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Low-temperature cohesive and adhesive strength testing of contact surface between bitumen and mineral aggregates by image analysis

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HIGHLIGHTS

- Test technology of asphalt cohesive and adhesive strengths was investigated.
- Image analysis was employed to identify the cohesive and adhesive failure areas.
- Least-squares method was adopted to address the discreteness of the data.

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ABSTRACT

The quantitative test technology of asphalt cohesive and adhesive strengths was investigated. An accurate force measuring device was used to perform a destructive test. The cohesive and adhesive strengths of bitumen were determined according to the relationship among tensile failure load, failure area, and strength. Image processing technology was employed to accurately identify the cohesive and adhesive failure areas. Least-squares method was adopted to address the discreteness of the data. Results show that this quantitative testing technology can be used to accurately determine the cohesive and adhesive strengths of the contact surface between bitumen and mineral aggregates under different low-temperature conditions. The proposed quantitative testing technology provides an experimental basis for future work.

1. Introduction

The contact surface between bitumen and mineral aggregates exhibits two mechanical failure modes: cohesive failure (bitumen destroys itself), and adhesive failure at the bitumen and mineral interface [1–4]. The cohesive and adhesive effects of the bitumen binder indicate low-temperature cracking resistance and anti-stripping property [5–10].

Low-temperature cracking is a typical failure mode of flexible pavement in seasonal frost areas [1]. Pavement cracking in winter can severely affect the normal operation of traffic [2]. Currently, direct tensile strength, indirect tensile strength of bitumen mixtures, and Bending-Beam Rheometer derived from the Strategic Highway Research Program are the main evaluation technologies to evaluate the cold performance of asphalt. For asphalt concrete material, the properties of bitumen are major factors that influence low-temperature pavement performance, and the cohesive and adhesive strengths of the bitumen are critical mechanical parameters [1].

In material engineering, solid–liquid adhesion theory can be adopted to address adhesion problems between hot-melt bitumen and mineral aggregates. Numerous studies have adopted this theory to analyze adhesion at the bitumen and mineral interface in high-temperature states [11]. For example, Hefer and other researchers determined the contact angle of bitumen and the mineral surface through various techniques [12,13]. Zhang et al. analyzed the effects of temperature, loading frequency, and rheological property on asphalt–filler interaction ability [14]. Yao et al. analyzed the effects of aging on the water resistance of a mixture [15]. The crack disadvantages of bitumen pavement have critical relationships with the cohesive and adhesive properties of bitumen [16–21]. Thus, confirming the cohesive and adhesive strengths is important in the study of the crack resistance abilities of a mixture. The cohesive and adhesive strengths of bitumen under low-temperature conditions need to be investigated.

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Zhang J. et al. used the pneumatic adhesion tensile testing instrument (PATTI) to evaluate the bonding properties of asphalt and mineral aggregates at −10 °C, 10 °C, 20 °C, 30 °C, and 40 °C and obtained the change law of the bonding strength of bitumen and mineral interface [22]. Gonzalo Valdes Vidal et al. presented a new methodology based on Fenix test procedure to analyze the adhesion of bitumen and mineral interface; the experiment considered the effects of water and aging at −10 °C to −20 °C [23]. L. T. MO. et al. [24] investigated the tensile fatigue behavior of bitumen–aggregate adhesion under stress-controlled mode and the failure mechanisms by using finite element analysis based on stress distribution. Asa Laurell Lyne et al. used Hamaker's constant to evaluate bitumen and aggregates based on their refractive indices [25].

The concept of cohesion and adhesion of asphalt and mineral interface has been gradually accepted by researchers at home and abroad. Many scholars analyzed the mechanical properties of the asphalt and mineral interface. The cohesive and adhesive properties of the asphalt and mineral interface at present stage can be analyzed through surface tension theory, measurement of mechanical parameters, and finite element modeling technology.

Asphalt is a significant temperature-sensitive material, and its mechanical properties vary significantly at different temperatures. Thus, the author used a technology for measurement of mechanical parameters to analyze the cohesive and adhesive properties of asphalt and mineral interface under low-temperature conditions. Based on the proposed quantitative testing technology, cohesion and adhesion damages simultaneously exist under low-temperature conditions obtained through various experiments. In the present study, image processing was adopted to recognize and analyze failure areas of cohesion and adhesion. The adhesive strength of the bitumen and mineral aggregate interface and the cohesive strength of bitumen itself were quantitatively measured via least-squares principle.

