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Mixed-Mode cracking behavior of cold recycled mixes with emulsion using Arcan configuration

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HIGHLIGHTS

- A newly developed Arcan test was utilized to investigate Mixed-Mode cracking behavior of CIR mix.
- Using Digital Image Correlation allowed for full-field displacement/strain fields to be captured.
- The proposed indicators can reflect the characteristics of CIR mixtures in Mixed-Mode cracking.

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ABSTRACT

Cold In-place Recycling (CIR) has gained popularity in recent years and it shows a good resistance to reflective cracking from underlying concrete pavement. The objective of this research is to investigate the Mixed-Mode cracking behavior of CIR mixtures, as there are indications that reflective cracks do not form in a 100% Mode I fashion. A newly developed Arcan configuration was utilized to simulate five levels of Mixed-Mode cracking. The peak load, crack angle, and three types of fracture energies were obtained to compare the Mixed-Mode cracking characteristics of CIR mixture. Utilizing Digital Image Correlation (DIC) allowed for full-field displacement/strain fields to be captured, along with the more traditional readings from attached gauges. The accuracy of DIC was verified and the effect of rigid displacement in Arcan test was eliminated. The results of this study indicates that crack initiation in 100% Mode II cracking produces the highest peak load, but it propagates rapidly once the crack is initiated. The peak load is more sensitive than fracture energy to temperatures. A strong correlation was found between crack angle and the level of Mixed-Mode cracking: it increases as the percentage of Mode II increases. A common feature of the five strain maps for Mixed-Mode cracking is that the strains near crack tip are higher than other strains, which results in the crack initiation. However, the crack path formed along higher strains changes significantly with five levels of Mixed-Mode cracking. Overall, this research provides a solid foundation for future research in exploring reflective cracking characteristics of CIR mixtures.

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 asphalt pavement is first milled and subsequently mixed with emulsion, water, additional aggregate, and sometimes additives to produce a rehabilitated pavement without the application of heat [1]. The success of CIR performance in the field typically lies in the resistance to reflective cracking from underlying concrete pavement [2,3]. Therefore, the cracking behavior of CIR mixtures should be well understood in order to capture the mechanisms of cracking.

A number of test methods, such as Indirect Tension, Single-Edge Notch Beam, Four Point Bending Beam, Disk-Shaped Compact Tension, and Semi-Circular Bend tests, have all been used to examine the fracture characteristics of asphalt concrete [4–8]. These research mainly focused on the opening crack, or Mode I crack of hot mix asphalt (HMA). However, the cracks in the field can often form in a combination of Mode I (opening) and Mode II (sliding): this is called Mixed-Mode cracking [9]. Mixed-Mode cracking in asphalt concrete has been studied by using the Single-Edge Notch Beam testing configuration. Due to the geometric limitations, it

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cannot cover the high levels of Mode II cracking. A new testing configuration, the Arcan test method was introduced and developed for asphalt concrete which can simulate five different levels of Mixed-Mode cracking including the 100% Mode I and 100% Mode II [10]. The Arcan configuration has been used frequently for Mixed-Mode crack growth testing of many other materials, such as wood, plastics, composites, and metal. The out-of-plane bending was often discussed in the Arcan test of thin specimens, but this can be avoided in the area of asphalt concrete with the special design of Arcan configuration [11,12]. Therefore, the Arcan test was chosen to investigate the Mixed-Mode fracture characteristics of CIR mixtures in this paper.

Digital Image Correlation (DIC) technique was also applied to explore the cracking behavior of CIR mixtures in the process of Arcan test. DIC is a non-contact, full-field displacement/strain analysis method that compares images of deformed specimen with that of an initial, undeformed specimen [13]. It was proposed as a possible displacement/strain measurement method for asphalt mixtures to determine the proper gauge length of Indirect Tension Test specimen [14]. Comparing with the traditional strain measurement sensors (e.g. strain gauges and LVDTs), DIC technique can provide pointwise measurement, thus pinpointing the location of crack initiation and propagation and accounting for non-uniform strain distributions of asphalt concrete. The displacement measurement accuracy of DIC with least squares matching (LSM) technique was proved to be satisfied in the Indirect Tension and Semi-Circular Bend tests [15]. It was also found that the strain results of DIC matched strain gage data within ±200 micro-strains for standard testing conditions [13]. Thus, the Mixed-Mode cracking behavior of CIR mixtures could be better investigated with the DIC system.

