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EVALUATION OF SEMI-CIRCULAR BEND TEST FOR HMA SPECIALTY MIXES

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Submitted by

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16. Abstract

The Semi-Circular Bend (SCB) testing configuration was evaluated to determine its applicability to NJDOT Specialty Asphalt Mixtures. The SCB Flexibility Index utilizes a three-point loading arrangement to measure the fatigue cracking resistance of a semi-circular compacted asphalt specimen. A pre-cut notch in the specimen dictates where the crack initiates. The area under the load-displacement curve, known as fracture energy (G_f), and the post-peak slope of the load-displacement curve are used to calculate the SCB Flexibility Index (FI) value. In general, as the SCB FI value increases, the fatigue resistance of the asphalt mixture also increases.

The study showed that the SCB FI test is highly influenced by the test temperature, loading rate, notch width and compacted air voids. The sensitivity to air voids was found to be counter-intuitive, such as when the air voids increase, the SCB FI value also increases. It is hypothesized that this is simply due to the additional air voids/air pockets increasing the "flexibility" of the asphalt mixture, thereby reducing the mixture stiffness. A large database was generated consisting of companion specimens tested in the Overlay Tester and the SCB FI tests. The database resulted in a strong correlation between the Overlay Tester and SCB FI, which in turn was used to develop tentative performance criteria for future adoption by the NJDOT. A round robin study was conducted to evaluate the expected repeatability of the SCB FI value. Five different laboratories were provided compacted gyratory specimens comprising of three different asphalt mixtures. The single operator coefficient of variation (COV%) was determined to be 21.5%, with the multiple operator COV% being 26.1%.

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EXECUTIVE SUMMARY

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The study showed that the SCB FI test is highly influenced by the test temperature, loading rate, notch width and compacted air voids. The sensitivity to air voids was found to be counter-intuitive, such as when the air voids increase, the SCB FI value also increases. It is hypothesized that this is simply due to the additional air voids/air pockets increasing the "flexibility" of the asphalt mixture, thereby reducing the mixture stiffness. A large database was generated consisting of companion specimens tested in the Overlay Tester and the SCB FI tests. The database resulted in a strong correlation between the Overlay Tester and SCB FI, which in turn was used to develop tentative performance criteria for future adoption by the NJDOT. A statistical analysis of asphalt mixture parameters found that the SCB FI value is correlated to the Intermediate PG grade, Low Temperature PG grade as predicted by the m-value, asphalt content (total by mass and effective by volume), and elastic response of the asphalt binder as determined in the Multiple Stress Creep Recovery (MSCR) test. A round robin study was conducted to evaluate the expected repeatability of the SCB FI value. Five different laboratories were provided compacted gyratory specimens comprising of three different asphalt mixtures. Each laboratory was required to cut, notch and test the specimens in accordance with AASHTO TP124. All testing was conducted within 72 hours of cutting/notching and within 1 month after received the compacted and sealed test specimens. The single operator coefficient of variation (COV%) was determined to be 21.5%, with the multiple operator COV% being 26.1%.

INTRODUCTION

Currently, the New Jersey Department of Transportation (NJDOT) utilizes performance tests for their "Specialty Mixes" to ensure that rutting and fatigue cracking resistance of the different mixtures meet the NJDOT's requirements. These mixtures include:

1. High Performance Thin Overlay (HPTO);
2. Binder Rich Intermediate Course (BRIC);
3. High Recycled Asphalt Pavement mixtures (HRAP);
4. Bridge Deck Water Proof Wearing Course (BDWSC); and
5. Bottom Rich Base Course (BRBC).

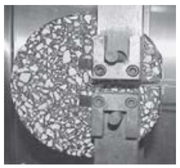
All of the mixtures utilize the Asphalt Pavement Analyzer (AASHTO T340) to ensure the mixture is rut resistant, while either the Overlay Tester (NJDOT B-10) or the Flexural Beam Fatigue (AASHTO T321) are used to evaluate the fatigue cracking resistance of the asphalt mixture. Although the NJDOT has fully embraced the Performance Related Specifications (PRS), the asphalt industry has some reservations. One of their biggest issues regarding PRS is that the test equipment used is costly, restricting them from purchasing their own equipment. Therefore, if an asphalt plant is interested in evaluating their mixtures during the design phase, they often must hire a consultant/research laboratory to conduct the work. However, if the asphalt industry had a means of evaluating the rutting and fatigue cracking performance of their mixtures, using existing or much cheaper equipment, the asphalt industry can ensure the performance of their Specialty Mixtures prior to NJDOT submittal, as well as evaluating the performance of their own asphalt mixtures when interested in utilizing newer technologies and recycled materials.

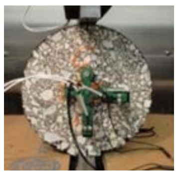
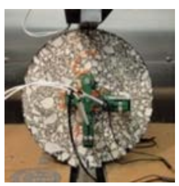
To help address this need, the NJDOT proposed this research study, *Evaluation of Semi-Circular Bend (SCB) Test for HMA Specialty Mixes (BRIC, High-RAP, and HPTO)*. The purpose of this project was to research and evaluate the different variations (temperature, notch dimensions, load rates, etc.) of the Semi-Circular Bend (SCB) tests that are being run by different states. This project was also aimed to develop a method of comparison of the fatigue performance results between the SCB and the Overlay Tester to help provide the industry with an alternate means of fatigue cracking evaluation that correlates to the NJDOT's Overlay Tester procedure.

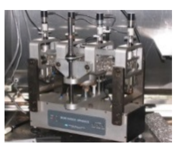
LITERATURE REVIEW

A number of fatigue cracking tests are currently being evaluated by a various researchers around the world. The researchers of NCHRP Project 9-57 have summarized the most commonly used asphalt mixture fatigue cracking tests, shown in Table 1. Table 1 was updated to include the SCB Flexibility Index (FI), which was not originally part of the NCHRP 9-57 study. As the table indicates, there are currently three existing test methods using the semi-circular

Table 1 – Current Asphalt Mixture Fatigue Cracking Tests (Adapted from Zhou et al., 2016)

Laboratory test						Correlation to field performance	Test variability	Test simplicity (or complexity)	Test sensitivity to mix design parameters[a]	Equipment cost and availability	Adoption by states
Test name	**Cracking type**	**Test standard**	**Test configuration**	**Specimen geometry**	**Cracking parameter**						
DCT	Low-temperature cracking and reflection cracking	ASTM D7313 (Monotonic test)		D = 6 in. T = 2 in. 2 holes D = 1 in. ND = 2.46 in.	Fracture energy	Good correlation with low-temperature cracking validated at MnROAD.	Low (COV=10-15%)	Training: little time Specimen prep: 4 cuts and 2 holes Instrumentation: gluing 2 studs Testing[2]: 1–6 min. Analysis: area integration Interpretation: quick and easy (pass/fail criteria).	Asphalt binder, aggregate, RAP/RAS, and aging; insensitive to AV[3] and P_b[3]	Commercially available; Cost: $49,000.	Adopted by Minnesota; being considered by Colorado, South Dakota, and Montana.
SCB	Low-temperature cracking	AASHTO TP105 (Monotonic test)		D = 6 in. T = 1 in. ND = 0.6 in.	Fracture energy	Good correlation with low-temperature cracking validated at MnROAD.	Medium (COV=20 %)	Training: medium time Specimen prep: 3 cuts Instrumentation: gluing 3 studs Testing: 30 min. Analysis: area integration Interpretation: quick and easy (pass/fail criteria).	Asphalt binder, aggregate, RAP/RAS, AV and P_a	Commercially available; Cost: $52,000	Being considered by Utah, South Dakota, Pennsylvania, and Montana.
	Bottom-up and top-down fatigue cracking	Illinois Flexibility Index (FI)		D = 6 in. T = 2 in. ND = 0.6 in.	Flexibility Index (FI)	Good correlation with PANYNJ Airfields & Illinois Pavements	Medium (COV=20 %)	Training: medium time Specimen prep: 3 cuts Instrumentation: gluing 3 studs Testing: 30 min. Analysis: area integration Interpretation: quick and easy (pass/fail criteria).	Asphalt binder, aggregate, RAP/RAS, AV and P_a	Commercially available; Cost: $15,000	Adopted by Illinois; being considered by Wisconsin & Minnesota
	Bottom-up and top-down fatigue cracking	LTRC (Monotonic test)		D = 6 in. T = 2.25 in. ND = 1, 1.25 and 1.5 in.	Energy release rate	Fair correlation to field cracking from the Louisiana Pavement	Medium (COV=20 %)	Training: very little time Specimen prep: 4 cuts Instrumentation: none Testing: 5–10 min. Analysis: area integration and regression	Asphalt binder, aggregate, RAP/RAS	Commercially available; Cost: $20,000	Adopted by Louisiana; being considered by

Laboratory test						Correlation to field performance	Test variability	Test simplicity (or complexity)	Test sensitivity to mix design parameters [a]	Equipment cost and availability	Adoption by states
Test name	**Cracking type**	**Test standard**	**Test configuration**	**Specimen geometry**	**Cracking parameter**						
						Management System.		Interpretation: quick and easy (pass/fail criteria).			Oklahoma and New Mexico.
IDT	Low-temperature cracking	AASHTO T322: D_t and tensile strength test (monotonic tests)		D = 6 in. T = 1.5-2.0 in.	Creep compliance and tensile strength	Creep compliance and tensile strength inputs to TCMODEL. Calibrated and validated through original SHRP-I and MEPDG.	Low (COV<11 %)	Training: medium time Specimen prep: 2 cuts Instrumentation: relatively easy Testing: 1–2 hours Analysis: short and easy with data analysis software Interpretation: longer time with cracking model to predict performance.	Asphalt binder, aggregate, RAP/RAS, aging	Hydraulic test machines can be used. With test machine, more than $100,000.	AASHTO T322 is required by AASHTOWare.
	Top-down cracking	University of Florida: M_r test, D_t test, and tensile strength test (cyclic and monotonic tests)		D = 6 in. T = 1.5–2.0 in.	Energy ratio	Validated with field cores in Florida study and confirmed at National Center for Asphalt Technology (NCAT) test track.	Possibly low, similar to AASHTO T322.	Training: medium time Specimen prep: 2 cuts Instrumentation: relatively easy with gauge point template Testing: 1–2 hours Analysis: easy with data analysis software Interpretation: short and easy (pass/fail criteria).	Insensitive to change in binder viscosity (Roque et al. 2010)		Being adopted by Florida.
TSRST /UTSST	Low-temperature cracking	(Monotonic test)		L = 10 in. W = 2 in. T = 2 in.	Fracture temperature	Validated with test sections during SHRP program. MnROAD test results showed moderate correlation	Low (COV = around 10%)	Training: long time and intensive Specimen prep: difficult and long Instrumentation: easy and short Testing: 3–5 hours Analysis: easy and short	Asphalt binder, aggregate, AV, P_b, and aging	Commercially available; Cost: $98,000	Being considered by Nevada.

