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Mixed-mode fracture modeling of cold recycled mixture using discrete element method

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HIGHLIGHTS

- A rotatable test device was specially designed for the Arcan test.
- A three-dimensional numerical specimen of CR mixture was set up in PFC3D 4.0.
- A modified bilinear fracture model was established for asphalt mastic.

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ABSTRACT

Cold recycling (CR) consists of recycling asphalt pavement without the application of heat during the recycling process to produce rehabilitated pavements. Compared to other reconstruction methods, CR has advantages in energy conservation and economic saving. This paper aims to develop a three-dimensional (3D) numerical model of the Arcan test to simulate the mixed-mode cracking behavior of CR mixtures and to find the differences between CR and hot-mix asphalt (HMA) mixture. A rotatable test device was specially designed for the Arcan test to evaluate the mixed-mode cracking of specimens. A 3D numerical specimen of CR mixture was set up in the program PFC3D 4.0. A modified bilinear fracture model was established for asphalt mastic and the material parameters in the model were determined from laboratory tests. The results of virtual Arcan test verifies that three of five mixed-mode cracking simulations are reliable compared to the experimental results and 50% Mode I cracking shows the minimum error among three modes. During the cracking process of any mode, the stress concentration always occurs at the tip of cracking, and the stress value of cracking tip decreases as the cracking propagates. Compared with HMA mixtures, the emulsified CR mixture has a larger failure strain and a smaller failure stress, which can show a better anti-cracking performance in the practical engineering.

1. Introduction

Asphalt recycling and reclaiming has been a technically and environmentally preferred way of rehabilitating the existing pavements. Cold recycling (CR) is one of the rehabilitation techniques. It consists of recycling asphalt pavement without the application of heat during the recycling process. Compared to other reconstruction methods, CR has advantages in energy conservation and economic saving. It has been applied in many countries to maintain existing roadways and it is generally overlain with a layer of hot mix asphalt (HMA) mixture in the construction field [1]. The success of CR performance typically lies in the resistance to reflective cracking from underlying concrete pavement [2].

It is widely accepted that the reflective cracks are not only represented in Mode I (opening) or Mode II (sliding) cracking. The cracks in the field often form in a combination of both two which are called mixed-mode cracking. Due to the geometric limitations, most fracture testing methods were used to evaluate the opening cracking behavior of asphalt mixtures [3–5]. However, in recent years, a new testing configuration, the Arcan test was introduced and developed for asphalt concrete to simulate five levels of mixed-mode cracking including the 100% Mode I and 100% Mode II [6–8]. The mixed-mode cracking behavior of CR mixtures was studied in laboratory using Arcan configuration and numerical image correlation (DIC) system. It was concluded that the Arcan test showed promise for capturing mixed-mode characteristics of asphalt mixtures [9]. However, the whole process of laboratory Arcan test is very time consuming and it requires specific experimental devices. Therefore, the numerical simulation method needs

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to be studied to model the crack initiation and propagation of CR mixture in the mixed-mode cracking.

The heterogeneous fracture model based on the discrete element method (DEM) was developed to study various crack mechanisms of asphalt mixtures with image processing technique [10,11]. The numerical simulations of single-edge notched beam (SENB) test showed good agreement with the experimental results [12]. The heterogeneous fracture model was also developed to investigate various fracture toughening mechanisms of asphalt materials using a high-resolution image processing technique, which had the potential capability to understand various crack mechanisms of quasi-brittle materials [13]. A user-defined micromechanical model was established using DEM to find the cracking behavior of asphalt concrete by simulating the indirect tensile (IDT) test and three-point bending beam test. In the three-dimensional (3D) model, a clump of spheres of different sizes was utilized to produce individual aggregate particles with irregular shape and the input material parameters for the numerical simulation were obtained from experimental tests of mastics and aggregates [14,15]. Compared with the three dimensional DEM, 2D simulations could have some limitations in investigating the fracture characteristics of asphalt mixture in SENB test. Two discrepancies were found in the crack-path deviation angle and the critical fracture load considering the test results [16]. Thus, the 3D DEM was recommended to be applied in the numerical simulations of mixed-mode cracking for CR mixtures.