2. Materials and mix design

There is no universally accepted method for design of CIR mixtures, and most local agencies have their own CIR mix design procedures [16]. The CIR mixtures in this research were all designed according to the CIR specification in Jiangsu Province, China [17]. 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. Fig. 1 shows the two gradations used.

A CSS-1 asphalt emulsion was chosen to be compatible with the RAP materials and to control breaking time. Using properties from Marshall Stability and Flow, Indirect Tensile Strength, and Resilient Modulus, the optimum asphalt emulsion contents for CIR-20 and CIR-13 were 3.5% and 3.8% respectively. 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%.

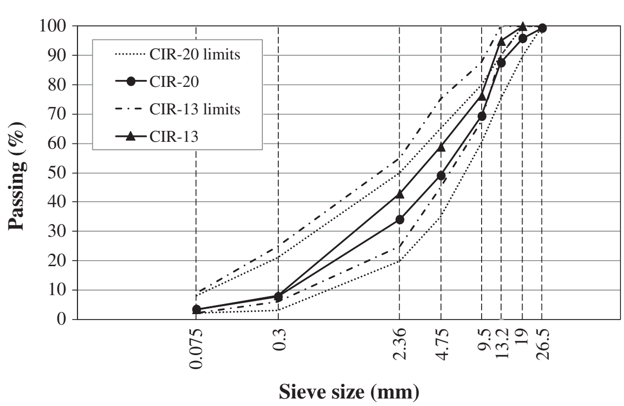

Fig. 1. Aggregate gradations of CIR mixtures.

During specimen fabrication, the mixing and compaction were accomplished at ambient temperatures (20 to 25 °C) without heating the materials. The Arcan specimen was formed in the size of 80 mm × 80 mm × 60 mm with a designed mold under static-load to a target air voids of 11% [17]. After compaction and long-term curing, the specimen was cut with a masonry saw into a thickness of 50 mm to get a smooth front surface. Finally, a 4 mm wide, 40 mm long, notch was mechanically inserted placing the notch tip at the center of the specimen. In addition to the 40 mm long notch length, three other notch lengths (10 mm, 20 mm, 30 mm) were also prepared to find the effect of notch length on the Arcan test.

3. Test methods

3.1. Arcan configuration

The Arcan testing geometry is shown in Fig. 2. 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. 2, 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.

3.2. DIC application

3.2.1. Specimen surface treatment

To fully use the power of the DIC, the front surface of the Arcan specimen can be treated to obtain a full grey scale image. First, the font surface was cleaned using sandpaper and an airbrush. Second, it was painted matt white with an ordinary spray paint, and third, matt black spray paint was speckled onto the white surface of specimen. This process provides a random, uniform speckle pattern, producing well-contrasted images. The surface treatment was also applied to the fixture as show in Fig. 3.

An image processing software was used for post-processing analysis to measure the displacement/strain field across the entire sample. Fig. 3 shows four groups of targets and four displacements that were captured by DIC, including the Load-Line Displacement (LLD) of the target on the surface of loading axis in Group 1, the rigid displacement of fixture obtained from four targets on the corner of fixture in Group 2, the Crack Mouth Opening Displacement (CMOD) between the two targets in Group 3, and the Crack Tip Opening Displacement (CTOD) between the two targets in Group 4.

3.2.2. Accuracy of DIC application

To verify the accuracy of DIC system in Arcan test, the LLD estimated by DIC system from the target on the surface of loading axis in Group 1 was compared with the measurement from an externally mounted linear variable differential transformer (LVDT). The DIC results were converted from pixels to millimeters, ranging from 0.16 to 0.17 mm/pixel in this study. The verification was performed in 100% Mode I cracking with a displacement-controlled system moving at a constant rate of 0.5 mm/min. Computing the Root Mean Square Error (RMSE) between estimated and measured LLD values, the result shows that the DIC system accuracy matches well with the displacement sensor and the error (RMSE = 0.012 mm) was acceptable. The accuracy of this DIC system for obtaining strains has been discussed by comparing the DIC values with strain gauge measurements [18] and the error is about 0.04% in Arcan test. It is confirmed that the DIC system can be used successfully in collecting accurate displacement and strain data during the Arcan testing.

3.2.3. Rigid displacement in Arcan test

Geometrically based equipment error of the Arcan configuration leads to rigid displacement during the tests, that can be incorrectly interpreted as displacement due to cracking if not accounted