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The prediction of adhesive failure between aggregates and asphalt mastic based on aggregate features

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HIGHLIGHTS

- Coupling effect of aggregate features on ITZ can be evaluated by multi-parameters.
- 3DFD increases with the increase of aggregate volume, but 3DTS is stable.
- 3DTS affects the damage initiation time of adhesive failure.
- ANN-BP model is effective to predict energy consumption during fracture.

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ABSTRACT

The interface stripping between aggregates and asphalt mastic deteriorates the strength of asphalt mixture, causing disease such as cracks and pits of asphalt pavement. This paper aim to quantify the effect of aggregate on interface, and develop a method to predict the adhesive failure. At first, microstructural models of aggregate particles were reconstructed based on computed tomography (CT) images, then aggregate features and energy consumption of interface during fracture were determined by digital image processing and numerical simulation respectively; dissipation damage energy (DDE) quantified the adhesive failure, and an effective method was established by artificial neural network based on back-propagation (ANN-BP) to present the relationship between DDE and aggregate features. Results show that the influence of aggregate on interface damage can be evaluated by multiple parameters of aggregate features; ANN-BP is an effective tool to synthesize the coupling influences of different aggregate features and determine a prediction model; ANN-BP model presents a prediction for adhesive failure according to the states of aggregates, the prediction results are acceptable to show the damage of asphalt mixture.

1. Introduction

Skeleton built by aggregates is a critical structure that contributes to load-bearing capacity of asphalt mixture, changing the constitution and shape of aggregates cause obvious influences on mechanical performance. Interfaces between aggregates and asphalt mastic are weak areas in asphalt mixture, some common diseases, such as cracks and pits, are mainly affected by adhesive failure of interfaces. It is well known that aggregates have a significant effect on interfacial property, however, evaluating the adhesive failure is difficult because the shape and size of aggregates are random and complicated, a simple parameter cannot indicate aggregate's features effectively. Therefore, a comprehensive evaluation that considers aggregate features should be determined before predicting the adhesive failure.

Researches show that there is an interfacial transition zone (ITZ) between aggregates and asphalt mastic, it is regarded as the weakest link in concrete and governs the crack disease [1–5]. To evaluate ITZ mechanical characteristics, advance techniques were employed, such as nano-indentation, field emission scanning electron microscope and energy dispersive X-ray spectrometer [6]. X-ray CT is a useful tool that investigates ITZ. Using X-ray CT device, crack disease of concrete can be observed, and fracture behavior during crack initiation and propagation in ITZ region was researched [7,8]. Based on CT images, numerical simulation for meso-scale structures has become an effective method used to analyze the mechanical behavior of ITZ, for instance, 2D or 3D microstructure models were reconstructed by CT images to investigate the influence of mortar matrix, aggregates and ITZ on con-

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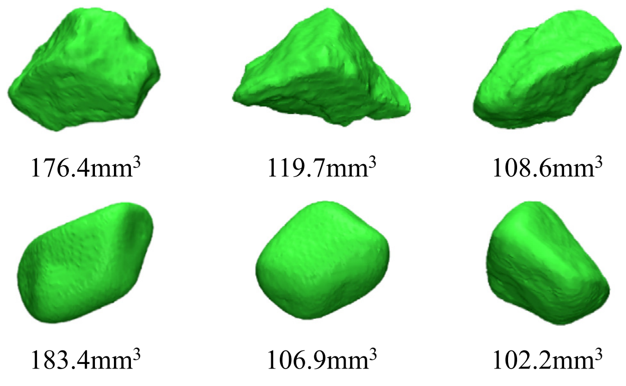
crete strength, and fracture appeared in ITZ was simulated through cohesive element [9,10]. ITZ is a special interface that impacts the mechanical performance of concrete, it's properties are affected by both aggregate and asphalt mastic [11]. For the influence of aggregate on ITZ, chemistry and structure of aggregate, such as surface property, sizes, angularity and texture, have been investigated, results show that aggregate polarity, surface roughness and texture of aggregate affect ITZ obviously [12,13]. Besides, membrane thickness and contact angles between aggregate and asphalt mastic were proved to change ITZ properties [14,15]. Therefore, aggregate is the main factor affecting ITZ, and causing adhesive failure of ITZ, it is necessary that quantifying the influence of aggregate on ITZ, and establishing a relationship used to evaluate adhesive failure of ITZ.

