Innovations Deserving Exploratory Analysis Programs

NCHRP IDEA Program

Development of an IDEAL Cracking Test for Asphalt Mix Design, Quality Control and Quality Assurance

Final Report for
NCHRP IDEA Project 195

Prepared by:
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EXECUTIVE SUMMARY

Asphalt pavement cracking is a nationwide problem faced by every highway agency. As asphalt mix designs become more complex with the use of recycled materials, rejuvenators, and asphalt binders with various additives, pavement engineers and asphalt industry urgently need a simple, repeatable, and reliable cracking test for mix design, quality control (QC), and quality assurance (QA). This research project developed an Ideal Cracking Test (IDEAL-CT), as shown in FIGURE 1. The IDEAL-CT is typically run with cylindrical specimens at the room temperature and a loading rate of 50 mm/min. using the indirect tensile loading frame. Different from other cracking tests, the IDEAL-CT integrates all seven desirable features listed below:

1. Simplicity: no instrumentation, cutting, gluing, drilling, or notching.
2. Practicality: minimum training needed for routine operation.
3. Efficiency: test completion within 1 min.
4. Test equipment: existing or low cost equipment (< $10,000).
5. Repeatability: coefficient of variation (COV) less than 20 percent.
6. Sensitivity: sensitive to asphalt mix characteristics.
7. Good correlation with field cracking performance: validated with many field test sections.

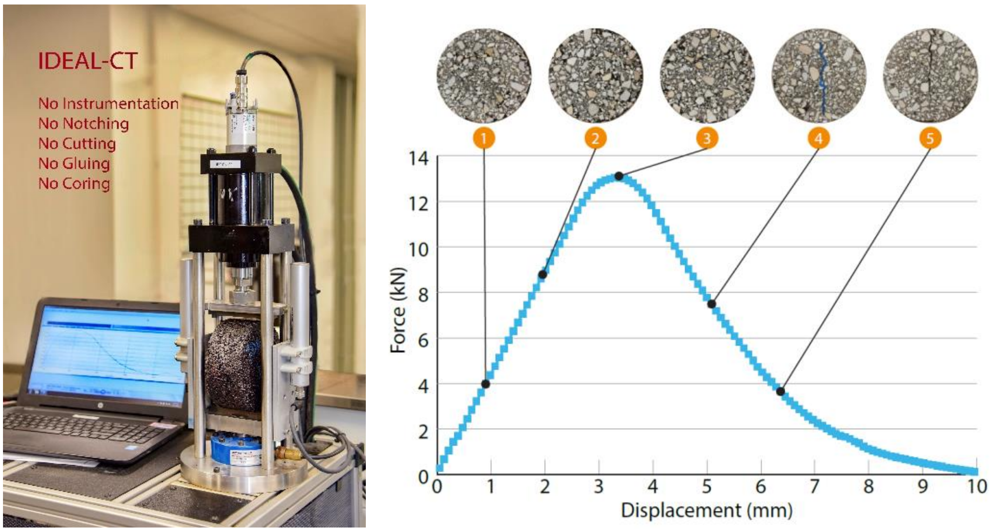


FIGURE 1 IDEAL-CT setup and a typical test result.

The IDEAL-CT determines cracking resistance of asphalt mixes through a fracture mechanics–based parameter: Cracking Tolerance Index (CT_{Index}). The larger the CT_{Index}, the better the cracking resistance. The IDEAL-CT and CT_{Index} are sensitive to Reclaimed Asphalt Pavements (RAP) and Recycled Asphalt Shingles (RAS), asphalt binder type and binder content, and aging conditions. Three replicates of IDEAL-CT specimens are enough to achieve a 20 percent or less the COV. Furthermore, the IDEAL-CT compares well with two established laboratory cracking tests including Texas Overlay test (OT) and Illinois Flexibility Index test (I-FIT). Most importantly, the IDEAL-CT has very good correlation with field cracking performance data collected from the accelerated loading facility at the Federal Highway Administration, Long Term Pavement Performance (LTPP)-SPS10 warm mix test sections in Oklahoma, as shown in FIGURE 2, and many in-service pavements in Texas. The good correlation with field cracking performance was further confirmed by the cracking sections constructed at the test track of the National Center for Asphalt Technology (NCAT), as reported by Mr. Adam Taylor (*1*) at the 2018 NCAT test track conference.

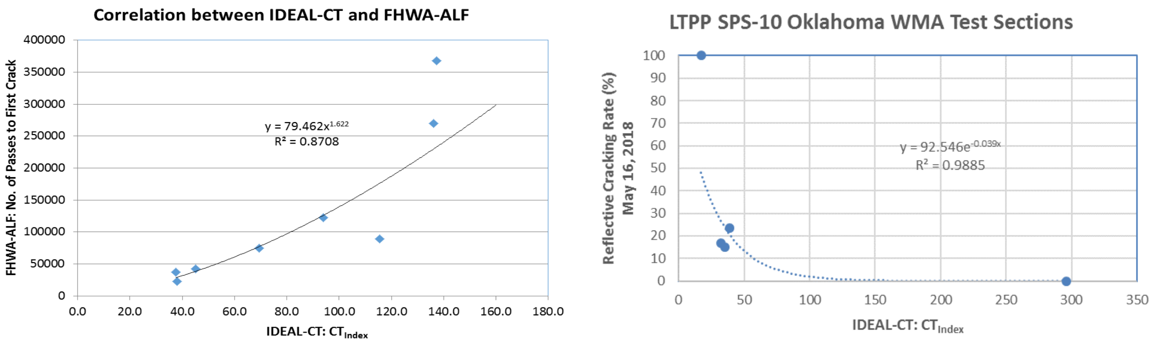


FIGURE 2 Good correlation between IDEAL-CT (CT_{Index}) and field cracking performance.

To facilitate implementation, the research team developed an ASTM test standard for the IDEAL-CT, as well as partnering with three equipment manufacturers to develop standalone test machines, data processing software, and accessories for running the IDEAL-CT. Also, a step-by-step plan was developed for implementing the IDEAL-CT in highway agencies.

Every year, around 360 million tons of asphalt mixes are designed, produced, and placed in the United States, and the associated cost is more than $20 billion with the assumption of $60/ton of asphalt mix. Given this large amount of taxpayers' money and the unsatisfactory cracking performance, implementing the IDEAL-CT ensures durable asphalt mixes lasting 20 percent longer than existing mixes through directly evaluating and verifying cracking resistance of asphalt mixes. The estimated saving will be significant. It will also reduce the maintenance cost, associated traffic delays, and the travel time of every road user.

INTRODUCTION TO IDEA PRODUCT AND APPLICATION

In the 1990s, the asphalt industry used various 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 (*1*). However, these measures resulted in premature cracking problems (*2*, *3*, *4*), which has now become the primary mode of distress that creates the need for pavement rehabilitation. The cracking problem may get even worse in the coming years, 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 re-refined engine oil bottom). Thus, there is an urgent need for a cracking test that is simple, repeatable, and reliable for routine uses in mix design, quality control (QC), and quality assurance (QA) testing.

Various laboratory tests have been developed in the literature. A critical review on these laboratory cracking tests was conducted 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* (*5*). NCHRP 9-57 identified seven desirable features for an Ideal Cracking Test (IDEAL-CT):

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 variation (COV) less than 25 percent.
6. Sensitivity: sensitive to asphalt mix composition (aggregates, binder, etc.).
7. Correlation to field performance: a good correlation with field cracking.

The integration of all these seven features into one cracking test has not yet been accomplished. The objective of this study was to develop and validate such an IDEAL-CT for routine mix designs and QC/QA testing by contractors, departments of transportation (DOTs), and researchers in academia.

Current practices for mix design and QC/QA do not include a widely accepted performance-related cracking test. Consequently, crack resistance of asphalt mixes is not directly evaluated and verified in the process of asphalt mix design and QC/QA testing, although it is critical today for those mixes with high contents of recycled materials (such as RAP, RAS, and re-refined engine oil bottom). This innovation will not only fulfill the urgent need of DOTs and contractors for a simple, repeatable, and reliable cracking test, but it will also make direct consideration of cracking resistance of asphalt mixes possible as a routine process. Thus, this innovation will significantly transform mix design procedures and QC/QA testing being employed today by DOTs and asphalt industry.

THE PROPOSED SOLUTION—CONCEPT AND INNOVATION

IDEAL-CT DESCRIPTION AND IDEAL-CT SPECIMEN

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 50 mm/min. in terms of cross-head displacement. Note that this test could be performed at other test temperatures (such as a temperature lower than the room temperature). The reason for recommending the room test temperature is to use existing loading frames which are often equipped without a temperature chamber. Any size of cylindrical specimens with various diameters (100 or 150 mm) and thicknesses (38, 50, 62, 75 mm, etc.) can be tested. For mix design and laboratory QC/QA, researchers proposed using 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 DOTs and asphalt industry are familiar with molding such specimens. Either lab-molded cylindrical specimens or field cores can be directly tested with no need for instrumentation, gluing, cutting, notching, coring, or any other preparation. FIGURE 3 shows a typical IDEAL-CT set-up and the measured load versus displacement curve.

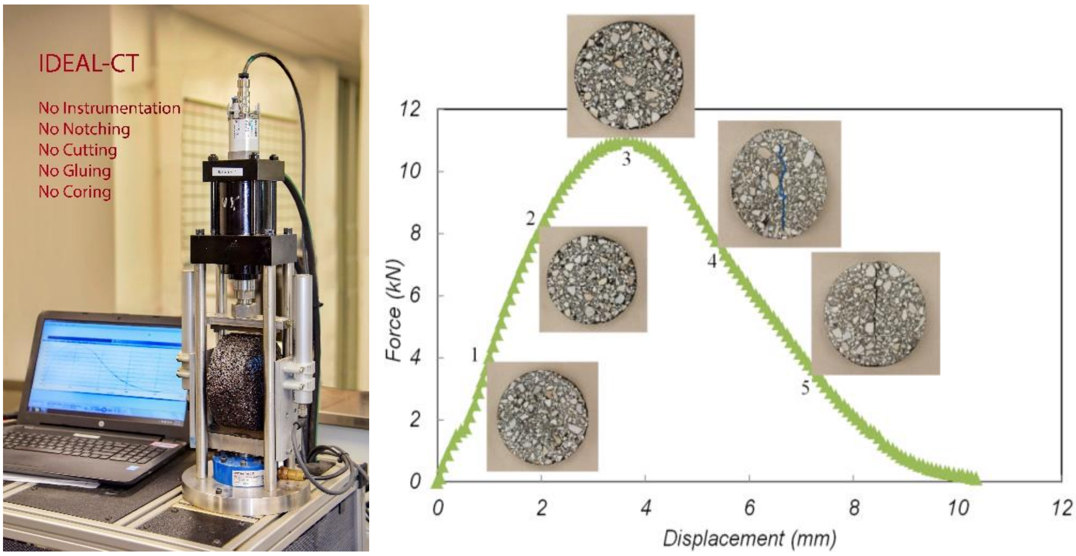


FIGURE 3 IDEAL-CT test setup and typical result.

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 versus displacement curve. The form of the new cracking parameter is inspired by the well-known Paris' law (*6*) and the work done by Bazant and Prat (*7*) for crack propagation (Equations 1 and 2):

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

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

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; $G = \frac{K_I^2}{E}$ is energy release rate; K_I is stress intensity factor; and E is modulus. Substitute G with K_I and E, Equation 2 becomes:

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

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 (*8*):

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

where t is the thickness of the cylindrical specimen.