Laboratory test						Correlation to field performance	Test variability	Test simplicity (or complexity)	Test sensitivity to mix design parameters [a]	Equipment cost and availability	Adoption by states
Test name	Cracking type	Test standard	Test configuration	Specimen geometry	Cracking parameter						
						with field performance.		Interpretation: quick and easy (pass/fail criteria).			
Texas Overlay Test (OT)	Reflection cracking and bottom-up fatigue cracking	Tex-248-F (cyclic tests)		L= 6 in. W = 3 in. T = 1.5 in.	No. of cycles (or fracture parameters: A and n)	Good correlation with reflection cracking validated in Texas, California, and New Jersey; promising correlation with fatigue cracking validated with FHWA-ALF and NCAT test track.	Relatively high (COV=30–50%)	Training: little time Specimen prep: 4 cuts Instrumentation: none Testing: 1 min–3 hr Analysis: easy and short Interpretation: quick and easy (pass/fail criteria).	Binder, aggregate, P_b, RAP/RAS, aging, etc.	Commercially available; Cost: $46,000	Adopted by Texas and New Jersey; being considered by Montana, Nevada, Florida, and Ohio.
Bend Beam Fatigue (BBF) Test	Bottom-up fatigue cracking	AASHTO T321 (cyclic tests)		L = 15 in. W = 2.5 in. T = 2 in.	No. of cycles (or fatigue equation)	Correlation with bottom-up fatigue cracking historically validated.	Very high (COV>50%)	Training: medium time Specimen prep: difficult and long Instrumentation: almost none Specimen testing: hours to days Data analysis: easy and quick Date Interpretation: quick and easy (or combine with pavement analysis program to predict pavement fatigue life.)	Binder, aggregate, P_b, RAP/RAS, aging, etc.	Frame (fixture) commercially available. Universal testing machine needed; could be > $100,000.	California—special pavement design; being considered by Nevada and Georgia.

Laboratory test						Correlation to field performance	Test variability	Test simplicity (or complexity)	Test sensitivity to mix design parameters [a]	Equipment cost and availability	Adoption by states
Test name	Cracking type	Test standard	Test configuration	Specimen geometry	Cracking parameter						
S-VECD	Bottom-up and top-down fatigue cracking	AASHTO TP107 (cyclic tests) (AASHTO TP79 E* test for data analysis)		S-VECD: D = 4 in. L = 5.1 in. (E*: D = 4 in. L = 6 in.)	Fatigue equation and damage parameters (or predicted no. of cycles)	S-VECD used with MEPDG or more advanced models (LVECD and VECD-FEP++) to simulate pavement performance. Validated with FHWA-ALF test lanes and verified in North Carolina.	Not defined	Training: very long time Specimen prep: 2 cuts and 1 coring Instrumentation: easy with a special glue jig Testing: hours to 1 day (3 more days if E* test is considered) Analysis: easy if using ALPHA-fatigue software Interpretation: quick and easy if only number of cycles is concerned (or combine with pavement analysis programs [LVECD and VECD-FEP++] to predict pavement fatigue life).	Not available	Commercially available; Cost: $97,000	Being considered by Oklahoma, Georgia, and Pennsylvania.
Direct tension (DT)	Bottom-up and top-down fatigue cracking	Texas A&M University (cyclic tests)		D = 4 in. L = 6 in.	Paris' law parameters (or No. of cycles)	Correlations with bottom-up and top-down fatigue cracking being developed under several research projects. Model and methods being validated with LTPP data.	Not defined	Training: very long time Specimen prep: 2 cuts and 1 coring Instrumentation: medium time and difficulty Testing: 1–2 hours Analysis: need special software Interpretation: still under development.	Model coefficients functions of AV, P_b, gradation; modulus, aging, etc.	Universal test machine needed for direct tension test; >$100,000.	Unknown

Note: D = diameter; L = length; W = width; T = thickness; ND = notch depth; AV = Air voids; P_b = Percent asphalt binder.

[a] Testing refers to the time for running the test only

bend configuration: 1) Low Temperature Cracking (AASHTO TP105); 2) Illinois Flexibility Index (FI); and 3) Louisiana Transportation Research Consortium (LTRC). Since the AASHTO TP105 is primarily used for low temperature cracking evaluation, the two SCB test procedures recommended for intermediate fatigue cracking performance is the Illinois SCB Flexibility Index and LTRC SCB Critical Strain Energy Release Rate (J_C), both of which pertained to this specific research project. Meanwhile, also shown in Table 1 is the Overlay Tester. These test methods will be discussed in further detail in the upcoming sections.

Louisiana Transportation Research Center (LTRC) SCB Fracture Release Energy

The LTRC-SCB test is similar to the SCB for low temperature (AASHTO TP105), but there are five main differences; 1) Test temperature is recommended to be 25^{o}C; 2) SCB test specimen thickness is 2.5 inches; 3) three different notch depths are required (1.0, 1.25, and 1.5 inches); 4) loading rate is 0.5 mm/min.; and 5) fracture property measured is critical strain energy release rate (J_C). Figure 1 shows the LTRC-SCB set-up and typical test results.

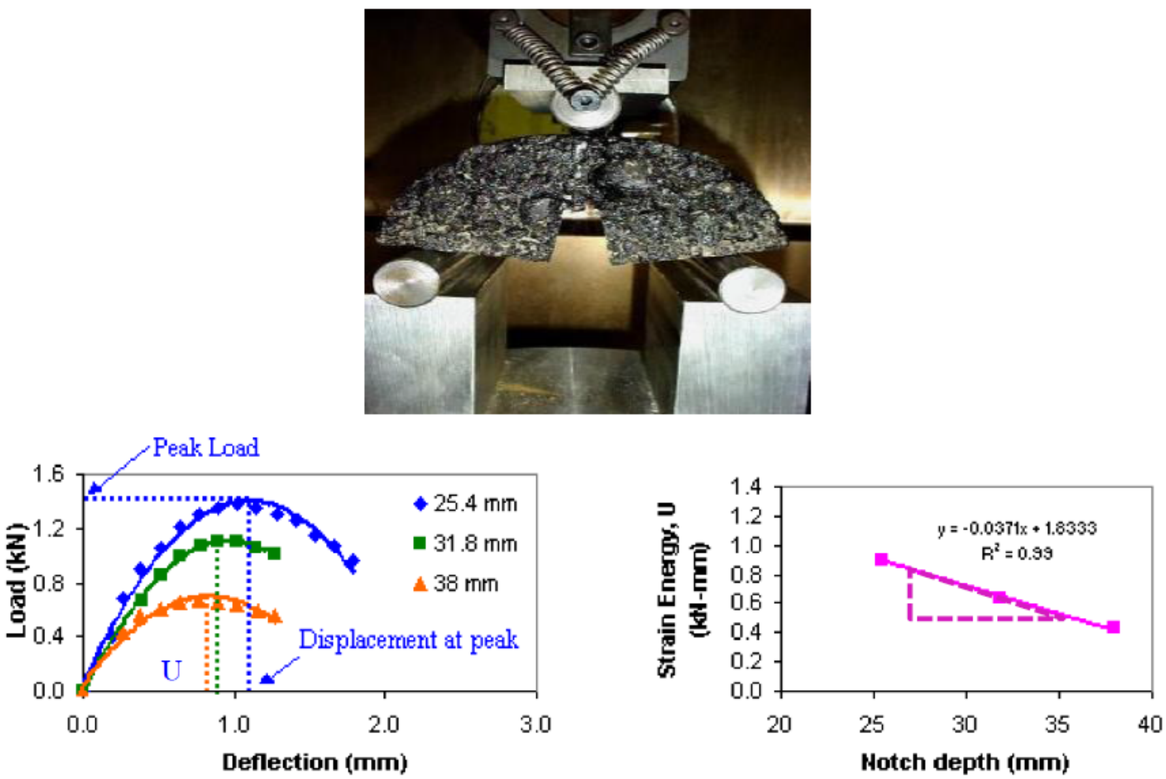


Figure 1 – LTRC-SCB Critical Strain Energy Release Rate

The critical strain energy release rate (J_C) is the absolute value of the ratio of the slope of the fracture energies vs the notch depths to specimen thickness ratio. Higher J_C values are desirable for better fracture-resistant mixtures. A threshold value of a minimum of 0.65 kJ/m^2 has been suggested as a failure criterion (Elseifi et al., 2012) for fatigue cracking resistant asphalt mixtures. Research conducted by Kim et. al (2012) reported that the LTRC SCB JC showed a fair correlation with field cracking in Louisiana (Figure 2).

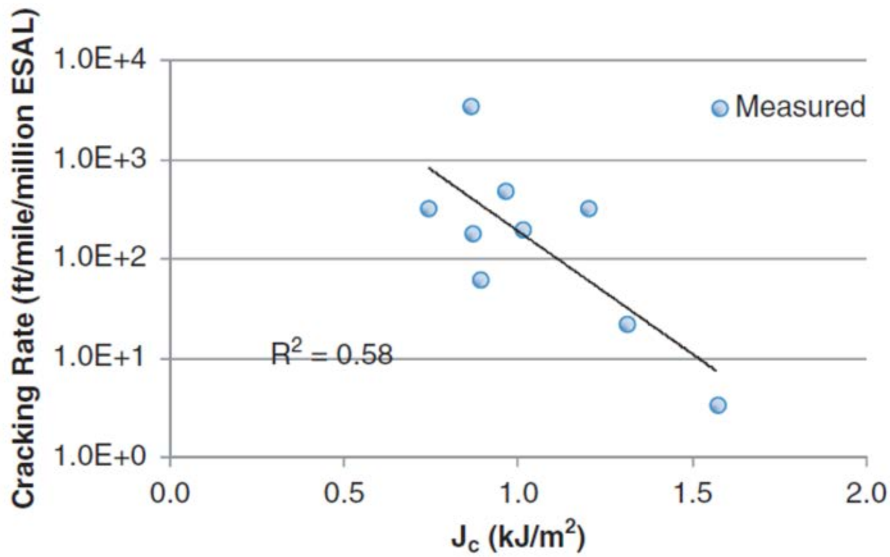


Figure 2 – Correlation Between LTRC SCB JC and Field Cracking Data (After Kim et al., 2012)

Bennert, T., C. Ericson, D. Pezeshki, E. Haas, R. Shamborovskyy, and R. Corun (2016), "Laboratory Performance of Re-refined Engine Oil Bottoms (REOB) Modified Asphalt" ***Journal of the Association of Asphalt Paving Technologists (AAPT)*****, Vol/ 85, p. 163 – 207.**

Bennert et al., (2016) conducted a research effort to evaluate the laboratory performance of asphalt binders and mixtures modified with REOB. Two different sources of REOB were blended with different base asphalt grades at varying dosage rates in the study to achieve "softer" asphalt binders – similar to the current practice of REOB modification in the asphalt industry. Performance grading, master stiffness curves, double-edged notch tension test, and Black Space analysis were conducted on the asphalt binders at different levels of laboratory aging. Additionally, the asphalt binders were used to produce asphalt mixtures for stiffness, permanent deformation, fatigue cracking and low temperature cracking performance.

