An Introduction of the Arcan Testing Configuration for Mixed-Mode Cracking in Asphalt Concrete

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ABSTRACT: Fracture mechanics has been extensively used to quantify cracking characteristics of asphalt concrete, but most of the research to date has focused on Mode I, or opening, cracking. Cracking in the field usually occurs in a combination of Mode I and Mode II, or sliding, cracking. This combination of Mode I and Mode II cracking is called Mixed-Mode cracking. After a thorough review of various construction materials, the Arcan test configuration was chosen and developed for asphalt concrete. One asphalt concrete mixture with 13.2NMAS aggregate and a SBS modified PG76-22 was tested at 10C at a 1.0mm/min load-line displacement at five levels of Mixed-Mode: 100% Mode I, 75% Mode I, 50% Mode I, 25% Mode I, and 0% Mode I. Surprisingly, the first four levels of Mode I had very similar fracture curves and fracture energy. In addition, the first three levels of Mode I had similar crack angles. More types of asphalt concrete mixtures, at different temperature, loading rates, and air voids, should be analyzed to more fully understand Mixed-Mode cracking in asphalt concrete.

KEY WORDS: Fracture mechanics, Mixed-Mode, cracking, Arcan

1 MOTIVATION

Cracking in asphalt concrete pavements is a severe problem around the world. Research has shown that cracking characteristics in asphalt concrete can be captured through fracture mechanics. The Single-Edge Notch Beam, Disk-Shaped Compact Tension, and Semi-Circular Bend tests are all used to examine opening cracks, or Mode I cracks. However, cracks in the field rarely form in pure Mode I. Cracks usually form in a combination of opening and sliding, or Mode I and Mode II. The combination of these two types of cracks is called Mixed-Mode cracking.

Mixed-Mode cracking in asphalt concrete has been researched, but not with high levels of Mode II (Wagoner et al., 2005a; Braham et al., 2009a). The Mixed-Mode work completed for asphalt concrete to date has had a low percentage of Mode II due to geometric limitations (Wagoner et al., 2006; Song et al., 2006; Kim et al., 2009; Braham et al., 2009b). There has also been limited analytical work in other viscoelastic material (Pitti et al., 2008) such as wood. Some research has been performed in pure Mode II (Bouhas et al., 2008; Braham et al., 2009c), but that leaves large gap of Mixed-Mode cracking analysis. Therefore, the Arcan testing configuration is proposed. This configuration allows for theoretical pure Mode I, theoretical pure Mode II, and all values in between.

2 OBJECTIVES

There were three objectives to this research developing the Arcan configuration for Mixed-Mode testing of asphalt concrete:

- Investigate Arcan test methods in wood, plastics, composites, and metals to determine the best testing configuration for asphalt concrete
- Design fixtures for use in an UTM-25 load frame, performing design iterations if necessary
- Collect Mixed-Mode fracture data for one asphalt concrete mixture

3 ARCAN LITERATURE

The Arcan testing configuration has proved very successful testing many different materials, including wood, plastics, composites, and metal. The basic configuration of the Arcan test is a sample with a notch that can be rotated (Arcan et al., 1978). If the notch in the sample is perpendicular to the loading direction, the test is in Pure Mode I, or opening. If the notch is parallel to the loading direction, the test is in Pure Mode II, or sliding. The notch can be set at various angles between Mode I and Mode II, which creates a Mixed-Mode situation. In order to design the fixtures for the test, four different test configurations were evaluated to determine the best configuration for asphalt concrete. Each of the four configurations will be briefly discussed below to justify the final configuration chosen for this paper.

The first configuration analyzed was attaching the sample directly to the fixture on top and bottom, (Hallback and Jonsson, 1996; Liu et al., 1996; Pang and Seetoh, 1997; Rikards et al., 1998; Deng and Newman, 1999; Stenberg et al., 2001; Lo et al., 2003; Mahgoub et al., 2003; El-Hajjar and Haj-Ali, 2004; Li et al., 2004; Hay-Ali et al., 2006). The largest advantage to this configuration is that only two fixtures are needed, one to attach to the top ram and one to the bottom. This decreases the amount of fixture fabrication. In addition, this decreases the amount of compliance in the fixtures, as there is only one attachment on the top and bottom. There are several disadvantages to this setup. First, it is very difficult to attach the specimens to the fixtures. Most of the literature reviewed with this configuration was with metals and plastics. These materials often used bolts to attach the specimen to the fixture. However, very small holes can be drilled in metal without fear of failure at the holes. Since asphalt concrete is much weaker in tension, the pins pulling on the holes during the test could cause failure at the hole instead of failure at the notch. In addition, it would be difficult to attach a sample to a fixture from the side, as an asphalt concrete specimen can not be threaded.