Similarly, the stress intensity factor K_I can be estimated by Equation 5 (*9*):

$$K_I = \sigma \times f(c) \quad [5]$$

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

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

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

After a series of simplification and the consideration of low variability requirement of a cracking test, a new cracking resistance parameter, $t \times \frac{G_f}{\frac{P}{l}} \times \left(\frac{l}{D}\right)$ was derived. When used for laboratory mix design and QC/QA where specimen thickness can always be 62 mm, the proposed new cracking tolerance index (CT_{Index}) is given in Equation 7. The larger the CT_{Index}, the slower the cracking growth rate:

$$CT_{Index} = \frac{G_f}{\frac{P}{l}} \times \left(\frac{l}{D}\right) \quad [7]$$

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

$$CT_{Index} = \frac{t}{62} \times \frac{G_f}{\frac{P}{l}} \times \left(\frac{l}{D}\right) \quad [8]$$

where fracture energy G_f is the work of fracture (the area of the load versus 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 3) 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.

SELECTION OF CRITICAL CT_{INDEX} POINT

Generally the load-displacement curve of the IDEAL-CT (FIGURE 3) 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, researchers 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 **1**. As clearly observed from TABLE **1**, 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 (*7*) 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 1 Seven Stages of Load-Displacement Curve

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

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, researchers found 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, researchers analyzed more than 200 IDEAL-CT load-displacement curves generated from varieties of asphalt mixes (dense-graded and gap-grade mixes, virgin mixes vs. mixes with RAP/RAS, mixes with PG64-22, PG70-222, PG76-22, PG58-28, PG64-28, and PG64-34), and determined most of the inflection points of these curves with the approach proposed by Al-Qadi et al. (*10*). 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 σ =5. Furthermore, PPP_{75} can always be easily identified without a sophisticated program or software. Thus, researchers propose to use the post-peak point (PPP_{75}) where the load is reduced to 75 percent the peak load (see FIGURE 4).

Furthermore, both parameters, P/l (or $|m| = \left|\frac{\Delta P}{\Delta l}\right|$) 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}.

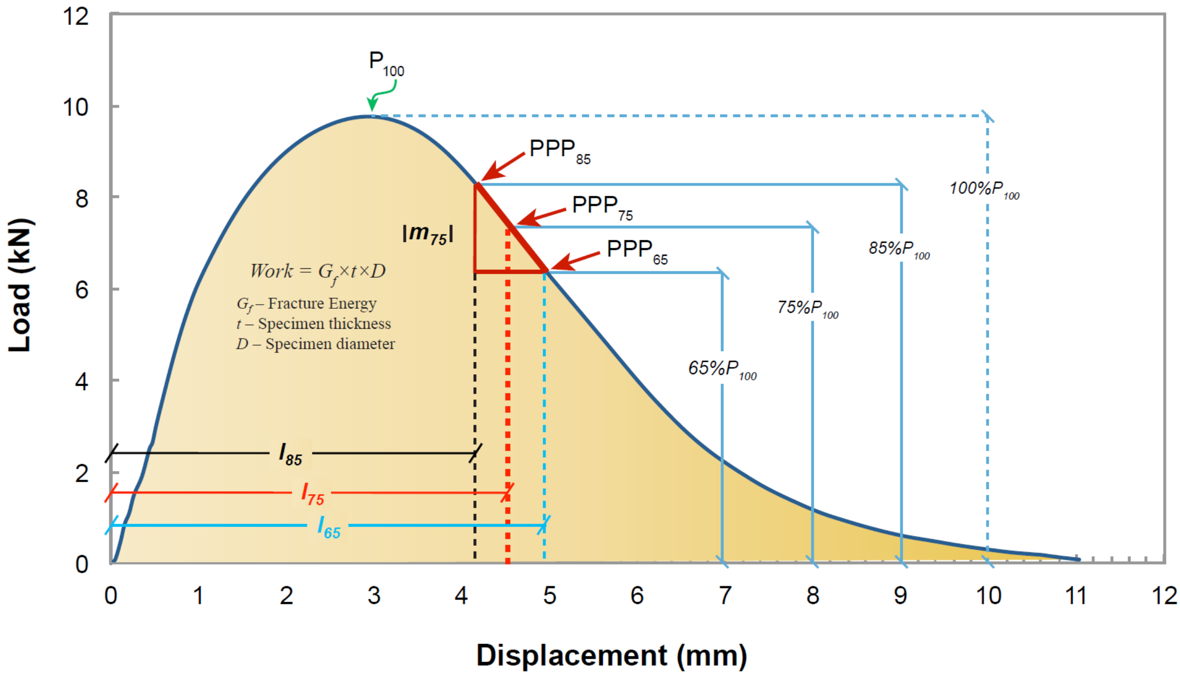


FIGURE 4 Illustration of the *PPP₇₅* point and its slope $|m_{75}|$.

FINALIZATION OF THE CT$_{\text{INDEX}}$ 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 if the load versus displacement curve is known. After selecting the CT$_{\text{Index}}$ 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. 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 4, parameter P/l is calculated as the absolute value of the slope ($|m_{75}| = \left|\frac{P_{85}-P_{65}}{l_{85}-l_{65}}\right|$) between PPP_{85} and PPP_{65}. There are two reasons for using the slope of an interval rather than the tangent slope of the PPP_{75} point: (1) the interval between PPP_{85} and PPP_{65} is two times standard deviation (σ =5) of the inflection point around its average (=75 percent peak load) so that 95.4 percent probability is assured; and (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$_{\text{Index}}$ 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 represent parameter P/l is justifiable.

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

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

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

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, or instrumentation. Thus, the IDEAL-CT automatically meets the first two desirable features: simplicity and practicality. Furthermore, the IDEAL-CT is run at the loading rate is 50 mm/min., and the test is done within 1 minute. Thus, the third desirable feature, efficiency, is met. Additionally, the same indirect tensile strength test equipment with a displacement measurement or any other loading frame can be used for the IDEAL-CT. Most DOTs and contractors already have such equipment. Even if a new test machine is purchased, its cost is often less than \$10,000. Therefore, the fourth desirable feature is met as well. The remaining portion of this research is to evaluate and validate the IDEAL-CT sensitivity, repeatability, and correlation to field performance through CT_{Index} (Equation 9 or 10), which is discussed in the following sections.

INVESTIGATION AND VALIDATION

IDEAL-CT SENSITIVITY

For any cracking test to be used for mix design and QC/QA testing, it must be sensitive to asphalt mix characteristics and aging conditions. Five variables were evaluated in this study: RAP and RAS content, asphalt binder type, binder content, and aging conditions. A series of laboratory-mixed and laboratory-molded specimens were used 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.

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 5 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 5).

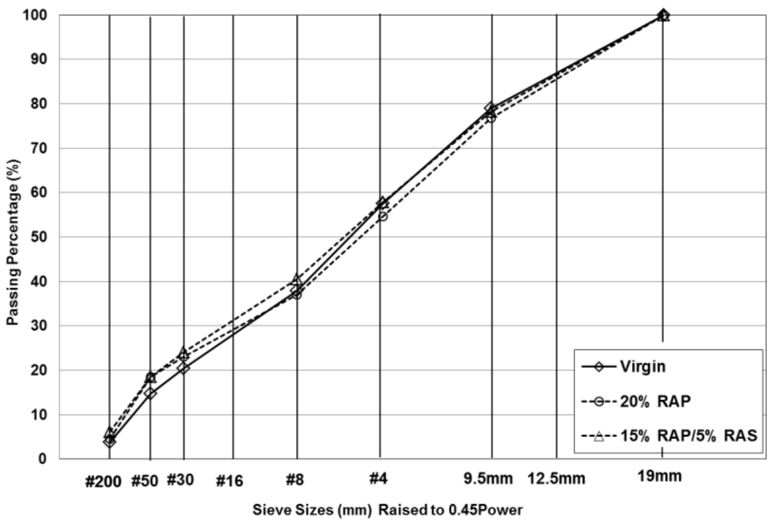


FIGURE 5 Aggregate gradations used for sensitivity analysis.

For each mix, three replicates of 150 mm diameter and 62 mm height 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 6 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 6 clearly show that the IDEAL-CT is sensitive to RAP and RAP/RAS. The additions of RAP and RAP/RAS reduce cracking resistance of the asphalt mix. Thus, the IDEAL-CT is sensitive to the addition of RAP and RAP/RAS to asphalt mixes.

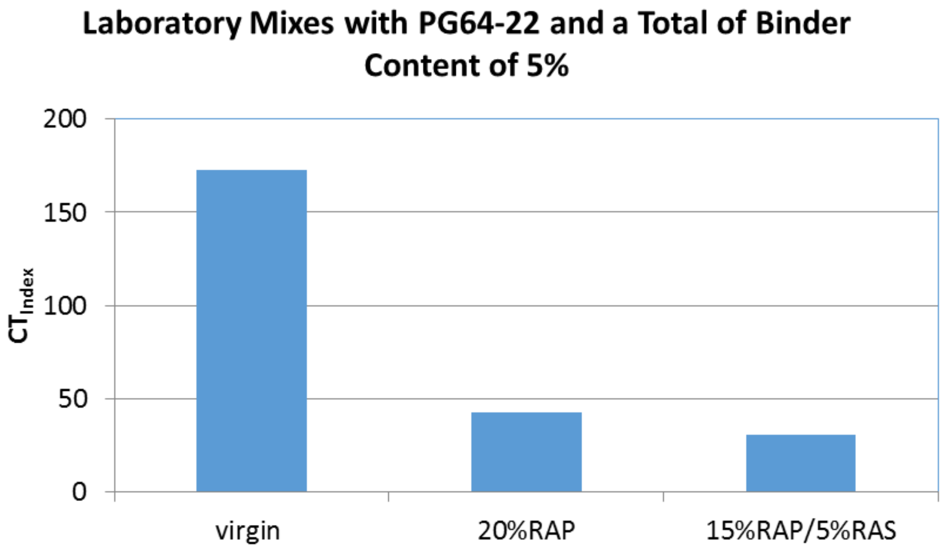


FIGURE 6 IDEAL-CT sensitivity to RAP and RAP/RAS.

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 (*11*). Thus, similar results were anticipated from the IDEAL-CT.

For each binder type, 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 7 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.

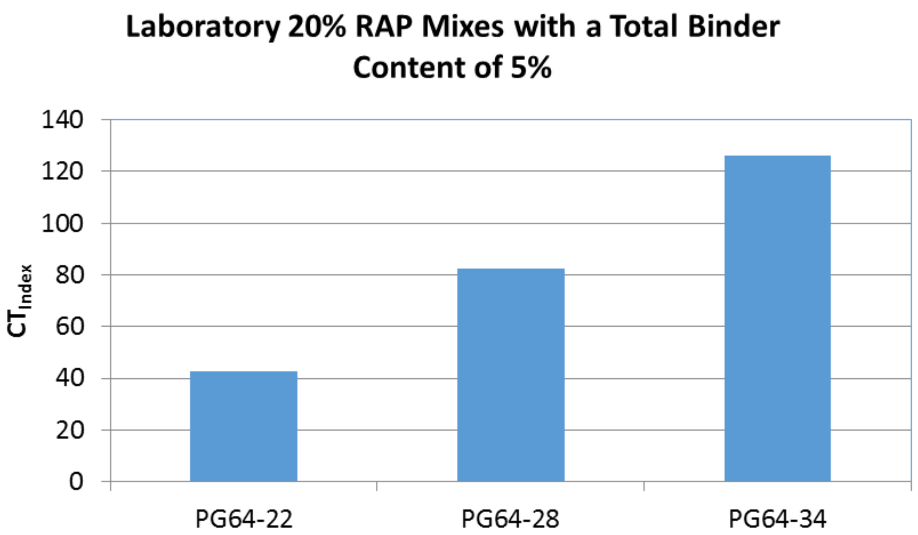


FIGURE 7 IDEAL-CT sensitivity to binder type.