The research study showed that the LTRC SCB method did not rank asphalt mixture fatigue performance as would be expected. In particular, asphalt mixtures that showed to have stiffer, more oxidized asphalt binders, performed well in the LTRC SCB test method when they were expected to be highly brittle. Figures 3 and 4 show LTRC SCB comparisons to two different asphalt binder parameters: 1) Glover-Rowe and 2) Master Curve Crossover Frequency. Both asphalt binder parameters are known to have a good relationship regarding durable asphalt binders. In both figures, the lack of a relationship between the LTRC SCB and the asphalt binder parameters raises concerns as to whether or not the test method favours highly oxidized/stiffened asphalt binders.

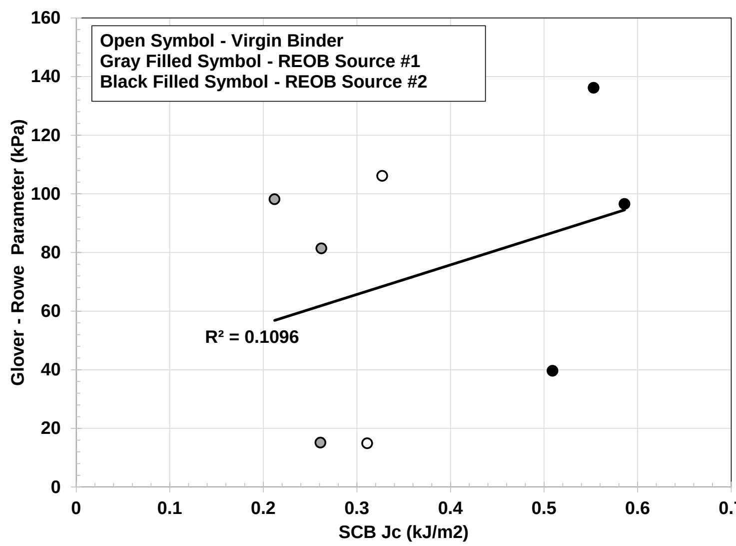


Figure 3 – LTRC SCB Jc Parameter Compared to Asphalt Binder Glover-Rowe Parameter

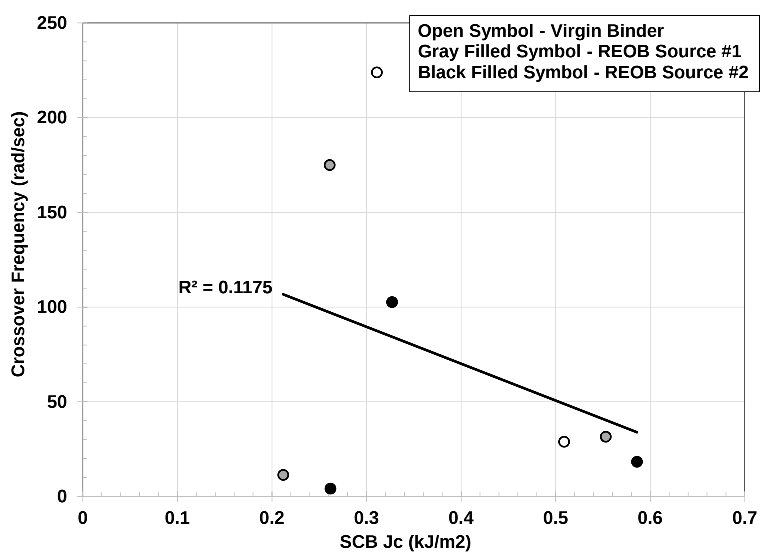


Figure 4 – LTRC SCB Jc Parameter Compared to Asphalt Binder Crossover Frequency

The researchers were also able to evaluate how the different asphalt mixture performance tests compared to one another. Figure 5 shows the comparison between the SCB LTRC Jc parameter and the Overlay Tester. The test results show that for both the Short Term Oven Aged (STOA) and Long Term Oven Aged (LTOA) no correlation was found between the two test methods.

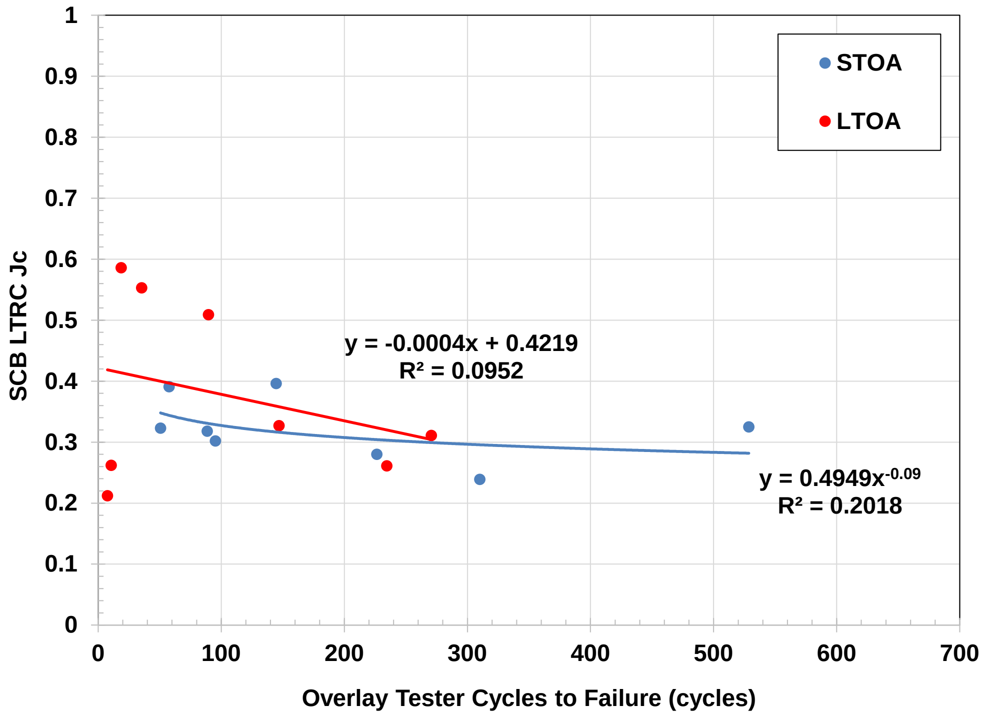


Figure 5 – Comparison of SCB LTRC Jc Parameter and Overlay Tester Results for REOB Mixtures (After Bennert et al., 2016)

Bonaquist, R. (2016), *Critical Factors Affecting Asphalt Concrete Durability,* WisDOT Report No. 0092-14-06, Wisconsin Department of Transportation, 128 pp.

In a research study conducted for the Wisconsin Highway Research Program (WHRP), Bonaquist (2016) evaluated how to improve the durability of Wisconsin asphalt mixtures. In the study, Bonaquist (2016) originally intended to evaluate the LTRC SCB test method and develop correlations between critical asphalt mixture properties and the critical strain energy release rate (Jc). According to Bonaquist (2016):

> "There was no apparent relationships between the critical strain energy release rate and any of the recovered binder properties."

Figure 6 was taken from the report as an example of the lack of relationship between the mixture cracking parameter (Jc) and the intermediate temperature continuous grade temperature. Bonaquist (2016) also found that the Jc parameter was less sensitive to asphalt mixture aging than the SCB Flexibility Index. This verifies some of the findings discussed earlier by Bennert et al., (2016).

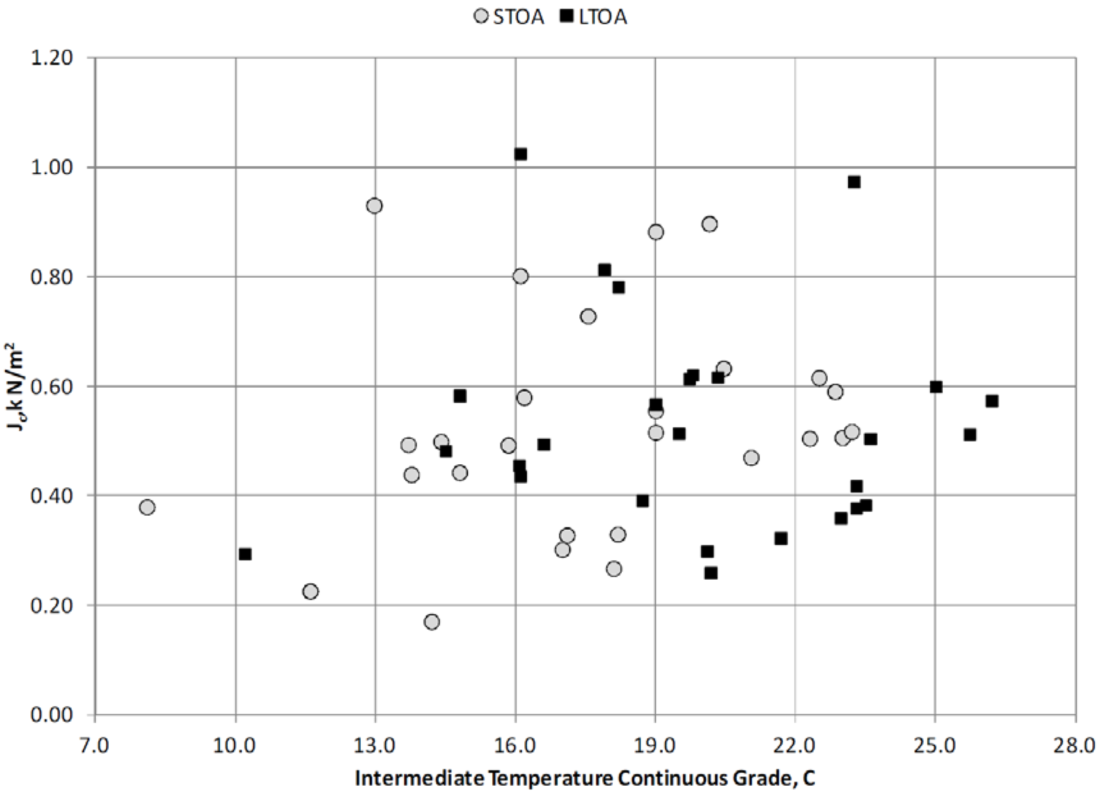


Figure 6 - Relationship Between SCB Critical Strain Energy Release Rate and Continuous Intermediate Temperature Grade of the Binder in SCB Specimens (After Bonaquist, 2016)

Mandal, T., C. Ling, P. Chaturabong, and H. Bahia, (2017), "Effects of Mixture Design Factors on Results of Semi Circular Bend (SCB LSU) Test", ***Presented at the 96th Annual Meeting of the Transportation Research Board*****, Washington, D.C., January 8-12, 2017.**

The research study focused on evaluating the possible use of the SCB LTRC test method to measure the effect of various important mix design parameters on asphalt mixtures' fracture properties, including peak load, peak displacement, fracture energy, and Jc (critical strain energy release rate). The results show inconsistent trends for most mixtures and no clear relationship was observed between the responses from the

SCB LTRC test (Jc parameter) and the mixture design factors (i.e. – binder modification, PG grade properties, aging). In fact, the researchers conclude that their work could not show any logical trend in Jc to differentiate between the asphalt mixtures.

