Development of an IDEAL Cracking Test for Asphalt Mix Design and QC/QA

Fujie Zhou*, Soohyok Im*, Lijun Sunb, and Tom Sculliona

aTexas A&M Transportation Institute, College Station, Tx, 77843
bTongji University, Shanghai, China, 200092.

ABSTRACT. The focus in recent years has been to make asphalt mixes more affordable and this has led to the increased use of recycled materials and binder modifications. Consequently, one often-heard complaint is that the recent mixes are more susceptible to cracking. There is an urgent need for a practical cracking test for routine use in the process of mix design, quality control and quality assurance testing. This paper develops an indirect tensile asphalt cracking test (IDEAL-CT). The IDEAL-CT is typically run at the room temperature with 150 mm diameter and 62 mm high cylindrical specimens with a loading rate of 50 mm/min. The IDEAL-CT is a simple (no instrumentation, cutting, gluing, drilling, or notching of specimens), practical (minimum training needed for routine operation), and efficient test (test completion less than 1 minute). The test can be performed with regular indirect tensile strength test equipment. As described in this paper the IDEAL-CT is sensitive to key asphalt mix components and volumetric properties including reclaimed asphalt pavement and recycled asphalt shingles content, asphalt binder type, binder content, aging conditions, and air voids. The proposed test also has a much lower coefficient of variation than traditional repeated load cracking tests. Furthermore, the IDEAL-CT results were compared with field cracking data collected from the Federal Highway Administration’s accelerated load facility, Texas SH15 and SH62, and MnROAD. The IDEAL-CT characterization correlated well with field performance in terms of fatigue, reflective, and thermal cracking. Last but not the least, ruggedness test performed in this study indicated that the IDEAL-CT, after combining both statistical and practical views, could be considered as rugged with all four variables: specimen thickness, loading rate, test temperature, and air voids.

KEYWORDS: Mix Design, Cracking Test, QC/QA, IDEAL-CT.
1. Introduction

In the 1990s, the asphalt industry used a variety of measures to reduce rutting in asphalt layers, which included the use of polymer modified binders, trials of coarser aggregate gradations, and the use of lower asphalt contents, or a combination of all of them. Consequently, the rutting problem was significantly minimized (Brown 1998). However, these measures resulted in early cracking problems (Watson 2003, Brown 2005, Zhou and Scullion 2005), which has now become the primary mode of distress that creates the need for pavement rehabilitation. The cracking problem may get even worse, because the mixes are designed to lower costs with the increasing use of recycled materials (such as reclaimed asphalt pavements [RAP] and recycled asphalt shingles [RAS]) and binder additives (such as polyphosphoric acid and recycled engine oil bottom). Thus, there is an urgent need for a cracking test that is not only performance-related but also simple, repeatable, sensitive to asphalt mix composition, and practical enough for routine uses in the process of mix design, quality control (QC) and quality assurance (QA).

Various cracking tests have been identified in the comprehensive literature review completed under the National Cooperative Highway Research Program (NCHRP) 9-57: Experimental Design for Field Validation of Laboratory Tests to Assess Cracking Resistance of Asphalt Mixtures (Zhou et al. 2016). Seven cracking tests were finally selected by the NCHRP 9-57 panel members and invited experts for further field validation, namely bending beam fatigue (BBF) test, overlay test (OT), disk-shaped compact tension (DCT) test, indirect tensile creep and strength test (IDT-CST) with full instrumentation, and three versions of semi-circular bend (SCB) tests (Zhou et al. 2016). Meanwhile, NCHRP 9-57 identified seven desirable features for an ideal cracking test, as listed below:

(1) Simplicity: no instrumentation, cutting, gluing, drilling, and notching to specimen;
(2) Practicality: minimum training needed for routine operation;
(3) Efficiency: test completion within 1 minute;
(4) Test equipment: cost less than $10,000;
(5) Repeatability: coefficient of variance (COV) less than 25 percent;
(6) Sensitivity: sensitive to asphalt composition (aggregates, binder, etc.); and
(7) Correlation to field performance: a good correlation with field cracking.

As presented in Table 1, the integration of all these seven features into one cracking test has never been done before (Zhou et al. 2016). The objective of this study is to develop and validate such an ideal cracking test, named \textit{indirect tensile asphalt cracking test} (IDEAL-CT). The IDEAL-CT is intended for routine uses for mix designs and QC/QA by contractors, DOTs, and even researchers in academia.
<table>
<thead>
<tr>
<th>Cracking tests</th>
<th>Test limitations and equipment cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>DCT</td>
<td>• Specimen prep: 3 cuts, 1 notch, and 2 holes</td>
</tr>
<tr>
<td></td>
<td>• Instrumentation: glue 2 studs, mount 1 clip gauge</td>
</tr>
<tr>
<td></td>
<td>• Equipment cost: $50,000</td>
</tr>
<tr>
<td>SCB-AASHTO TP105</td>
<td>• Specimen prep: 3 cuts and 1 notch</td>
</tr>
<tr>
<td></td>
<td>• Instrumentation: glue 3 studs, mount 1 extensometer + 1 clip gauge</td>
</tr>
<tr>
<td></td>
<td>• Testing: 30 min.</td>
</tr>
<tr>
<td></td>
<td>• Equipment cost: $50,000</td>
</tr>
<tr>
<td>SCB-Louisiana transportation research center</td>
<td>• Specimen prep: 9 cuts and 3 notches</td>
</tr>
<tr>
<td></td>
<td>• Testing: around 30 min.</td>
</tr>
<tr>
<td></td>
<td>• Equipment cost: less than $10,000</td>
</tr>
<tr>
<td>SCB-Illinois</td>
<td>• Specimen prep: 3 cuts and 1 notch</td>
</tr>
<tr>
<td></td>
<td>• Equipment cost: $10,000-$18,000</td>
</tr>
<tr>
<td>IDT-CST</td>
<td>• Specimen prep: 2 cuts</td>
</tr>
<tr>
<td></td>
<td>• Instrumentation: Glue 8 studs, mount 4 extensometers</td>
</tr>
<tr>
<td></td>
<td>• Testing: 1-2 hours</td>
</tr>
<tr>
<td></td>
<td>• Equipment cost: more than $50,000</td>
</tr>
<tr>
<td>OT</td>
<td>• Specimen prep: 4 cuts, glue specimen to bottom plates</td>
</tr>
<tr>
<td></td>
<td>• Testing: 30 min. - 3 hr.</td>
</tr>
<tr>
<td></td>
<td>• Equipment cost: $40-50,000</td>
</tr>
<tr>
<td>BBF</td>
<td>• Specimen prep: large slab, 4 cuts</td>
</tr>
<tr>
<td></td>
<td>• Instrumentation: glue 1 stud and mount 1 linear variable differential transformer</td>
</tr>
<tr>
<td></td>
<td>• Specimen testing: 1 hour to days</td>
</tr>
<tr>
<td></td>
<td>• Equipment cost: more than $100,000</td>
</tr>
<tr>
<td>IDEAL-CT</td>
<td>• No cutting, notching, drilling, gluing, or instrumentation</td>
</tr>
<tr>
<td></td>
<td>• Test completion within 1 min.</td>
</tr>
<tr>
<td></td>
<td>• Repeatable (or low variability) with COV&lt;25 percent</td>
</tr>
<tr>
<td></td>
<td>• Practical for routine uses in Departments of Transportation (DOTs) and contractors’ laboratories</td>
</tr>
<tr>
<td></td>
<td>• Low cost test equipment (&lt;$10,000)</td>
</tr>
<tr>
<td></td>
<td>• Sensitive to asphalt mix composition</td>
</tr>
<tr>
<td></td>
<td>• Cracking performance related</td>
</tr>
</tbody>
</table>

This paper first describes the IDEAL-CT and the derivation of a new cracking index based on fracture mechanics. Then the seven desirable features of the IDEAL-CT are discussed one by one. Additionally, a ruggedness test is performed on the
IDEAL-CT and the results are presented in this paper. Finally, this paper concludes that the IDEAL-CT meets all these criteria.

