Reintroducing the poker chip direct tension test for asphalt concrete mixtures

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ABSTRACT: Mode I fracture in flexible pavements occurs due to the inability of asphalt concrete (AC) mixtures to resist tensile stresses. At binder scale, microcracks nucleate and gradually coalesce into macrocracks at mixture scale. Various laboratory test procedures have been developed to simulate cracking mechanism. This study reintroduces the AC poker chip test to evaluate cracking mechanisms in three AC mixes with varying Recycled Asphalt Pavement (RAP) content and compares the energy dissipated curves with two additional test methods: Indirect Tensile Test (IDT) and Illinois Flexibility Index Test (I-FIT). The results indicate that the AC poker chip test is a useful test geometry, as it allows for total energy dissipation into crack initiation and propagation. Specimens with higher aspect ratios were better suited for testing due to more uniform stress distributions. Finally, a unified energy-based characterization revealed that high RAP mixtures require greater energy for crack initiation but exhibit brittle crack propagation behavior.

1 INTRODUCTION

Cracking is a prevalent distress in asphalt concrete (AC) pavements, arising from tensile forces induced either by vehicular loads or temperature variations. While AC withstands compressive stresses well, it is inherently weak under tensile loading, leading to mode I fracture at critical tensile strain regions, such as the bottom of the AC layer. Cracks nucleate at the binder scale, where microcracks coalesce into macrocracks. Traditional dynamic shear rheometer (DSR) tests evaluate binders within the linear viscoelastic (LVE) range but fail to capture higher, nonlinear strain behavior. To address this, the poker chip test has emerged as a reliable method for evaluating cracking resistance, offering realistic ductility measurement compared to bulk testing (Vyas *et al.* 2023). Though effective at the binder scale, its application at the fine aggregate matrix (FAM) and AC scales remains underexplored, with the only known study taking place more than 40 years ago (Bynum, 1979).

Various tests have been developed to evaluate AC cracking resistance at intermediate temperatures. Strength-based tests, such as the Indirect Tensile Strength (IDT) and IDEAL-CT, assess cracking potential by applying compressive loads to cylindrical specimens, inducing tensile stresses along the horizontal diameter. However, concerns remain regarding the efficacy of these tests for ductile AC mixtures, as they produce non-uniform strain distribution and permanent deformation beneath the loading strip (Al-Qadi *et al.* 2022). The Illinois Flexibility Index Test (I-FIT) (Ozer *et al.* 2016), a notch-based SCB fracture test, effectively captures crack propagation but places less emphasis on crack initiation. Studying crack initiation effectively requires evaluating AC properties in an undamaged state, free from notch-induced effects. Additionally, energy dissipated during testing should be solely attributed to crack initiation and propagation, necessitating a testing mechanism involving pure tensile loading.

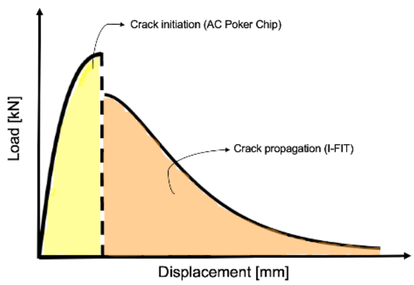

Figure 1. Isolating crack initiation and propagation.

To isolate the crack initiation process, a Direct Tension (DT) test, hereafter referred to as the AC poker chip test, was employed. The test involves applying uniaxial tension to an AC specimen sandwiched between two metal plates under displacement control. Initially used during the SHRP studies in the 1990s, the DT test faced challenges with eccentric loading and complex specimen preparation. Issues with the gluing process and specimen debonding were also prevalent. However, this test holds potential for studying crack initiation and total energy dissipation, if conducted diligently. This study reintroduces the AC poker chip test (Bynum 1979), evaluating different aspect ratios and analyzing stress distribution using finite element modeling (FEM), aiming to develop a unified energy-based characterization (Figure 1) by combining crack initiation and propagation mechanisms.

2 MATERIALS AND MIX DESIGN

A U.S. Federal Aviation Administration P-401 mix, designed as per AC 150/5370-10H using Type 2 gradation, was obtained from an airport paving contractor. Component materials—aggregates, binder, and anti-strip additives—were collected. Two additional AC mixtures were designed by incorporating 10% and 30% RAP into the control P-401 mix with no RAP. Figure 2 presents aggregate gradation curves within FAA specification limits.