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. Researchers 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 8 presents the IDEAL-CT results. As expected, the higher the binder content, the larger CT_{Index} value. Thus, the IDEAL-CT is sensitive to binder content.

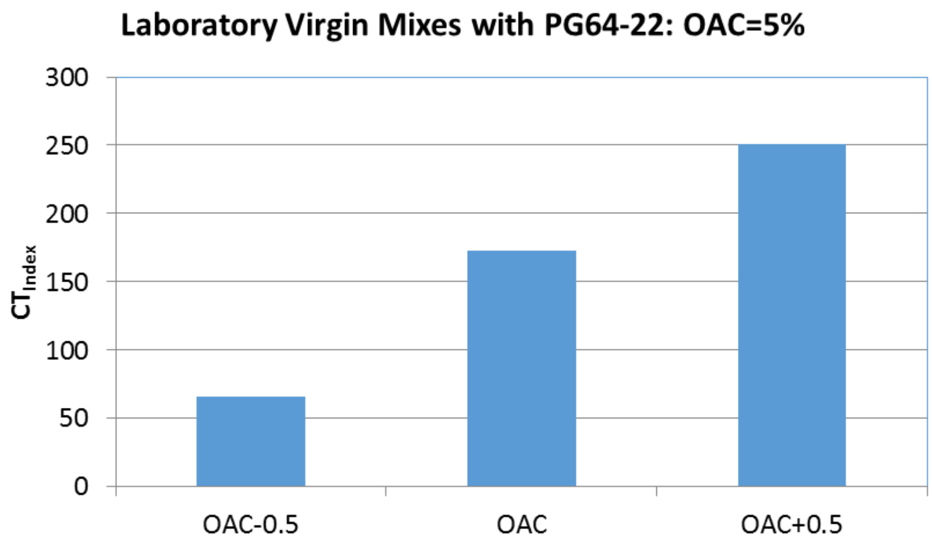


FIGURE 8 IDEAL-CT sensitivity to binder content.

Sensitivity to Aging Conditions

Asphalt aging with time 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 9 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.

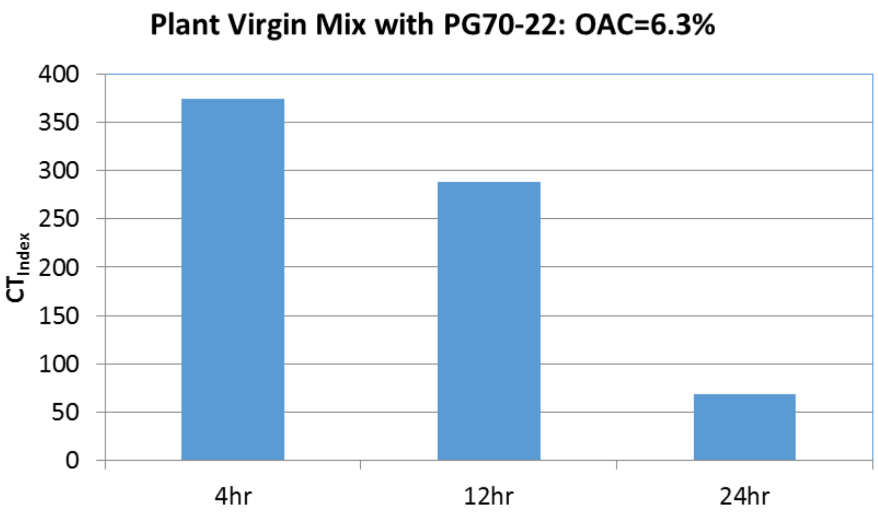


FIGURE 9 IDEAL-CT sensitivity to aging conditions.

In summary, the IDEAL-CT results shown in FIGURE 6–FIGURE 9 clearly indicate that the IDEAL-CT is sensitive to key asphalt mix components and volumetric properties: RAP and RAP/RAS, asphalt binder type, binder content, and aging conditions.

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, researchers 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, the maximum COV is 23.5 percent and most of them are less than 20 percent, which is much less than those of repeated load cracking tests including flexural beam fatigue cracking test (*12*) and OT (*13*, *14*). Additionally, the COVs of the IDEAL-CT are similar to or even better in some cases than those of the I-FIT semi-circular bend test (*10*).

TABLE 2 IDEAL-CT Repeatability

Asphalt Mixes			**CT_{Index}**	**COV (%)**
Laboratory mix	Sensitivity to RAP and RAP/RAS	Virgin	172.9	5.5
		20%RAP	42.8	23.5
		15%RAP/5%RAS	30.8	9.0
	Sensitivity to binder type	PG64-22	42.8	23.5
		PG64-28	82.4	13.8
		PG64-34	126.2	1.8
	Sensitivity to binder content	OMC-0.5	66.0	1.7
		OMC	172.9	5.5
		OMC+0.5	251.0	20.5
Plant mix	Sensitivity to aging conditions	4hr	374.5	12.1
		12hr	287.6	20.0
		24hr	68.9	15.1

IDEAL-CT CORRELATION WITH OTHER CRACKING TESTS

As mentioned earlier, there are many cracking test methods in the literature. Among the various options, the Texas OT and I-FIT were selected in this study to compare with the IDEAL-CT. A brief description on each test method is described as follows.

Texas Overlay Test

The Texas OT is used to represent the reflective cracking potential of the asphalt mixes. Detailed test procedure is described in Tex-248-F, *Test Procedure for Overlay Test (OT).* The OT testing specimen is placed inside the environmental chamber of a mechanical testing machine for temperature equilibrium targeting the testing temperature of 25°C. The sliding block applies tension in a cyclic triangular waveform to a constant maximum displacement of 0.63 mm (0.025 inch). The sliding block reaches the maximum displacement and then returns to its initial position in 10 seconds. The time, displacement, and load corresponding to a certain number of loading cycles are recorded during the test.

Illinois Flexibility Index Test (I-FIT)

The I-FIT has been recently developed to quantify cracking potential of asphalt mixtures (*10*). This test suggested a testing temperature of 25°C with a loading rate of 50 mm/min. The I-FIT uses the so-called flexibility index (FI), as defined in Equation 11, to characterize cracking resistance of asphalt mixes. Typically, the FI values vary from 1 to 30 for the poorest to best performing asphalt mixes.

$$FI = \frac{G_f}{|m|} \times A \tag{11}$$

where, G_f = fracture energy (J/m^2).

$|m|$ = absolute value of post-peak load slope (kN/mm).

A = unit conversion and scaling factor equal to 0.01.

Materials, Asphalt Mixes, and Specimen Preparation

Local limestone aggregates, RAP, and RAP/RAS were collected from a real field project in Texas to produce asphalt mixes for this correlation evaluation. The RAP binder content was 5 percent and its PG high temperature grade was PG103. While the RAS binder content was 20 percent and its PG high temperature grade was PG134. With these materials, four different dense-graded gradations for asphalt mixes were designed (FIGURE 10).

The virgin mix with a PG64-22 binder was first designed as the control mix in the laboratory following TxDOT's Superpave mix design procedure. Its OAC was 5 percent corresponding to the target air voids of 4 percent. Then, this control mix was modified to produce its counterparts of four different mixes. Brief information on each mix is:

- Mix-1 (control mix): Virgin mix with a PG64-22 binder at OAC (5.0 percent).
- Mix-2: 20 percent RAP mix with the PG64-22 binder at the total asphalt content of 5.0 percent.
- Mix-3: 15 percent RAP/5 percent RAS mix with the PG64-22 binder at the total asphalt content of 5.0 percent.
- Mix-4: 20 percent RAP mix with a PG64-28 binder. This mix is the same as Mix-2 except the binder type.
- Mix-5: 20 percent RAP mix with a PG64-34 binder. This mix is the same as Mix-2 except the binder type.

In addition to these above five mixes, five additional virgin mix samples were produced for further evaluation. The fine virgin mix with a PG64-22 binder was designed following TxDOT's Superpave mix design, and its OAC was 5.3 percent at the target air voids of 4 percent. Brief information on these five virgin mixes is:

- Mix-6: Fine virgin mix with a PG64-22 binder at OAC (5.3 percent).
- Mix-7: Fine virgin mix with a PG64-28 binder at OAC (5.3 percent).
- Mix-8: Fine virgin mix with a PG64-34 binder at OAC (5.3 percent).
- Mix-9: Fine virgin mix with a PG70-22 binder at OAC (5.3 percent).
- Mix-10: Fine virgin mix with a PG76-22 binder at OAC (5.3 percent).

For each mix, three IDEAL-CT, five OT, six I-FIT specimens were molded at 7±0.5 percent air voids after 4 hours aging in the oven at 135°C. Then, all testing specimens were tested at 25°C.

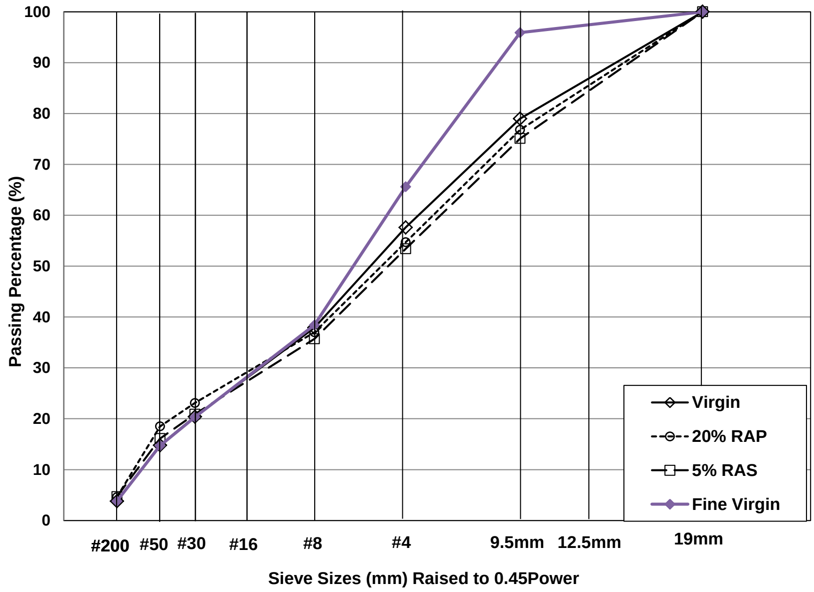
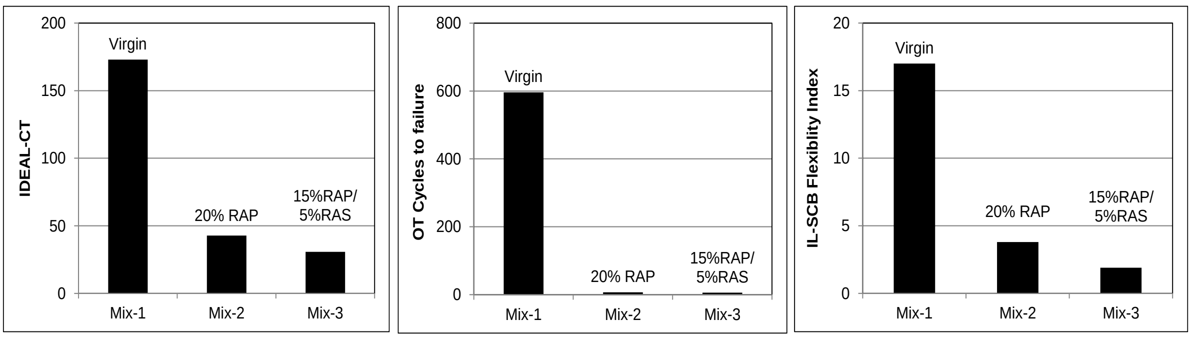


FIGURE 10 Aggregate gradations for asphalt mixes.