2. Objectives

The overall objective of this study is to develop three-dimensional microstructure modeling of the Arcan test to simulate the mixed-mode cracking behavior of CR mixtures and to find the differences between CR mixture and HMA mixture. Furthermore, the specific objectives of this paper are to:

(1) Modify the conventional bilinear fracture model and determine the material parameters from laboratory testing on aggregates and asphalt mastics;
(2) Verify the mixed-mode fracture simulations in the DEM of CR mixture with the experimental results from the Arcan test;
(3) Analyze the crack initiation and propagation in the mixed-mode cracking considering the stress distribution at different stages;
(4) Compare CR mixture with HMA mixture using the DEM and investigate the cracking mechanism of CR mixture.

3. Materials and experimental tests

3.1. Materials

The CR materials in this study were all obtained from a single worksite in Jiangsu Province, China and the mix design procedure was abiding by the specification developed by the local Department of Transportation. The RAP materials were collected by large milling machine during construction to ensure the representativeness of gradations. The RAP aggregates consisted of basalt and limestone. The gradation and quality of materials were experimentally tested and assured through the CR specification. The specific gravity of the extracted RAP aggregates was 2.55 with water absorption of 1.8%. The RAP materials were dried and sorted by a series of standard sieves. The CR mixture used 100% of RAP and no fresh aggregate was added. The aggregate gradation of CR mixture which fell within the medium sized gradation limits recommended by the specification are described in Table 1. The CR-20 (Cold Recycled mix with a fixed nominal maximum aggregate size of 19 mm) mixture with a typical gradation was designed. A cationic slow-setting (CSS-1) asphalt emulsion was selected as the recycling additive which provided adequate workability for CR mixture. According to the results from Marshall Stability, Flow, Indirect Tensile Strength, and Resilient Modulus, the optimum asphalt emulsion content Emulsified asphalt and cement were chosen as the recycling agent for CR mixture. Reclaimed asphalt pavement (RAP) materials were completely reused and reclaimed at outdoor temperatures.

According to the mix design method of CR-20 mixture, the content of CSS-1 emulsified asphalt was 3.5% and the content of additional water was 3.0%. To compare the cracking behavior between CR mixtures and HMA mixtures, AC-20 mixtures were also produced. For AC-20 mixture, limestone was used as aggregates and the 70# asphalt was chosen with optimum content of 4.1% according to the Marshall design method. The mix design results of CR-20 and AC-20 mixtures are described in Table 1.

3.2. Testing configuration

The Arcan test can be used to research the mixed-mode cracking behavior of asphalt mixture. The test device is specially designed to ensure its rotatable ability. With the rotation of test fixture, there are different angles between the direction of specimen notch and tensing loading, which leads to Mode I (opening) and Mode II (sliding) cracking, as well as the mixed-mode cracking. Fig. 1 shows five kinds of mixed-mode cracking in the Arcan test. 100% Mode I and 0% Mode II cracking test can be operated when the angle between the direction of specimen notch and tensile loading is 90°. If this angle turns to 67.5°, 45°, 22.5° and 0°, the corresponding tests are 75% Mode I and 25% Mode II cracking test, 50% Mode I and 50% Mode II cracking test, 25% Mode I and 75% Mode II cracking test, and 0% Mode I and 100% Mode II cracking test, respectively. The size of Arcan specimen is 80 mm × 80 mm × 50 mm.

There are three key parameters used in the Arcan test: peak load, cracking angle and fracture energy. Peak load refers to the largest load applied to specimen during the Arcan test. Cracking angle is defined as the acute angle between the direction of specimen notch and the cracking line. Fracture energy means the energy needed to produce new ligament areas. Fig. 1 also shows two groups of targets on the surface of Arcan specimen that can be captured to measure the corresponding displacements, including the crack mouth opening displacement (CMOD) and the crack tip opening displacement (CTOD). The fracture energies from CMOD and CTOD measurements are described as follows:

Table 1
Mix design results of CR-20 and AC-20 mixtures.

Mixtures	CR-20		AC-20	
Optimal asphalt content (%)	3.5 (CSS-1)		4.1 (70#)	
Sieve size	CR-20	Limits	AC-20	Limits
(mm)	Passing percent (%)			
26.5	100	100	100	100
19	96.7	100–90	97.5	100–90
16	92.4	–	87.3	92–78
13.2	84.3	–	72.5	80–62
9.5	70.1	80–60	55	72–50
4.75	50	65–35	39	56–26
2.36	36	50–20	28.6	44–16
1.18	22.2	–	21.7	33–12
0.6	14.5	–	15.3	24–8
0.3	8.3	21–3	8.9	17–5
0.15	6.1	–	6.6	13–4
0.075	3.7	8–2	4.3	7–3