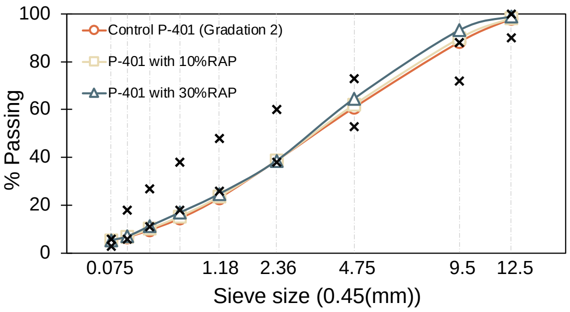

Figure 2. Gradation curves.

Aggregates were dried at 110°C for 24 hours, while recycled materials were dried at 50°C for 72 hours with periodic stirring. A Performance Grade (PG) 76-28 binder, modified with Styrene-Butadiene-Styrene (SBS), was used. To enhance adhesion and prevent stripping, a 0.4% liquid anti-strip additive (by binder weight) was added. Mixing and compaction temperatures were 173°C and 163°C, respectively. Short-term aging (STA) was performed at compaction temperature for one hour. Specimens were compacted using 75 gyrations with a Superpave Gyratory Compactor (SGC) to achieve 3.5% air voids and ≥15% Voids in Mineral Aggregates (VMA), per P-401 standards. ABR values in Table 1 (0%, 9.65%, and 28.97%) represent the percentage of asphalt binder replaced by RAP in the Control P-401, P-401 (10% RAP), and P-401 (30% RAP) mixes, respectively. The volumetric compositions of the mixes are shown in Table 1.

Table 1. Mix design parameters.

Mix type	Control P-401	P-401(10%RAP)	P-401(30%RAP)
Binder	PG 76-28	PG 76-28	PG 76-28
P_b (%)	6.2	6.2	6.2
Anti-strip	0.4%	0.4%	0.4%
ABR (%)	0	9.65	28.97
V_a (%)	3.46	3.53	3.51
VMA (%)	15.84	15.73	15.47

* P_b = Percent binder, ABR = Asphalt Binder Replacement, V_a = Air voids, VMA = Voids in Mineral Aggregates.

3 AC POKER CHIP TEST

3.1 *Specimen preparation*

AC cylindrical specimens with 7.5% air voids and dimensions of 150 mm in diameter and 180 mm in height were prepared. Specimens were cored from the center and saw-cut into dimensions of 100 mm in diameter and 150 mm in thickness, ensuring that air voids met the requirement of 7 ± 1%. Subsequently, these specimens were further saw-cut at the midpoint to produce two specimens with dimensions of 100 mm × 50 mm and 100 mm × 25 mm. Three replicates were prepared for each mixture. Prior to the gluing process, all specimens were dried under a fan for a minimum of 24 hours to eliminate surface moisture. A high-strength epoxy was used for gluing. Steel plates with grooves were employed to prevent bonding failures between the epoxy and steel. A gluing jig was utilized to attach the top and bottom steel plates to the specimens, applying 40 g of epoxy to each side. To minimize the risk of eccentric loading during testing, diligent care was taken during the sawing process to ensure that the average diameter and thickness of the specimens were within ±1 mm tolerances.

3.2 *Testing and results*

A Universal Testing Machine (UTM) was employed for the tensile testing. Each specimen was securely mounted onto the testing frame, and a displacement-controlled load was applied at a constant rate of 0.5 mm/min to the top plate (Figure 3). The results were analyzed by plotting the load-displacement curves. The area under the curve represents the work done or the energy dissipated during the test.

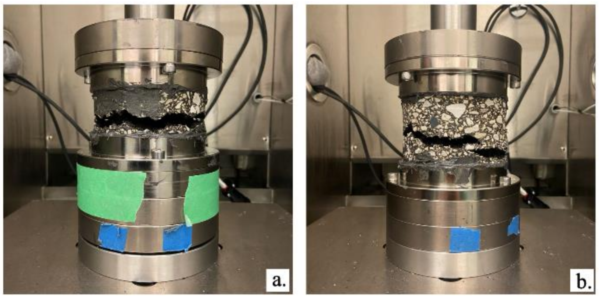

Figure 3. AC Poker chip test for: a. 25-mm and b. 50-mm specimens.

Figure 4 presents the load-displacement curves for the specimens. For both 50-mm and 25-mm specimens, it can be observed that an increase in RAP content consistently resulted in higher peak loads. Additionally, the post-peak behavior appeared significantly more brittle compared to the Control P-401. 25-mm specimens, compared to the 50-mm specimens, exhibited higher peak loads for both the Control P-401 and P-401 (10% RAP). However, the opposite trend was observed for the P-401 (30% RAP), where the 50-mm specimen demonstrated a higher peak load. It is important to note that, in this case, the discrepancy occurred due to debonding of the specimen from the top plate. However, based on majority results (for which debonding was not an issue), it can be inferred that specimens with a higher aspect ratio exhibited more brittle behavior and rapid crack propagation.