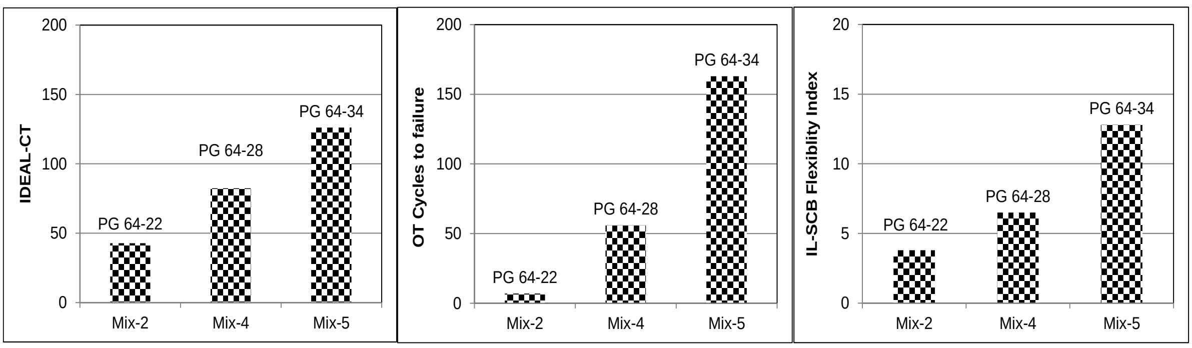
Test Results and Discussion

FIGURE 11, FIGURE 12, and FIGURE 13 show the test results of the IDEAL-CT, OT, and I-FIT on different mixes. All cracking test methods indicate the overall same trend for all these mixes. Thus, the IDEAL-CT, like the OT and I-FIT, can be used for characterizing cracking resistance of asphalt mixes.



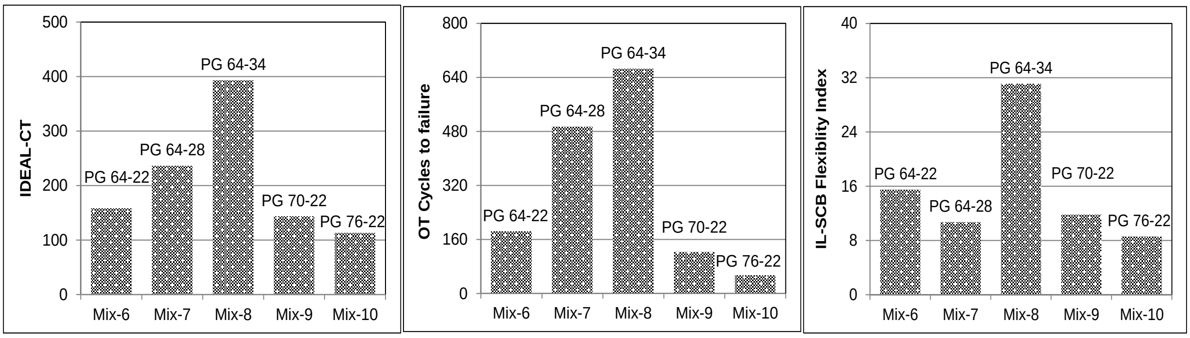
(a) IDEAL-CT test (b) OT test (c) I-FIT test

FIGURE 11 RAP and RAS sensitivity identified by different cracking methods.



(a) IDEAL-CT test (b) OT test (c) I-FIT test

FIGURE 12 Binder type sensitivity identified by different cracking methods.



(a) IDEAL-CT test (b) OT test (c) I-FIT test

FIGURE 13 Binder type sensitivity identified by different cracking methods.

VALIDATION OF THE IDEAL-CT WITH FIELD PERFORMANCE

This section focused on the IDEAL-CT correlation with field performance. 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), LTPP SPS-10 warm mix test sections in Oklahoma, and in-service roads in Texas to evaluate the correlation between the IDEAL-CT test and field performance.

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 (*15*). 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 lb 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 (*15*).

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 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. The average CT_{Index} and COV for each plant mix are tabulated in

TABLE **3** as well.

FIGURE 14 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 3 FHWA ALF Experimental Design

ALF lane	% Recycled binder ratio		Virgin binder	Hot/warm mix	No. of ALF passes for first crack observed	IDEAL-CT	
	RAP	RAS				***CT_{Index}***	**COV (%)**
1	0	-	PG64-22	Hot mix	368,254	137.2	10.7
2	40	-	PG58-28	Warm mix with water foaming	No result yet	123.5	23.2
3	-	20	PG64-22	Hot mix	42,399	45.2	7.9
4	20	-	PG64-22	Warm mix with chemical additive	88,740	115.5	5.6
5	40	-	PG64-22	Hot mix	36,946	37.5	21.6
6	20	-	PG64-22	Hot mix	125,000	93.9	19.2
7	-	20	PG58-28	Hot mix	23,005	38.0	19.6
8	40	-	PG58-28	Hot mix	No result yet	160.0	19.9
9	20	-	PG64-22	Warm mix with water foaming	270,058	136.0	12.5
11	40	-	PG58-28	Warm mix with chemical additive	81,044	69.5	23.9

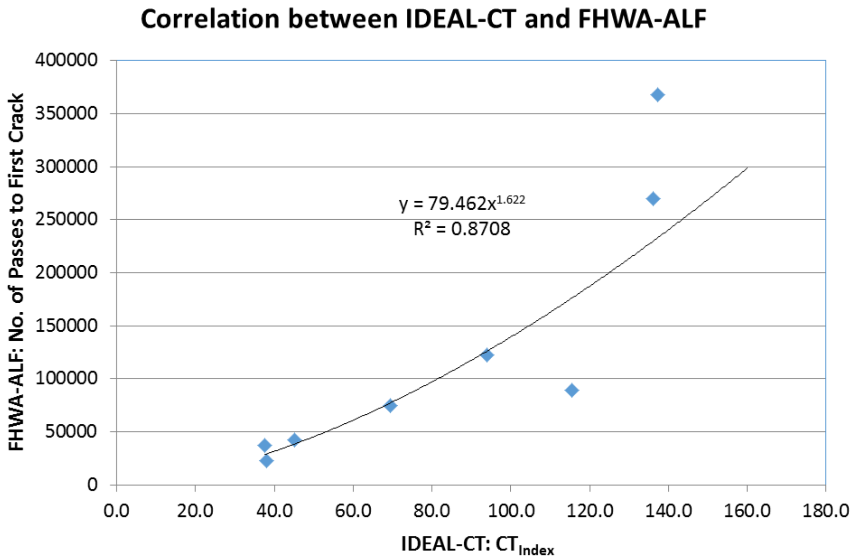


FIGURE 14 Correlation between IDEAL-CT and FHWA ALF full-scale testing.

LTPP SPS-10 Warm Mix Test Sections in Oklahoma: IDEAL-CT vs. Reflective Cracking

In the last several years, LTPP started a series of new experiments: Specific Pavement Studies-10 (SPS-10), Warm Mix Asphalt (WMA) Overlay of Asphalt Pavements. The SPS-10 test sections were designed to capture information on the performance of WMA and to compare their performance with hot-mix asphalt (HMA). Note that WMA is defined by LTPP as asphalt mixes produced at a temperature below 275°F. Six test sections (with the mixes from TABLE 4) were constructed on SH66, West of Yukon, Ok, in Nov. 2015. Before the 2-inch asphalt overlay, LTPP surveyed and recorded existing pavement distresses of the six test sections. All test sections exhibited a large amount of cracking except Section 400A62 with no transverse cracking. For the purpose of validating the IDEAL-CT for reflective cracking, Section 400A62 is excluded from this study. Thus, only five test sections (400A01, 400A02, 400A03, 400A61, and 400A63) are employed here for the IDEAL-CT validation. In May 2018, researchers surveyed the pavement distresses of these test sections. Section 400A61 had 100 percent reflective cracking after 30 months trafficking. Section 400A63 performed the best among these five test sections and no reflective cracking was observed. Sections 400A01, 400A02, and 400A03 had less than 30 percent reflective cracking.

Plant mix from each test lane was obtained for the IDEAL-CT. Three replicates of test specimens with 7±0.5 percent air voids were molded for each test section. 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 15 shows the relationship between CT_{Index} values and the field reflective cracking rate. $\mathrm{CT}_{\mathrm{Index}}$ has a very good correlation with field reflective cracking development.

TABLE 4 LTPP SPS-10 Test Sections on SH66, Ok

LTPP Section ID	Asphalt Binder	Mix Type	HMA/ WMA	WMA Additive	WMA Dose Rate (%)	Recycling Agent	RAP (%)	RAS (%)
400A01	PG 70-28	Superpave	HMA	NA	NA	NA	12%	3%
400A02	PG70-28	Superpave	WMA	Foam	2.00%	NA	12%	3%
400A03	PG 70-28	Superpave	WMA	EVOTHERM M1A	0.70%	NA	12%	3%
400A61	PG 64-22	Superpave	WMA	EVOTHERM M1A	0.70%	11%	12%	3%
400A62	PG 58-28	Superpave	WMA	EVOTHERM M1A	0.70%	NA	12%	3%
400A63	PG 70-28	SMA	WMA	EVOTHERM M1A	1.00%	NA	NA	NA

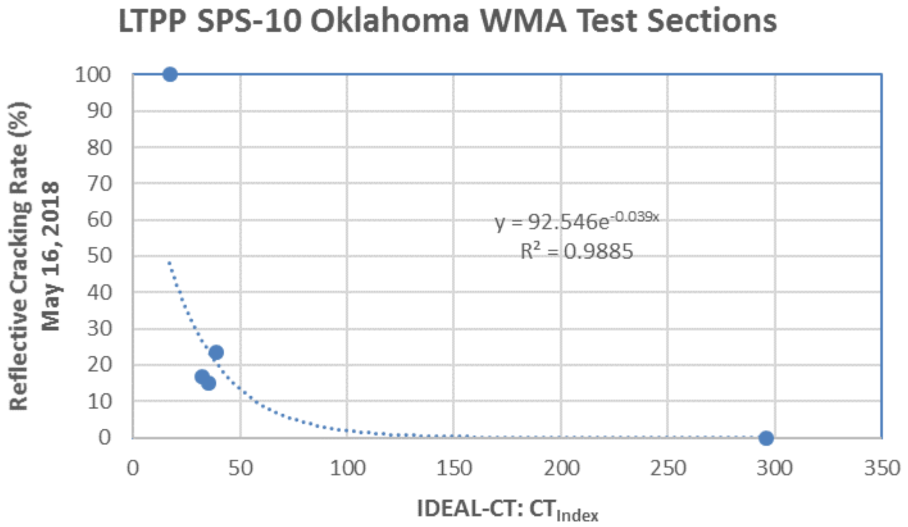


FIGURE 15 Correlation between IDEAL-CT and LTPP SPS-10 reflective cracking rate.

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 62.5 mm (2.5 in.) asphalt layer was milled, and then was filled with 25.0 mm (1 in.) dense-graded Type F mix and 38 mm (1.5 in.) 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 versus 5.8 percent. Six field surveys have been conducted since traffic opening. No rutting was observed on either test section. No cracks were observed on Section 1 until the last survey on March 3, 2016. As shown in FIGURE 16, 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 17 presents the average CT_{Index} values of the two plants mixes. Comparing the data in FIGURE 16 and FIGURE 17, the CT_{Index} values match exactly what was observed in the field. The higher CT_{Index} values, the less fatigue cracking in the field.