2. Development of the IDEAL-CT

2.1 IDEAL-CT Description

The IDEAL-CT is similar to the traditional indirect tensile strength test, and it is run at the room temperature with cylindrical specimens at a loading rate of 50mm/min. in terms of cross-head displacement. Any size of cylindrical specimens with various diameters (100 or 150mm) and thicknesses (38, 50, 62, 75mm, etc.) can be tested. For mix design and laboratory QC/QA, the authors proposed to use the same size specimen as the Hamburg wheel tracking test: 150 mm diameter and 62 mm height with 7±0.5 percent air voids, since agencies are familiar with molding such specimens. Figure 1 shows a typical IDEAL-CT: cylindrical specimen, test fixture, test temperature, loading rate, and the measured load vs. displacement curve.

![Test temperature: 25 °C. Loading rate: 50mm/min. Specimen: cylindrical specimen without cutting, gluing, instrumentation, drilling, and notching.](image)

**Figure 1. IDEAL-CT: Specimen, Fixture, Test Conditions, and Typical Result**

2.2 Derivation of a Cracking Parameter for the IDEAL-CT

The key to the IDEAL-CT is to derive a performance-related cracking parameter from the measured load vs. displacement curve. The form of the new cracking parameter is inspired by the well-known Paris’ law (Paris and Erdogan 1963) and the work done by Bazant and Prat (1988) for crack propagation (Equations 1 and 2):

\[
\frac{dc}{dN} = A(K_c)^n \quad [1]
\]

\[
\dot{c} = \nu_c \left( \frac{\sigma}{G_f} \right)^n \quad [2]
\]
where \(\frac{dc}{dN}\) and \(\dot{c}\) are cracking growth rate; \(c\) is crack length; \(N\) is number of load repetitions; \(v_c\) and \(A\) are constants; \(n\) is material constant, and \(G_f\) is fracture energy; \(G = \frac{k_f^2}{E}\) is energy release rate; \(K_I\) is stress intensity factor; and \(E\) is modulus.

Substitute \(G\) with \(K_I\) and \(E\), Equation 2 becomes:

\[
\dot{c} = v_c \left( \frac{k_f^2}{E \times G_f} \right)^n \tag{3}
\]

Since there is no instrumentation on the specimen at all, the modulus \(E\) can be approximately estimated by the applied load \((P)\) and the measured vertical deformation \((l)\) as shown in Equation 4 (Liu and Lovato 2008):

\[
E \approx \frac{P}{l \times t} \tag{4}
\]

where \(t\) is the thickness of the cylindrical specimen.

Similarly, the stress intensity factor \(K_I\) can be estimated by Equation 5 (Murakami 1988):

\[
K_I = \alpha \times f(c) \tag{5}
\]

where \(\alpha\) is tensile stress \((= \frac{2P}{\pi \times D \times t})\) for the IDEAL-CT and \(f(c)\) is a shape function.

Substitute Equations 4 and 5 into Equation 3, then Equation 3 becomes:

\[
\dot{c} = v_c \left( \frac{\alpha^2 \times (f(c))^2}{\pi \times \alpha \times G_f} \right)^n \tag{6}
\]

After a series of simplification and the consideration of low variability requirement of a cracking test, a new cracking resistance parameter, \(t \times G_f \times P / l \times t\) was derived.

Detailed derivation and rationales for this new parameter are described in the Appendix. When used for laboratory mix design and QC/QA where specimen thickness can always be 62 mm, the proposed new cracking test index \((CT_{\text{Index}})\) is given in Equation 7. The larger the \(CT_{\text{Index}}\), the slower the cracking growth rate:

\[
CT_{\text{Index}} = \frac{G_f}{t} \times \left( \frac{1}{D} \right) \tag{7}
\]

In case of field cores where the core thickness is not 62 mm, \(CT_{\text{Index}}\) is defined in Equation 8:

\[
CT_{\text{Index}} = \frac{t}{62} \times \frac{G_f}{t} \times \left( \frac{1}{D} \right) \tag{8}
\]

where fracture energy \(G_f\) is the work of fracture (the area of the load vs. vertical displacement curve) divided by area of cracking face; parameter \(P/l\) is a “modulus” parameter (or the slope of the load-displacement curve) and parameter \(l/D\) a “strain” tolerance parameter (or the deformation tolerance under a load).
Except that the fracture energy $G_f$ is constant, parameters: $P/l$ and $l/D$ vary from point to point (see Figure 1) due to the visco-elastic-plastic nature of asphalt mixes and the micro-or macro-cracking damage. Consequently, the $CT_{Index}$ value changes at each point. Thus, it is crucial to select a meaningful point for calculating the $CT_{Index}$ value, which is discussed in the following section.

### 2.3 Selection of Critical $CT_{Index}$ Point

Generally the load-displacement curve of the IDEAL-CT (Figure 1) can be split into two segments at the point of peak load: pre-peak and post-peak load. So the first question is in which segment is the location of the critical $CT_{Index}$? To answer this question, the authors carefully examined the typical load-displacement curve and associated specimen conditions at different stages. There were seven stages associated with different specimen conditions, as noted in Table 2. As clearly observed from Table 2, macro-crack occurs only after the peak load (or at the post-peak segment). With the initiation and growth of the macro-crack, load bearing capacity of any asphalt mix will obviously decrease, which is the characteristic of the post-peak segment. Specifically, what both Paris’ law and the cracking growth rate defined by Bazant and Prat (1988) describe is macro-crack propagation where the $CT_{Index}$ was derived from. Thus, the selection of the critical $CT_{Index}$ point should focus on the post-peak segment where the load is decreasing rather than the pre-peak segment where the load is increasing.

#### Table 2. Seven stages of load-displacement curve

<table>
<thead>
<tr>
<th>Segment</th>
<th>Stage</th>
<th>Load range and characteristic</th>
<th>Specimen status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-peak load</td>
<td>1</td>
<td>0–1/3 peak load; load increasing</td>
<td>No any visible crack</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1/3–2/3 peak load; load increasing</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>2/3–peak load; load increasing</td>
<td></td>
</tr>
<tr>
<td>Peak load</td>
<td>4</td>
<td>Peak load point; load peaking</td>
<td></td>
</tr>
<tr>
<td>Post-peak load</td>
<td>5</td>
<td>Peak load–2/3 peak load; load decreasing</td>
<td>Starting to see visible macro-crack</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>2/3–1/3 peak load; load decreasing</td>
<td>Crack propagating quickly and more visible</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>1/3 peak load–0 load; load decreasing</td>
<td>Specimen separation into 2 or more pieces</td>
</tr>
</tbody>
</table>

Then, the second question becomes which point of the post-peak segment should be selected as the critical $CT_{Index}$ point? Reviewing the characteristics of the post-peak segment, it was found that the absolute value ($|m|$) of the slope of the load-displacement curve varied from small at right after the peak load point to large in the early middle of the curve, and then becomes small again after the middle of the
curve. Thus, one reasonable choice is to use the inflection point where the \(|m|\) value is the largest among the whole post-peak segment. There is no doubt that the inflection point is a very good and mathematically sound concept. However, the reality is that it is often very difficult to accurately determine the inflection point, because the measured load-displacement data are not perfect and a mathematical function is required to pre-smooth the measured load-displacement curve. For one set of load-displacement data, different pre-smooth mathematical functions sometimes generate different inflection points. To avoid this problem, the authors propose to use the post-peak point (\(PPP_{75}\)) where the load is reduced to 75 percent the peak load (see Figure 2). The rationale for the selection of \(PPP_{75}\) is given below:

The authors analyzed more than 200 IDEAL-CT load-displacement curves generated from varieties of asphalt mixes, and determined most of the inflection points of these curves with the approach proposed by Al-Qadi et al. (2015). Except for a few curves, the inflection points were identified. It was found that the average value of the post-peak loads at the inflection points is 75 percent of the average value of the peak loads of those curves with a standard deviation: \(\sigma = 5\). Furthermore, \(PPP_{75}\) can always be easily identified without a sophisticated program or software.

