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Autonomous microscopic bunch inspection using region-based deep learning for evaluating graphite powder dispersion

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HIGHLIGHTS

- Project presents an application of convolutional neural networks (CNN) in evaluating graphite powder dispersion.
- Different Faster R-CNNs are established by the processes of structure design, training and testing.
- The optimal well-trained Faster R-CNN is able to locate graphite powder bunch with acceptable precision and high efficiency.
- The method based on the Faster R-CNN had the capacity of quasi real-time autonomous dispersion evaluation in GPU mode.

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ABSTRACT

The ice-snow melting performance of ice-snow pavement is significantly influenced by the dispersion of graphite powder, particularly through the distribution of graphite powder bunches. In recent years, optical microscope (OP) images have been utilized to detect graphite powder bunches and evaluate their dispersion. However, because graphite powder bunches and other objects in OP images often have various shapes, and conventional manually processed images of tasks have the disadvantage of low efficiency, it is a challenge to detect graphite powder bunches and evaluate their dispersion using OP images. Therefore, this paper presents a novel application of a Faster Region Convolutional Neural Network (Faster R-CNN) using OP images and video sequences for the autonomous detection of graphite powder bunches and an evaluation of their dispersion. The research procedure is as follows: (a) generate a database for the Faster R-CNN, (b) design 30 Faster R-CNNs to find the optimal one, and (c) conduct an analysis of the training and testing results, along with new image testing, comparative studies, and video testing. The results show that a Faster R-CNN with nine anchors and a ratio of 0.3, 1.0, and 1.6, and with the sizes of 32, 128, and 192, has an average precision of the bunches and a dispersion uniformity of 91.2% and 84.0%, respectively. Its mean average precision is 87.5%. The Faster R-CNN is considered optimal in this research. The test time required to evaluate an image with a pixel resolution of 1024 × 1024 pixel in GPU mode is approximately 0.04 s, which means the method based on a Faster R-CNN has the capacity of a quasi-real-time autonomous dispersion evaluation in GPU mode to replace a human-assisted microscopic dispersion evaluation in OP images. The results also provide the possibility for a quasi-real-time evaluation using OP video sequences. Compared with a Fast R-CNN, a Faster R-CNN provides more reasonable bounding boxes for bunches and reliable results in terms of the dispersion uniformity.

1. Introduction

A functional pavement has become an important part of pavement construction in China, including ice-snow melting pavements. The development of pavement materials that fit a functional pavement is a significant requirement. As a modifier of ice-snow melting pavements, graphite powder has been widely used in thermally and electrically conductive asphalt concrete [1,2]. Graphite powder has high thermal and electrical conductivity, obvious anisotropy, and porosity. Additionally, compared with other materials, such as carbon fiber, steel slag and copper slag [3], the large specific surface area and lubricating property of graphite powder make it easy to be uniformly dispersed in asphalt [4,5]. The dispersion of graphite powder uniformly in asphalt can form network channels in the interior of the asphalt mortar, which

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improves the ice-snow melting pavement properties, such as the temperature performance, fracture toughness, and electrical conductivity, as well as the optical absorption property and light-thermal conversion efficiency [6–8]. These improved properties have positive effects on the functional performance of thermally and electrically conductive asphalt concrete pavement. Clearly, the dispersion of graphite powder is an important factor for properties of ice-snow melting pavement. Therefore, it is important to develop methods to evaluate the dispersion of graphite powder in asphalt.