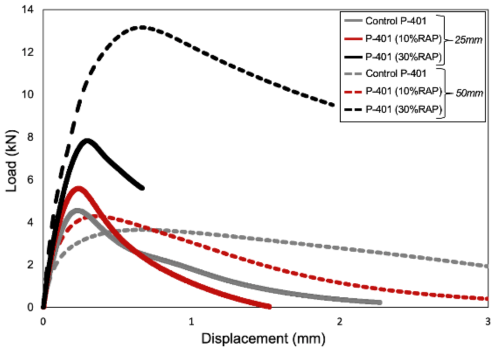

Figure 4. AC Poker chip output.

The stress distribution in the 50-mm specimens appeared to be non-uniform, as indicated by an observed diagonal failure slope, whereas the failure plane in the 25-mm specimens was predominantly horizontal. These observations align well with the load-displacement data, and theory of edge effects. Furthermore, it can be postulated that while the mix without RAP exhibited ductile behavior during crack propagation, as evidenced by the gradual post-peak slope, and the load required to initiate the crack was relatively low. It should be noted that the repeatability of the test results is poor, with the average coefficient of variation for peak load around 24%.

4 DIFFERENCES IN ENERGY DISTRIBUTION

Load-displacement curves were analyzed for three test setups: IDT test, I-FIT, and AC poker chip test. For the IDT test, three SGC specimens were prepared for each P-401 mixture. The specimens were compacted to dimensions of 95 mm in thickness and 150 mm in diameter, ensuring compliance with the air voids requirement of 7 ± 1%. The test involved applying a displacement-controlled diametrical load at a rate of 50 mm/min until specimen failure. The I-FIT was conducted following the AASHTO T 393-22 protocol. For each mixture, two SGC specimens were compacted with a diameter of 150 mm and a height of 160 mm. Each SGC specimen was then saw-cut into four SCB specimens, ensuring that the air voids satisfied the 7.0 ± 1% requirement. Load and displacement data were collected for both the IDT and I-FIT procedures. While the differences in loading rates and specimen dimensions contribute to the variations in the curves, the observed trends still offer valuable insights into how different test methods capture the cracking behavior. As observed in Figure 5, the area under the load-displacement curve for the IDT test is significantly larger compared to the I-FIT and AC poker chip tests. This inflated curve is primarily attributed to energy dissipation dominated by plastic deformation under the loading strip, with limited energy directed toward crack initiation and propagation. Consequently, the IDT test overestimates the energy associated with fracture formation, as it primarily captures the plasticity component rather than the energy dissipated exclusively for crack formation and propagation. In contrast, the area under the load-displacement curve for the I-FIT is comparatively smaller, reflecting its focus on measuring energy dissipation during crack propagation. The I-FIT is explicitly designed as a fracture test, with a loading scheme that minimizes energy dissipation toward plasticity and crack initiation. The inclusion of a notch effectively reduces plastic deformation energy, channeling the majority of the energy toward crack propagation. This makes the I-FIT particularly effective in distinguishing between brittle mixtures, where cracks propagate rapidly, and ductile mixtures, where crack growth is more gradual.

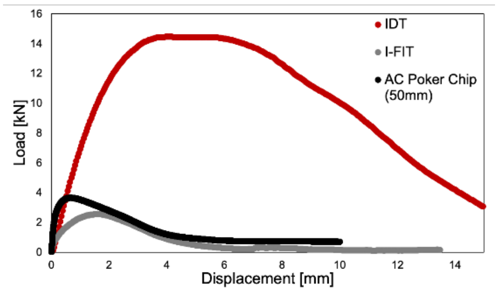

Figure 5. Avg. load-displacement curve for Control P-401.

However, while the I-FIT efficiently measures crack propagation, the presence of the notch limits its ability to capture crack initiation. The notch acts as a stress concentrator, bypassing the natural crack initiation process, which involves the nucleation and coalescence of microcracks from an undamaged state. The load-displacement curve from the AC poker chip test presents potential for an ideal setup, where the entire energy dissipation is associated with crack initiation and propagation. However, due to the randomness in crack formation, the energy dissipated toward crack propagation may not be as effectively captured as in the I-FIT, where the fracture is much more channelized. To address this limitation, the pre-peak portion of the AC poker chip test curve and the post-peak portion of the I-FIT curve were used to isolate the mechanisms of crack initiation and propagation, respectively.