The second configuration sandwiched the sample in between two fixtures (Sutton et al., 2003; Sutton et al., 2006). There are two pros to this configuration. First, friction could help hold the sample in place, as the sample would be surrounded by fixtures transferring the load. Second, there would be no moment on the sample. If the fixture is only on one side of the specimen, the sample could rotate slightly as the load is applied, creating forces out of the opening/sliding plane, essentially introducing a potential tearing, or Mode III, force. The largest con of this fixture is that it could be difficult to see the sample through the fixtures, and it is impossible to see the sample at the connection point with the fixtures. If there was any deformation during the test at the connection points, it would be hidden from view. If Digital Image Correlation was used, displacements could only be measured where the sample was not covered. Since asphalt concrete is a viscoelastic material, it is assumed that there will be some deformation away from the crack tip; this deformation could not be measured with this configuration.

The third configuration does not utilize fixtures, and the notched specimen has holes inserted directly into it where the load is applied (Arcan et al., 1978; Freire and Riley, 1980; Banks-Sills and Arcan, 1983; Banks-Sills et al., 1984a; Banks-Sills et al., 1984b; Hinderliter et al., 1991; Niu et al., 1999; Mohr and Doyoyo, 2003). Like the other two configurations, this set-up had several pros and cons. By drilling the holes directly into the sample, fixtures would not need to be fabricated. This would eliminate any cleaning of fixtures (if attached by glue) and reduce any compliance of the testing equipment. It would also allow for the maximum flexibility with choosing the percentage of Mode I and percentage of Mode II. Fixtures need pre-drilled holes to attach to the load frame, so only predetermined levels of Mixed-Mode could be tested. However, this configuration introduces the possibility of failure at the loading heads and requires uncommon equipment in most pavement laboratories. The final disadvantage is that the infinite values of Mixed-Mode would mean that each test could have slightly different values of alpha, and the repeatability would decrease. Each sample would have uniquely drilled holes. Therefore, when comparing one sample to a second sample, with theoretically the same value of Mixed-Mode, there would be a small variation of Mixed-Mode due to drilling variation, adding another variable to the test.

The forth, and final, configuration found used intermediate fixtures. The sample was attached to a fixture with glue, which is in turn attached to the main fixture, which attached to the loading ram above and below the sample (Hung and Liechti, 1997; Chakkarapani et al., 2006; Choupani, 2008). The largest advantage to this configuration is that it overcomes all of the cons listed in the previous three fixtures (hole failure, sample viewing obstruction, variable alpha value, etc.), but also decreases the time during testing because of easier fixture cleaning. With intermediate fixtures, several sets of intermediate fixtures could be fabricated at a lower cost, so tests can be run more rapidly. It is difficult to use glue at either below room temperatures or above room temperatures without loosing the bond between the sample and fixture during the test, so it is advantageous to glue the fixtures to the sample before starting testing. However, some cons do exist. Since each sample would need to be glued to the fixtures, the purchasing of high quality adhesives would increase testing cost. In addition, failures could occur at the glue interface instead of at the crack. Regardless of the type of adhesive, there is a chance of the test failing between the specimen and fixture, versus at the notch of the sample. This will ruin the sample and render the test results useless. Despite these disadvantages, the forth configuration was deemed best for asphalt concrete, and was used in this research.

4 MATERIAL CHARACTERISTICS

One asphalt concrete mixture was used in this research. A basalt/limestone aggregate blend was used, with basalt as the larger aggregate and limestone as the smaller. The final blend was a 13.2 NMAS (known as AC-13 in China). A SBS modified PG76-22 was used for the asphalt cement, at an optimal asphalt content of 4.58%. The asphalt cement was heated to 180C and the aggregate to 160C for mixing. A roller compactor (similar to the compactor used in European Standard EN 12697-33), as seen in Figure 1, compacted the 30x30x5cm slabs to a target 4 percent air voids.