Furthermore, both parameters, \(P/l\) (or \(|m| = \frac{|m|}{\Delta l}\)) and \(l/D\) at \(PPP_{75}\), as shown later, are very stable and consistent, so \(PPP_{75}\) was selected as the critical point for calculating the \(CT_{index}\).

![Figure 2. Illustration of the PPP75 Point and Its Slope \(|m|_{75}\)](image)

2.4 Finalization of the \(CT_{index}\) Equation

The three main parameters in Equation 7 (and 8) are \(G_f\), \(l/D\), and \(P/l\). The fracture energy \(G_f\) can be easily calculated as long as the load vs. displacement curve is
known. After selecting the $CT_{index}$ point ($PPP_{75}$), parameter $l/D$ (or $\frac{l_{75}}{D}$) is readily determined. Note that parameter $\frac{l_{75}}{D}$ is the “strain” tolerance of the asphalt mix when the load is reduced to 75 percent the peak load. It is obvious that the mix with a larger $\frac{l_{75}}{D}$ and better “strain” tolerance has significantly more cracking resistance than the mix with a smaller $\frac{l_{75}}{D}$.

The only parameter to be finalized in Equation 7 (and 8) is $P/l$. Parameter $P/l$ originates from asphalt mix modulus in Equation 4. When dealing with the post-peak segment of the load-displacement curve, parameter $P/l$ is not the true asphalt mix modulus, but it still can be treated as some kind of overall “modulus” of a cracked asphalt mix specimen. As shown in Figure 2, parameter $P/l$ is calculated as the absolute value of the slope ($|\frac{m_{75}}{\Delta m_{75}}|$) between $PPP_{85}$ and $PPP_{65}$. There are two reasons for using the slope of an interval rather than the tangent slope at the $PPP_{75}$ point: (1) the interval between $PPP_{85}$ and $PPP_{65}$ is two times standard deviation ($\sigma =5$) of the inflection point around its average (=75 percent peak load) so that 95.4 percent probability is assured; (2) the interval slope between $PPP_{85}$ and $PPP_{65}$ is much less variable than the tangent slope at the $PPP_{75}$ single point so that the parameter $CT_{index}$ has smaller variability. Additionally, it must be an absolute value, since it represents the overall “modulus” of a cracked asphalt mix specimen. Generally, the stiffer the mix, the faster the cracking growth, the higher the load reduction, the higher the $|m_{75}|$ value, and consequently the poorer the cracking resistance. Therefore, the use of $|m_{75}|$ to representing parameter $P/l$ makes sense.

In summary, the final equations for $CT_{index}$ are provided below:

For 62 mm thick specimens: $CT_{index} = \frac{\sigma_f}{|m_{75}|} \times \left( \frac{l_{75}}{D} \right)$  \[9\]

For non-62 mm thick specimens: $CT_{index} = \frac{t}{62} \times \frac{\sigma_f}{|m_{75}|} \times \left( \frac{l_{75}}{D} \right)$  \[10\]

2.5 Discussion of the IDEAL-CT Features

As described previously, either lab-molded cylindrical specimens or field cores can be directly tested without cutting, notching, drilling, gluing, and instrumentation. Thus, the IDEAL-CT automatically meets top two features: simplicity and practicality. Furthermore, the IDEAL-CT is run at the loading rate is 50mm/min., and the test is done within 1 minute. Thus, the third feature, efficiency, is met. Additionally, the same indirect tensile strength test equipment with a displacement measurement or any other loading frame (such as MTS, UTM, or Interlaken) can be used for the IDEAL-CT. Most of contractors and DOTs already have such equipment. Even if a new test machine is purchased, its cost is often less than $10,000. Therefore, Feature No. 4 is met as well. The key to this entire study from now on is to evaluate and validate the IDEAL-CT sensitivity, repeatability, and...
correlation to field performance through $CT_{\text{Index}}$ (Equation 9 or 10), which is discussed in the following sections.

3. IDEAL-CT Sensitivity

For any cracking tests to be used for mix design and QC/QA, it must be sensitive to the characteristics and volumetric properties of asphalt mixtures and aging conditions. A total of five variables were evaluated in this study, and they are RAP and RAS content, asphalt binder type, binder content, air voids, and aging conditions. A series of laboratory-mixed and laboratory-molded specimens were utilized to evaluate the sensitivities of RAP and RAS content, binder type, and binder content, which are much easier controlled in the laboratory than the field plant. A plant mix collected from one field test section was used in this study for sensitivities of air voids and aging conditions. Details are described below.

3.1 Sensitivity to RAP and RAS

The use of RAP and RAS in asphalt mixes has become a new norm. Any valid cracking test should be sensitive to impact of RAP and RAS on cracking resistance of asphalt mixes. To investigate the sensitivity of the IDEAL-CT to RAP and RAS, this study employed a virgin mix as the control mix. It is a typical 12.5 mm Superpave virgin mix with a PG64-22 binder and limestone aggregates, and Figure 3 shows the gradation of this control mix. The control mix was designed according to TxDOT’s Superpave mix design procedure, and its optimum asphalt content (OAC) at 4 percent design air voids was 5.0 percent. Then this control mix was modified to produce two mixes: one with 20 percent RAP and the other with 15 percent RAP and 5 percent RAS:

- 20 percent RAP mix: RAP binder was very stiff (PG103) and its content was 5 percent. It was expected that the 20 percent RAP mix would have worse cracking resistance than the virgin mix.
- 15 percent RAP/5 percent RAS mix: The same RAP used in the 20 percent RAP mix was used here as well. The RAS was manufacturer waste shingles with extremely stiff binder (PG141) and its binder content was 20 percent. Again, it was expected that the 15 percent RAP/5 percent RAS mix would have the worst cracking resistance among the three mixes.

Note that neither the PG64-22 binder nor the total asphalt content (5 percent) was changed for either modification. For the control mix, the 5 percent asphalt was 100 percent virgin binder; as is normal DOT policy for the modified mixes, some of the virgin binder was replaced with the binder from the RAP/RAS. Meanwhile, the aggregate gradations for all three mixes were kept as close as possible (see Figure 3).
Figure 3. Aggregate Gradations Used for Sensitivity Analysis

For each mix, three replicate specimens with 7±0.5 percent air voids were compacted using the Superpave Gyratory Compactor (SGC). Before the compaction, the loose mixes were conditioned in the oven for 4 hours at 135 °C. The IDEAL-CT was then run at a room temperature of 25 °C and a loading rate of 50 mm/min. Figure 4 presents the IDEAL-CT results: $CT_{Index}$ value for each mix. Note that $CT_{Index}$ can vary from 1 to 1000 with a higher number indicating better crack resistance.