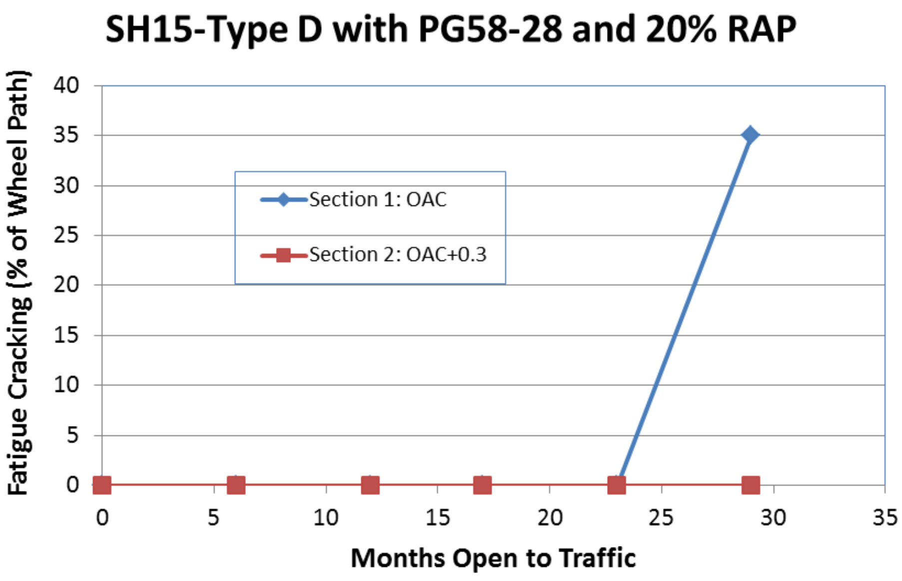


FIGURE 16 Fatigue cracking development observed on SH15, Texas.

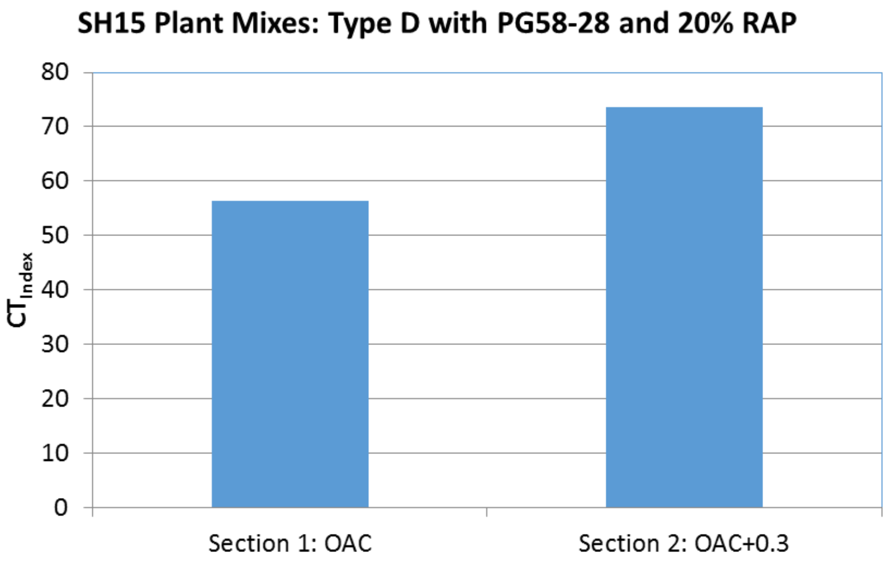


FIGURE 17 IDEAL-CT results of SH15 plant mixes.

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 in.) asphalt layer and then refilling with a 75 mm (3 in.) dense-graded Type B mix and 50 mm (2 in.) 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. FIGURE 18 shows performance survey results and 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 19 presents the average CT_{Index} values of the two plants mixes. Comparing the data in FIGURE 18 and FIGURE 19, the IDEAL-CT values match very well with what was observed in the field. The higher CT_{Index} value means less reflective cracking in the field.

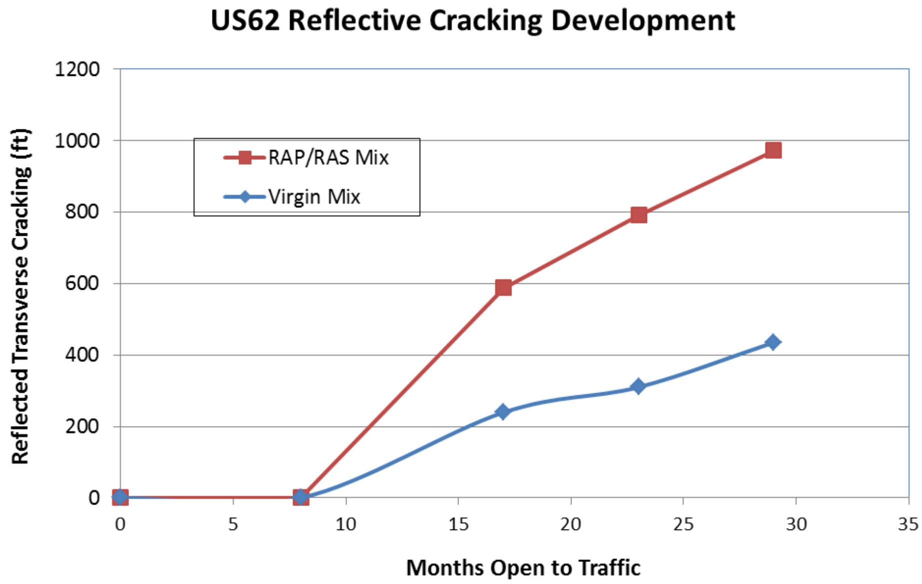


FIGURE 18 Cracking development observed on US62, Texas.

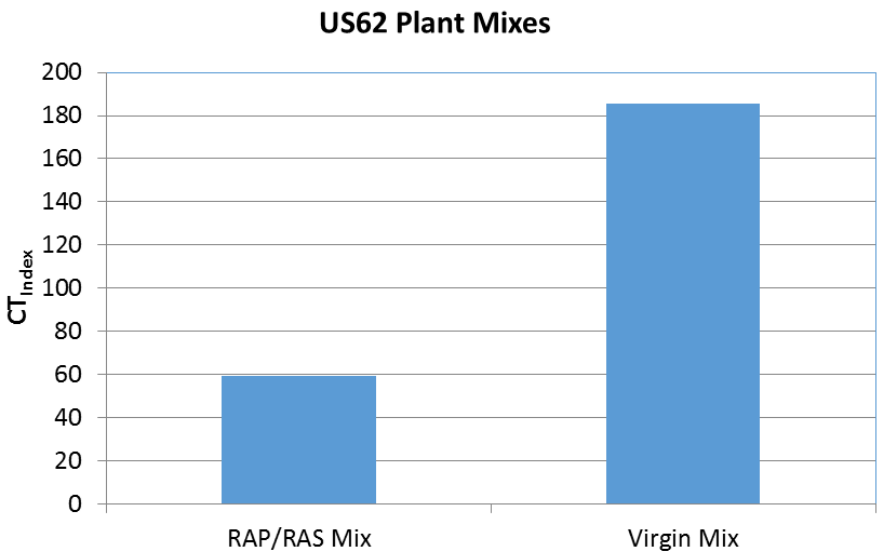


FIGURE 19 IDEAL-CT results of US62 mixes.

In summary, various field test sections including FHWA ALF, LTPP SPS-10 Oklahoma test sections, and Texas in-service roads were used to validate the IDEAL-CT. The good correlation with field cracking performance was further confirmed by the cracking sections constructed at the test track of the National Center for Asphalt Technology, as reported by Mr. Adam Taylor (*1*) at the 2018 NCAT test track conference. All test results indicate that the IDEAL-CT compares well with field fatigue cracking and reflective cracking. With the confidence of the IDEAL-CT in differentiating mix cracking resistance, researchers took another step toward standardizing the IDEAL-CT through ruggedness test. Detailed information is presented in the next section.

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 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, researchers recommended the experiment design for the IDEAL-CT with four variables and associated high and low levels (TABLE 5).

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 5. 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 6 presents the test results.

Following the procedures described in ASTM E 1169, 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_{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. TABLE 6 and TABLE 7 list all the calculations, and FIGURE 20 presents the half-normal plot. A line for comparison to factor effects is plotted with the slope determined by $1/S_{effect}$. 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.

$$s_{effect} = \sqrt{\frac{4s_r^2}{N\times Rep}} \quad [11]$$

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

where N is number of runs in the design (N = 8); Rep is number of replicates of design (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 6).

Based on the statistical analysis results presented above, the IDEAL-CT can be considered as rugged in 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, because the air voids measurement has a relatively high variability with a standard deviation of 0.5 percent. Thus, the IDEAL-CT, after combining both statistical and practical views, is considered as rugged with all four variables tested in this study.

TABLE 5 Eight Run Combinations for IDEAL-CT with Four Test Variables

PB order, run #	**Specimen thickness 62±2 mm (A)**	**Loading rate 50±1 mm/min (B)**	**Test temperature 25±1°C (C)**	**Air voids 7±0.5% (E)**
1	+1 (62+2=64)	+1 (50+1=51)	+1 (25+1=26)	+1 (7+0.5=7.5)
2	−1 (60)	+1 (51)	+1 (26)	−1 (6.5)
3	−1 (60)	−1 (49)	+1 (26)	+1 (7.5)
4	+1 (64)	−1 (49)	−1 (24)	+1 (7.5)
5	−1 (60)	+1 (51)	−1 (24)	+1 (7.5)
6	+1 (64)	−1 (49)	+1 (26)	−1 (6.5)
7	+1 (64)	+1 (51)	−1 (24)	−1 (6.5)
8	−1 (60)	−1 (49)	−1 (24)	−1 (6.5)
Ave +				
Ave −				
Main Effect				

TABLE 6 Ruggedness Test Results and Statistical Analysis

PB Order	A	B	C	E	Rep 1	Rep 2	Ave	Difference (Rep 2-Rep 1)
1	**1**	**1**	**1**	**1**	127.1	106.1	116.6	–21.0
2	**–1**	**1**	**1**	**–1**	100.0	112.3	106.2	12.3
3	**–1**	**–1**	**1**	**1**	108.5	92.8	100.6	–15.7
4	**1**	**–1**	**–1**	**1**	109.1	120.4	114.8	11.3
5	**–1**	**1**	**–1**	**1**	112.6	126.4	119.5	13.8
6	**1**	**–1**	**1**	**–1**	113.1	87.9	100.5	–25.2
7	**1**	**1**	**–1**	**–1**	91.5	87.4	89.5	–4.1
8	**–1**	**–1**	**–1**	**–1**	101.3	99.1	100.2	–2.2
Ave +	105.34	107.93	105.98	112.87	-		S_d	14.5
Ave –	106.61	104.02	105.97	99.09			S_r	10.3
Main Effect	–1.27	3.91	0.01	13.78			S_{effect}	4.2

TABLE 7 Statistical Significance of Effects for the IDEAL-CT Ruggedness Test

Effect Order	Effect	Est. Effect	Student's t	*p*-value[a]	Half-Normal
4	E	13.78	3.28	0.013[b]	1.534
3	B	3.91	0.93	0.383	0.887
2	A	–1.27	–0.30	0.772	0.489
1	C	0.01	0.00	0.998	0.157

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.

