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Three-dimensional fracture simulation of cold in-place recycling mixture using cohesive zone model

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HIGHLIGHTS

- The X-ray CT and DIP techniques were employed to create numerical model of CIR mixture.
- Cohesive zone model was utilized to simulate the fracture behaviour of CIR mixture.
- Numerical Arcan tests were carried out and compared to the experimental Arcan tests.

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ABSTRACT

Cold in-place recycling (CIR) shows a good performance in the resistance to cracks in the field and a newly developed Arcan configuration has been used to investigate the Mixed-Mode cracking behaviour of CIR mixture. In this research, a three-dimensional (3D) heterogeneous fracture modeling method was presented to simulate complex cracking development in CIR mixture. The X-ray computed tomography (CT) technique and digital image processing (DIP) method were employed to create 3D heterogeneous numerical model of CIR mixture. In the modeling, a cohesive zone model (CZM) was utilized to estimate the crack resistance of the interface based on laboratory fracture test. The coalescence of micro-cracks and the inception and propagation of macro-cracks in CIR mixture were carefully studied under fracture Mode I and Mode II, respectively. The fracture process zone was also investigated. Three types of displacements, including the Load-Line Displacement (LLD), Crack Mouth Opening Displacement (CMOD), and Crack Tip Opening Displacement (CTOD) were utilized to plot load-displacement curves and the corresponding fracture energies were calculated. The analyzing results of virtual numerical test are proved to be quite consistent with the actual experimental test. The validity of numerical model is verified.

1. Introduction

Cold in-place recycling (CIR) has been widely used as a cost effective and sustainable treatment for pavement rehabilitation around the world in recent years. The success of CIR performance in the field typically lies in the resistance to reflective cracks from underlying concrete pavement [1,2]. Due to the advantages of Arcan test in exploring Mixed-Mode cracking propagation between 100% Mode I and 100% Mode II, the Arcan configuration was developed to study the Mixed-Mode cracks in asphalt concrete pavement [3,4]. With the application of Digital Image Correlation (DIC) technique, the Arcan test was chosen to investigate the Mixed-Mode fracture characteristics and the cracking behaviour of CIR mixtures [5].

In recent years, asphalt mixture fracture simulation was performed to better understand fundamental mechanisms behind initiation and propagation of cracks. Two dimensional and three dimensional heterogeneous fracture simulations with cohesive crack model were carried out for asphalt mixture. Random aggregate generation and packing algorithm was employed to create 2D and 3D heterogeneous numerical model of asphalt mixture, and the cohesive elements with the tension/shear softening laws were inserted into both the mastic matrix and the aggregate-mastic interfaces as potential cracks [6,7]. However, the aggregate particles are commonly generated and distributed artificially and the model cannot truly describe the mesostructure of asphalt mixture, especially for CIR mixture. The X-ray Computed Tomography (CT) and Digital Image Processing (DIP) methods were utilized to research the mesostructure of CIR mixture [8,9]. The distribution of aggregates and air-voids for CIR mixtures could be measured. Three dimensional finite element model (3D-FEM) of asphalt

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mixture was reconstructed by X-ray CT and DIP tomographic data, then the shear modulus and dynamic modulus of asphalt mixture were simulated [10,11]. Furthermore, the effects of aggregate characteristics on mechanical response and distribution of asphalt mastic and air-voids were investigated respectively [12]. However, these 3D numerical models reconstructed from CT tomographic data are mainly adopt to carry on stress/strain analysis and they cannot simulate the fracture behaviour of asphalt mixture.

The objectives of this paper are to propose a numerical approach for CIR mixture with cohesive zone model, and make fracture behaviour simulation according to Arcan test results. The laboratory Arcan tests with five levels of Mixed-Mode cracking of CIR mixture were carried out, and the Digital Image Correlation (DIC) technique was applied to explore the cracking behaviour in process of Arcan test. Cylindrical CIR specimens were scanned by X-ray CT and the Matlab software was used to process the tomographic data. Then, hexahedral elements of aggregates, mastic and air-voids were developed based on layers of binary images. The zero-thickness bilinear CZM elements were inserted into both mastic matrix and the aggregate-mastic interfaces as potential cracks in advance to simulate 3D crack initiation and propagation. The fracture parameters of CZM were determined according to laboratory Mixed-Mode Arcan test results. Finally, 3D-FE model built according to CIR mixture heterogeneous mesostructure was imported into ABAQUS software and calculated in ABAQUS/Explicit module. Comparison was made between virtual Arcan test and laboratory Arcan test, and validity of the simulation approach was verified. Besides, the mesoscale fracture phenomena in the numerical specimens were observed, and more Mixed-Mode fracture behaviours of CIR mixtures were described and evaluated.

