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Effects of steel slag fillers on the rheological properties of asphalt mastic

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HIGHLIGHTS

- Steel slag fillers can be utilized in asphalt pavements.
- With the increase of raw steel slag's particle size, the Fe content in it presents a growing trend.
- Compared to limestone fillers, steel slag fillers present outstanding rheological properties.

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ABSTRACT

The primary objective of this article was to investigate the feasibility of steel slag as fillers, particularly the fillers milled from raw steel slag with different particle size, also the steel slag fillers' effects on rheological properties of asphalt mastics. Four types of fillers were analyzed, including limestone filler (LF) and three steel slag fillers obtained by milling different raw Basic Oxygen Furnace (BOF) steel slags whose original particle sizes were 0–9.5 mm (ASSF, type A Steel Slag Filler), 9.5–13.2 mm (BSSF, type B Steel Slag Filler) and 13.2–26.5 mm (CSSF, type C Steel Slag Filler) separately. Surface characteristics, chemical compositions, phase distributions, thermal properties of fillers were first studied. By applying Bending Beam Rheometer (BBR) at lower temperature and Dynamic Shear Rheometer (DSR) at higher temperature, the rheological properties of asphalt mastics were also investigated. Results show that along with the increase of raw steel slag's particle size, the Fe content in steel slag filler presented a growing trend obviously. Besides that, compared with LF, steel slag fillers have different surface characteristics, chemical compositions, phase distributions and thermal properties. Furthermore, all steel slag fillers presented outstanding rheological properties, which indicated that they can be used as potential materials to replace LF. Moreover, ASSF corresponding mastic owned the best high-temperature rheological properties while BSSF corresponding mastic revealed the most balanced low-temperature rheological properties.

1. Introduction

Asphalt mixture is a superior pavement material used in road construction, which consists of filler, bitumen and aggregate [1]. In order to enhance the bond between each other, filler and bitumen are primarily found to form mastic that fills the interstices between aggregates [2,3]. Previous researches have indicated that asphalt mixture should be regarded as a mixture comprised with mastic-coated aggregates rather than pure bitumen-coated aggregates [4]. On account of the dual role in mastic, the properties of filler are closely associated with the asphalt mixture.

Experimental investigations show that the addition of filler has following main effects: (i) stiffen the bitumen to improve the mechanical properties of mixture, particularly the resistance to permanent deformation at high temperatures, fatigue life at intermediate temperatures and cracking resistance at low temperatures [4–6], (ii) extend the asphalt to increase the asphalt volume in the mixture to reduce optimum asphalt content [7], (iii) meet the aggregate gradation specification and (iv) enhance "bond" in the aggregate-asphalt system [8]. Researchers have proved that these effects are intimately related to the volume concentration and performances of fillers like size, alkalinity, shape, and surface characteristics, as well as the physical-chemical interaction between fillers and bitumen [2,4,9–14]. However, in consideration of the actual conditions that high-quality natural mineral fillers have been consumed faster and faster with the rapid development of road construction. Hence it is urgent to find other high-quality fillers to replace natural mineral fillers. The application of industrial waste like steel slag is a prospective way to save natural resources.

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Steel slag, a by-product produced in steel-making industry, accounts for more than 10% of raw steel output in the world [15,16]. With strong alkalinity, rich angularity, tough surface characteristics and excellent mechanical properties, the steel slag has been widely used as aggregates in asphalt mixture [17–19]. Literatures demonstrate that steel slag can improve functional performances of asphalt mixture such as moisture stability, high-temperature deformation resistance, abrasion and skid resistance [20–22]. These performances make steel slag an ideal alternative to natural aggregates. Nevertheless, the utilization of steel slag as filler in asphalt mixture attracts little concern. In addition, steel slags with different particle size show different properties, previous studies pointed that the cleanliness of steel slag fine aggregate would get worse during storage [19,23]. Also steel slag fine aggregate contained more free lime (f-CaO) than steel slag coarse aggregate and its hydration products could result in volume instability [24]. So if fillers milled from raw steel slag with different particle size, whether these effects may influence the properties of fillers or not is unclear and needed more attention.

The primary objective of this article was to investigate the feasibility of steel slag as fillers, particularly the steel slag fillers obtained by milling different raw Basic Oxygen Furnace (BOF) steel slags whose particle sizes were 0–9.5 mm (ASSF, type A Steel Slag Filler), 9.5–13.2 mm (BSSF, type B Steel Slag Filler) and 13.2–26.5 mm (CSSF, type C Steel Slag Filler) separately, also the steel slag fillers' effects on rheological properties of asphalt mastics. Firstly the surface characteristics and chemical compositions of fillers were characterized by Scanning Electron Microscope (SEM) and X-ray Fluorescence (XRF). Then the phase distributions and thermal properties of fillers were analyzed by X-ray diffraction (XRD) and Thermo Gravimetric-Differential Scanning Calorimetry (TG-DSC). Bending Beam Rheometer (BBR) and Dynamic Shear Rheometer (DSR) were applied to investigate the rheological properties of different asphalt mastics both at lower and higher temperature.

2. Materials and methods

2.1. Raw materials

The 80/100 penetration graded asphalt binder (AH-90), supplied by Guochuang Co., Ltd., Hubei, and China, was used in this research. The basic properties of applied bitumen were shown in Table 1. Four types of fillers were also included and one of these fillers was limestone filler (LF) obtained from Agoura Stone Processing Factory, Inner Mongolia. Three other fillers named ASSF, BSSF and CSSF were steel slag fillers milled from raw Basic Oxygen Furnace (BOF) steel slags supplied by Wuhan Iron and Steel, whose original particle sizes were 0–9.5 mm, 9.5–13.2 mm and 13.2–26.5 mm respectively.