Figure 1: The rolling compactor at Southeast University.

The sample moves to the left and right 12 times, with one cycle taking approximately 11 seconds. The manufacturer pressure is set at 300N/cm2. After compaction, the samples were cut with a masonry saw into 80x80 squares with the 50mm thickness remaining the same. After the square samples were cut, a 4mm wide, 40mm long, notch was mechanically inserted using the same masonry saw.

5 INITIAL ARCAN CONFIGURATION

Two different Arcan testing configurations were used. The first configuration, seen in Figure 2, was tested at 25C.

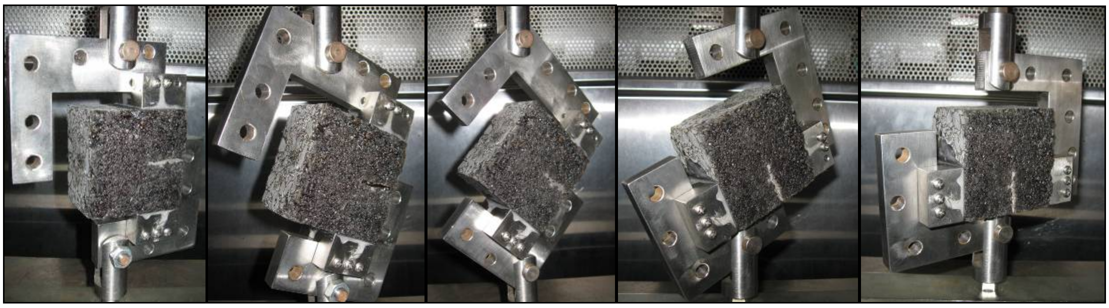


Figure 2: Initial Arcan test configuration, pure Mode I on the left, pure Mode II on the right, with Mixed-Mode conditions in between.

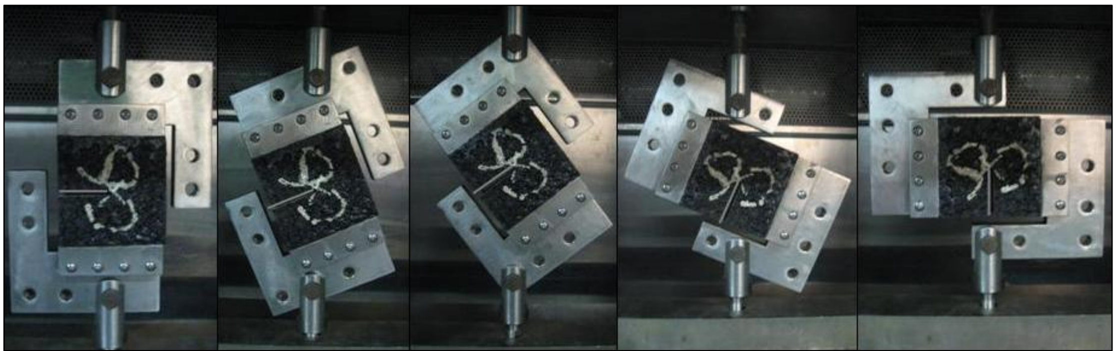
In this first configuration, the fixture was only attached to the faces parallel to the notch for 40mm, or only the length of the notch (half of the 80mm surface). Several problems developed with this initial configuration. First, visual deformation was occurring at the loading heads on top and bottom, as seen in Figure 3. This indicates that energy was being consumed away from the notch, diminishing the effectiveness of the fracture test. The second problem included a measurement error in the initial fixture design, preventing proper alignment of the specimen with the fixtures. Again, in Figure 3, when the load was applied, the right corner of the fixtures was not always parallel with the right corner of the specimen, introducing a moment on the sample. Third, at the higher levels of Mode II, the glue at the fixture/sample interface failed several times before the crack initiation and propagation at the notch. Therefore, the test had to be stopped before recording any useful data and the sample had to be discarded due to potential damage.

Figure 3: Deformed specimen and misaligned fixture on initial Arcan configuration.