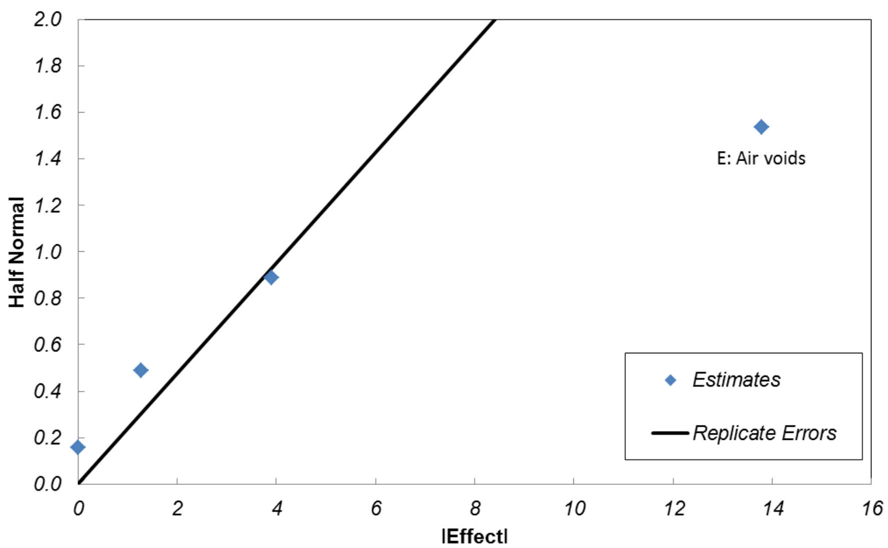


FIGURE 20 Half-normal plot for ruggedness test results.

PLANS FOR IMPLEMENTATION

Researchers worked with ASTM International to develop a test standard for the IDEAL-CT (see Appendix A). Test equipment and accessories for running the IDEAL-CT are commercially available in the market. In the last two years, the IDEAL-CT gained many attentions from DOTs and asphalt industry. Researchers are working with the NCHRP Implementation program to implement the IDEAL-CT. As of writing this final report, six DOTs have committed to participate in the NCHRP implement project (Texas, Oklahoma, Virginia, Kentucky, Minnesota, and Maine). The proposed implementation plan is described as follows:

- Task 1: Demonstration of the use of the IDEAL-CT for mix design and QC/QA testing: The Texas A&M Transportation Institute (TTI) owns state-of-the-art laboratory test equipment for characterizing asphalt pavements materials, including a full set of IDEAL-CT test machines. Thus, it is proposed to have an equipment demonstration at TTI's Center for Infrastructure Renewal in College Station, Texas. One representative from each participating DOT will be invited, and travel costs and expenses will be provided by the implementation project. The demonstration will include specimen preparation, conditioning, testing, and data interpretation and application for both mix design and QC/QA. Each participating DOT can send two plant mixes (for example one good mix and one mix with poor cracking resistance) in advance, and these mixes will then be used for the demonstration. Each attendee at the demonstration will be asked to critique the test procedures and provide recommendations and guidance on what would assist its implementation in their state. A technical memo will be written to document all the demonstration activities and the mixes tested for each participating DOT and then be submitted at the end of this task.

- Task 2: Development of training videos and detailed successful case studies: The demonstration process in Task 1 will be professionally videotaped and then edited for developing training videos, including all aspects of specimen preparation, conditioning, testing, and data interpretation and application for mix design and QC/QA. As with all implementation efforts, it is important to provide successful case studies on how DOTs have implemented this technology, from shadow testing to full implementation. The cost/benefit of test implementation to local contractors will be highlighted.
- Task 3: Implementation group webinars/conference calls and TRB webinars: Researchers and the participating DOTs will have bi-monthly webinars or conference calls to update and exchange implementation progress, issues encountered, and lessons learned. Additionally, at least one TRB webinar will be held to reach other DOTs and a national audience.
- Task 4: Two one-page flyers and videos will be developed. One for DOT senior management, describing the benefits, consequences of not adopting a cracking test, and the cost implications. A second flyer for DOT bituminous engineers and hot mix specialists will be developed with more technical information on test set up, proposed criteria, and step by step implementation recommendations. Short high definition professionally produced videos will also be provided to accompany each flyer.

CONCLUSIONS

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

- The IDEAL-CT is a simple (no instrumentation, cutting, gluing, drilling, or notching), practical (minimum training needed for routine operation), and efficient (test completion within 1 minute) cracking test that 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 RAP/RAS content, asphalt binder type, binder content, and aging conditions), 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 and reflective 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.
- The IDEAL-CT is ready for implementation. A draft ASTM standard test procedure and test equipment and accessories are available.

Currently, researchers are working with the NCHRP Implementation program to implement the IDEAL-CT among six DOTs: Texas, Oklahoma, Virginia, Kentucky, Minnesota, and Maine. Since the IDEAL-CT test can be performed with existing loading frames and it is a simple and quick test, both DOTs and asphalt industry can save a large amount of money in terms of test equipment purchasing, technician training, and testing time. With the implementation of the IDEAL-CT, DOTs and asphalt industry will benefit substantially from the simpler, cheaper, and more efficient cracking testing. More importantly, the IDEAL-CT makes it practically possible to check the mix quality in terms of cracking resistance during the plant production.

APPENDIX A: STANDARD TEST METHOD FOR DETERMINATION OF CRACKING TOLERANCE INDEX OF ASPHALT MIXTURE USING THE INDIRECT TENSILE CRACKING TEST AT INTERMEDIATE TEMPERATURE [1]

This standard is issued under the fixed designation X XXXX; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers the procedures for preparing, testing, and measuring asphalt mixture cracking resistance using cylindrical laboratory prepared asphalt mix samples or pavement core. Testing temperatures are selected from the Long Term Pavement Performance (LTPP) database intermediate temperatures. The test method describes the determination of the cracking tolerance index CT_{Index}, and other parameters determined from the load-displacement curve. These parameters can be used to evaluate the resistance of asphalt mixtures to cracking.

1.2 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.3 The text of this standard references notes and footnotes which provide explanatory material. These notes and footnotes (excluding those in tables and figures) shall not be considered as requirements of the standard.

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

1.5 The within-laboratory repeatability standard deviation of cracking tolerance index has been determined to be 13.5, based on 1 lab, 30 test replicates, and 10 different samples. The between-laboratory reproducibility of this test method is being determined and will be available on or before May 31, 2021. Therefore, this standard should not be used for acceptance or rejection of a material for purchasing purpose.

2. Referenced Documents

2.1 *ASTM Standards:*

D8 Terminology Relating to Materials for Roads and Pavements
D3203/D3203M Test Method for Percent Air Voids in Compacted Asphalt Mixtures
D3666 Specification for Minimum Requirements for Agencies Testing and Inspecting Road and Paving Materials
D6373 Specification for Performance Graded Asphalt Binder
D6925 Test Method for Preparation and Determination of the Relative Density of Asphalt Mix Specimens by Means of the Superpave Gyratory Compactor

2.2 *AASHTO Standards:*

R30 Practice for Mixture Conditioning of Hot Mix Asphalt (HMA)
M320 Standard Specification for Performance-Graded Asphalt Binder
M332 Standard Specification for Performance-Graded Asphalt Binder Using Multiple Stress Creep Recovery (MSCR) Test

3. Terminology

3.1 *Definitions:*

3.1.1 For definitions of terms used in this standard, refer to Terminology D8.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 CT_{Index}, *n*— cracking tolerance index, value used to evaluate mixture resistance to cracking.

3.2.2 W_f, *n* — work of failure (Joules) calculated as the area under the load-displacement curve.

3.2.3 G_f, *n* — failure energy (Joules/m^2) required to induce a unit surface area of a crack and calculated as the work of failure divided by specimen diameter (150±2 mm) and normalized thickness of 62 mm.

3.2.4 P_{85}, *n* — 85 percent of the peak load (kN) at the post-peak stage (FIGURE 21).

3.2.5 P_{75}, *n* — 75 percent of the peak load (kN) at the post-peak stage (FIGURE 21).

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[1] This test method is under the jurisdiction of ASTM Committee D04 on Road and Paving Materials and is the direct responsibility of Subcommittee D04.26 on Fundamental/Mechanistic Tests.
Current edition approved XXX. XX, XXXX. Published XX XXXX. DOI:10.1520/XXXXX-XX

3.2.6 P_{65}, *n* — 65 percent of the peak load (kN) at the post-peak stage (FIGURE 21).

3.2.7 l_{85}, *n* — displacement (mm) corresponding to the 85 percent of the peak load at the post-peak stage (FIGURE 21).

3.2.8 l_{75}, *n* — displacement (mm) corresponding to the 75 percent of the peak load at the post-peak stage (FIGURE 21).

3.2.9 l_{65}, *n* — displacement (mm) corresponding to the 65 percent of the peak load at the post-peak stage (FIGURE 21).m_{75}, *n* — slope (N/m) calculated as $\left|\frac{P_{85}-P_{65}}{l_{85}-l_{65}}\right|$ (FIGURE 21).

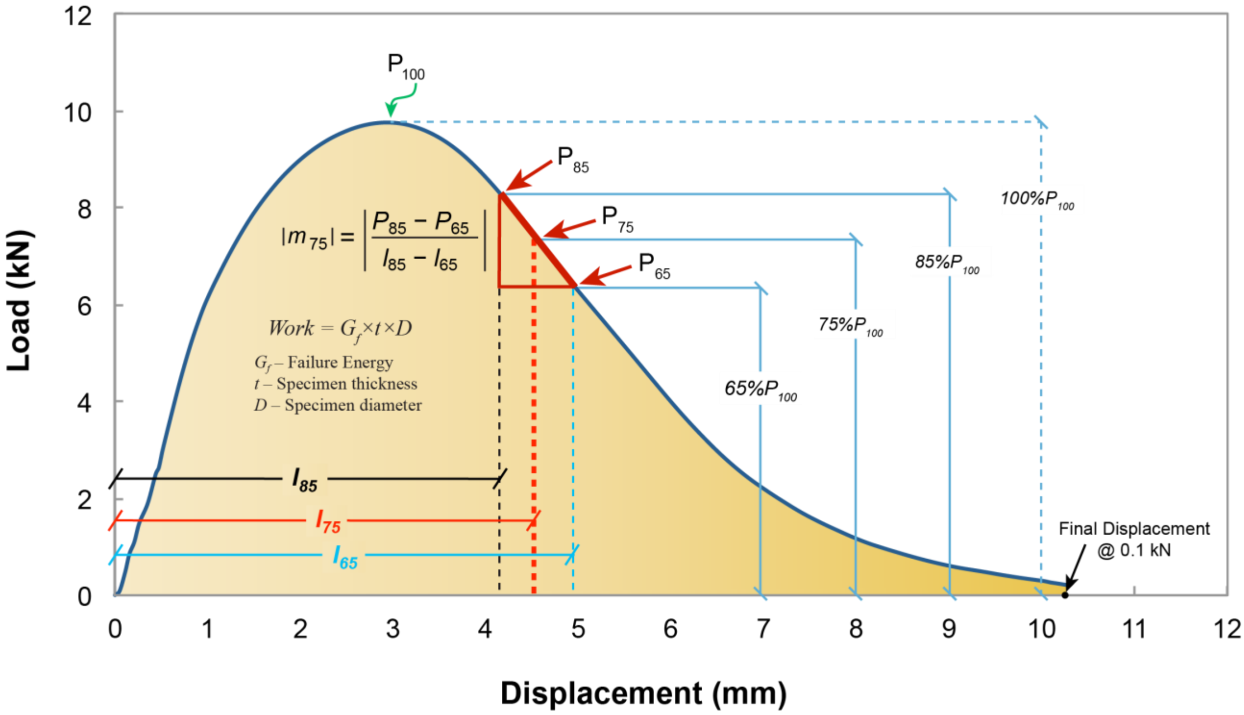

FIGURE 21 Recorded load (P) versus load-line displacement (l) curve.

4. Summary of Test Method

4.1 A cylindrical specimen is centered in the fixture. The load is applied such that a constant load-line displacement (LLD) rate of 50.0 ± 2.0 mm/min is obtained and maintained for the duration of the test. Both the load and LLD are measured during the entire duration of the test and are used to calculate the cracking tolerance index (CT_{Index}).

4.2 This test procedure considers both crack initiation and propagation in asphalt mixtures and is developed based on fracture mechanics (*16*).

