Determining the Fracture Energy Density of Asphalt Binder Using the Binder Fracture Energy (BFE) Test

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Background

- The fatigue resistance of asphalt binder strongly influences the fatigue performance of asphalt mixture and pavement.

- None of the existing test methods for asphalt binder was able to provide parameters consistently correlated with relative cracking performance of mixtures, including:
  - DSR $(G^* \sin \delta)$, Elastic Recovery (ER), and
  - Force-Ductility (FD)
Fracture energy is a good indicator of fatigue resistance of asphalt mixtures.

Cumulative energy to failure from FD results showed improved ability to predict cracking performance at intermediate temperatures. FD was not optimized to determine fracture energy accurately.

A test designed to obtain fracture energy could provide a better parameter related to fatigue resistance of binder.
Traditional Direction Tension (DT) test has limitations.

- Long middle part with uniform area:
  - Specimen may crack anywhere → high deviation in measured failure strain
  - Often results in premature failure
  - Difficult to apply high enough strain rate to reduce excessive deformation
  - May exceed loading rate capacity of equipment without fracture.
Background (Cont.)

- There is a need to develop a new DT test that allows for accurate determination of stress-strain relationships and fracture energy density (FED) of binder at intermediate temperatures.

- UF research group developed a binder fracture energy (BFE) test with:
  - Specially designed specimen geometry; and
  - Data interpretation procedure.
Geometry Development
No.1: 3-D FEA

A 5×5 mm uniform stress distribution area
Stress Concentration Factor is around 11.0
Geometry Development
No. 1: Prototype Test

- Adhesion between asphalt and loading head was less than Cohesion of asphalt
- Need to modify the specimen shape

Test on MTS Machine

Asphalt peeled off from load head
Geometry Development
No.2: 3-D FEA

- Fairly uniform stress concentration area at the center
- Stress concentration factor is greater than 5
Geometry Development
No.2: Prototype Test

- Adhesion between asphalt and loading head was less than Cohesion of asphalt
- Need to strengthen connection between asphalt and loading head and reduce any high stress at the corners of loading head
Geometry Development No.3: 3-D FEA

- Fairly uniform stress concentration area at center
- Stress concentration at contact surface of loading head eliminated
Geometry Development
No.3: Prototype Test

Testing Equipment

Crack at Center
Data Interpretation

- Data analysis procedure
  - FEM modeling
  - Large strain deformation

True stress & true strain

Account for ductile cracks that clearly exhibit necking because of larger deformation to failure
Data Interpretation
Determination of True Strain and Stress

- Up to the first stress peak

- FEA based on large deformation formulation was used

Transforming Extension to True Strain

True Stress: \[ \sigma = \frac{F}{A} \]
Data Interpretation
Determination of True Strain and Stress (Cont.)

- At the first stress peak

- Length and Cross-sectional Area can be determined using FEA with large deformation formulation

Figure 3: Calculating Length of 3mm Part at Peak

Figure 2: Calculating Area of Cross-Section at Peak
Data Interpretation
Determination of True Strain and Stress (Cont.)

Length of Middle Part:

A. Before testing
   - Length = 3mm

B. At the first stress peak
   - Length = L₁

C. After the first stress peak
   - The middle part undergoes necking
After the first stress peak

Assume most strain occurs in the middle 3mm of the specimen, and use large strain formulation

\[ A = \frac{(A_1 \cdot L_1)}{L} \]

True Stress:
\[ \sigma = \frac{F}{A} \]

True Strain:
\[ \varepsilon = \ln \left( \frac{L}{L_1} \right) \]
After applying these calculation procedures, the point of initial fracture is clear.

The post-peak energy after the point of initial fracture should not be considered.

Example:
Binder Type: PG 67-22
Testing temperature: 15 °C
Displacement rate: 500mm/min
Premature Failure Identification

- At low temperatures and/or faster loading rates, any imperfection of specimen may result in premature failure.