With these three issues, the fixtures were redesigned to eliminate design errors and increase the surface area of the fixture/specimen interface. In addition, testing temperature was decreased to 10C in order to reduce deformation of the specimen away from the notch.

6 FINAL ARCAN CONFIGURATION

The second configuration, or the final configuration, with a longer fixture/sample interface is shown in Figure 4.



100% Mode I 0% Mode II	75% Mode I 25% Mode II	50% Mode I 50% Mode II	25% Mode I 75% Mode II	0% Mode I 100% Mode II

Figure 4: Final Arcan test configuration, pure Mode I on the left, pure Mode II on the right, with Mixed-Mode conditions in between.

In Figure 4, the fixture was attached to the surfaces parallel to the notch, along the entire length of the specimen. This allowed for an even distributed load across the sample, decreasing the deformations seen in Figure 3. Figure 5 confirms that after a test was performed, the fixtures stay parallel to all four sides of the specimen, indicating that the energy put into the system was spread evenly across the sample perpendicular to the notch.

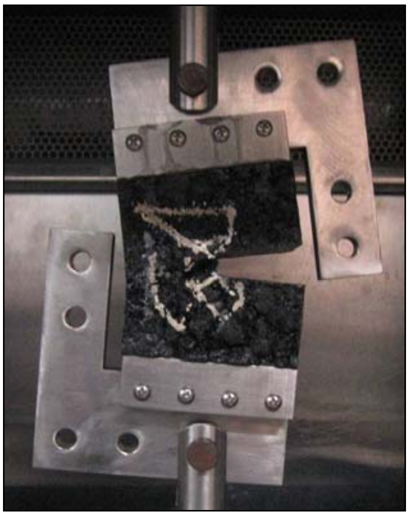


Figure 5: Properly aligned fixtures on final Arcan configuration.

7 TEST RESULTS AND DISCUSSION

Due to testing restraints and specimen preparation issues, an unequal number of tests were run for each level of Mixed-Mode. Four samples were run at 100% Mode I, five samples were run at 75% Mode I, three samples were run at 50% Mode I, three samples were run at 25% Mode I, and two samples were run at 0% Mode I. A UTM-25 load frame was utilized, and load and load-line displacement were recorded. For these tests, the machine's LVDT was utilized, however, during testing an external LVDT was procured and will be used in all future testing. Figure 6 shows the load/load-line displacement curves from each level of Mixed-Mode. The curves were obtained from averaging the replicate curves. All tests were run at 10C and run under load-line displacement control at 1.0mm/min. Tests began with a pre-load of 0.2kN and were stopped when the load reach 0.1kN.

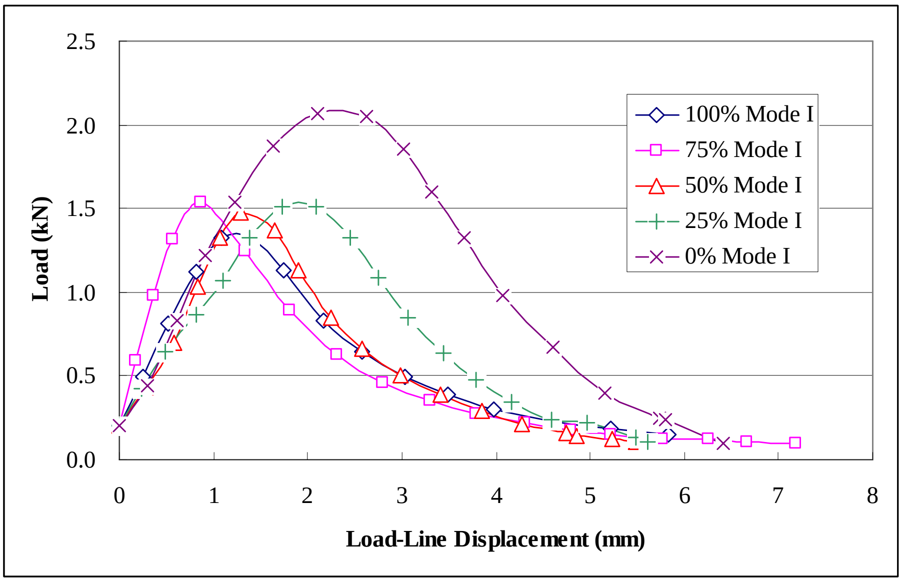


Figure 6: Average load/load line displacement curves for five levels of Mixed-Mode.

