography. They found RTFO to be less effective for binder aging than short-term oven aging for asphalt mixtures. Mohamed et al. [9,16–19] investigated the effects of common laboratory short- and long-term aging methods on the rheological properties of binders and compared them to the effects of field aging. The hardening of asphalt binders is mainly caused by oxidation, volatilization of light components, and the selective adsorption of the asphalt components by aggregates, and it is considered that oxidation runs through the whole process of asphalt service life. Ala et al. [20] used both base binder and RTFO residue for PAV aging to determine if the suggested sequence of the two aging procedures is necessary. They concluded that using RTFO residue for PAV has a significant effect on rheological properties measured by DSR and Bending Beam Rheometer (BBR) tests. Yut et al. [11] employ DSR test to evaluate the change of dynamic shear modulus and phase angle of asphalt binders after RTFO and PAV aging. The results show that measuring the dynamic shear modulus and phase angle can not only evaluate viscosity and elastic properties of asphalt binders before and after aging but also predict the ability to resistance rut and fatigue cracking. A linear relationship between $\ln G^*$ and δ with the aging time can also be shown in this test From the above discussion, we can see that the views varies from scholar to scholar, but there are also similarities, that is, the aging of asphalt binder aging is not a single reaction, but the comprehensive result of multiple reactions including oxidation, volatilization, adsorption, aggregation, agglomeration, fracture.

With the development of science and technology for domestic and international, a higher requirement has been put forward for the means of characterization of asphalt. Due to the complex structure of the asphalt and its traits, it is particularly to represent the asphalt using the pure material test method, while FT-IR, as a widely used test methods, has attracted a lot of attention and study from scholars [21–24]. Li et al. [25] used the FT-IR to measure 16 kinds of base asphalt binders, they classified and distinguished the infrared spectrum of natural asphalt, coal tar pitch and petroleum asphalt, and they pointed out that 2920 cm^{-1}, 1600 cm^{-1}, 1460 cm^{-1}, 1380 cm^{-1} and 910 cm^{-1} are the common absorption peaks of the three major types of asphalt. And the ratio of the unknown spectrum to the characteristic absorption peak can tell which petroleum asphalt is. Liu et al. [18,22] chose four different kinds of matrix asphalts and studied their thermal-oxidizing aging and chemical composition through infrared spectrum. By comparing the size of the peak area of the oxygen functional groups in the range of 1800–600 cm^{-1} before and after aging of each asphalt binder, they found out that different asphalts changed differently after aging, and that sulfoxide increased significantly in asphalt with higher sulfur after aging, on the contrary, its carbonyl peak increased significantly. Chen et al. [26] used Perkin Elmer 1700 infrared spectrometer to measure the FT-IR of the base asphalt binders before and after aging. The results showed that the formation of oxygen functional groups, such as ketone and carbonyl group, caused the aging of asphalt binder. In addition, the discovery of asphalt after aging brought out carbonyl C=O and sulfoxide S=O, and the reaction degree deepened with the prolonging of aging time. WRI et al. [11,27] reported that the concentration of carbonyl functional group in a binder correlates very well with the complex modulus of the binder. The logarithm of the complex shear modulus (G^*) value of the binder was found to be linearly related to the absorption intensity of carbonyl groups in FT-IR spectra, and the relationship was inversely linear for the phase angle (δ) value. Zahid et al. [28] used FT-IR and DSR test were used to analyze the rheological properties of modified asphalt binder. It was found that the predicted value $G^*/\sin\delta$ of FT-IR test had the same trend as DSR test value.

On the other hand, among the different climatic agent, the presence of moisture in the asphalt mixtures is defined as one of the major contributors to the degradation of the pavements as well as the effect of freeze-thaw cycles and prolonged warm periods also induce the acceleration of their deterioration [29–31]. Due to water freezing the presence of moisture can lead to the asphalt mixture damaged by the expansion of water in cold regions [32]. The effect of freeze-thaw cycles also causes the loss of aggregate-binder adhesion [33]. The study of Sayadi et al. [34] showed that asphalt binder became hard and brittle after the freeze-thaw cycle aging, which was prone to cracking for the asphalt pavement. Xu et al. [35,36] adopted X-ray CT to do the mapping test on the internal structure of three kinds of asphalt mixtures, which showed that after freeze-thaw cycles the void structure of asphalt mixture increased with expansion forming new space, thus the formed new cracks had a serious impact on the stability of the internal structure. Tested for Direct Tensile Strength (DTS) of asphalt mixture before and after freeze-thaw cycles by Hamzah [37] showed that the freeze-thaw cycles had a serious impact on the tensile strength and adhesion of asphalt mixture. Sol-Sánchez et al. [30,38] used BBR test evaluating the rheological properties of asphalt binder after freeze-thaw cycles, and showed that the climate characteristics and traffic load characteristics of the seasonally frozen zone are the factors of the deterioration of the road performance of the asphalt mixture, and then proposed that the anti-fatigue and cracking properties of the asphalt mixture need further study because of the large difference of climate in each region.

In conclusion, the chemical composition, rheological properties and road performance of asphalt binder are mainly studied in the analysis of physical and chemical changes and rheological parameters of base asphalt or modified asphalt after aging by RTFO and PAV with evaluation. Meanwhile, some modern testing techniques (such as FT-IR, X-ray CT, etc.) are introduced to test and represent the structure and properties of materials. However, it needs to be studied further that the performance parameters of asphalt binder are established by combining the modern test structure and the traditional performance test method. In addition, the study on the performance of asphalt and asphalt mixture mainly focuses