There are many methods used to evaluate the dispersion of modifiers, such as a digital image method, mathematical morphology measurement, and alternating current impedance spectroscopy (AC-IS). Kang et al. [9] quantitatively evaluated the dispersion of modified particles by extracting the characteristic parameters of the dispersed phase in microscopic images. Fang et al. [10] segmented a scanning electron microscope (SEM) photograph of rubber filled with carbon black (CB), and evaluated the dispersion of CB particles by acquiring the geometric characteristics of the particles based on the principle and method of mathematical morphology. Woo et al. [11] evaluated the dispersion of fiber based on the intrinsic electrical conductivity of the cement composites using AC-IS. Wang et al. [12] evaluated the cracking resistance of cement mortar and the dispersion of its modifiers using SEM. Compared with other evaluation methods, the microscopic digital image method has certain advantages: (1) visualization of the material morphostructure, and (2) the potential to be combined with advanced image processing techniques. In recent years, a dispersion evaluation using a microscopic digital image method has obtained certain achievements. Xiao et al. [13] continuously observed the dispersion of Styrene-Butadiene-Styrene (SBS) in asphalt during the mixing process using a fluorescence microscope (FM), and qualitatively analyzed the microscopic dispersion of SBS modified asphalt. Yao et al. [14] observed the dispersion state of a nanomaterial modified asphalt using an atomic force microscope (AFM), and analyzed the modified effects of three types of nanomaterial on the matrix asphalt. Gao et al. [15] captured microstructural images of carbon-fiber-reinforced cement-based composites (CFRC) using SEM, and analyzed the dispersion of carbon fiber in the concrete composites. Huang et al. [16] used a transmission electron microscope (TEM) to analyze the effects of the carbonization pressure on the microstructure of graphitized pitch-derived carbons. The results indicate that the dispersion and orientations of the sample prepared at 30 MPa are better than those of the sample prepared at 60 MPa. Shen et al. [17] measured the microstructure and dispersion of asphalt at different diffusion positions using AFM, and analyzed the diffusion mechanism of different types of regenerant. Wang et al. [18] determined the gray thresholds of different components in OP images, and analyzed the dispersion of carbon fiber. In summary, microscope methods play an important role in analyzing the dispersion of modifiers. Although the above methods can be used to evaluate the dispersion through the application of digital microscopic images, certain problems remain: (1) some human assistance is required to locate the bunches and evaluate the dispersion in digital microscopic images, (2) the stability of algorithms used to locate the bunches and evaluate the dispersion can be affected by the image quality, and (3) only static images can be analyzed. Therefore, the development of a graphite powder dispersion evaluation system based on static OP images and videos, which possess sufficient stability toward different real-world conditions, is a key research issue.

With the continuous development of deep learning techniques, first proposed by Lecun et al. [19,20], convolutional neural networks (CNNs) have demonstrated significant advantages in the field of object recognition [21,22] and property evaluation [23,24]. In recent years, CNNs have been successfully applied in civil engineering. For example, Tong et al. [23,25,26] employed CNNs to calculate the lengths of the pavement surface cracks and reflection cracks based on digital images and ground penetrating radar data, respectively. The results of these studies demonstrated that CNNs have stability against the influence of pavement materials and highway structures. Additionally, a CNN was utilized to recognize different subgrade defects based on ground penetrating radar images [27]. Cha et al. [28,29] detected pavement damage and visual structure defects using deep learning, and the results demonstrated that CNNs can be used to find visual defects in different structures in real-world situations. Lin et al. [30] detected structural damage using automatic feature extraction through deep learning. Liao et al. [31] presented a deep-learning method for a reduction in carbon emissions. Additionally, there have been some studies combining CNNs with images for damage detection during the past few years [32–35]. In general, two properties of a CNN, stability and automation during feature extraction, are considered attractive in the inspection of bunches and a dispersion evaluation system. Stability indicates a strong tolerance for translation and distortion when learning deep features from input images. Automation indicates the learning of deep features with no assistance from humans. These two properties are important for evaluation problems in a dispersion analysis when handling complex backgrounds and feature information in OP images. Therefore, it is reasonable to employ CNNs to construct the relationship between OP images and graphite powder dispersion based on the major factors introduced above.

In this study, we use Faster R-CNNs to locate graphite powder bunches in OP images and construct a relationship between OP images and graphite powder dispersion. The novelty of this study is that Faster R-CNNs can locate graphite powder bunches and evaluate the dispersion in OP images autonomously. Additionally, an optimal Faster R-CNN has acceptable stability, which is not affected by the lighting conditions. Compared with former research methods for evaluating the dispersion, we realized a method based on a Faster R-CNN with no human assistance and better algorithm stability. The rest of this article is organized as follows. In Section 2, the procedure for generating a database of OP images is explained followed by the description of the Faster R-CNN and training implementation in our research. In Section 3, the results of the training and validation processes, as well as testing, are discussed and compared with a conventional Fast R-CNN. In Section 4, the testing of an optimal Faster R-CNN on OP videos is presented to realize a continuous detection and dispersion evaluation of graphite powder bunches in asphalt.

2. Research approaches

2.1. Generation database for CNNs

2.1.1. Raw materials

(1) Asphalt

The asphalt used in this research was 90# petroleum asphalt for heavy traffic road pavement (AH-90#). The basic indexes and corresponding requirements are shown in Table 1.

(2) Graphite

The graphite powder used in this research was analytically pure DK graphite powder. The main physicochemical properties are given in Table 2.