5 EFFECT OF ASPECT RATIO

To evaluate the effect of aspect ratio on stress distribution, a simplified 3D AC specimen was modeled using the ABAQUS Finite Element Modeling (FEM). Three specimen thicknesses, all with a diameter of 100 mm, were simulated: 50 mm, 25 mm, and 3.125 mm, corresponding to aspect ratios of 2, 4, and 32, respectively. Although the 3.125 mm specimen is practically challenging to produce, it was included to examine the effects of a very high aspect ratio. The specimens were assigned viscoelastic properties and assumed to be homogeneous for the purposes of the simulation. The bottom face was constrained with an encastre boundary condition, restricting all structural degrees of freedom, while the top face was subjected to uniform tension at a displacement rate of 0.5 mm/min. The specimens were meshed using standard linear elements. Figure 6 shows the top view of the maximum principal (absolute) stresses on the top plate. The results indicate that an increase in aspect ratio leads to a more uniform stress distribution, corroborating the laboratory findings from the AC poker chip test presented in Section 3. However, in this study, the aspect ratio was not further increased due to the nominal maximum aggregate size (NMAS) of the AC mixtures being 12.5 mm. Bynum (1979) demonstrated the feasibility of conducting tests on specimens with higher aspect ratios in mixtures with smaller NMAS.

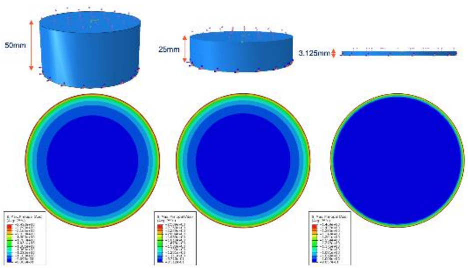

Figure 6. FEM results.

6 UNIFIED ENERGY-BASED ANALYSIS

The load-displacement curves from the AC poker chip test and the I-FIT were combined into a single curve to isolate the mechanisms of crack initiation and propagation (Figure 7). The pre-peak region from the AC poker chip test was used to represent crack initiation, while the post-peak region from the I-FIT was used for crack propagation. These two regions were merged into one curve to analyze the energy dissipated during each phase.

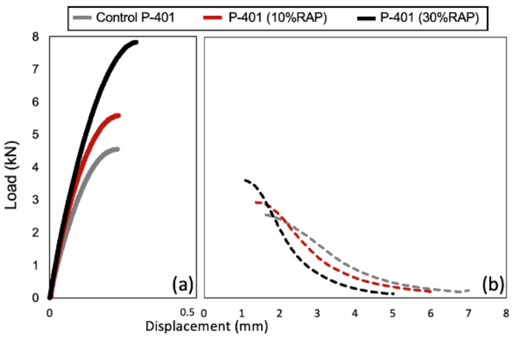

Figure 7. (a) Pre-peak AC poker chip, and (b) Post-peak I-FIT.

The results showed that the energy dissipated (or work done) to initiate cracking, as obtained from the AC poker chip test curve, was different, and the peak load was significantly higher than that observed in a typical I-FIT output. This difference is attributed to the presence of a notch in the I-FIT specimens, which bypasses the natural crack initiation process that begins from an undamaged state. However, the I-FIT setup is well-suited for studying crack propagation behavior, as seen in the post-peak region (Figure 7b). As the RAP content increases, the results indicate that a higher peak load is required to initiate a crack, and the propagation becomes brittle, as evidenced by the steep slope of the post-peak curve.

7 CONCLUSION

This study aimed to reintroduce the AC poker chip test as a method for evaluating cracking resistance in AC mixtures. Three airfield AC mixtures containing 0%, 10%, and 30% RAP were prepared and tested using IDT, I-FIT, and the AC poker chip test. The primary focus was on analyzing the load-displacement curves obtained from each test. It was observed that the IDT test tends to overestimate the energy associated with fracture formation, as it primarily captures the plasticity component rather than isolating the energy dissipated for crack initiation and propagation. In contrast, the I-FIT curve, which represents energy dissipation during crack propagation, yielded a smaller area under the curve. The presence of a pre-existing notch in the I-FIT limits its capability to evaluate crack initiation. AC poker chip test demonstrated significant potential as an ideal setup for evaluating crack initiation and propagation, as the entire energy dissipation could be directed solely toward these mechanisms. However, concerns regarding specimen preparation, epoxy debonding for high RAP mixtures, and the repeatability of results still remain. Results indicated that an increase in the aspect ratio (or a decrease in specimen thickness) led to a more uniform stress distribution, which was further validated through finite element modeling. Finally, a unified energy-based characterization approach was introduced. This approach revealed that, for high RAP mixtures, a larger amount of work is required to initiate a crack, while the crack propagation behavior is brittle, as indicated by the steeper post-peak slope.

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