5. Significance and Use

5.1 The indirect tensile cracking test is used to determine asphalt mixture cracking resistance at an intermediate temperature which could range from 5°C to 35°C, depending on local climate. The specimens are readily obtained from SGC compacted cylinders with a diameter of 150 mm, with no cutting, gluing, notching, drilling, or instrumentation required. Similarly, field cores can be tested to measure remaining cracking resistance of in-place asphalt mixtures.

5.2 The cracking tolerance index (CT_{Index}) of an asphalt mixture is calculated from the failure energy, the post peak slope of the load-displacement curve and deformation tolerance at 75 percent of the peak load. The CT_{Index} is a performance indicator of the cracking resistance of asphalt mixtures containing various asphalt binders, asphalt binder modifiers, aggregate blends, fibers, and recycled materials. Generally, the higher the CT_{Index} value, the better the cracking resistance and consequently the less the cracking amount in the field. The range for an acceptable CT_{Index} will vary with mix types and associated specific applications (*16*). Users can employ the CT_{Index} and associated criteria to identify crack-prone mixtures during mix design and production quality control/assurance.

Note 1 – The quality of the results produced by this standard are dependent on the competence of the personnel performing the procedure and the capability, calibration, and maintenance of the equipment used. Agencies that meet the criteria of Standard Practice D3666 are generally considered capable of competent and objective testing/sampling/inspection/etc. Users of this standard are cautioned that compliance with D3666 alone does not completely assure reliable results. Reliable results depend on many factors; following the suggestions of D3666 or some similar acceptable guideline provides a means of evaluating and controlling some of those factors.

6. Apparatus

6.1 *Test Apparatus* –An indirect tensile cracking test apparatus consists of an axial loading device, a load cell, loading strips, specimen deformation measurement devices, and a data acquisition system. Alternatively, the load cell, loading strips, specimen deformation measurement devices, and/or data acquisition system can be integrated into a test fixture.

6.1.1 *Axial Loading Device* –The loading apparatus shall be capable of delivering loading in compression with a capacity of at least 25 kN. It shall be capable of maintaining a constant deformation rate of 50 ± 2.0 mm/min., which may require a closed loop, feedback-controlled servo-hydraulic load frame. An electromechanical, screw-driven frame may be used if it can maintain the constant deformation rate.

6.1.2 *Load Cell* –The load cell shall have a resolution of 10 N and a capacity of at least 25 kN.

6.1.3 *Loading Strips* –Steel loading strips with a concave surface having a radius of curvature equal to the nominal radius of the test specimen. For specimens with a nominal diameter of 150 mm, the loading strips shall be 19.05 ± 0.3 mm wide. The length of the loading strips shall exceed the thickness of the specimen as in FIGURE 22. The outer edges of the loading strips shall be beveled slightly to remove sharp edges.

6.1.3.1 *Option A* –The loading strips can be part of a test fixture, similar to that shown in FIGURE 22, in which the lower loading strip is mounted on a base having two perpendicular guide rods or posts extending upward. The upper loading strip shall be clean and freely sliding on the posts. Guide sleeves in the upper segment of the test fixture shall direct the two loading strips together without appreciable binding or loose motion in the guide rods.

6.1.3.2 *Option B* –The upper and lower loading strips, as shown in FIGURE 23, are parts of axial loading device. They are permanently attached to the top loading actuator and the base plate, respectively.

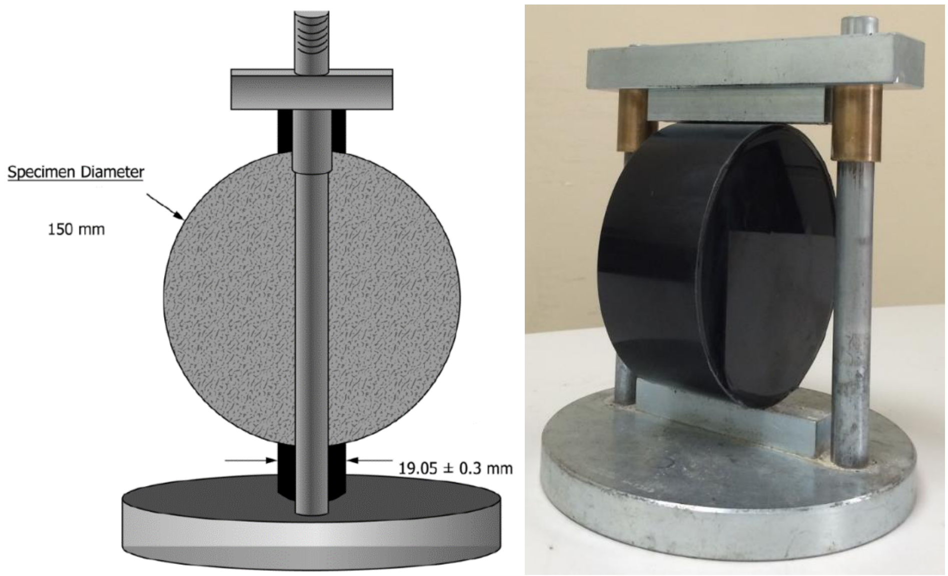

FIGURE 22 Traditional indirect tension test fixture.

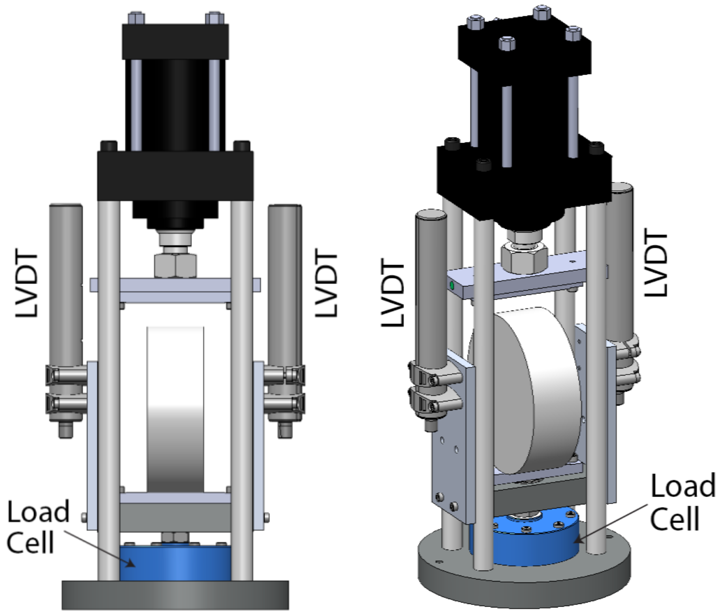

FIGURE 23 Loading strips embedded in an axial loading device.

6.1.3.3 *Option C* –The upper and lower loading strips (FIGURE 24) are part of a test fixture integrated with a load cell, loading strips, specimen deformation measurement devices, and a data acquisition system.

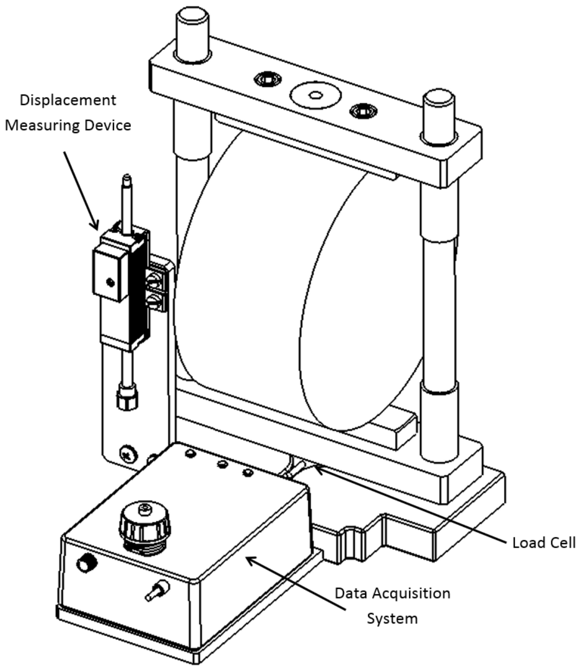

FIGURE 24 Loading strips embedded in a test fixture with load cell, displacement measurement device, and data acquisition system.

6.1.4 *Internal Displacement Measuring Device* –The displacement shall be measured to a resolution of ± 0.01 mm. The machine stroke Linear Variable Differential Transformer (LVDT) or other type of displacement transducer can be used if its resolution is sufficient to meet the requirement. The displacement data measured during the test may need to be corrected for system compliance through standardizing the test system.

6.1.5 *External Displacement Measuring Device* –If an internal displacement measuring device does not exist or has insufficient precision, one or more external displacement measuring devices such as LVDTs can be used (FIGURE 23).

6.1.6 *Data Acquisition System* –Time, load, and LLD (using either internal or external displacement measuring devices) data are collected at a minimum of 40 sampling data points per second to obtain a smooth load-LLD curve.

6.2 *Conditioning Chamber* –An environmental chamber or water bath capable of maintaining the target intermediate test temperature ± 1.0 ºC for conditioning specimens before testing.

6.3 *Gyratory Compactor* −A gyratory compactor and associated equipment for preparing laboratory specimens in accordance with Test Method D6925 are needed.

6.4 *Saw* −A laboratory saw capable of trimming field cores, if needed.

6.5 *Sample Measurement Device* −A caliper accurate to ± 0.1 mm shall be used to for measure specimen thickness and diameter.

7. Hazards

7.1 Standard laboratory caution should be exercised when handling, compacting, and fabricating test specimens and asphalt mixtures.

8. Sampling, Test Specimens, and Test Units

8.1 The indirect tensile cracking test may be conducted on laboratory-prepared test specimens or field cores.

8.2 *Laboratory Compacted Asphalt Mixture Samples*:

8.2.1 *Specimen Size* – For the mixes with a nominal maximum aggregate size (NMAS) of 19 mm or smaller, the specimens are 150 mm in diameter by 62 ±1 mm thick; for the mixes with a NMAS of 25 mm or larger, specimens are 150 mm in diameter by 95 ±1 mm thick. All specimens are prepared without cutting or trimming.

8.2.2 *Aging* – Laboratory-compacted test specimens shall be properly conditioned before the compaction.

Note 2: For laboratory-mixed and laboratory-compacted (LMLC) mixes, specimens should be short-term conditioned for 4 hours according to AASHTO R 30 for Mixture Mechanical Property Testing. For plant-mixed and laboratory-compacted mixes (PMLC), specimens may be compacted after reheating the mix to its compaction temperature. The acceptable CT_{Index} criteria are dependent on the aging method used. It may be necessary to adjust CT_{Index} criteria or establish LMLC and PMLC to account for the effect of aging. A Superpave Gyratory Compactor according to Test Method D6925 is preferred for compacting test specimens, but other types of compactors (such as Marshall hammer) are allowed as well as long as the specimens meet the requirements.

8.2.3 *Air Void Content* – Prepare a minimum of three specimens at the target air void content ± 0.5 percent.

Note 3 – The specimen air voids can be calculated using Test Methods D3203/D3203M. The typical air void target for highway pavements is 7.0 percent. Other target air voids can be used, but specimens with significantly different air voids (larger than ± 0.5 percent) are not comparable.

8.3 *Samples cored from asphalt pavements*:

8.3.1 Roadway cores can be used if pavement layer thickness is greater than 38 mm. Roadway core specimens shall be 150 ± 2 mm in diameter with all surface of the perimeter perpendicular to the surface of the core within 6 mm. Trim top and bottom surface of all cores to the same thickness with these guidelines. Roadway core test specimens shall be prepared as thick as possible, but in no case be less than 38 mm. While a thickness correction is applied in the calculation of CT_{Index}, testing specimens at a uniform thickness will reduce test error.