Xie, Z., N. Tram, G. Julian, A. Taylor, and L.D. Blackburn (2017), "Performance of Asphalt Mixtures with High Recycled Contents Using Rejuvenators and Warm Mix Additives: Field and Laboratory Experiments", ***Presented at the 96th Annual Meeting of the Transportation Research Board*****, Washington, D.C., January 8-12, 2017.**

The study evaluated the effect of two rejuvenators on the mechanistic and performance properties of recycled binders and mixtures with 25% RAP plus 5% RAS through laboratory testing and field evaluation. A control mixture was also included in the study that only contained 20% RAP, far less recycled asphalt binder content than the experimental mixtures. According to the SCB LTRC results, the experimental mixtures with the high recycled contents had slightly higher critical strain energy release rate (Jc) than the control mixture, which would indicate the high recycled mixes should perform better against intermediate temperature fatigue cracking. Meanwhile, based on the Overlay Tester and SCB Flexibility Index, the control mixture had significantly better resistance to cracking than both the experimental mixtures. This research again appears to indicate that the SCB LTRC method is not sensitive enough to asphalt aging and asphalt binder brittleness.

Bennert, T., C. Ericson, E. Haas, and E. Wass Jr., 2017, "Asphalt Mixture and Binder Performance at the FHWA ALF", In Preparation for Submittal to the 2018 Meeting of the Transportation Research Board.

The researchers utilized the recent testing cycle at the FHWA to evaluate the asphalt binder and mixture performance tests and compare those results to the observed fatigue cracking on the different testing lanes. The ALF testing lanes consisted of 10 different asphalt mixtures containing varying amounts of recycled asphalt from RAP and RAS, as well as some of the lanes utilizing warm mix asphalt technologies. Table 2 shows a description of each of the ALF testing lanes and the respective asphalt mixture.

Table 2 – Test Lanes and Respective Asphalt Mixtures at the FHWA ALF

ALF Lane	% RBR		Virgin Binder PG	WMA Process
	RAP	RAS		
1	0	-	64-22	-
2	40	-	58-28	Water
3	-	20	64-22	-
4	20	-	64-22	Chemical
5	40	-	64-22	-
6	20	-	64-22	-
7	-	20	58-28	-
8	40	-	58-28	-
9	20	-	64-22	Water
11	40	-	58-28	Chemical

The FHWA ALF looked at two different distress indexes to measure the observed fatigue cracking: 1) Number of Loading Cycles Until 1st Crack Observed; and 2) Cracking Rate. The researchers utilized the bottom portion of the field cores for the asphalt binder and mixture characterization to help eliminate any differential aging that may have occurred in the field core. Therefore, the asphalt binder and mixture specimens represented a condition as close to the asphalt material as it was originally placed in the field.

Figure 7 shows the SCB LTRC Jc parameter compared to the Number of Loading Cycles Until 1st Crack for the different ALF lanes. As the figure shows, a poor to average relationship was found.

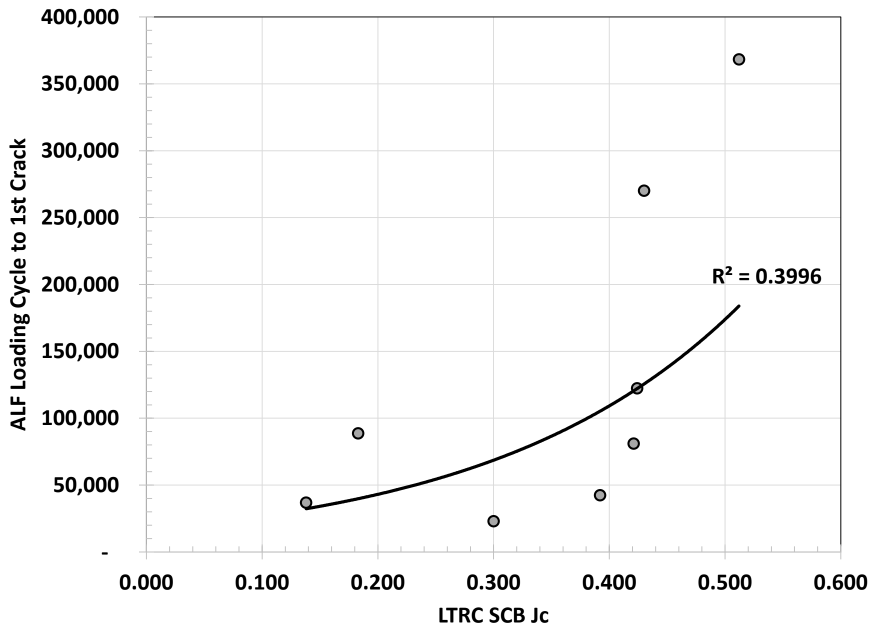


Figure 7 – SCB LTRC Jc Parameter vs ALF Loading Cycles Until 1st Crack

Figure 8 shows the SCB LTRC Jc parameter compared to the cracking rate of the different lanes at the ALF. The results show a slightly better relationship between the ALF cracking rate than the Number of Cycles to 1st Crack. However, the final correlation was still found to be moderate at best.

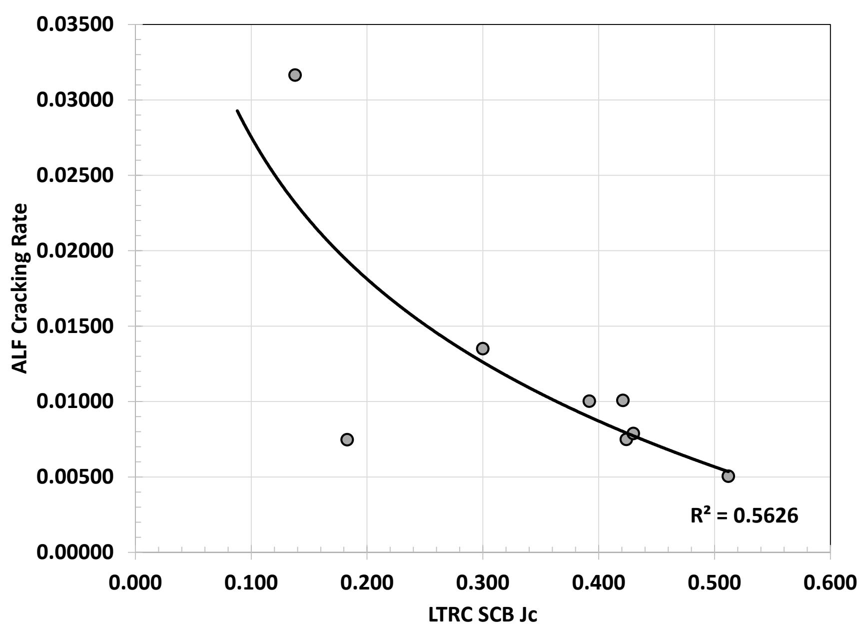


Figure 8 – SCB LTRC Jc Parameter vs ALF Cracking Rate

The researchers also had the opportunity to compare the test results of the SCB LTRC Jc parameter and the Overlay Tester performance using the FHWA ALF mixtures. Figure 9 shows that the comparison between the two indices show no correlation to one another. This confirms some of the earlier data shown regarding the lack of relationship between the Overlay Tester and the SCB LTRC Jc parameter.

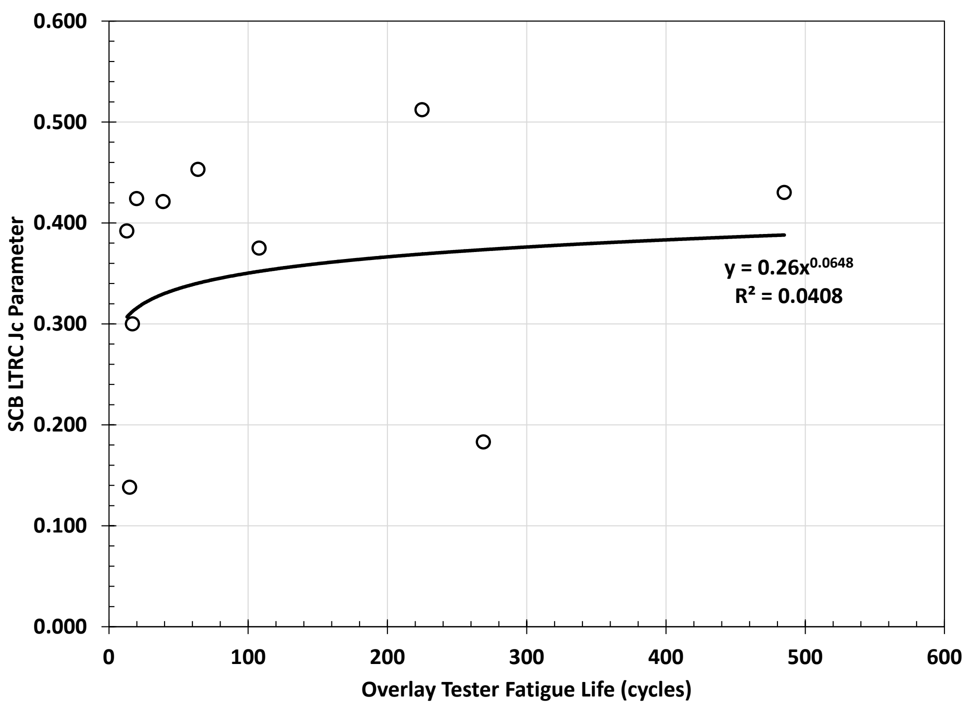


Figure 9 – Comparison of SCB LTRC Jc Parameter and Overlay Tester Results for FHWA ALF Mixtures

Semi-Circular Bend (SCB) Flexibility Index (aka I-FIT)

The Illinois SCB Flexibility Index (FI) is conducted using the same specimen geometry as the LTRC test specimen, except only one notch depth of 15.0 mm (0.6 inches) is used. The FI is equal to the fracture energy divided by the slope of the post peak load-displacement curve at the inflection point, as shown in Figure 10. In general, as the SCB Flexibility Index (FI) value increases, the asphalt mixture's fatigue cracking resistance increases. Preliminary information suggests that a Flexibility Index > 8.0 would represent a high fatigue cracking resistant mixture (Illinois DOT, 2015). The Flexibility Index is conducted at a much faster rate of loading (mm/min.) when compared to the SCB LTRC test procedure. It also requires less testing when compared to LTRC method when testing in triplicate. For example, with the 3 notch depths, the LTRC SCB requires 9 test specimens, while the SCB Flexibility Index requires only 3 specimens.