In order to remove the free water, all fillers were dried at 105 °C for more than 6 h before being added into asphalt. Fig. 1 demonstrates the appearances of four fillers, as can be seen that LF is in a dense state with white color. While steel slag fillers appear much duskier, thereinto ASSF presents olive green, and along with the increase of raw material's particle size, the color of steel slag filler becomes darker and CSSF appears gray finally. This may attribute to the augment of Fe particles in fillers as pure Fe powders are black.

Table 2 shows the basic properties of different fillers. It can be inferred that the density of LF is 24.51% lower than the density of steel slag fillers on average. This may attribute to the content of Fe in steel slag fillers. The chemical compositions of four fillers will be discussed in the following XRD analysis. The difference on hydrophilic coefficients of four fillers is negligible. Nevertheless, the specific surface area and water absorption were not coincident like hydrophilic coefficient, the values of steel slag fillers are significantly higher than that of LF, which are due to the porous structure in steel slag that will be revealed in SEM analysis.

Table 1
Basic properties of AH-90 bitumen.

Properties	Values
Density (g/cm^3)	1.034
Penetration at (25 °C, 0.1 mm)	92.0
Softening point (°C)	45.8
Ductility at (10 °C, cm)	120.5
Viscosity at (135 °C, Pa·s)	0.365

2.2. Experimental methods

2.2.1. Material characteristics of fillers

A JSM-5610LV Scan Electronic Microscope (SEM) made by JEOL, Japan was used to characterize the surface characteristics of four fillers. The chemical compositions of these fillers were determined by AXIOS X-ray Fluorescence (XRF) manufactured by PANalytical B.V, Netherlands. D8 Advance X-ray diffraction (XRD) was used to explore the difference of phase distributions between all fillers. To obtain the thermal properties of fillers, samples for Thermo Gravimetric-Differential Scanning Calorimetry (TG-DSC) analysis were measured by a NETZSCH STA449C Thermo Gravimetric analyzer, Germany, whose temperature range was between 20 °C and 1000 °C with a 10 °C per minute heating rate.

2.2.2. The rheological properties of asphalt mastics

Dynamic Shear Rheometer (DSR) was used to evaluate the rheological properties of asphalt mastics at higher temperatures, which can be successfully used to represent the rutting potential of asphalt pavement [25,26]. Both temperature sweep analysis and frequency sweep analysis were conducted in this research. Temperature sweep analysis was conducted in a fixed-frequency of 10 rad/s with a temperature range varying from 30 °C to 60 °C. Frequency sweep analysis was performed at a dynamic frequency from 0.1 rad/s to 400 rad/s under different fixed temperature conditions (30 °C, 40 °C, 50 °C and 60 °C). All specimens for temperature sweep analysis and frequency sweep analysis were placed on a parallel plate geometry whose diameter was 25 mm, and the thickness of specimens was 1 mm. Meanwhile, Bending Beam Rheometer (BBR) was used to investigate their low temperature properties that relate to the low temperature resistance of mixtures [27]. Asphalt mastic was transferred to aluminum mold to prepare mastic beam with 102.0–125.0 mm length, 12.7 ± 0.5 mm width and 6.25 ± 0.5 mm thickness. Then specimens were tested under a constant stress of 0.985 N for 240 s. Each test for different mastic included five duplicate specimens and the average value was adopted.

3. Results and discussions

3.1. Material characteristics of fillers

3.1.1. Surface characteristics

The SEM images of four fillers are shown in Fig. 2. It is obvious that all fillers contain different particles with variable sizes from nearly 0.3 μm to 50 μm. Therefore the particle size can meet the Chinese standard of road construction. These three pics of disparate steel slag fillers (Fig. 2 a–c) have a number of resemblances. Obviously they all possess a coarse and bumpy surface texture. Smaller particles cling together or attach to the bigger particles, which makes steel slag filler's surface much tougher. Compared to steel slag filler, Fig. 2 (d) illustrates that limestone filler exists a so smooth surface that has little roughness, lumps or holes. Steel slag, which recognized as a porous aggregate, although has been crushed into filler with diameter less than 0.075 mm, small pores still exist in the filler particles. These pores can absorb bitumen while applied steel slag to asphalt mixture, and may consequently enhance the cohesion between fillers and bitumen together with the effect of coarse surface characteristics.

3.1.2. Chemical compositions

The XRF results of different fillers are shown in Table 3. Based on the chemical compositions analysis, it can be inferred that CaO and SiO_2 are the main components in all fillers. However, steel slag fillers are quite complex that contain a certain amount of Fe_2O_3 and P_2O_5, which is mainly generated by the residues of iron ore during steel-making process. High content of CaO let limestone recognized as a basic rock which has a great interaction between bitumen and LF itself. However for steel slag, the alkalinity $M = w(CaO)/[w(SiO_2) + w(P_2O_5)]$ is usually applied to evaluate the quality and activity of steel slag [28]. According to the criteria of China, ASSF and BSSF are both high alkalinity steel slag ($M > 2.5$), CSSF is intermediate steel slag ($1.8 < M < 2.5$) [29]. Because of the