- Premature failure can be identified based on:
  - Geometric characteristics of failed specimen
  - Fracture energy density
  - True stress-strain curve

- Implication: there is an optimal combination of temperature and loading rate range to consistently obtain fracture energy of binder.
Premature Failure Identification (Cont.)

Proper Fracture

Premature Fracture

FE=208 psi

FE=12 psi
Tests and Analyses of Binders

- Preliminary Tests
- SUPERPAVE Section Recovered Binders
- Hybrid and Highly Polymer-modified Binders
Preliminary Tests

- Tests were run on the MTS machine
- Test temperatures: 0, 5, 10, 15, 20 °C
- Various loading rates: depend on the test temperature
- PAV-aged Binders:
  - PG 67-22 (unmodified)
  - PG 76-22 (SBS Polymer modified)
Fracture Energy Density at 15 °C:

- Consistent for the same binder at different loading rates
- Clearly differentiates between SBS-modified and unmodified binders
The average FED values are consistent for the same binder at different temperatures.

The difference between PG 76-22 and PG 67-22 is clear.
Summary of Preliminary Tests

- 15 °C appeared to be the optimal test temperature for both PG 67-22 and PG 76-22

- An optimal or acceptable range of loading rate should be used to obtain consistent and accurate fracture energy
  - Avoid premature fracture and excessive deformation
Binders Recovered from Superpave Sections (Cont.)

- Recovered from asphalt mixtures of 12 Superpave Projects:
  - Unmodified binders: AC-30, AC-20, PG 64-22
  - SBS polymer modified binder: PG 76-22
  - Rubber modified binder: ARB-5

Of note, RAP binder was present in the recovered binders because RAP is routinely used in Florida.
Binders Recovered from Superpave Sections (Cont.)

- Test temperature: 15 °C
- Multiple loading rates

- FED was consistent at different loading rates.

AC-20 recovered, FED vs. Loading Rate
The BFE test clearly distinguished between different types of binder.

Fracture Energy of binders recovered from Superpave sections

- The BFE test clearly distinguished between different types of binder.
Hybrid Binders and Highly Polymer Modified Binder

- All the binders are PAV residues
  - 3 types of hybrid binder:
    - Wright: rubber and SBS
    - Hudson: 3.5% rubber + 2.5% SBS
    - Geotech: 8% of rubber + 1% SBS
  - 1 type of highly SBS modified binder: PG 82-22
Hybrid Binders (Wright, Hudson, Geotech)

- For the same binder, FED is consistent.
- The difference between different hybrid binders is clear.
FED of PG 82-22 is consistent regardless of loading rate and temperature.
Binder FED Results: PAV residue

Fracture Energy Density of various binders

- Unmodified
- Rubber-modified
- SBS-modified
- Hybrid

Fracture Energy Density (psi)

Binder Types

PG 82-22
Results of Statistical Analyses

- Statistical analyses showed:
  - The BFE test effectively differentiated between binders in terms of FED.
  - For the same binder, the FED is independent of loading rate and temperature in a certain range.

- It indicates that FED is a fundamental property of binder:
  - It can be determined by tests performed at a single temperature and loading rate.
Testing Standard Development

- Binder conditioning
  - RTFO +PAV (AASHTO 315)
- Displacement rate and testing temperature
  - 500 mm/min at 15°C (Recommended)
- A broad range of asphalt binders
## Materials