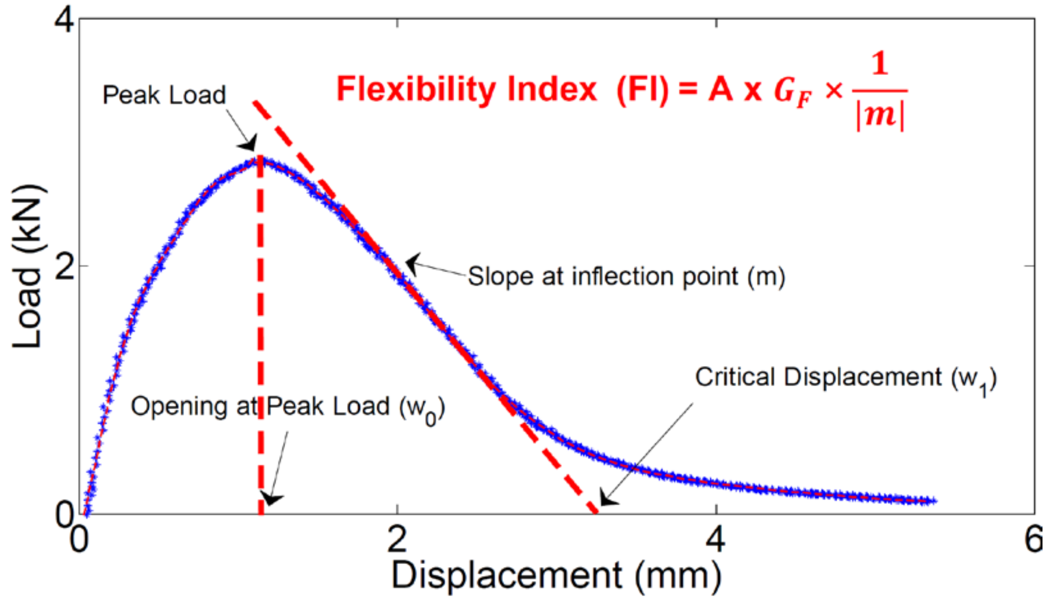


Figure 10 – Illinois SCB Flexibility Index (FI)

Al-Qadi, I., H. Ozer, J. Lambros, A. El Khatib, P. Singhvi, T. Khan, J. Rivera-Perez, and B. Doll, 2015, *Testing Protocols to Ensure Performance of High Asphalt Binder Replacement Mixes Using RAP and RAS*, Research Report No. FHWA-ICT-15-017, Illinois Center for Transportation, 209 pp.

The researchers evaluated different test procedures and methods to determine how to improve the durability of RAP and RAS asphalt mixtures in Illinois. The major outcome of the research study was the development of the SCB Flexibility Index test procedure. The researchers also concluded the following from the study:

- The development of the Flexibility Index parameter provided greater separation between asphalt mixtures to capture some of the mixture changes that could not be captured by fracture energy alone.
- A good correlation was found between the field cracking performance of nine different field sections with the SCB Flexibility Index parameter.
- The researchers found a good agreement between the ALF measured cracking and the SCB Flexibility Index.

Bonaquist, R. (2016), *Critical Factors Affecting Asphalt Concrete Durability,* WisDOT Report No. 0092-14-06, Wisconsin Department of Transportation, 128 pp.

Bonaquist (2016) showed that the SCB Flexibility Index parameter was highly sensitive to effective asphalt content by volume, continuous low temperature PG grade, effective

RAP binder ratio, and percent recovery from AASHTO M332 (Multiple Stress Creep Recovery). In fact, Bonaquist (2016) proposed a prediction equation that could be used to evaluate the sensitivity of asphalt mixture specifications to help achieve more durable asphalt mixtures. Figure 11 shows the results of measured vs estimated SCB Flexibility Index.

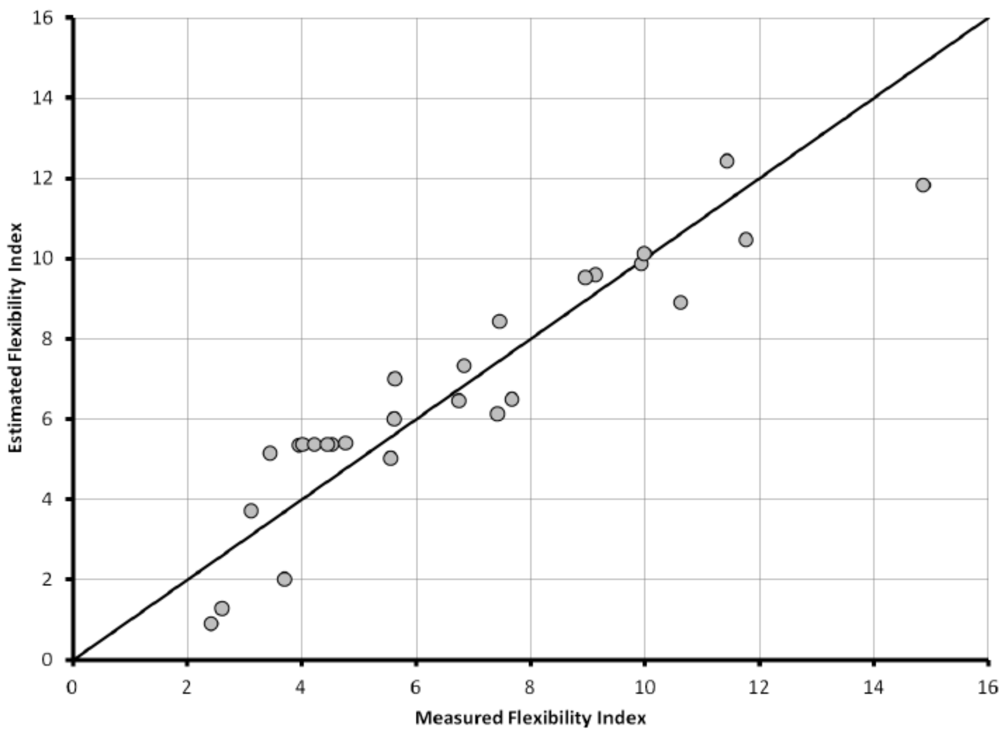


Figure 11 – Measured vs Estimated SCB Flexibility Index (After Bonaquist, 2016)

Bennert, T., C. Ericson, D. Pezeshki, R. Shamborovskyy, and C. Bognacki, 2017, "Moving Towards Asphalt Binder and Mixture Protocols to Minimize Fatigue Cracking on Asphalt Airfields", In Publication in the *Journal of the Transportation Research Record*, Transportation Research Board of the National Academies, Washington, D.C..

The researchers evaluated fatigue cracking performance on five different asphalt airfields and compared the magnitude of the fatigue cracking to different asphalt binder and mixture tests reported to show correlations to asphalt durability and cracking. The researchers showed that the SCB Flexibility Index correlated to the level of observed field cracking at both JFK and Newark International airports. Figure 12 shows the results of the SCB Flexibility Index compared to the PANYNJ engineers' visual observations and time of cracking. The figure clearly indicates that good performing airfields (i.e. – little to no cracking after more than 12 years) achieved a SCB Flexibility Index greater than 7.0. Meanwhile, poor performing airfield pavements (i.e. – severe cracking after < 7 years) achieved a SCB Flexibility Index under 4.0.

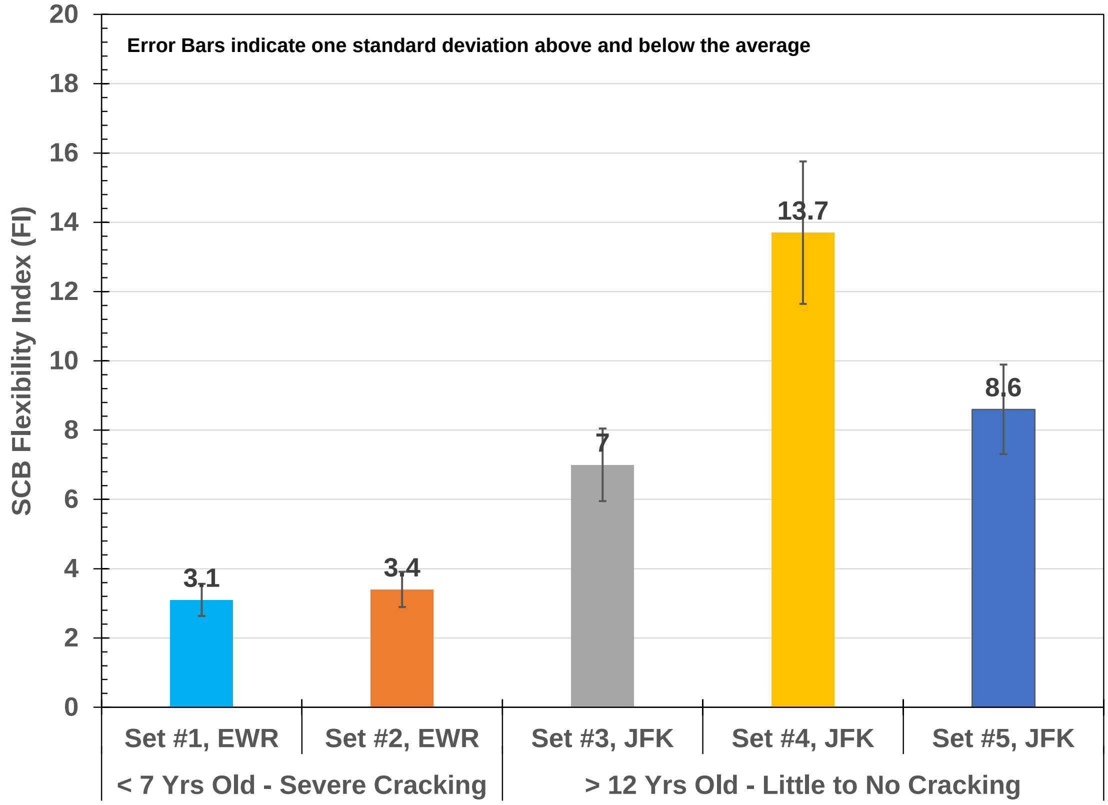


Figure 12 – SCB Flexibility Index vs Observed Level of Field Cracking

Bennert, T., C. Ericson, E. Haas, and E. Wass Jr., 2017, "Asphalt Mixture and Binder Performance at the FHWA ALF", In Preparation for Submittal to the 2018 Meeting of the Transportation Research Board.