The $CT_{Index}$ values in Figure 4 clearly show that the IDEAL-CT is sensitive to RAP and RAS. The additions of RAP and RAS reduce cracking resistance of the asphalt mix. Thus, the IDEAL-CT is sensitive to the addition of RAP and RAS to asphalt mixes.

Figure 4. IDEAL-CT Sensitivity to RAP and RAS
3.2 Sensitivity to Asphalt Binder Type

The 20 percent RAP mix with PG64-22 binder was further modified with two other virgin binders, PG64-28 and PG64-34, to check the sensitivity of the IDEAL-CT to binder type. Among these three mixes, all variables (including virgin aggregates, RAP, and the total binder amount) were kept the same except the virgin binder type. Note that both PG64-28 and PG64-34 binders were SBS polymer modified binders. Past experience indicated that the PG64-34 binder generally had better cracking resistance than PG64-28 binder and PG64-22 has the worst among the three (Zhou et al. 2013). Thus, similar results were anticipated from the IDEAL-CT.

For each binder type, three replicates of 150 mm diameter and 62mm height specimens with 7±0.5 percent air voids were compacted using SGC. Before the compaction, the loose mixes were conditioned in the oven for 4 hours at 135 ºC. The IDEAL-CT was run at a room temperature of 25 ºC and a loading rate of 50 mm/min. Figure 5 presents the IDEAL-CT results: $CT_{index}$ value for each binder type. Obviously, the IDEAL-CT is sensitive to binder type. As expected, the 20 percent mix with PG64-34 binder has the largest $CT_{index}$ value, followed by the one with PG64-28 and then the one with PG64-22. Thus, the IDEAL-CT is sensitive to asphalt binder type.

![Figure 5. IDEAL-CT Sensitivity to Binder Type](image)

3.3 Sensitivity to Asphalt Binder Content

Asphalt binder content is one of the key parameters for asphalt mix designs, and has significant influence on asphalt mix cracking performance. Generally, the higher the binder content, the better the cracking performance in the field. To evaluate the sensitivity of the IDEAL-CT to binder content, the control mix was modified through varying asphalt content only, ±0.5 percent. It was expected that this mix with +0.5 percent asphalt binder would have the largest $CT_{index}$ value, followed by the control mix, and the one with –0.5 percent having the least $CT_{index}$ value.
For each binder content, three replicates of 150 mm diameter and 62 mm height specimens with 7±0.5 percent air voids were compacted using SGC. Before the compaction, the loose mixes were conditioned in the oven for 4 hours at 135 °C. The IDEAL-CT was run at a room temperature of 25 °C and a loading rate of 50 mm/min. Figure 6 presents the IDEAL-CT results. As expected, the higher the binder content, the larger $C_{\text{Index}}$ value. Thus, the IDEAL-CT is sensitive to binder content.

![Bar chart showing IDEAL-CT sensitivity to binder content](image)

**Figure 6. IDEAL-CT Sensitivity to Binder Content**

### 3.4 Sensitivity to Aging Conditions

Aging makes the mixes brittle and less cracking resistance. To be a valid cracking test, the IDEAL-CT must be sensitive to aging conditions of asphalt mixes. In this study, three levels of oven conditioning at 135 °C (4, 12, and 24 hours before the compaction) were investigated with a plant mix collected from one field test section in Laredo, Texas. The plant mix was a 12.5 mm Superpave virgin mix with an asphalt binder content of 6.3 percent. For each level of aging condition, three replicates of 150 mm diameter and 62 mm height specimens with 7±0.5 percent air voids were compacted using SGC. The IDEAL-CT was run at a room temperature of 25 °C and a loading rate of 50 mm/min. Figure 7 presents the IDEAL-CT results.

As expected, the longer the aging time in the oven, the poorer the cracking resistance. Thus, the IDEAL-CT is sensitive to aging conditions.
3.5 Sensitivity to Air Voids

Air voids (or density) is another key volumetric property of asphalt mixes and plays critical roles in QC/QA. In this study, three levels of air voids (5, 7, and 9 percent) were investigated with the same plant mix used for evaluating the sensitivity to the aging conditions. For each level of air voids, three replicates of 150 mm diameter and 62 mm height specimens were compacted using SGC. Before the compaction, the plant mix was conditioned in the oven for 4 hours at 135 °C. Similarly, the IDEAL-CT was conducted and Figure 8 presents the test results.

Figure 8 clearly indicates that the IDEAL-CT is sensitive to air voids of asphalt mixes. Thus, for the purpose of comparison among different asphalt mixes, all the specimens should be compacted to the same level of air voids (e.g., 7±0.5 percent). Also, a correction factor for air voids may be needed.
In summary, the IDEAL-CT results shown in Figures 4–8 clearly indicate that the IDEAL-CT is sensitive to key asphalt mix components and volumetric properties: RAP and RAS, asphalt binder type, binder content, aging conditions, and air voids.

4. IDEAL-CT Repeatability

The repeatability (or variability) of the IDEAL-CT is critical for being adopted by DOTs and contractors, because if the test has high variability, not only will more specimens will be needed, but it may also have difficulty in differentiating the poor from the good performers. There are different ways to evaluate repeatability (or variability) of a laboratory test. This paper simply uses COV as an indicator for the repeatability. A smaller COV means the test is more repeatable.

Instead of testing new mixes, the authors simply analyzed the COVs of the IDEAL-CT results of the previous sensitivity study. Table 2 shows the average $CT_{Index}$ value and associated COV for each mix. From Table 2, it can be seen that the maximum COV is $23.5\%$ and most of them are less than $20\%$, which is much less than those of repeated load cracking tests including BBF test (Tayebali et al. 1994) and OT (Walubita et al. 2012, Ma et al. 2015). Additionally, the COVs of the IDEAL-CT are similar to or even better in some cases than those of the I-FIT SCB test (Al-Qadi et al. 2015).
Table 2. IDEAL-CT repeatability

<table>
<thead>
<tr>
<th>Asphalt Mixes</th>
<th>( CT_{Index} )</th>
<th>COV (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laboratory mix</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensitivity to RAP and RAS</td>
<td>Virgin</td>
<td>172.9</td>
</tr>
<tr>
<td></td>
<td>20%RAP</td>
<td>42.8</td>
</tr>
<tr>
<td></td>
<td>15%RAP/5%RAS</td>
<td>30.8</td>
</tr>
<tr>
<td>Sensitivity to binder type</td>
<td>PG64-22</td>
<td>42.8</td>
</tr>
<tr>
<td></td>
<td>PG64-28</td>
<td>82.4</td>
</tr>
<tr>
<td></td>
<td>PG64-34</td>
<td>126.2</td>
</tr>
<tr>
<td>Sensitivity to binder content</td>
<td>OMC-0.5</td>
<td>66.0</td>
</tr>
<tr>
<td></td>
<td>OMC</td>
<td>172.9</td>
</tr>
<tr>
<td></td>
<td>OMC+0.5</td>
<td>251.0</td>
</tr>
<tr>
<td>Plant mix</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensitivity to aging conditions</td>
<td>4hr</td>
<td>374.5</td>
</tr>
<tr>
<td></td>
<td>12hr</td>
<td>287.6</td>
</tr>
<tr>
<td></td>
<td>24hr</td>
<td>68.9</td>
</tr>
<tr>
<td>Sensitivity to air voids</td>
<td>5%</td>
<td>322.0</td>
</tr>
<tr>
<td></td>
<td>7%</td>
<td>374.5</td>
</tr>
<tr>
<td></td>
<td>9%</td>
<td>505.2</td>
</tr>
</tbody>
</table>

5. IDEAL-CT Correlation to Field Performance

More than 25 laboratory and field plant mixes have been used to compare the IDEAL-CT with the Texas OT and the Illinois SCB test. All three tests provided exactly the same rankings for all these mixes in terms of cracking resistance. Due to page limit, the good correlations among these three tests are omitted. Instead, this paper focused on the IDEAL-CT correlation to field performance, because for any test to be used for mix design, it must have good correlation with field performance. Field validation is a crucial step in the process of developing the IDEAL-CT. This study used the accelerated pavement testing data from the Federal Highway Administration’s accelerated loading facility (FHWA ALF), full-scale test road in Minnesota (MnROAD), and in-service roads in Texas to evaluate the correlation between the IDEAL-CT test and field performance.