<table>
<thead>
<tr>
<th>Binder Types</th>
<th>Modifying Components</th>
</tr>
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<tbody>
<tr>
<td><strong>Unmodified binders</strong></td>
<td></td>
</tr>
<tr>
<td>PG 52-28</td>
<td>None</td>
</tr>
<tr>
<td>PG 58-22</td>
<td></td>
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<tr>
<td>PG 64-22</td>
<td></td>
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<tr>
<td>PG 67-22</td>
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<tr>
<td><strong>Rubber-modified binders</strong></td>
<td></td>
</tr>
<tr>
<td>ARB-5</td>
<td>5% Type B GTR</td>
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<tr>
<td>ARB-12</td>
<td>12% Type B GTR</td>
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<tr>
<td><strong>Hybrid binders (rubber plus polymer)</strong></td>
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</tr>
<tr>
<td>Hybrid A</td>
<td>1% SBS (approximately 30 mesh, incorporated dry), 8% of Type B GTR, 1% hydrocarbon</td>
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<tr>
<td>Hybrid B</td>
<td>3.5% crumb rubber, 2.5% SBS, 0.4%-plus Link PT-743-cross linking agent</td>
</tr>
<tr>
<td>Hybrid C</td>
<td>10% rubber, 3±0.1% radial SBS</td>
</tr>
<tr>
<td>PG 76-22 ARB I</td>
<td>7 - 7.5 % GTR and SBS (optional)</td>
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<tr>
<td>PG 76-22 ARB II</td>
<td></td>
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<tr>
<td><strong>Polymer-modified binders</strong></td>
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<tr>
<td>PG 64-34 PMA</td>
<td>7.5% SBS content</td>
</tr>
<tr>
<td>PG 76-22 PMA I</td>
<td>2-3.5 % SBS</td>
</tr>
<tr>
<td>PG 76-22 PMA II</td>
<td>2-4.25 % SBS</td>
</tr>
<tr>
<td>PG 82-22 PMA</td>
<td>8.5% SBS</td>
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</tbody>
</table>
Typical True Stress-True Strain Curve

- **Unmodified**
- **Rubber modified**
- **Hybrid**
- **SBS modified**
Fracture Energy Density Values

- **Unmodified**
- **Rubber**
- **Hybrid**
- **SBS**

Binder Fracture Energy Density (psi):

- PG 52-28: 354 psi
- PG 58-22: 432 psi
- PG 64-22: 461 psi
- PG 67-22: 488 psi
- ARB-5: 720 psi
- ARB-12: 698 psi
- Hybrid-A: 944 psi
- Hybrid-B: 967 psi
- Hybrid-C: 1,062 psi
- Hybrid-ARB I: 1,031 psi
- Hybrid-ARB II: 1,021 psi
- SBS: 2,431 psi
- PG 76-22 PMA I: 1,199 psi
- PG 76-22 PMA II: 1,260 psi
- PG 64-29 PMA: 1,684 psi
- PG 82-22 PMA: 2,431 psi

% SBS ↑
AASHTO Provisional Standard

Standard Method of Test for

Determining the Fracture Energy Density of Asphalt Binder Using the Binder Fracture Energy (BFE) Test

AASHTO Designation: TP-XXX (BFE)

1. SCOPE

1.1. This test method covers the determination of fracture energy density of asphalt binder by means of a direct tension test. For evaluation of relative cracking performance, it is recommended that this test procedure be used with asphalt binder aged using AASHTO T240 (RTFOT) plus AASHTO R28 (PAV). However, this test can be used for determination of binder fracture energy for any binder including any un-aged or aged neat binder, modified binder, and asphalt binder extracted and recovered from pavement. The test apparatus is designed for testing within the intermediate temperature range, from 0°C to 30°C.

1.2. This standard may involve hazardous materials, operations, and equipment. This standard does not purport to address all of the safety concerns associated with its use. It is the responsibility of the user of this procedure to establish appropriate safety and health practices and to determine the applicability of regularity limitations prior to use.
Conclusion

- The BFE test and data interpretation system developed suitably measures FED of asphalt binders, including:
  - Unmodified binder
  - Modified binder (rubber, polymer, hybrid)
  - Binder recovered from pavement (except rubber)
Recommendation

- The BFE test may be an effective tool for binder specification by state highway agencies to:
  - Identify the presence of modifiers
  - Provide a quantitative assessment of relative binder performance based on FED values