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Computation of fractal dimension on conductive path of conductive asphalt concrete

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HIGHLIGHTS

- The fractal feature of the conductive path was studied.
- SEM pictures, fractal theory were used to calculate the fractal dimension.
- The fractal dimension is 1.22–1.89. When the graphite content is 4 vol.%–14 vol.%.
- The fractal dimension reflects the changes of the conductive paths in the asphalt mixture.

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ABSTRACT

Distribution of the conductive paths in the conductive asphalt concrete seems as rough, disorder and random, but it has self-similar fractal characteristics in statistics. It use the fractal theory to study on the distribution characteristics of the conductive paths. The conductive process of asphalt concrete turned from insulator to conductor could be described quantitatively by fractal dimensions. When the graphite content is 4 vol.%–14 vol.%, the fractal dimension which is measured by box-counting is 1.22–1.89. Comparing the relationship between fractal dimension and resistance change, it can be found that the changes in fractal dimension and resistivity have a similar trend with the changes of graphite content. There exists a percolation threshold when fractal dimension and the resistivity change, and the fractal dimension and resistivity change little once the graphite content exceeds the threshold. The physical significance of fractal dimension reflects the changes of the conductive paths in the asphalt mixture.

1. Introduction

Conductive asphalt has received a lot of attention due to its multiple functions. Studies revealed that [1,2] conductive asphalt concrete, widely used in roads, bridges, airports, etc., not only has its own structural function, but also has deicing or snow-melting, the structure self-monitoring, anti-magnetic radiation, and many other functions. Therefore, there is a big demand in the field of conductive asphalt mixture which has excellent performance. But currently, around the world, conductive asphalt concrete still has not been applied widely. Firstly, the large-scale application is based on fully understanding of the electrical properties of the conductive asphalt concrete. Although recent studies on the conductive asphalt concrete have developed rapidly, there is not a perfect and universal conductive mechanism to explain the formation of conductive network and conductive behavior. Study on conductive mechanism for conductive concrete is only confined to theoretical deduction and qualitative explanation [3,4], and it is difficult to further learn the performance of conductive asphalt concrete and further optimize the performance of these materials. In addition, any good model should be able to explain various properties of conductive concrete, such as the relation on electrical conductivity and conductive material or asphalt concrete (AC) frequency, temperature sensitivity, V-I characteristic, piezo-resistive property and etc. Some researchers [5] have investigated many conductive mechanism such as conductive effect caused by contacting particles, tunnel effect and effect of electric field emission. However, the above conductive mechanism is difficult to explain the various complex conductive behaviors. Secondly, it is difficult to obtain a stable performance of conductive asphalt concrete, this includes two things: conductive material such as graphite could lead pavement performance to reduction; furthermore, structure differences of concrete which includes the same content and kind of conductive materials could lead to much different electrical properties. Therefore it is important that combine this fractal

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dimensions with material properties and preparation methods to furtherly use conductive asphalt concrete widely.

Due to the characteristics of disordered structure, the percolation theory is one of the best methods to explain the conductive mechanism [6]. It deals with the effects caused by the change of mutual coupling in disordered systems. Asphalt mixture is actually composed of insulating phase and conductive phase, in which the conductive phase is extremely complex. Currently only theoretical speculation was used to explain the conductive mechanism. Researchers found that the conductivity and the content of conductive materials are related closely and could be built a percolation model [7,8]. It is feasible to use percolation theory to explain the whole process that conductive particles from isolating to forming a conductive path gradually, and constituting the conductive network finally [9,10]. The conductive paths of conductive asphalt concrete have obvious fractal characteristics of self-similarity and scale invariance. Using digital image processing techniques to select the conductive path, and calculating the fractal dimension by the method of boxing-counting based on *Matlab* platform. The fractal dimension is a good explanation of the conductive behavior of conductive asphalt concrete. Furthermore, the studies can also improve the preparation technology and performances of the conductive asphalt concrete.

2. The fractal feature of the conductive path

It is necessary to meet the following characteristics for the fractal percolation theory before used:

(1) Conductive material and its paths both have elaborate structure [11], i.e. there are arbitrarily small proportion details in a special yardstick;
(2) It is an irregular [12] structure either in whole or partial that cannot using Euclidean geometry to describe it. The concrete gap of conductive particles and paths are all randomly distributed in the concrete;
(3) Conductive paths have statistical self-similarity with the content of conductive materials increase;
(4) Fractal dimension of the system is greater than its topological dimension;
(5) Fractal dimension of the conductive path can be calculated by simple methods [13] such as iterating method.