5.1 FHWA ALF Test Sections: IDEAL-CT vs. Fatigue Cracking

In 2013, 10 test lanes were constructed at the FHWA ALF in McLean, Virginia, to evaluate fatigue performance of RAP and RAS mixes. The overall pavement structure is composed of 100 mm (4 inch) asphalt layer, 650 mm (26 inch) granular base, and subgrade. Both the base layer and subgrade are the same for all lanes (Li
The only difference among the 10 lanes is the surface asphalt mix type, as shown in Table 3. All these mixes were 12.5 mm Superpave mixes with a $N_{design}$=65. The ALF testing was performed in the cooler seasons, and the testing temperature of 20 °C at a depth of 20 mm beneath the surface was controlled through radiant heaters when needed. All lanes were loaded with a 425 super-single tire wheel (14,200 pounds load and 100 psi pressure) at a speed of 11 mph with a normal distributed wander in lateral direction. At the time of writing this paper, ALF testing is still ongoing and only 8 lanes of ALF fatigue data were available (Li and Gibson 2016). Table 3 presents the number of ALF passes corresponding to the first crack observed.

One 5-gallon bucket of plant mix from each test lane was obtained for the IDEAL-CT. For each plant mix, three replicate specimens of 150 mm diameter and 62 mm height were molded. Before the molding, each plant mix was conditioned in the oven for 4 hours at 135 °C. The IDEAL-CT was performed at a room temperature of 25°C with a loading rate of 50 mm/min. The average $CT_{index}$ and COV for each plant mix are tabulated in Table 3 as well.

Figure 9 shows the correlation between the $CT_{index}$ values and the ALF passes to first crack occurrence. $CT_{index}$ correlates very well with field cracking observation. The higher the $CT_{index}$ value, the better the cracking performance in the field.

<table>
<thead>
<tr>
<th>ALF lane</th>
<th>% Recycled binder ratio</th>
<th>Virgin binder</th>
<th>Hot/warm mix</th>
<th>No. of ALF passes for first crack observed</th>
<th>IDEAL-CT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RAP</td>
<td>RAS</td>
<td></td>
<td></td>
<td>$CT_{index}$</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>-</td>
<td>PG64-22</td>
<td>Hot mix</td>
<td>368,254</td>
</tr>
<tr>
<td>2</td>
<td>40</td>
<td>-</td>
<td>PG58-28</td>
<td>Warm mix with water foaming</td>
<td>No result</td>
</tr>
<tr>
<td>3</td>
<td>-</td>
<td>20</td>
<td>PG64-22</td>
<td>Hot mix</td>
<td>42,399</td>
</tr>
<tr>
<td>4</td>
<td>20</td>
<td>-</td>
<td>PG64-22</td>
<td>Warm mix with chemical additive</td>
<td>88,740</td>
</tr>
<tr>
<td>5</td>
<td>40</td>
<td>-</td>
<td>PG64-22</td>
<td>Hot mix</td>
<td>36,946</td>
</tr>
<tr>
<td>6</td>
<td>20</td>
<td>-</td>
<td>PG64-22</td>
<td>Hot mix</td>
<td>125,000</td>
</tr>
<tr>
<td>7</td>
<td>-</td>
<td>20</td>
<td>PG58-28</td>
<td>Hot mix</td>
<td>23,005</td>
</tr>
<tr>
<td>8</td>
<td>40</td>
<td>-</td>
<td>PG58-28</td>
<td>Hot mix</td>
<td>No result</td>
</tr>
<tr>
<td>9</td>
<td>20</td>
<td>-</td>
<td>PG64-22</td>
<td>Warm mix with water foaming</td>
<td>270,058</td>
</tr>
<tr>
<td>11</td>
<td>40</td>
<td>-</td>
<td>PG58-28</td>
<td>Warm mix with chemical additive</td>
<td>81,044</td>
</tr>
</tbody>
</table>
5.2 Texas Field Test Sections on SH15: IDEAL-CT vs. Fatigue Cracking

Different from the well-controlled FHWA ALF testing (fixed temperature and traffic loading), in-service pavements experience real world traffic and daily changing weather. This study used two more field test sections in Texas to validate the IDEAL-CT for fatigue cracking. A series of field test sections were constructed back to back on SH15 close to Perryton, Texas, in October 2013. The original objective of these field test sections was to investigate the approaches for improving cracking resistance of asphalt mixes with RAP. It was a milling and inlay job. A total of 62.5 mm (2.5 inch) asphalt layer was milled, and then was filled with 25.0 mm (1 inch) dense-graded Type F mix and 38 mm (1.5 inch) Type D surface mix. The Type F mix was used for the whole project. The focus of test sections was on the Type D surface mixes. Two of these test sections were selected for validating the IDEAL-CT:

- Section 1: A dense-graded Type D mix with a PG58-28 virgin binder, 20 percent RAP, and the total asphalt binder content of 5.5 percent.
- Section 2: the same mix as Section 1 but a total asphalt binder content of 5.8 percent.

The only difference between these two test sections is the total asphalt binder content: 5.5 vs. 5.8 percent. Six field surveys have been conducted since traffic opening. No rutting was observed on either test section. No any crack was observed on Section 1 until the last survey on March 3, 2016. As shown in Figure 10, significant low severity of fatigue cracking was observed on March 3, 2016. Section 2 with higher binder content still performed very well and no any cracking was observed, which was expected, since Section 2 has higher binder content.
Plant mixes were collected during the construction. For each plant mix, three replicates of 150 mm diameter and 62 mm height specimens with 7±0.5 percent air voids were molded. Before the molding, each plant mix was conditioned in the oven for 4 hours at 135 °C. The IDEAL-CT was performed at a room temperature of 25 °C with a loading rate of 50 mm/min. Figure 11 presents the average $CT_{\text{index}}$ values of the two plants mixes. Comparing the data in Figures 10 and 11, the $CT_{\text{index}}$ values match exactly what was observed in the field. The higher $CT_{\text{index}}$ values, the less fatigue cracking in the field.