Figure 6 has several interesting trends. First, softening curves exist for all levels of Mixed-Mode. This is contrary to Braham et al., 2009b, that observed the disappearance of the soften curve with an increase of Mode II influence. There are two reasons that the softening curve appeared for all levels of Mixed-Mode. First, with a testing temperature of 10C, the asphalt concrete was much less quasi-brittle than the mixtures from the previous study (which were run at -12C). Second, the loading rate was 1.0mm/min versus 5.0mm/min. This decrease in loading rate could have allowed softening characteristics to develop in the mixtures, thus eliminating the quasi-brittle failure (no softening curve). Both the testing temperature and loading rate warrant more investigation. A second interesting trend is that the 100, 75, 50, and 25% Mode I curves all look quite similar, both in shape and size. However, the 0% Mode I (or 100% Mode II) has a longer time before peak load and a larger softening curve.

In order to further investigate the five levels of Mixed-Mode, the fracture energy for each level was calculated. The fracture energy was found by taking the area under the load/load-line displacement curve, and dividing this area by the fracture face area of the specimen after failing. When computing the fracture face area, the crack was assumed to be a straight 2D plane.

Figure 7 shows the fracture energy for the five percentages of Mode I. Similar to the trends seen in Figure 10, the trends in Figure 7 show that the four highest percentages of Mode I have similar fracture energy. The bars in are the standard deviation of the replicates for each percentage of Mode I. Only 0% Mode I, or 100% Mode II, has a significant difference. This was highly unexpected, as Mixed-Mode fracture testing from other materials showed a difference between these five percentages of Mode I. A potential confounding factor is that the fracture energy was only calculated using Load-Line Displacement, which combines both Mode I and Mode II fracture energy. If fracture energy was calculated using different quantities of displacement, such as opening displacement and sliding displacement, fracture energy values may have varied between these four levels of Mixed-Mode. In addition, since this is a newly developed test for asphalt concrete, there are probably unforeseen effects occurring that will become apparent when testing more asphalt concrete mixtures, with different types of binders and aggregates, and at different temperatures and loading rates.

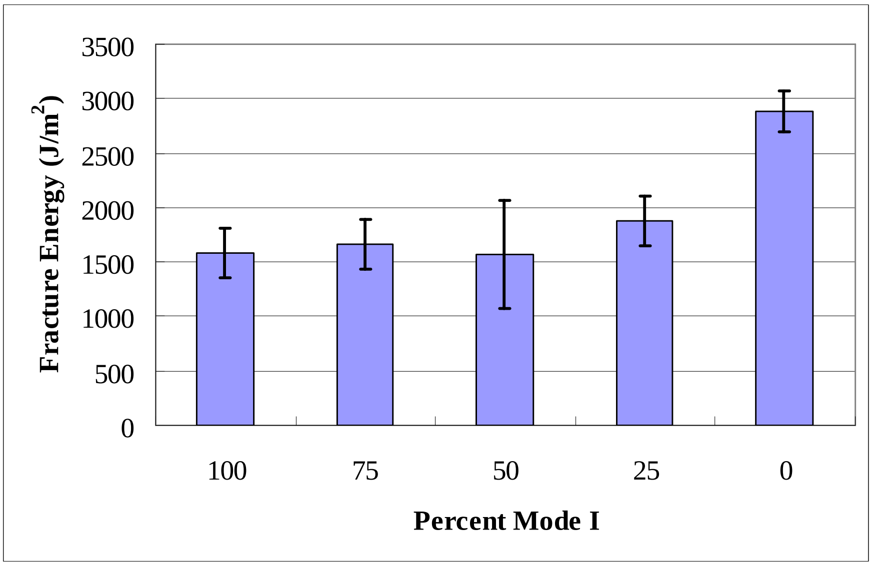


Figure 7: Fracture energy for five levels of Mixed-Mode with standard deviation error bars.

The final test result examined was the angle of the crack that developed during testing. After specimen failure, the length of the crack was measured. Assuming a straight line crack, and knowing the ligament length, the angle of the crack could be calculated using trigonometry. Figure 8 shows the average crack angle for the five percentages of Mode I.