Note 4 – Care shall be taken to avoid damage to the cores during handling, and transportation prior to testing. A core bit of 156 mm in diameter may be needed in order to obtain cores with 150 ± 2 mm in diameter. The air voids of the core specimens should be determined if possible. Additionally, the CT_{Index} values of core specimens are relatively comparable but may not be equal to those of laboratory compacted specimens due to different aging conditions.

8.4 A minimum of three specimens shall be tested for LMLC or PMLC specimens. A minimum of three roadway core specimens shall be tested.

9. Procedure

9.1 Precondition test specimens in an environmental chamber or water bath at a target intermediate test temperature ± 1.0ºC for 2 hours ± 10 minutes.

Note 5 – The typical target intermediate test temperature is 25°C. Other target intermediate test temperatures can be used. One choice for the target intermediate test temperature is PG IT defined in Specification D6373, AASHTO M320, or M332 and provided below in Eq 1:

$$PG\ IT = \frac{PG\ HT + PG\ LT}{2} + 4 \qquad (1)$$

where:

PG IT = Intermediate performance grade temperature (ºC).

PG HG = Climatic high-performance grade temperature (ºC).

PG LT = Climatic low performance grade temperature (ºC).

Note 6 – If water bath is used, wrap up test specimens with plastic and then seal them within bags before the water bath conditioning to ensure that the test specimens are kept in a dry condition.

9.2 Inspect the fixture to ensure all contact surfaces are clean and free of debris.

9.3 Insert the specimen in the fixture, ensuring the specimen is centered and making uniform contact on the support. Generally, it is sufficient to center the specimen by eye.

9.4 Apply load to specimen in LLD control at a rate of 50 ± 2.0 mm/min. Stop the test when the load drops below 100 N. During the testing, record the time, load, and displacement at a minimum sampling rate: 40 data points per second.

9.5 Testing shall be completed in 4 minutes or less after removal from the environmental chamber to maintain a uniform specimen temperature.

10. Calculation or Interpretation of Results

10.1 The work of failure (W_f) is calculated as the area under the load vs. LLD curve (FIGURE 21) through the quadrangle rule provided in Eq 2:

$$W_f = \sum_{i=1}^{n-1}\left((l_{i+1} - l_i) \times P_i + \frac{1}{2} \times (l_{i+1} - l_i) \times (P_{i+1} - P_i)\right) \quad (2)$$

where:

P_i = applied load (kN) at the i load step application.

P_{i+1} = applied load (kN) at the $i+1$ load step application.

l_i = LLD (mm) at the i step.

l_{i+1} = LLD (mm) at the $i+1$ step.

10.2 Failure energy (G_f) is calculated by dividing the work of failure (the area under the load versus the average LLD curve; see FIGURE 21) by the cross-sectional area of the specimen (the product of the diameter and thickness of the specimen):

$$G_f = \frac{W_f}{D \times t} \times 10^6 \quad (3)$$

where:

G_f = failure energy (Joules/m^2)

W_f = work of failure (Joules)

D = specimen diameter (mm)

t = specimen thickness (mm)

10.3 Post-peak slope (m_{75}) is the slope of tangential zone around the 75 percent peak load point (P_{75}) after the peak (FIGURE 21).

10.4 Deformation tolerance (l_{75}) is the displacement at 75 percent peak load (P_{75}) after the peak (FIGURE 21).

10.5 Cracking tolerance index (CT_{Index}) is calculated from the parameters obtained using the load-displacement curve, as listed below:

$$CT_{Index} = \frac{t}{62} \times \frac{l_{75}}{D} \times \frac{G_f}{|m_{75}|} \times 10^6 \quad (4)$$

where:

CT_{Index} = cracking tolerance index

G_f = failure energy (Joules/m^2)

$|m_{75}|$ = absolute value of the post-peak slope m_{75} (N/m)

l_{75} = displacement at 75 percent the peak load after the peak (mm)

D = specimen diameter (mm)

t = specimen thickness (mm)

Note 7 – $\frac{t}{62}$ is a correction factor for specimen thickness. 10^6 is a scale factor in Eq. 4.

11. Report

11.1 The report shall include the following parameters for each test specimen:

11.1.1 Asphalt mixture type.

11.1.2 Test temperature, ºC.

11.1.3 Specimen preparation method and aging condition.

11.1.4 Specimen air voids, %.

11.1.5 Specimen thickness, mm.

11.1.6 Specimen diameter, mm.

11.1.7 Deformation tolerance (l_{75}), mm.

11.1.8 Post-peak slope m_{75}, N/m.

11.1.9 Failure energy G_f, Joules/m^2.

11.1.10 Work of failure, W_f, Joules.

11.1.11 Cracking tolerance index, CT_{Index}.

12. Precision and Bias

12.1 The within-laboratory repeatability standard deviation of the cracking tolerance index (CT_{Index}) has been determined to be 13.5, based on 1 lab, 30 test replicates, and 10 different samples. The between-laboratory reproducibility of this test method is being determined and will be available on or before May 31, 2021. Therefore, this standard should not be used for acceptance or rejection of a material for purchasing purpose.

Note 8 –The CT_{Index} mean ranged from 31 to 255 for the 10 different materials used to develop this preliminary within laboratory precision statement and the specimens were molded with a Superpave Gyratory Compactor and were tested with the fixture shown in FIGURE 23.

12.2 Bias – No information can be presented on the bias of the procedure in this Test Method for measuring the cracking tolerance index because no material having an accepted reference value is available

13. KEYWORDS

13.1 failure energy; work of failure; asphalt mixture cracking resistance; indirect tensile cracking test; cracking tolerance index

APPENDIX B: RESEARCH RESULTS

WHAT WAS THE NEED?

Asphalt pavement cracking is a nationwide problem faced by every highway agency. As asphalt mix designs become more complex with the use of recycled materials, rejuvenators, and asphalt binders with various additives, pavement engineers and asphalt industry urgently need a simple, repeatable, and reliable cracking test for mix design, QC, and QA. Many cracking tests have been developed in the past, but most of them are not simple, repeatable, and reliable enough for being used in part of mix design and QC/QA.

WHAT WAS OUR GOAL?

The goal of this research project is to develop a simple, repeatable, practical, reliable, and cracking performance-related test with low cost test equipment so that it can be used for mix design and QC/QA.

WHAT DID WE DO?

This research project developed an IDEAL Cracking Test (IDEAL-CT), as shown in FIGURE 25. The IDEAL-CT is typically run with cylindrical specimens at the room temperature and a loading rate of 50 mm/min. using the indirect tensile loading frame. Different from other cracking tests, the IDEAL-CT integrates all seven desirable features listed below:

1. Simplicity: no instrumentation, cutting, gluing, drilling, or notching.
2. Practicality: minimum training needed for routine operation.
3. Efficiency: test completion within 1 min.
4. Test equipment: existing or low cost equipment (< $10,000).
5. Repeatability: COV less than 25 percent.
6. Sensitivity: sensitive to asphalt mix characteristics.
7. Good correlation with field cracking performance: validated with many field test sections.

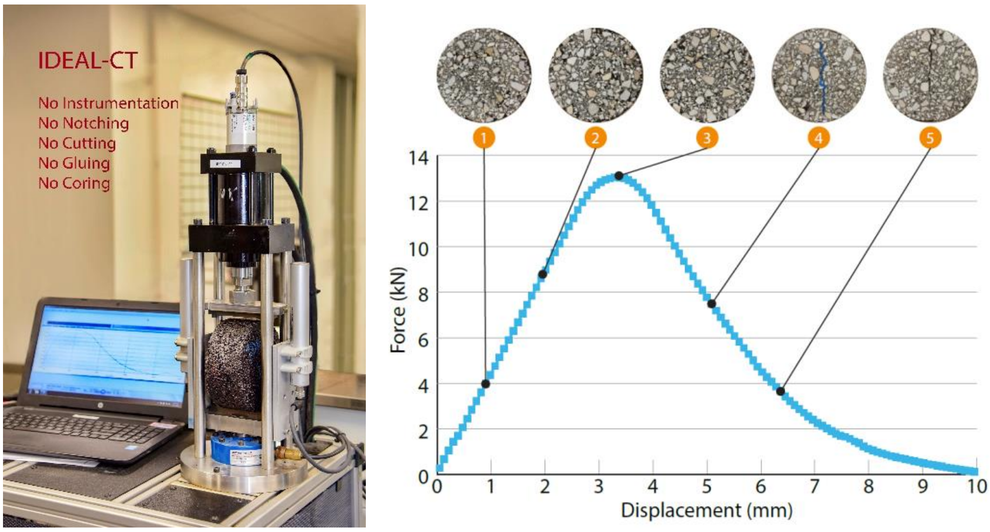

FIGURE 25 IDEAL-CT setup and a typical test result.

The IDEAL-CT determines cracking resistance of asphalt mixes through a fracture mechanics–based parameter: CT_{Index}. The larger the CT_{Index}, the better the cracking resistance. The IDEAL-CT and CT_{Index} are sensitive to RAP and RAS, asphalt binder type and binder content, and aging conditions. Three replicates of IDEAL-CT specimens are enough to achieve a 20 percent or less the COV. Furthermore, the IDEAL-CT compares well with several established laboratory cracking tests including Texas OT and I-FIT. Most importantly, the IDEAL-CT has very good correlation with field cracking performance data collected from accelerated loading facility at the FHWA, LTPP-SPS10 warm mix test sections in Oklahoma, and many in-service pavements in Texas, as shown in FIGURE 26. The good correlation with field cracking performance was further confirmed by the cracking sections constructed at the test track of the National Center for Asphalt Technology, as reported by Mr. Adam Taylor (*1*) at the 2018 NCAT test track conference.

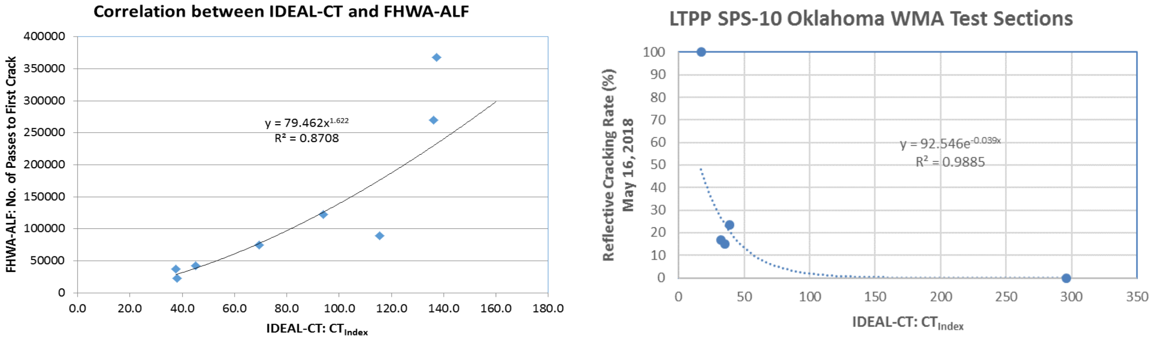

FIGURE 26 Good correlation between IDEAL-CT (CT_{Index}) and field cracking performance.

WHAT WAS THE OUTCOME?

The outcome of this research project includes an ASTM test standard for the IDEAL-CT, standalone test machines, data processing software, and accessories for running the IDEAL-CT, and a step-by-step implementation plan for implementing the IDEAL-CT in highway agencies.

WHAT IS THE BENEFIT?

Every year, around 360 million tons of asphalt mixes are designed, produced, and placed in the United States, and the associated cost is more than $20 billion with the assumption of $60/ton of asphalt mix. Given this incredibly large amount of taxpayers' money and the well-established unsatisfactory cracking performance, implementing the IDEAL-CT ensures durable asphalt mixes lasting 20 percent longer than existing mixes through directly evaluating and verifying cracking resistance of asphalt mixes. The estimated saving will be significant. It will also reduce the maintenance cost, associated traffic delays, and the travel time of every road user.

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