As mentioned above, microstructure analysis is useful to evaluate the interface property, it is important to present a method to determine the influence of aggregates on interface according to microstructure features of aggregates. Experiment is a direct method that measures the interface property and adhesive failure, however, it is hard to reflect the influence of real aggregate particle on ITZ [16,17], therefore, numerical simulation become an effective technique that investigates ITZ behavior. Randomly generated model is a common method that launches microstructure analysis, aggregates and air-voids are reconstructed by algorithm [18,19], however, it cannot reflect the real state of aggregates. Based on the X-CT images, researchers reconstructed and analyzed actual microstructures of asphalt mixture [20–22], and combined with fracture simulation, crack disease was investigated [23–25]. Therefore, establishing a microstructural numerical model is an effective way that investigates the influence of microstructures on adhesive failure.

In this paper, multiple parameters that represent the aggregate features were determined, and the influence of aggregates on adhesive failure of interface was investigated according to aggregate features. The critical step was building a model to analyze the coupling effect of aggregate features, such as size, shape and angularity.

2. Quantification of aggregate features

Adhesive failure of interface is a serious damage caused by aggregates, defining multiple parameters to quantify the aggregate features is helpful in evaluating the adhesive failure. In order to study the aggregate features, 286 aggregate particles were scanned by X-Ray CT: resolution was 0.08 mm and interval of CT images was 0.1 mm. Binary images were identified and extracted using digital image processing (DIP), then 3D models of different aggregates were reconstructed. Some typical models are shown in Fig. 1.


176.4mm^3 119.7mm^3 108.6mm^3

183.4mm^3 106.9mm^3 102.2mm^3

Fig. 1. Reconstructed 3D models of different aggregates.

Due to the complicated and random states of aggregates, multiple parameters should be synthetically used to present the microstructural features. Fractal dimension is an effective non-integer number for indicating the angularity of irregular objects such as the micropatten of aggregate particle [26], and evaluating crack disease in concrete over multiple scale [27]. 3D fractal dimension (3DFD) is determined using 3D Box-counting method according to Eq. (1):

$$3DFD = \lim_{r \to 0} \frac{log(N(r))}{-log(r)} \tag{1}$$

Spatial grids with side length r are used to divide the aggregate model into different cubes, the number of cubes which contain the aggregate is $N(r)$, and $N(r)$ changes with the change of side length r. Least square method fits the data of r and $N(r)$ at double logarithmic coordinate system, the slope D of fitting curve is 3D fractal dimension that represent the complexity of aggregate angularity.

Besides, 3D true sphericity (3DTD) is widely used to quantify the aggregate shape, the aggregate particle is similar with a sphere if the 3DTD closes to 1, as shown at below:

$$3D\,True\,Sphericity = \frac{\pi}{S}\left(\sqrt[3]{\frac{6V}{\pi}}\right)^2 \tag{2}$$

where, S and V represent the surface area and volume of aggregate particle, respectively.

In addition to 3DFD and 3DTD, Volume (Vol) and Surface (Surf) are conventional parameters of aggregate. Actually, size, shape and angularity are three parameters that indicate aggregate features. Parameters of Vol and Surf are calculated to represents the size of aggregate, and 3DTD and 3DFD are used to indicate the shape and angularity respectively. Therefore, in order to describe the aggregate features, these four parameters are used as multiple parameters that define the aggregate, relationship between adhesive failure of interface and aggregate is investigated through multiple parameters. Fig. 2 shows 3DTS and 3DFD distribution of aggregates investigated in this paper, tendency of 3DTS is stable, indicating aggregates with different sizes present similar shape. However, 3DFD increases with the increase of volume, great aggregate shows more complicated angularity compared with that of fine aggregate.

3. Numerical simulation

3.1. Characteristics of adhesive failure

It is difficult to study the adhesive failure of interface by experiment. Finite element models are created to simulate the interface failure, and damage states caused by different aggregates are counted. Fig. 3 illustrates the finite element model: a cylinder whose radius and height are 50 mm is created to represent the asphalt mastic, and centroid of aggregate superposes with the center of cylinder. The bottom is fixed and a displacement which rate of 0.02 mm/s is applied on the top surface; the simulation time is 100 s so the total displacement is 2 mm.

In order to reflect the interfacial behavior, a constitutive model should be selected to present the mechanical property. Surface based cohesive behavior (SBCB) is a proper model that simulates the traction-separation property of interface, it follows linear softening feature, as shown in Fig. 4.

Reaction function $T(\Delta)$ can be characterized by a bilinear constitutive model including cohesive fracture energy G, cohesive strength T^o and separation Δ. The cohesive surfaces behave linearly until the initial damage threshold is reached and then stage of damage evolution follows. The maximum separation criterion is adopted to control the damage initiation. This criterion assumes