2. Experimental materials and test method

2.1. Experiment materials

Bitumen with a penetration grade of 90 was the main raw material used in this experiment. The bitumen was modified by styrene butadiene styrene block copolymer (SBS). SBS was mixed into hot-melt bitumen at the weight ratio of 5.0% using a high-speed shearing machine. The size of the specimen, which was made of limestone, was $1.8 \times 1.8\ cm^2$. The technical parameters of materials are shown in Table 1. During the experiments, the tensile load was applied to the specimens using HC-40 small-loading equipment. The ultimate loads of the specimens ranged from 0.30 to 0.60 KN. Performance indicators of asphalt and limestone mineral materials all meet the requirements of the specification of JTGD50-2017 and JTGF40-2004, respectively.

Table 1
Technical parameters of materials.

Physical properties of bitumen	Unit	Test result	
		Normal bitumen	Modified bitumen
Penetration (100 g, 5 s, 25 °C)	0.1 mm	85	63
Ductility (5 cm/min, 15 °C)	cm	>100	>100
Softing point	°C	48.5	67.2
Ductility (5 cm/min, 5 °C)	cm	53	37.7
Standard viscosity (60 °C)	pa.s	4120	6246
Standard viscosity (90 °C)	pa.s	2658	3820
Limestone mineral materials	Density ($g.cm^{-3}$)	Roughness (μm)	Water absorption rate (%)
	2.73	2.235	0.85

2.2. Experiment method

The modified bitumen specimens were placed in the heating oven for 10 min at 163 °C to reach the hot-melt state. Simultaneously, the surfaces of the mineral aggregates were also preheated with the hot knife. The hot-melt bitumen then needed to be evenly spread on the surface of the mineral aggregate by the hot knife to bind the two mineral aggregates. After cooling at room temperature for 45 min, the specimens were frozen for 4 h under a constant low-temperature test environment at −5 °C, −15 °C, and −25 °C, respectively. When one specimen had been prepared, this technology was used in the load test, which has been authorized as a patented Chinese invention (Patent No. ZL 201210359254.3). The test principle is shown in Fig. 1. The mineral aggregates on the equipment are made of limestone mineral materials and prepared in advance, installed on both ends of the stretching contact. The tensile load was slowly imposed on the specimen until it was destroyed, and the tensile strength was recorded using this technology. The loading rate was 5 mm/min, and the average bitumen film thickness was 0.2 mm maintaining through a 2 mm prefabricated annular hollow test pad. The surface of the mineral test mode retained the original microstructure. The failure surfaces of adhesion and cohesion could be distinguished by naked eyes. However, owing to environmental conditions, such as the exposure rate, the texture of the failure surface, and the humidity, the appropriate picture cannot be easily obtained during the experiment. Excessive light might produce specular reflection, but weak light might influence the resolution. In addition, the water film can make the picture unclear. Therefore, before the water film is formed on the surface, some pictures need to be taken and processed to ensure that the ideal one could be obtained. The tensile experiment is shown in Fig. 2. To accurately determine the cohesive and adhesion strengths, we chose around 10 parallel samples at each temperature for testing, which can guarantee that the number of valid samples is 7. Three low-temperature conditions, namely, −5 °C, −15 °C, and −25 °C, were considered in this experiment by using environmental chambers to keep their cryogenic temperatures.

2.3. Testing of cohesive and adhesive failure ratios

Statistical results have shown that the bitumen and mineral material interface presents surface damages caused by the effect of direct tensile load. These damages include bitumen cohesive failure destruction and adhesive failure destruction, which refer to separation between the bitumen and mineral aggregate surface. The damaged area of the bitumen and mineral material interface consists of the adhesive and cohesive failure areas. As shown in Fig. 3(a), their ratio is difficult to obtain because the adhesive and cohesive failure areas are random and discrete at the damage interface. Therefore, image processing technology needs to be employed to distinguish the failure destruction image by various gray levels and to identify the cohesive and adhesive failure areas.

Maximum class-square error method, which is also called Otsu algorithm, is employed in image processing technology [26]. The gray image pixels obtained in this method can be divided into two categories: object and background. The cohesive and adhesive failure areas are considered as the target and background in the gray image, respectively. The size of the image is $M \times N$; the gray value of the image pixels is less than the threshold value t, which represents the pixels of the adhesive failure N_a; and the number of other pixels is N_c. The total average gray of the image is defined as