The researchers utilized the recent testing cycle at the FHWA to evaluate the asphalt binder and mixture performance tests and compare those results to the observed fatigue cracking on the different testing lanes. The ALF testing lanes consisted of 10 different asphalt mixtures containing varying amounts of recycled asphalt from RAP and RAS, as well as some of the lanes utilizing warm mix asphalt technologies. The FHWA ALF utilized two different means of indexing fatigue cracking on the test lanes: 1) Number of Loading Cycles to First Crack Observed; and 2) Cracking Rate.

Figure 13 shows the comparison between the SCB Flexibility Index and the Number of Loading Cycles to First Cracking Observed. There is a good relationship between the two parameters and clearly shows that as the SCB Flexibility Index increases, so does the fatigue life of the asphalt material.

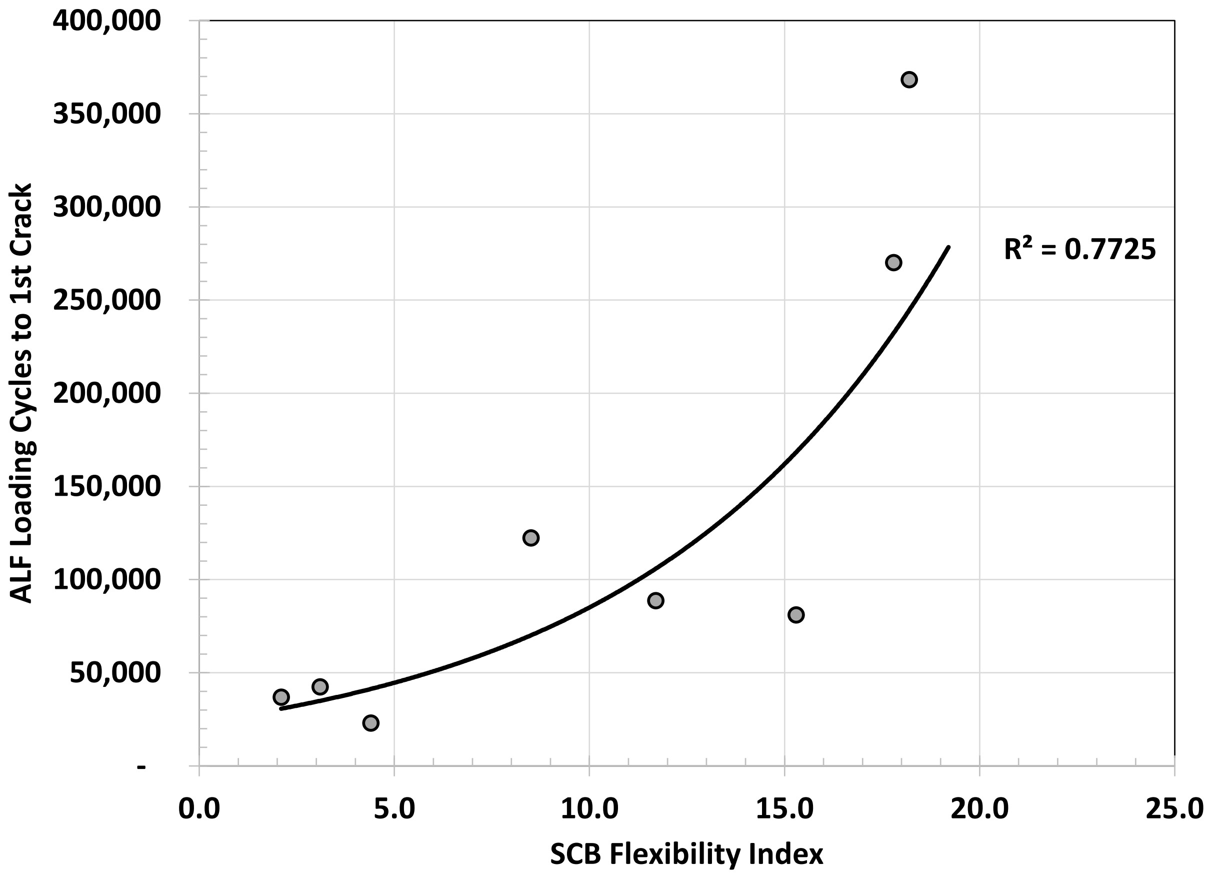


Figure 13 – SCB Flexibility Index vs FHWA ALF Number of Loading Cycles Until 1st Cracking Observed

The SCB Flexibility Index measured on the FHWA ALF field cores was also compared to the Cracking Rate measured for each of the trafficked lanes. The comparison is shown in Figure 14, and once again, a good relationship exists. The results indicate that as the SCB Flexibility Index increases, the crack growth, or cracking rate, decreases. The comparison of the results would indicate that higher SCB Flexibility Index values results in more crack initiation and crack propagation resistant asphalt mixtures.

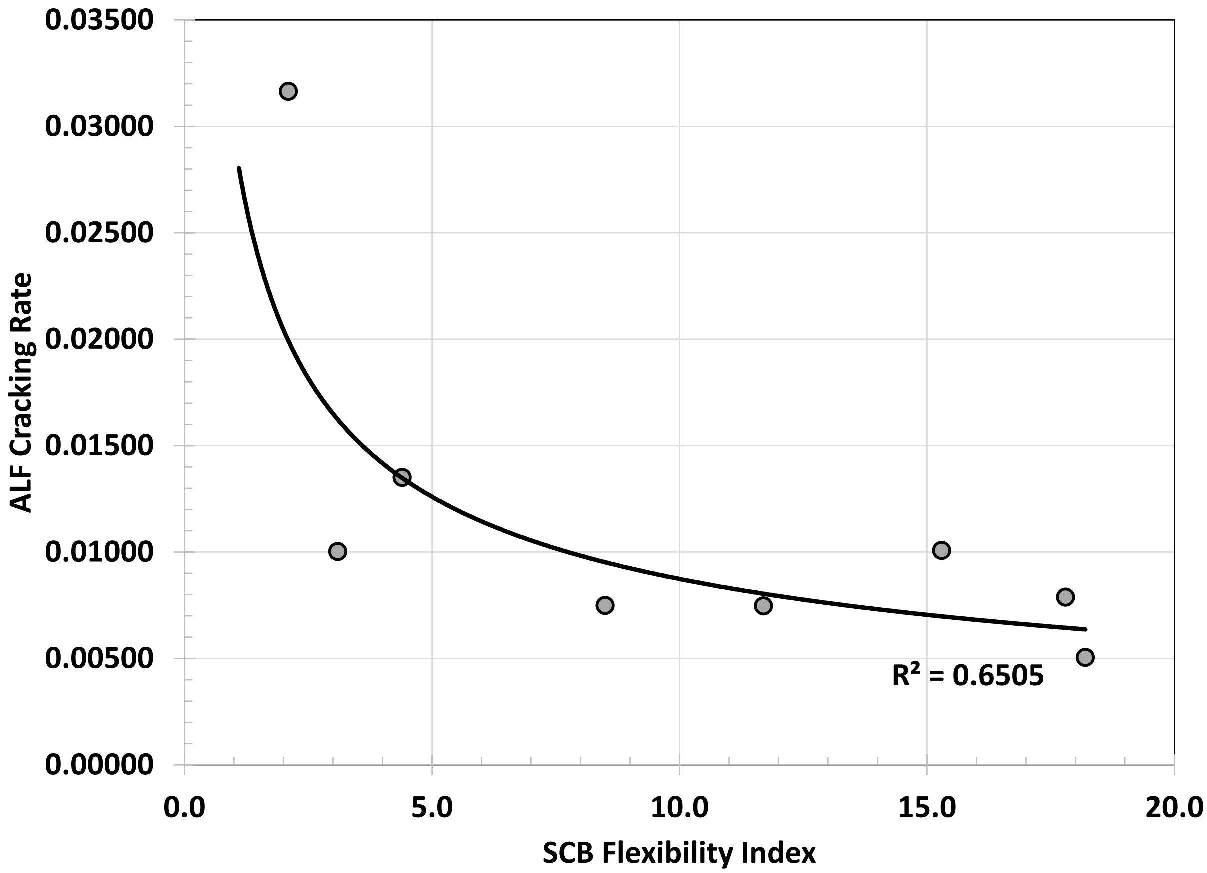


Figure 14 – FHWA ALF Cracking Rate vs SCB Flexibility Index

Overlay Test Fatigue Cracking Test

The Overlay Tester was originally developed by Lytton and his co-workers in the late 1970's (Germann and Lytton, 1979). Zhou and Scullion (2004) updated the testing device and procedure and standardized the test method under TxDOT TEX-248-F, which in turn was eventually adopted by NJDOT under NJDOT B-10. The Overlay Tester consists of two steel plates underlying the asphalt specimen. One plate is fixed while the other is allowed to move horizontally to simulate the opening and closing of joints or cracks in the pavement. The test specimens are 6 inches long, 3 inches wide and 1.5 inches in height. The test is a cyclic displacement-controlled test with a triangular waveform that is conducted within a 10 second cycle (i.e. – 5 seconds to open to 0.025 inches, 5 seconds to close to zero from 0.025 inches opening).

