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Comprehensive performance evaluation of low-carbon modified asphalt based on efficacy coefficient method

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ABSTRACT

This study addresses the difficulty in systematically and scientifically evaluating the comprehensive performance of low-carbon modified asphalt. Sixteen technical indexes were selected as evaluation indicators. The corresponding weight of each evaluation index was determined by the coefficient of variation method. The fundamental performance, environmental protection effect, and economic effect of low-carbon modified asphalt were analyzed systematically. A comprehensive performance evaluation system for low-carbon modified asphalt was established based on the efficacy coefficient method. Low-carbon modified asphalt using tourmaline anion powder was selected as an example for inspection. Its comprehensive performance was evaluated, and the optimal content of tourmaline anion powder was determined. The results showed that the comprehensive performance evaluation of low-carbon modified asphalt using tourmaline anion powder reflects well the actual situation, meaning that a comprehensive performance evaluation system for low-carbon modified asphalt based on the efficacy coefficient method is relatively reliable and useful. This study lays the foundation for the comprehensive performance evaluation and further application of low-carbon modified asphalt.

1. Introduction

At present, the development of a low-carbon economy and the construction of a low-carbon society have become a strategic focus for China and the world at large (Jang et al., 2018). With the increase in environmental protection awareness, more stringent requirements for the utility of pavement materials have been put forward (Broin and Guivarch, 2016; Colbert et al., 2016). Road material utility is not limited to the goal of good road performance, durability, and longevity. New low-carbon pavement materials have become one of the main research directions for road researchers (Wang et al., 2013). Low-carbon pavement materials are environmentally-friendly pavement materials with low pollution and low energy consumption. That is, the material offers multiple environmental benefits while ensuring good fundamental performance.

In recent years, research on the behavior and performance improvement of low-carbon pavement materials have been undertaken by many scholars (Guo et al., 2015; Zhao et al., 2017; Xiao et al., 2017). In particular, considerable research has been done on inorganic fine powder modified asphalt (Zhang et al., 2017). Tourmaline anion powder modified asphalt was prepared using the melt blending method. The systematic effect of tourmaline type and amount on asphalt pavement performance was studied (Wang et al., 2014a; b; 2015, 2017a; b; c). Nano-Silicon dioxide modified asphalt was prepared by using chemical grafting method in the ratio of 5% nano-SiO_2 plus 2% SiH_4 as a coupling agent (Sun et al., 2016). The results showed that SiO_2 nanoparticles can significantly improve the high-temperature performance of asphalt. The effects of carbon black on high-temperature and low-temperature performance of asphalt were researched (Geckil et al., 2016). The results showed that the addition of carbon black made the asphalt less susceptible to temperature changes. Diatomite-modified asphalt, rubber-powder-modified asphalt, and diatomite-rubber-powder-modified asphalt were prepared by using physical blending method (Liu et al., 2017). The effect of short-term aging on the performance of these materials was systematically analyzed. Modified coal-tar pitch with SiC nanoparticles was prepared, and the microstructure of the modified coal-tar pitch was studied systematically by using a scanning electron microscope (SEM) (Gubernat et al., 2017). Styrene-butadiene rubber modified asphalts

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with surface modified nano-ZnO was developed (Zhu et al., 2017). The rheological characteristics of styrene-butadiene rubber modified asphalt were studied before and after different subjecting to different aging methods. Based on physical blending method, a new modified asphalt was prepared by using inorganic nanoceramic powder from ceramic waste (Hussein et al., 2017). The morphological properties and rheological characteristics of the modified asphalt were characterized. Overall, most early studies focused on improving the performance of low-carbon modified asphalt materials with inorganic micro powders. However, studies concerning the systematic evaluation of the comprehensive performance, and determination of the optimal content of inorganic micro powders in low-carbon modified asphalt materials have not been thorough or comprehensive enough. This trend obviously limits the development and application of low-carbon modified asphalt materials.

While evaluating the comprehensive performance of low-carbon modified asphalt materials, it is necessary to consider the evaluation indexes comprehensively, such as the fundamental performance, environmental protection effect, and economic effect. These evaluation indexes are usually contradictory. Thus, it is difficult to evaluate the comprehensive performance of low-carbon modified asphalt materials. Therefore, the question of how to use scientific theories and methods to coordinate contradictory evaluation indicators, and how to perform a scientific and rational comprehensive evaluation on the performance of low-carbon modified asphalt materials are key issues that need to be solved in research and application processes.