2. Materials and mix design

In this research, CIR mixtures were all designed according to the CIR specification in Jiangsu Province, China [13]. Representative samples of reclaimed asphalt pavement (RAP) were obtained from CIR worksite and evaluated to determine RAP gradation and binder content. The collected RAP materials were processed through a series of standard sieves after they were dried. 3% of mineral filler was added to improve the gradation of CIR mixtures. To improve the initial strength of CIR mixtures, Portland cement was added at 1.5% by weight of RAP materials as recommended by Jiangsu's specifications. Apart from these additives, water was added to the RAP before to ensure adequate coating and easy compaction. After hand-mixing and coating tests, the optimum moisture content including adding water and the water from emulsion was determined to be 4.3%.

3. Arcan test methods

3.1. Arcan configuration

The Arcan test configuration has been used in many engineering material applications, including woods, plastics, composites and metals. After a thorough review of the literature, initial testing

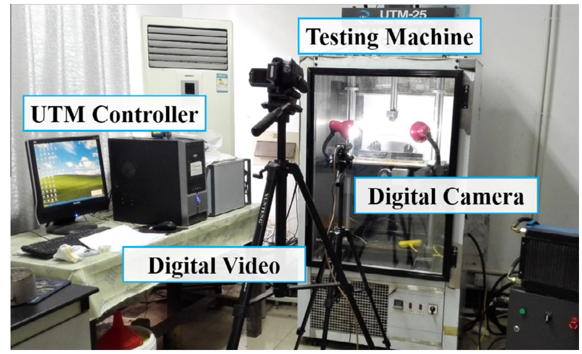

Fig. 2. Photograph of DIC experimental setups.

and test modification, Ni, Braham et al. proposed the final Arcan test configuration for asphalt concrete [4], as shown in Fig. 1. The fixture is attached to the surface parallel to notch, along the entire length of the specimen. This allows for an even tensile pull across the sample and keeps the fixture parallel to the specimen during the test. As seen in Fig. 1, if the notch in the specimen is perpendicular to the loading direction, the test is in 100% Mode I. If the notch is parallel to the loading direction, the test is in 100% Mode II and the other three levels of Mixed-Mode cracking fall in between. In this study, only 100% Model I and 100% Mode II have been investigated.

3.2. Experimental testing setups

A UTM-25 load frame equipped with a temperature control chamber was utilized for Arcan testing. The DIC experimental setups are shown in Fig. 2. An industrial digital camera (resolution 1626 × 1236, focal length 25 mm, pixel size 4.4 μm, 14 fps @max resolution) was employed to capture frames during the process of Mixed-Mode cracking. The camera was positioned perpendicular to a specimen and at a constant distance away from it. A lighting system, composed of two white lights, provided adequate illumination of the specimen inside the chamber. The camera was set to acquire five frames per second and started capturing images at the beginning of the testing. The loading rate of UTM-25 was set to be 0.5 mm/min. All tests began with a pre-load of 0.1 kN and were stopped when the load dropped to 0.1 kN.

4. Three dimensional modeling methodology

4.1. X-ray CT scanning and digital image processing

A CIR-20 cylindrical specimen was compacted using the superpave gyratory compactor and scanned by X-ray CT system in the

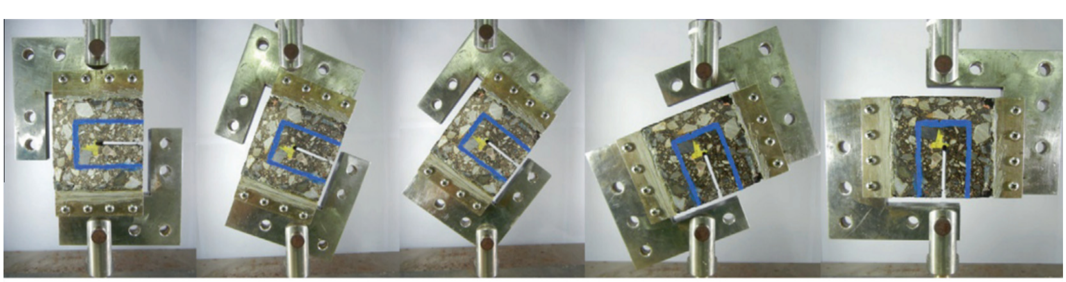

Fig. 1. Arcan test configuration with five levels of Mixed-Mode cracking.