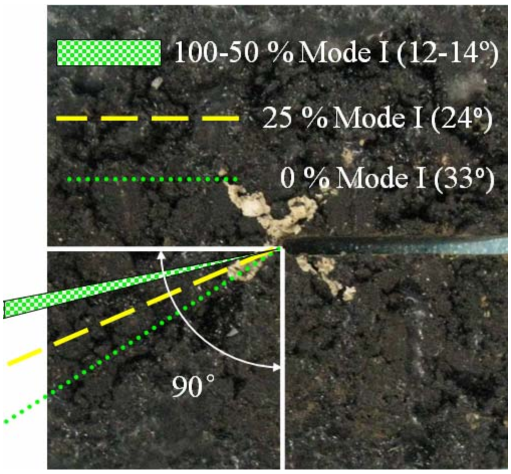


Figure 8: Average crack angle for five levels of Mixed-Mode.

For the first three levels of Mode I (100, 75, and 50%), the average crack angles were all between 12 and 14°. This is shown as the checkered band in Figure 8. However, unlike the fracture curves and fracture energy, 25% Mode I and 0% Mode I had a statistically different angle of 24° and 33° respectively. There did appear to be unsymmetrical loading in 100% Mode I, as one side of the sample's crack angle was 0-5°, while the other side was 10-15°. More testing, assuring even loading, may decrease the crack angle at 100% Mode I. A larger crack angle actually decreases the fracture energy, as the ligament area is increased.

8 CONCLUSIONS, RECOMMENDATIONS, AND ACKNOWLEDGEMENTS

Fracture mechanics is a growing research area to investigate cracking characteristics of asphalt concrete. Most research to date has investigated Mode I, or opening, cracking. However, cracks in the field rarely form in pure Mode I, but usually are a combination of Mode I and Mode II, or sliding cracking. This combination is called Mixed-Mode cracking. While there has been some research on Mixed-Mode cracking, it has been at very low levels of Mode II. Therefore, after a thorough review of mechanical testing in metals, wood, and plastics, the Arcan test was developed for asphalt concrete that allowed for theoretical pure Mode I, theoretical pure Mode II, and all values in between. A configuration that used intermediate fixtures that are glued directly to the asphalt concrete was chosen, as this configuration was deemed the most practical.

An initial configuration was developed, but proved to have several shortcomings, so the fixtures were revised for a final configuration. One mixture, a 13.2mm NMAS aggregate with a SBS modified PG76-22, was tested at 10C at a 1.0mm/min load-line displacement. Five levels of Mixed-Mode were tested: 100% Mode I, 75% Mode I, 50% Mode I, 25% Mode I, and 0% Mode I. There were several interesting trends from the tests:

- Each level of Mixed-Mode had softening curves, contrary to previous research
- Surprisingly, the first four levels of Mode I (100, 75, 50, and 25%) had very similar fracture curves and fracture energy
- Crack angles for the first three levels of Mode I (100, 75, and 50%) were similar, at 12-14°, but the angles of 25% Mode I and 0% Mode I were statistically different at 24° and 33°

The common fracture energies could have occurred because only load-line displacement was being measured, which does not differentiate between Mode I and Mode II, but is a combination of those two measurements. From this preliminary research using the Arcan configuration to measure Mixed-Mode cracking characteristics of asphalt concrete, several recommendations are proposed:

- In order to examine currently unknown factors of the Arcan test, investigate more types of asphalt concrete mixtures, including different binders and aggregates, at different temperatures, loading rates, and air voids
- Capture more detailed data, including crack mouth opening displacement, crack tip opening displacement, and crack tip sliding displacement, in order to analyze the specific components of Mode I (opening) and Mode II (sliding)
- Capture the bulk deformations of the Arcan sample between the notch and the fixtures to determine if deformations occurring in these areas are compromising the displacement component of fracture energy data collection. This could be attained by using Digital Image Correlation, which would photograph the entire sample during testing.

The authors gratefully acknowledge financial support provided from the National Natural Science Foundation of China and the China Post-Doctoral Science Foundation. Without their generous funding, this research would not have been possible.

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