This study addresses the difficulty in systematically and scientifically evaluating the comprehensive performance of low-carbon modified asphalt materials, and introduces the efficacy coefficient method into the evaluation. The comprehensive performance evaluation index system for low-carbon modified asphalt is constructed, and an evaluation model based on the efficacy coefficient method is established. Tourmaline anion powder low-carbon modified asphalt is selected as an example for comprehensive evaluation, and the optimal content of tourmaline anion powder is determined.

2. Test materials and methods

2.1. Raw materials

Based on the environmental protection effect of low-carbon modified asphalt materials, tourmaline anion powder with piezoelectric and thermoelectric properties was selected through a large number of investigations and tests. A new type of low-carbon asphalt modified by tourmaline anion powder was developed with matrix asphalt and dispersant. The composition of raw materials and technical indicators is shown in Table 1.

2.2. Preparation of low-carbon modified asphalt

The preparation process must be strictly controlled at each step when preparing low-carbon asphalt modified by tourmaline anion powder. A suitable amount of dispersant added during the preparation process can improve the performance of the asphalt. The specific steps of the preparation process are as follows:

(1) Sodium polyphosphate and hexametaphosphate were mixed in a 1:1 ratio as dispersant. The tourmaline anion powder and a suitable amount of dispersant (5% of the mass of tourmaline anion powder) were added to a beaker containing ethanol solution. The beaker was placed in an ultrasonic cleaner and shaken with ultrasonic vibration for 30 min to mix it evenly, so that the tourmaline anion powder was fully activated on the surface. Then, the beaker was placed in a drying oven. The temperature was controlled at $105 \pm 5\,^{\circ}C$.
(2) The SBS I-D modified asphalt was heated for dehydration at $160 \pm 5\,^{\circ}C$. The content of tourmaline anion powder was adjusted to 0%, 5%, 10%, 15%, and 20% of the mass of SBS I-D modified asphalt. Quantitatively dehydrated SBS I-D modified asphalt and dried tourmaline anion powder were weighed to prepare different types of tourmaline anion powder low-carbon modified asphalt. The scheme numbers were C1, C2, C3, C4, and C5.
(3) After grinding, the dried and surface-activated tourmaline anion powder was slowly added to the dehydrated SBS I-D modified asphalt while the mixture was stirred. After this, the liquid was stirred for 5 min at a constant rate. This process is called premixing.
(4) A high-speed shearing instrument was used to stir the premixed modified asphalt, and the speed was varied from slow to fast. It was first stirred at 1000 rpm for 10 min, then stirred at 4000 rpm for 30 min, and finally slowed to a stop. During the shearing process, the blades were moved with a vertical motion to distribute the tourmaline anion powder uniformly throughout the modified asphalt. The temperature was controlled at $150 \pm 5\,^{\circ}C$ during this process.
(5) The prepared low-carbon modified asphalt was stirred manually with a stirrer for 10 min to remove air bubbles, and then stored for later use.

The production process of low-carbon asphalt modified by tourmaline anion powder is shown in Fig. 1.

2.3. Test methods

2.3.1. SEM test

The compatibility of asphalt with tourmaline anion powder is a key factor affecting the fundamental performance of low-carbon modified asphalt. The SEM tests of tourmaline anion powder and

Table 1
Technical indexes of raw materials.

No.	Types	Materials	Technical indexes
1	Modified materials	Tourmaline anion powder	White powder, Fineness 1000 mesh, Mohs hardness 7.0–7.2, Anion release 5500–7000/(s·cm^3), Density 3.06 g/cm^3, Infrared wavelength 4–14 μm, Emissivity > 90, pH value 7.0–7.3
2	Matrix asphalt	SBS I-D modified asphalt	Penetration (25 °C, 100 g, 5 s) 45 (0.1 mm), Durability (5 mm/min 15 °C) 33 cm, Softening point (ring and ball method) 87 °C
3	Dispersant	Sodium polyphosphate	White powder, Phosphate (P2O5) content ≥ 50.0–70.0%, Arsenic (As) content ≤ 0.0003%, Heavy metal (Pb) content ≤ 0.001%, Fluoride (F) content ≤ 0.005%, Water insoluble content ≤ 0.1%, pH value 7.2–9.0
4	Dispersant	Hexametaphosphate	White powder, Phosphate (P2O5) content ≥ 65–75%, Arsenic (As) content ≤ 0.0003%, Heavy metal (Pb) content ≤ 0.001%, Fluoride (F) content ≤ 0.003%, Water insoluble content ≤ 0.05%, pH value 5.8–7.3
5	Auxiliary materials	Ethanol	Colorless transparent liquid, Density 0.789 g/cm^3, Boiling point 78.4 °C, Melting point,-114.3 °C, Volatile