Graphite has good electrical conductivity, chemical stability, acid and alkali resistance, good anti-oxidation ability, and etc.; it requires more graphite powder in asphalt concrete binder to form conductive path. Graphite powders accounted for 4%, 6%, 8%, 10%, 12%, 14% (volume fraction) of asphalt were used to prepare conductive asphalt mixture.

Graphite particles were dispersed randomly in the asphalt binder and formed two-phase conductive composites. With the increase of graphite content, the isolated particle gathered and formed a continuous conductive path. Fig. 1 describes vividly the formation of seepage.

Percolation transition would occur in the system when the content of graphite increased from P to a critical value P_c which is called the percolation threshold. According to the percolation theory, there is a relationship between the correlation length "L" and the volume fraction of the conductor as follows:

$$\mathrm{L} \propto (p - p_c)^{-\upsilon} \tag{1}$$

where, P is the volume fraction of graphite, P_c is the percolation threshold, υ is a threshold constant.

- □ When $P < Pc$, L is limited and some clusters whose linear dimension is "L" start appear in the system. Cluster is formed gradually and it is self-similar at a limited content of graphite.
- □ When $p \rightarrow p_c$, when the content approaching P_c, there is many clusters appear in the system, called as the initial infinite position, which indicate it entered a critical state and the initial infinite clusters still have self-similarity.
- □ When $P > P_c$, there is a large number of infinite clusters appear in the system, which develop into uniform distribution and has not the self-similarity.

3. Calculation of the fractal dimension on conductive path

3.1. Calculation method of the fractal dimension

According to the definition of fractal [14–18], when L represents the length of the conductive paths, it will satisfy the following law.

$$\mathrm{L} \propto \varepsilon^{-(D-1)} \tag{2}$$

where: ε is the yardstick. The conductive paths in the asphalt concrete are self-similar and the fractal dimension is D.

It is a limited level fractal and is not a strict self-similarity. There is not self-similarity when the yardstick is very small. Because aggregate size generally more than 100 mm, so yardstick is limited in centimeters scope when studying the conductive path of asphalt concrete by scanning electron microscopy (SEM). Moreover, it can form conductive paths only when the conductive particles are in contact with each other. Therefore the minimum yardstick size is not equal to zero, and should be equal to or greater than the size of the conductive particles. Research on *KOCH* curve length has pointed out that the minimum length of iterative curve is $\varepsilon = \left(\frac{1}{3}\right)^n$, when n is finite, its length L does not tend to infinity. L is the maximum length of the conductive path, ε_0 is atomic spacing that will not tend to infinity.

The Fractal dimension D measured by experiment is related to yardstick. It is different with different yardstick. Therefore, the range of the yardstick is not arbitrary when measuring the fractal dimension. The yardstick is limited within a certain range, at least not less than one pixel scale [19–21].

According to the formula $\mathrm{L} \propto \varepsilon^{-(D-1)}$, the sand box method is available to measure the fractal dimension of the conductive paths, (where ε is the length of the sand box, L is the total length of all the conductive paths included this box). When using a grid to cover the conductive paths maps, there is a relationship between L and the check number N as follows:

$$\mathrm{L} = \mathrm{N}\varepsilon \tag{3}$$

It can be calculated the dimension of distribution of the conductive path by the box counting method and the *Matlab* program.

3.2. Calculation process of the fractal dimension

Two groups of specimens were observed by scanning electron microscopy (SEM). Fig. 2 showed the morphology of graphite particles and Fig. 3 described the distribution of graphite particles in the asphalt binder.

Using digital image processing techniques to separate the graphite from the asphalt mortar, and detect the image edge on *Matlab* platform. Edge detection technology is trying to make the edge between graphite and asphalt mortar outstanding by using some edge enhancement algorithms, and then acquiring a set of edge points by the way of setting threshold for image accurately. Some gradient operators, such as LOG operator, Prewitt operator, *Roberts* operator, Sobel operator, and etc. are usually used to