**Figure 10.** Fatigue Cracking Development Observed on SH15, Texas

**Figure 11.** IDEAL-CT Results of SH15 Plant Mixes
5.3 Texas Field Test Sections on US62: IDEAL-CT vs. Reflective Cracking

Reflective cracking is another major pavement distress, especially for asphalt overlays. Two 1500 ft long field test sections were constructed on eastbound US62 close to Childress, Texas, on October 3, 2013. The original purpose was to evaluate the impact of RAP/RAS on pavement performance. The existing pavement had multiple overlays and severe transverse cracking before the milling and inlay. The mill/fill pavement design called for milling the top 200 mm (8 inch) asphalt layer and then refilling with a 75 mm (3 inch) dense-graded Type B mix and 50 mm (2 inch) dense-graded Type D surface mix. The two test sections had the same Type B mix as the base course but the Type D surface course varied as follows:

- Virgin Section: Type D virgin mix with PG 70-28 binder.
- RAP/RAS Section: Type D with PG 70-28 binder and 5 percent RAP and 5 percent RAS.

The asphalt binder content of the virgin mix was 5.4 percent, and the total asphalt binder content of the RAP/RAS mix was 5.7 percent and recycled binder replacement was 23.6 percent from RAP and RAS. Performance survey results are shown in Figure 12. As seen in Figure 12, the virgin section performed much better.

Similarly, each plant mix collected during construction was compacted to obtain three replicates of 150 mm diameter and 62 mm height specimens with 7±0.5 percent air voids. Again, each plant mix was conditioned in the oven for 4 hours at 135 °C before molding the specimens. The IDEAL-CT was performed at a room temperature of 25°C with a loading rate of 50 mm/min. Figure 13 presents the average $CT_{Index}$ values of the two plant mixes. Comparing the data in Figures 12 and 13, clearly the IDEAL-CT has very good correlation with field reflective cracking observed on US62. The higher $CT_{Index}$ value means less reflective cracking in the field.

![US62 Reflective Cracking Development](image)

**Figure 12. Cracking Development Observed on US62, Texas**
Figure 13. IDEAL-CT Results of US62 Mixes

5.4 MnROAD Test Sections: IDEAL-CT vs. Thermal Cracking

Various test sections (or cells) were constructed at MnROAD Phase II in 2008 (Johnson et al. 2009). Three of them (Cells 20, 21, and 22) were designed for evaluating thermal cracking, which is the most common distress in cold climates. These three cells had the same pavement structure thickness, base materials, and subgrade, but the asphalt wearing course varied among the three cells, as listed below:

1. Cell 20: PG58-28 virgin binder and 30 percent non-fractionated RAP.

MnROAD crews have been monitoring the three cells since the completion of construction in 2008. Figure 14 shows thermal (transverse) cracking development history for each cell in both driving and passing lanes. Three observations can be made from Figure 14: (1) Cell 22 performed much better than Cells 20 and 21, which is expected due to softer virgin binder (PG58-34) in Cell 22; (2) traffic loading had significant impact on thermal cracking development since the driving lane had more transverse cracking; and (3) when reviewing the measured transverse cracking development on the passing lane, it seems that Cell 21 performed a little bit better than Cell 20, although there is no big difference.

Recently, the authors obtained the plant mixes of Cells 20, 21, and 22 collected during the construction. Again, each plant mix was compacted to obtain three replicates of 150 mm diameter and 62 mm height specimens with 7±0.5 percent air voids. Similarly, each plant mix was conditioned in the oven for 4 hours at 135 °C.
before molding the specimens. The IDEAL-CT was performed at a room temperature of 25 °C with a loading rate of 50 mm/min. Figure 15 present the average $CT_{Index}$ values of the three plants mixes.

Figure 15 indicates that Cell 22 having the highest $CT_{Index}$ value should perform the best, followed by Cells 21 and 20. Overall, the IDEAL-CT results match what has been observed in the field. More test sections are being constructed in the 2016 MnROAD, and the performance data will be used for further validating the IDEAL-CT.

**Figure 14. Thermal Cracking Development History for Cells 20, 21, and 22**
Figure 15. IDEAL-CT Results of MnROAD Cells 20, 21, and 22.

In summary, various field test sections including FHWA ALF, MnROAD, and Texas in-service roads were used to validate the IDEAL-CT. All test results indicate that the IDEAL-CT has good correlations with field fatigue cracking, reflective cracking, and thermal cracking. With the confidence of the IDEAL-CT in differentiating mix cracking resistance, the authors took another step toward standardizing the IDEAL-CT through ruggedness test. Detailed information is presented in next section.

6. IDEAL-CT Ruggedness Test

The main purpose of performing ruggedness testing was to identify the factors that significantly influence the cracking resistance measurement of the IDEAL-CT and to estimate how closely these factors need to be controlled. The ruggedness test for the IDEAL-CT was conducted following the ASTM E 1169-14: Standard Practice for Conducting Ruggedness Tests. The ruggedness test is a kind of sensitivity test on variables of the IDEAL-CT rather than materials so that ASTM E1169-14 recommends that the ruggedness test should be done by a single laboratory with a uniform material. This study employed a 9.5 mm typical Superpave dense-graded mix, and a virgin mix with PG64-22 binder was used here to further reduce impact of mix components on the final result. For the IDEAL-CT, the variables being tested include test temperature, specimen thickness, air voids, and loading rate. The fractional factorial Plackett-Burnam (PB) designs are often used with ruggedness tests to determine the effects of the test variables. The PB designs only consider two levels for each variable, and the levels chosen should be reasonably large relative to measurement error. Based on the PB design table documented in ASTM E 1169-14, the authors recommended experiment design for the IDEAL-CT with four variables and associated high and low levels, as shown in Table 4.
A replicated PB design was employed in this study. A total of 16 IDEAL-CT specimens were molded for all test combinations listed in Table 4. The loose mixes were conditioned in the oven for 4 hours at 135°C before molding. The IDEAL-CT was conducted for the specific test conditions. Table 5 presents the test results.

Following the procedures described in ASTM E1169, the statistical analysis of ruggedness test was performed in two steps:

1. Estimate variable effects: The main variable effects are the differences between average responses at the high (+1) and the low (−1) levels. When the effect of a variable is the same regardless of the levels of other variables, then the main effect is the best estimate of the variable’s effect. The calculated main effects for variables A, B, C, and E are −1.27, 3.91, 0.01, and 13.87, respectively.

2. Statistical tests of variable effects: The variable effects are determined using the Student’s t-test. The t-test statistic for a variable is the main effect divided by the standard error of effects (S\text{effect}) which is defined in Equations 11 and 12. If the calculated t-value for a variable is greater than the t-value corresponding to a 0.05 significance level, the variable is statistically significant at a level of 0.05. Tables 5 and 6 list all the calculations, and Figure 16 presents the half-normal plot. A line for comparison to factor effects is plotted with the slope determined by 1/S\text{effect}. The only significant factor is air voids (E) with a p-value of 0.013 (<0.05), which falls farthest to the right of the line.

\[
S_{\text{effect}} = \sqrt{\frac{4s^2}{N \times \text{Rep}}}
\]  
[11]

\[
S_r = S_d / \sqrt{2}
\]  
[12]

where \(N\) is number of runs in the design (\(N = 8\)); \(\text{Rep}\) is number of replicates of design (\(\text{Rep}=2\)); \(S_r\) is estimated standard deviation of the test results, defined by equation; and \(S_d\) is standard deviation of the differences between replicates (Table 5).

