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Study on the effective composition of steel slag for asphalt mixture induction heating purpose

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HIGHLIGHTS

- Effect of iron and Fe_3O_4 on induction heating of steel slag were investigated.
- Size effect on steel slag's induction heating had been studied.
- How iron element proportion affect the induction heating were tested.
- The induction heating mechanisms of Fe_3O_4 and iron are analyzed.

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ABSTRACT

Reuse steel slag as aggregate for induction heating has grown up to an important subject of asphalt pavement. However, how the composition and size of steel slag affect its induction heating efficiency still requires further study. This paper investigated steel slags' induction heating efficiency by components, size and iron element proportion dependency analysis. Steel slags and powders of iron, Fe_3O_4, natural mineral as well as steel slags were employed to fabricate samples that simulate steel slags as various composition. Their corresponding heating efficiencies were acknowledged through infrared camera. Moreover, X Ray Fluorescence and Electron Probe Micro Analyzer are used to characterize the element compositions of the samples and elements distribution within steel slags.

Results showed that, the effective components of steel slag' induction heating were Fe_3O_4 and iron. Fe_3O_4 contributed the dominant part to steel slags' induction heating efficiency at micron size (smaller than 75 μm). In addition, the size increase of steel slags showed negative effect on their induction heating efficiency, and steel slags of higher iron element proportion generally had higher heating efficiency. Alternatively, the induction heating mechanisms of Fe_3O_4 and iron are distinct. The dominant mechanism of iron is eddy current loss, while hysteresis loss and residual loss contribute the main part to Fe_3O_4's induction heating. Through the superposition of the mechanisms, Fe_3O_4 consequently shows better induction heating efficiency than iron. This study provides laboratory foundation for selection and utilization of steel slags which is used as the heated material in further steel slag based asphalt mixture.

1. Introduction

Rapid developing construction all over the world sharply consumes engineering materials. Excessive extraction of natural mineral resources such as basalt and limestone has already become a serious threat to ecological environment. To address this issue, researchers tried to use industrial solid waste [1] and marginal aggregate [2] to replace natural aggregate.

Steel slag [3–5] is a kind of solid waste that has been utilized widely in civil engineering, and its utilization has benefit the environment as well as the entire industry. Researchers also found that steel slag also can be used as a material for induction heating. Li et al. [6] claimed that conductive asphalt concrete consists of steel slag has a higher temperature rise compared to the natural aggregates through induction heating. Addition of steel slag could improve the self-healing efficiency of asphalt pavement. Induction heating [7] has been widely used in industry and engineering. In pavement engineering, it had been employed as an approach to heat asphalt pavement that consist of magnetic materials [8–10].

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The damages in pavement can be therefore healed by the flow of asphalt [11] due to the increment of temperature.

The main elements of steel slag are Ca, Fe, Si, C and O. Researchers conclude that, metallic oxides such as MgO, CaO, Fe_3O_4 and nonmetallic oxides like SiO_2 and C_2S are the main components in steel slag [12–14]. To realize the induction heating on an object, it is indispensable that the heated object should contain magnetic components [15,16], such as iron and carbon steel. Without which induction heating will consequently fail. In this paper, the components that assist in the steel slag's induction heating are defined as the "effective component".

Among these components of steel slag, the most metallic oxide, nonmetallic oxides, covalent compounds and metallic salt are not magnetic materials. Hence they do not contribute to induction heating. Nevertheless, after analysis and elimination, there are still two possible components, Fe_3O_4 and iron. They are commonly used as induction heating materials, their effect on steel slags still require further study.

Iron is considered as the residual product after steelmaking, magnetic separation and aging process. The formation and existing form of Fe_3O_4 are more complicated, and the possible source is steel slag's long-term outdoor complex aging. It should be pointed out that there may be other objects that can also be induction heated. However, considering their low mass proportion and few contributions to induction heating, they are not discussed. This study also investigated how the size and iron element proportion of steel slag affect steel slags' induction heating efficiency, which are important issues in steel slag asphalt pavement engineering [17] for induction heating purpose.