The Overlay Tester has shown to provide an excellent correlation to field cracking for both composite pavements (Zhou and Scullion, 2007; Bennert et al., 2009) as well as flexible pavements (Zhou et al., 2007; Bennert and Maher, 2013; Bennert et al., 2016). Figure 15 shows a picture of the Overlay Tester at Rutgers University. Rutgers

University has extensive testing experience with the Overlay Tester test and actually developed NJDOT's B-10 test procedure, as well as its inclusion in the NJDOT's BRIC and HRAP performance based specifications.

Figure 15 – Picture of the Overlay Tester (Chamber Door Open)

Asphalt material performance in the Overlay Tester has been well documented in New Jersey over the past 5 years. Therefore, only new and unpublished literature regarding correlations with field performance will be noted here.

Bennert, T., C. Ericson, E. Haas, and E. Wass Jr., 2017, "Asphalt Mixture and Binder Performance at the FHWA ALF", In Preparation for Submittal to the 2018 Meeting of the Transportation Research Board.

Researchers evaluated the fatigue cracking performance of asphalt mixtures with varying amounts of recycled asphalt binder, warm mix asphalt technologies and base asphalt binder grade on the FHWA ALF test lanes. The Overlay Tester test was conducted on the bottom 1.5 inches of field cores to compare the field performance to the results of the Overlay Tester.

Figure 16 shows the Overlay Tester fatigue life compared to the Number of Cycles to 1st Observed Crack on the FHWA ALF. The results in Figure 16 show that a good relationship exists between the Overlay Tester and the observed start of cracking on the FHWA ALF. Figure 17 once again shows the Overlay Tester results now compared to the Cracking Rate at the FHWA ALF. The results in Figure 17 again show the Overlay Tester compares well to field cracking of asphalt mixtures. These results mirror what the NJDOT has witnessed with their asphalt mixtures and pavements.

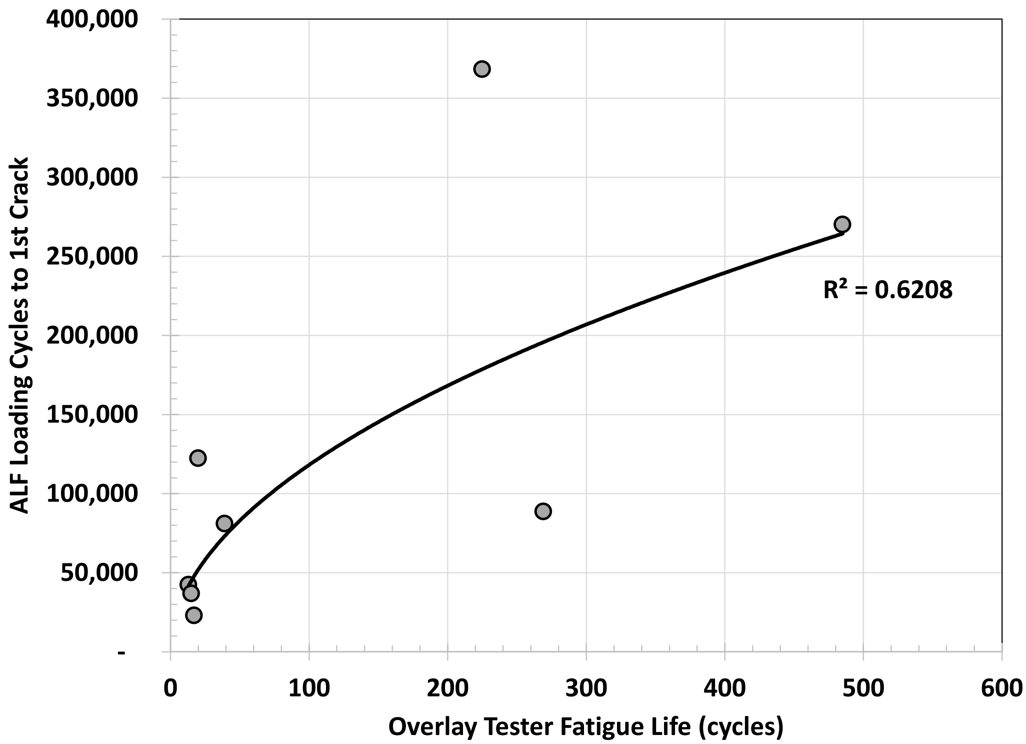


Figure 16 – Overlay Tester Results Compared to FHWA ALF Number of Cycles Until 1st Crack Observed

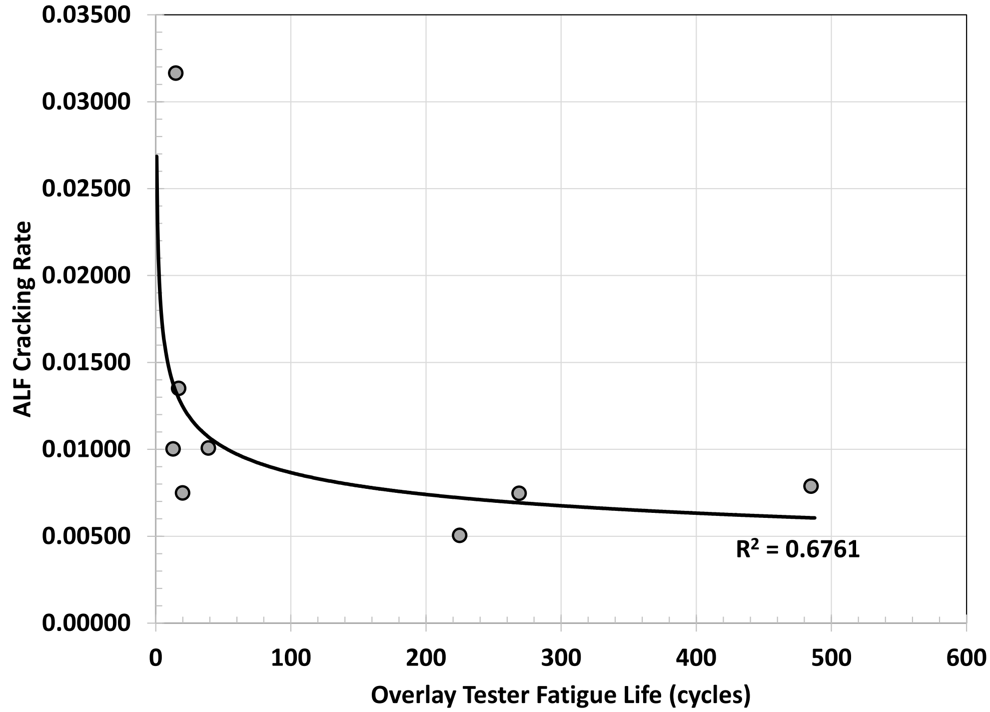


Figure 17 – Overlay Tester Results Compared to FHWA ALF Cracking Rate

Relationship Between the Overlay Tester and SCB Tests

Using the test results generated from the ALF FHWA research, comparisons between the Overlay Tester and SCB Flexibility and SCB LTRC Jc parameter were evaluated. The results are shown in Figures 18 and 19. The figures show a good correlation between the Overlay Tester and the SCB Flexibility. Meanwhile, a very poor correlation was found between the SCB LTRC Jc parameter and the Overlay Tester. A comparison of both SCB test procedures actually shows a poor correlation as well (Figure 20). This would indicate that even though both test methods use a similar specimen configuration and loading system, the test parameters and analysis results in very different performance trends. Similar conflict of results was noted earlier by Xie et al., (2017).

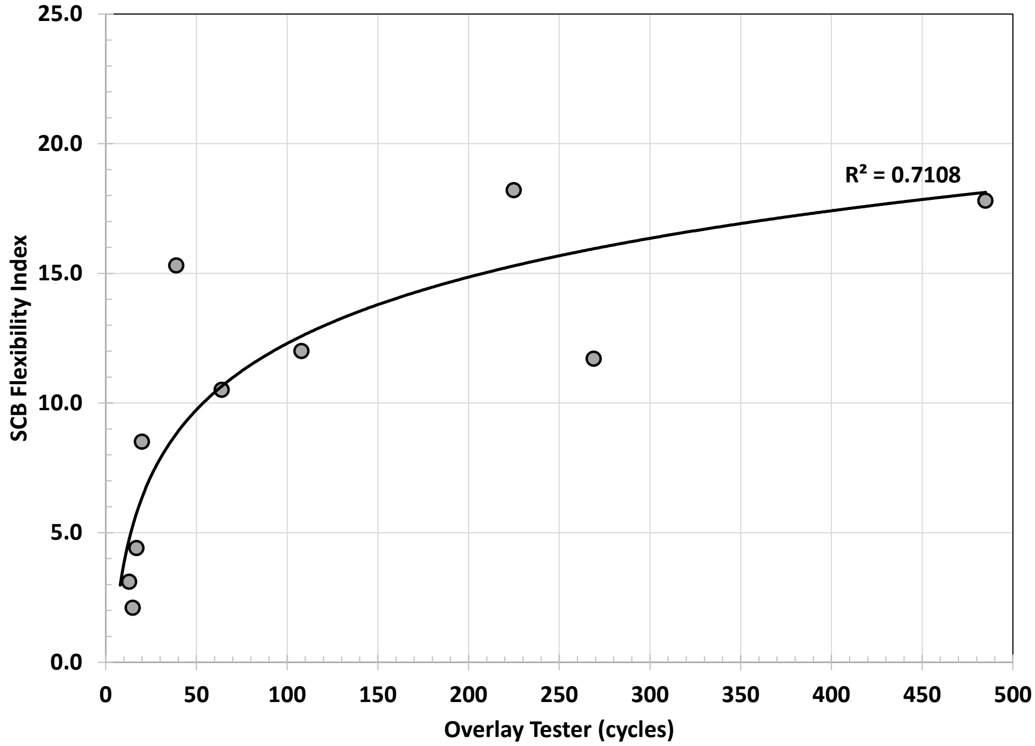


Figure 18 – Overlay Tester Comparison to SCB Flexibility Index Using FHWA ALF Field Cores