Based on the statistical analysis results presented above, the IDEAL-CT can be considered as rugged with regard to specimen thickness, loading rate, and test temperature tested. The variable of air voids is identified as statistically significant variable, but it is not practical to further limit the range of the air voids of the specimens. Thus, the IDEAL-CT, after combining both statistical and practical views, is considered as rugged with all four variables tested in this study.
Table 4. Eight run combinations for IDEAL-CT with four test variables

<table>
<thead>
<tr>
<th>PB order, run #</th>
<th>Specimen thickness 62±2 mm (A)</th>
<th>Loading rate 50±1 mm/min (B)</th>
<th>Test temperature 25±1 °C (C)</th>
<th>Air voids 7±0.5% (E)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>+1 (62+2=64)</td>
<td>+1 (50+1=51)</td>
<td>+1 (25+1=26)</td>
<td>+1 (7+0.5=7.5)</td>
</tr>
<tr>
<td>2</td>
<td>1 (60)</td>
<td>+1 (51)</td>
<td>+1 (26)</td>
<td>-1 (6.5)</td>
</tr>
<tr>
<td>3</td>
<td>-1 (60)</td>
<td>-1 (49)</td>
<td>+1 (26)</td>
<td>+1 (7.5)</td>
</tr>
<tr>
<td>4</td>
<td>+1 (64)</td>
<td>-1 (49)</td>
<td>-1 (24)</td>
<td>+1 (7.5)</td>
</tr>
<tr>
<td>5</td>
<td>-1 (60)</td>
<td>+1 (51)</td>
<td>-1 (24)</td>
<td>+1 (7.5)</td>
</tr>
<tr>
<td>6</td>
<td>+1 (64)</td>
<td>-1 (49)</td>
<td>+1 (26)</td>
<td>-1 (6.5)</td>
</tr>
<tr>
<td>7</td>
<td>+1 (64)</td>
<td>+1 (51)</td>
<td>-1 (24)</td>
<td>-1 (6.5)</td>
</tr>
<tr>
<td>8</td>
<td>-1 (60)</td>
<td>-1 (49)</td>
<td>-1 (24)</td>
<td>-1 (6.5)</td>
</tr>
</tbody>
</table>

Ave +
Ave -
Main Effect

Table 5. Ruggedness test results and statistical analysis

<table>
<thead>
<tr>
<th>PB Order</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>E</th>
<th>Rep 1</th>
<th>Rep 2</th>
<th>Ave</th>
<th>Difference (Rep 2-Rep 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>127.1</td>
<td>106.1</td>
<td>116.6</td>
<td>-21.0</td>
</tr>
<tr>
<td>2</td>
<td>-1</td>
<td>1</td>
<td>1</td>
<td>-1</td>
<td>100.0</td>
<td>112.3</td>
<td>106.2</td>
<td>12.3</td>
</tr>
<tr>
<td>3</td>
<td>-1</td>
<td>-1</td>
<td>1</td>
<td>1</td>
<td>108.5</td>
<td>92.8</td>
<td>100.6</td>
<td>-15.7</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>-1</td>
<td>-1</td>
<td>1</td>
<td>109.1</td>
<td>120.4</td>
<td>114.8</td>
<td>11.3</td>
</tr>
<tr>
<td>5</td>
<td>-1</td>
<td>1</td>
<td>-1</td>
<td>1</td>
<td>112.6</td>
<td>126.4</td>
<td>119.5</td>
<td>13.8</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>113.1</td>
<td>87.9</td>
<td>100.5</td>
<td>-25.2</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>1</td>
<td>-1</td>
<td>-1</td>
<td>91.5</td>
<td>87.4</td>
<td>89.5</td>
<td>-4.1</td>
</tr>
<tr>
<td>8</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>101.3</td>
<td>99.1</td>
<td>100.2</td>
<td>-2.2</td>
</tr>
</tbody>
</table>

Ave + 105.34 107.93 105.98 112.87
d Sd 14.5
Ave - 106.61 104.02 105.97 99.09
Sv 10.3
Main Effect -1.27 3.91 0.01 13.78
S_effect 4.2
Table 6. Statistical significance of effects for the IDEAL-CT ruggedness test

<table>
<thead>
<tr>
<th>Effect Order</th>
<th>Effect</th>
<th>Est. Effect</th>
<th>Student's t</th>
<th>p-value</th>
<th>Half-Normal</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>E</td>
<td>13.78</td>
<td>3.28</td>
<td>0.013⁰</td>
<td>1.534</td>
</tr>
<tr>
<td>3</td>
<td>B</td>
<td>3.91</td>
<td>0.93</td>
<td>0.383</td>
<td>0.887</td>
</tr>
<tr>
<td>2</td>
<td>A</td>
<td>–1.27</td>
<td>–0.30</td>
<td>0.772</td>
<td>0.489</td>
</tr>
<tr>
<td>1</td>
<td>C</td>
<td>0.01</td>
<td>0.00</td>
<td>0.998</td>
<td>0.157</td>
</tr>
</tbody>
</table>

Note: a: p-value is the two-sided tail probability of Student’s t with 7 degree freedom; b: the marked value is statistically significant at the 5 % level.

Figure 16. Half-Normal plot for Ruggedness test results

7. Summary and Conclusions

Based on the work presented in this paper, the following conclusions and recommendations are made:

- The IDEAL-CT is a simple (no instrumentation, cutting, gluing, drilling, and notching to specimen), practical (minimum training needed for routine operation), and efficient (test completion within 1 minute) cracking test which can be performed with regular indirect tensile strength test equipment.

- The IDEAL-CT is sensitive to key asphalt mix components and volumetric properties (RAP and RAS content, asphalt binder type, binder content, aging conditions, and air voids), and it also has much lower COV than
traditional repeated load cracking tests. Most the IDEAL-CT results have COV less than 20 percent.

- The IDEAL-CT correlated well with field performance in terms of fatigue, reflective, and thermal cracking.
- The IDEAL-CT, after combining both statistical and practical views, is considered as rugged with all four variables: specimen thickness, loading rate, test temperature, and air voids.

Both laboratory evaluation and field validation presented in this paper are limited. Additional independent mixes, field data, varied traffic load spectrums, different environmental conditions, and different materials (mix types) are required for further evaluation and validation of the IDEAL-CT. Also, an inter-laboratory study is recommended to define the precision and bias of the IDEAL-CT. Additionally, $\text{CT}_{\text{Index}}$ criteria for different types of mixes should be developed for mix design and QC/QA.

8. Acknowledgments
The authors gratefully acknowledge Dr. Sheng Hu for kindly helping data processing. Appreciation is highly expressed to Mr. Richard Steger and Dr. Jason Bausano, Ingevity for sharing the FHWA plant mixes with us. Recognitions are due to Dave Van Deusen and his team at MnROAD for providing plant mixes of Cells 20, 21, and 22 with us.

9. Disclaimer
The contents and opinions of this paper reflect the views of the authors, who are solely responsible for the facts and the accuracy of the data presented herein. The contents of this paper do not necessarily reflect the official views or the policies of any agencies.

10. References


Ma, W., N. H. Tran, A. Taylor, J. R. Willis, and M. Robbins, Comparison of Laboratory Cracking Test Results and Field Performance, Journal of Association of Asphalt Paving Technologists, Portland, Oregon, March 8-11, 2015.


Zhou, F. and T. Scullion, Overlay Tester: A Rapid Performance Related Crack Resistance Test, Texas Transportation Institute, the Texas A&M University System, Report FHWA/TX-05/0-4667-2, College Station, Texas, 2005.