A components dependency experiment was developed to assess induction heating efficiency of the combination samples which are affected by iron and Fe_3O_4. Powders of Fe_3O_4, iron, mineral and steel slags were separately mixed to fabricate combination samples, which were then induction heated. Size effect on steel slags' induction heating efficiency had also been tested in this study. Steel slags were classified as three size ranges, and their corresponding induction heating efficiencies were tested. Furthermore, iron element dependency experiment was also included to investigate the correlation between steel slags' induction heating efficiency and its iron element proportion. Steel slags were classified according to their distinct induction heating efficiencies. Total element analysis [18] of these steel slags was conducted by X Ray Fluorescence (XRF) to characterize their corresponding element composition. Electron Probe Micro Analyzer (EPMA) [19,20] was also used to conduct EDS [21] map-scanning analysis on steel slags. This study provides an experimental foundation to researchers and engineers on steel slags selection and utilization in order to improve the induction heating efficiency of steel slag asphalt pavement.

2. Materials and methodologies

2.1. Materials

Powders of Fe_3O_4, iron, traditional mineral and steel slag were used in component dependency experiment for induction heating purpose. Steel slag powder throughout this study, with essentially the same element composition with steel slag particles, was prepared in Jiangxi province. All powders were screened to particle size of smaller than 75 μm. Detailed information about the powders is given in Table 1. Steel slags throughout this study were also provided from Jiangxi province. These steel slags were cleaned and divided into grading ranges of 1.18 mm–2.36 mm, 2.36 mm–4.75 mm and 4.75 mm–9.5 mm. The specific heat capacities of these steel slags are almost the same.

2.2. Research methodologies

Fig. 1 demonstrates the research outline of components, size and iron element proportion dependency experiments. Induction heating equipment is introduced to heat samples. Total element analysis and map-scanning analysis were conducted to characterize samples' element compositions and element distributions within steel slag. Powders were used to fabricate the combination samples for components dependency experiment. Steel slags were used in size and iron element proportion dependency experiment. Then the mechanism of the effective composition for induction heating had been analyzed.

2.2.1. Equipment

Fig. 2 presents the induction heating equipment, infrared camera and infrared picture of sample. Induction heating equipment is designed for laboratory use and offers an alternating magnetic field. An infrared camera is used to record samples' resulted induction heating temperatures. The parameters of induction heating are shown in Table 2. Every sample was heated according to the parameters. Total element analysis is conducted on steel slag powder and steel slags for component characterization by using XRF. Map-scanning analysis of steel slags is also conducted by using EPMA, in order to examine the distribution of the main elements of steel slags.

2.2.2. Components dependency experiment

Since iron and Fe_3O_4 are assumed as the main effective components in steel slags' induction heating. How the effective components affect induction heating efficiency of steel slag is discussed. Total element analysis of steel slag powder and map-scanning analysis of steel slag were conducted.

Components dependency experiment is designed to investigate the contributions of iron and Fe_3O_4 to induction heating efficiency of steel slag.

Fig. 3 illustrates the test program for components dependency analysis. Iron, Fe_3O_4, mineral and steel slag powders listed in Table 1 were mixed as combinations in round plastic containers, which were then being induction heated. Combinations of these powders are assumed to simulate steel slags and aggregates that consist of various compositions, which can be viewed as the "simulated aggregate and steel slags". By detecting the induction heating efficiency of the combination samples, influence of the effective components can be investigated.

Table 3 shows the component and their mass proportion in combinations, and the total mass of every sample is 30 g. Components effect on induction heating efficiency of steel slag was then evaluated based on corresponding induction heating efficiency. Mineral powder, steel slag powder, iron powder and Fe_3O_4 powder are abbreviated as M-powder, S-powder, I-powder and F-powder respectively.

Both induced temperature increment and heat quantity produced during induction heating process of samples were used to determine the samples' induction heating efficiency. Eq. (1) was used to determine induced temperature increment (ITI) of samples in this study.

$$\text{ITI} = \text{Final average temperature} - \text{Initial average temperature} \tag{1}$$

Temperature field and analysis method for ITI analysis is explained in Fig. 4. Since the upper surface of the container is circular, a same detection circle is set to calculate the overall temperature of samples. Radius of the detection circle is 80% of sample's surface circle, and the centers of the two circles are in same position. The average temperature within detection circle is calculated