Appendix: Derivation and Rationales for CT\textit{Index} for IDEAL-CT

The development of the IDEAL-CT and associated \textit{CT\textit{Index}} is inspired by the well-known Paris’ law (Equation 1) and the work done by Bazant and Prat in 1988 for crack propagation (Equation 2):

\[
\frac{dc}{dN} = A(K_i)^n \tag{1}
\]

\[
\dot{c} = v_c \left( \frac{G}{G_f} \right)^{\frac{n}{2}} \tag{2}
\]

where \(\frac{dc}{dN}\) and \(\dot{c}\) are cracking growth rate under a constant load; \(c\) is crack length; \(N\) is number of load repetitions; \(v_c\) and \(A\) are constants; \(n\) is material constant; and \(G_f\) is fracture energy; \(G = \frac{K_i^2}{E}\) is energy release rate; \(K_i\) is stress intensity factor; and \(E\) is modulus. Substitute \(G\) with \(K_i\) and \(E\), Equation 2 becomes:

\[
\dot{c} = v_c \left( \frac{K_i^2}{E \times G_f} \right)^{\frac{n}{2}} \tag{3}
\]

Since there is no instrumentation on the specimen at all, the modulus \(E\) can be approximately estimated by the applied load \((P)\) and the measured vertical deformation \((l)\) as shown in Equation 4 (Liu and Lovato 2008):

\[
E \approx \frac{P \times l}{t \times t} \tag{4}
\]

where \(t\) is the thickness of the cylindrical specimen.

Similarly, the stress intensity factor \(K_i\) can be estimated by Equation 5 (Murakami 1988):

\[
K_i = \sigma \times f(c) \tag{5}
\]

where \(\sigma\) is tensile stress \(\left(= \frac{2P}{\pi D t}\right)\) for the IDEAL-CT and \(f(c)\) is a shape function.

Substitute Equations 4 and 5 into Equation 3, then Equation 3 becomes:

\[
\dot{c} \approx v_c \left( \frac{4P}{\pi^2 D t} \times \frac{(f(c))^2}{E \times G_f} \right)^{\frac{n}{2}} \tag{6}
\]

Equation 6 is rearranged into Equation 7 and then after further simplification, it becomes Equation 8:

\[
\dot{c} \approx v_c \left( \frac{4}{\pi^2} \times \frac{(f(c))^2}{(D t)^2 \times \frac{P}{E \times G_f}} \right)^{\frac{n}{2}} \tag{7}
\]

\[
\dot{c} \approx v_c \left( \frac{(f(c))^2}{D^2 \times t \times \frac{G_f}{E \times P}} \right)^{\frac{n}{2}} \tag{8}
\]
Equation 8 can be further re-arranged into the formation of Equation 9:

\[
\dot{c} \approx v_c \left( \frac{(f_c)^2}{t \times \frac{GF_P}{T} \times \left( \frac{D}{t} \right)^2} \right)^{\frac{t}{2}} \tag{9}
\]

From Equation 9, it can be seen that cracking growth rate is highly related to parameter \( t \times \frac{GF_P}{T} \times \left( \frac{D}{t} \right)^2 \). For a repeated load test with a constant load, the larger the parameter \( t \times \frac{GF_P}{T} \times \left( \frac{D}{t} \right)^2 \), the slower the crack growth, and accordingly the better cracking resistance. Note that parameter \( t \times \frac{GF_P}{T} \times \left( \frac{D}{t} \right)^2 \) is not a fundamental indicator but a kind of index parameter. To become a true index (or unit less parameter), specimen thickness \( t \) must be normalized. Thus, for an indirect tensile cracking test under a repeated, constant load, the proposed CT Index is given below:

- For specimen with a thickness of 62 mm:
  \[
  CT_{\text{Index}} = \frac{GF_P}{T} \times \left( \frac{1}{D} \right)^{-2} = \frac{GF_P}{P \times t} \times D^2 \tag{10}
  \]

- For specimens with a thickness of other than 62 mm:
  \[
  CT_{\text{Index}} = \frac{t}{62} \times \frac{GF_P}{T} \times \left( \frac{1}{D} \right)^{-2} = \frac{t}{62} \times \frac{GF_P}{P \times t} \times D^2 \tag{11}
  \]

Basically, cracking resistance of an asphalt mix is determined by the three parameters: fracture energy \( G_f \), load \( P \), and displacement \( l \). Note that \( D \) is specimen diameter that is a constant after the specimen size is selected. When asphalt mix samples are tested under a repeated, constant load \( P \), the \( CT_{\text{Index}} \) in Equation 10 (and 11) is controlled by displacement \( l \). When \( G_f \) is kept constant, a stiffer mix will have a smaller \( l \), larger \( CT_{\text{Index}} \), and ultimately a better cracking resistance, which is consistent with the fact that stiffer mixes perform better under a stress controlled fatigue test. Inversely, for a repeated, constant displacement (\( l \)) test, those softer mixes with smaller modulus have smaller \( P \), larger \( CT_{\text{Index}} \), and consequently better cracking resistance, which is also consistent with the past experience on asphalt mix fatigue tests. Therefore, the \( CT_{\text{Index}} \) Equation 10 (or 11) is valid.

However, Equations 10 and 11 cannot be directly applied to the IDEAL-CT, because neither load nor displacement is kept constant in the process of the IDEAL-CT. Although the loading rate is constant 50 mm/min. for the IDEAL-CT, both load and displacement keep changing through the whole process of the IDEAL-CT, as seen in Figure 1 of the main text. Thus, the \( CT_{\text{Index}} \) Equation 10 (and 11) must be modified. The proposed \( CT_{\text{Index}} \) Formats for the IDEAL-CT are given in Equations 12 and 13 for 62 mm thick and non-62 mm thick specimens, respectively:

\[
CT_{\text{Index}} = \frac{GF_P}{T} \times \left( \frac{1}{D} \right) \tag{12}
\]
Compared Equation 10 with 12, the only difference is the exponent of parameter $\frac{l}{D}$ changing to 1 from $-2$. Actually, physical meanings of parameters, $p$ and $\frac{l}{D}$, are also different. The rationales and explanations for these changes are provided below:

- Fracture energy $G_f$: Regardless of loading or displacement status, asphalt mixes with larger fracture energy normally have better cracking resistance. Thus, $G_f$ is kept the same. For the IDEAL-CT, $G_f$ is calculated as the work of fracture divided by area of cracking face.

- “Modulus” parameter $\frac{P}{l}$ (or $\frac{|\Delta P|}{l}$): It is not the same original modulus concept as defined in Equation 4 anymore. But it is still a kind of “modulus” with a new definition: the slope at the point of the post-peak 75 percent maximum load. The larger $\frac{|\Delta P|}{l}$, the more brittle the mix, and the worse cracking resistance.

- “Strain” tolerance parameter $\frac{l}{D}$: $D$ is still the same specimen diameter, but $l$ (or $l_{75\%}$) is defined as the displacement the specimen can tolerate when the load reaches to 75 percent maximum load in the post-peak stage, which is completely different from the $l$ in Equation 4. The larger $l$, the better displacement tolerance the mix, and consequently the better cracking resistance. Thus, the exponent of parameter $\frac{l}{D}$ is changed to positive in Equation 12 from negative in Equation 10. Furthermore, asphalt mix cracking properties often have higher variability, and the more parameters (or higher order of the exponent), the higher the variability. To reduce the potential high variability of the $CT_{Index}$, the exponent of parameter $\frac{l}{D}$ is reduced to 1. Accordingly, all key parameters ($G_f, \frac{P}{l}, \frac{l}{D}$) are considered in the $CT_{Index}$, while maintaining its variability low enough to be accepted by asphalt industry and DOTs.

In summary, the $CT_{Index}$ equations for the IDEAL-CT are derived based on fracture mechanics, and are consistent with common sense and past experience on asphalt mix fatigue test results. Both laboratory and field validation are warranted.