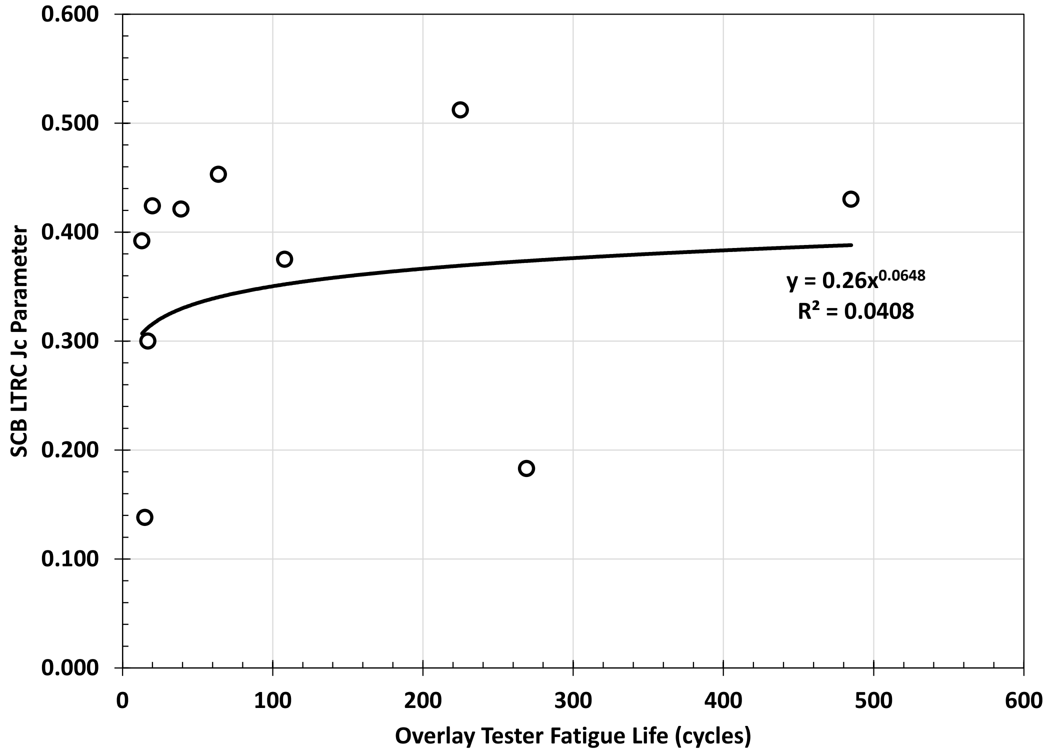


Figure 19 – Overlay Tester Comparison to SCB LTRC Jc Parameter Using FHWA ALF Field Cores

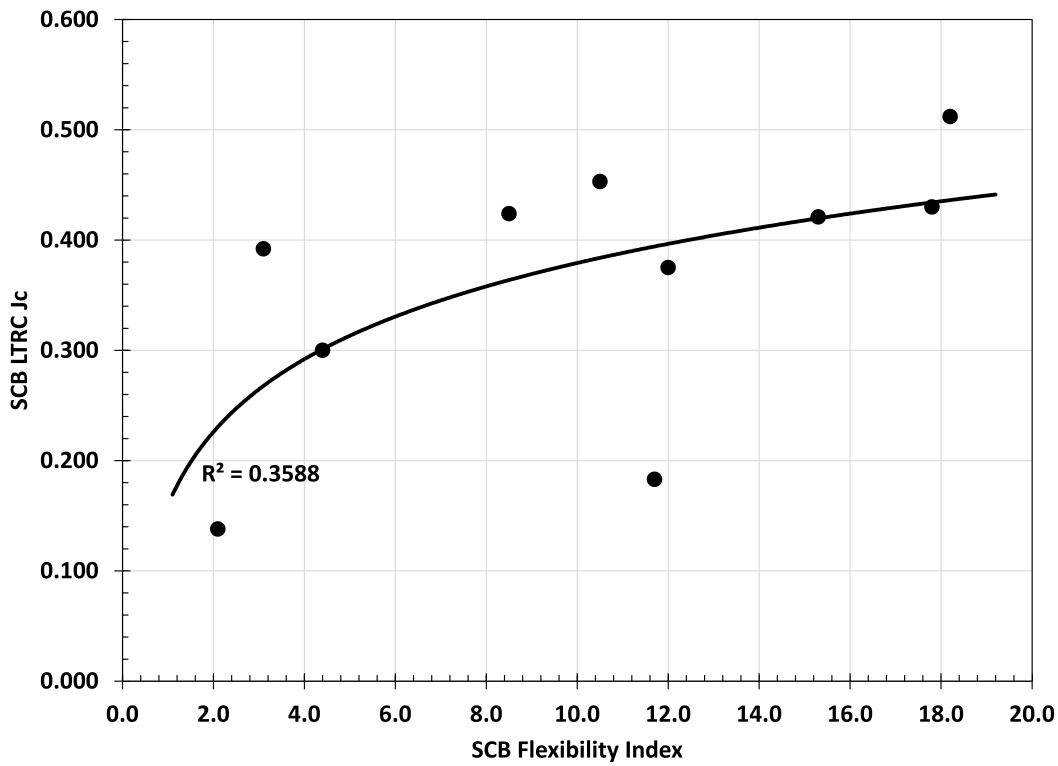


Figure 20 – Comparison of SCB Flexibility Index and SCB LTRC Jc Parameter Using FHWA ALF Field Cores

Bennert, T., 2017, *Lab Performance Testing Procedures for Asphalt Plants*, Presented at the 60th Annual New Jersey Asphalt Paving Conference, March 16th, 2017, Ewing, NJ.

After being awarded the research contract for this study, the researchers organized test data collected by Rutgers University over the past two years where both the Overlay Tester and the SCB Flexibility Index were conducted on the same materials (lab prepared, plant sampled loose mix, and field cores). This resulted in 31 different asphalt mixtures to compare the two fatigue cracking tests. The results of the data mining are shown in Figure 21. The results in Figure 21 show a very good relationship between the Overlay Tester and SCB Flexibility Index. The relationship showed enough promise to develop a preliminary fatigue performance threshold using the SCB Flexibility Index instead of the currently used Overlay Tester. Table 3 shows the preliminary minimum SCB Flexibility Index values necessary to pass the current, minimum Overlay Tester requirements. Both BRIC and HPTO would need to achieve a minimum value of 14 for the SCB Flexibility Index and the HRAP would need to meet a minimum of 8 on the SCB Flexibility Index to pass.

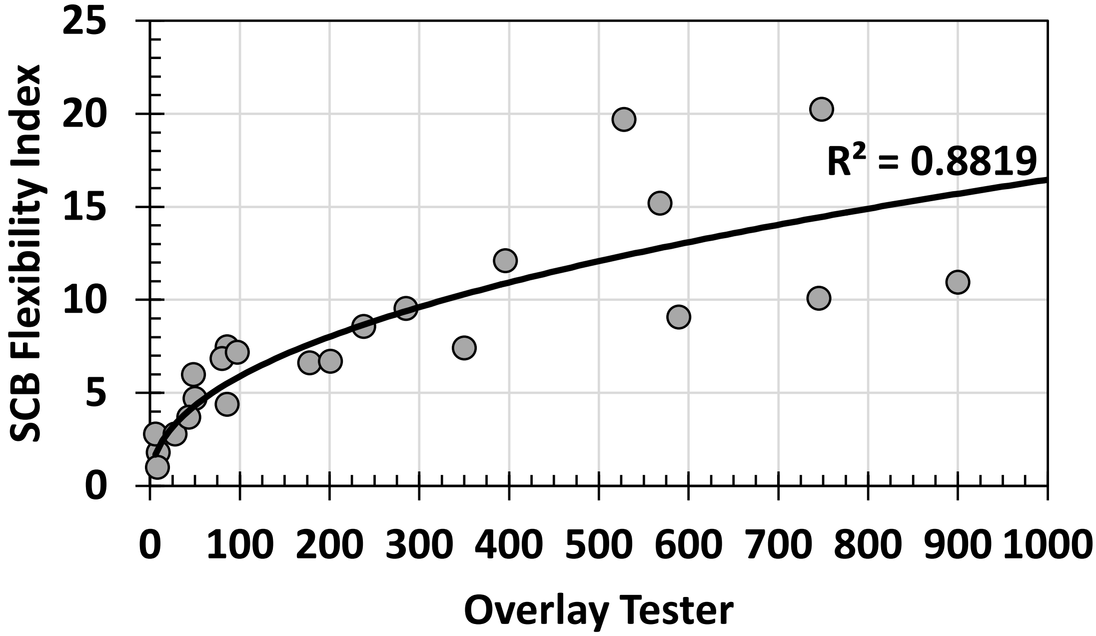


Figure 21 – Overlay Tester Comparison to SCB Flexibility Index for Different Asphalt Mixtures and Sample Types (After Bennert, 2017)

Table 3 – Preliminary Fatigue Cracking Criteria for BRIC, High-RAP and HPTO Using the Overlay Tester and SCB Flexibility Index Relationship (After Bennert, 2017)

Mix Type	OT (cycles)	SCB FI
HRAP	> 175	> 8
BRIC/HPTO	> 700/750	> 14

TASK 1 – MODIFIED RUGGEDNESS STUDY

The primary purpose of conducting Ruggedness Studies is to identify those factors that significantly influence the performance measurements of each specific test method and to estimate how closely these factors need to be controlled during the test. Basically, the Ruggedness Study is a sensitivity analysis on the variables of the test method itself, rather than the materials under the test. For a given test method, the variables generally include test temperature, specimen dimensions, loading rate, etc. Through a Ruggedness Study, the sensitive test variables will be identified and the associated tolerance for each sensitive variable will be assessed. ASTM E1169-14, *Standard Practice for Conducting Ruggedness Tests*, presents guidelines for ruggedness testing. It recommends that testing be done by a single laboratory with uniform materials and conduct an inter-laboratory study evaluating key parameters of the test method.

In Task 1, a modified Ruggedness Study was conducted to evaluate the significance of the different SCB test procedures. Based on the preliminary literature review, a workplan was developed to evaluate the Louisiana Transportation Research Center (LTRC) SCB procedure (Mohammad et al., 2016) and the SCB Flexibility Index (Illinois DOT, 2016), as these tests appeared to be the only two intermediate temperature SCB test currently being used in Performance Based Specifications within the United States. The LTRC SCB is being used in Louisiana, while the SCB Flexibility Index is being proposed in Illinois, Wisconsin, and Minnesota.

In the Ruggedness Study, the first set of test results were generated using the "Standard Factor" parameters. This is basically the test conducted under normal conditions. After this set of data was developed, one Ruggedness Testing Variable was selected at a time and tested under its respective High and Low level to evaluate the sensitivity of the fatigue cracking property to that test parameter. Each set of test specimens were tested within 5 days after mixing and compaction to eliminate any potential change in the material properties simply due to oxidative aging in the laboratory. In addition, two different air void levels, 4% and 7% (+/- 0.5%) were used to determine whether or not specification air void level was significant. For example, 4% air voids would be utilized if plant produced QC or mixture design samples were to be specified for performance testing. Meanwhile, 7% air voids, which corresponds more closely to field density, is commonly used when conducting laboratory experiments. If found significant, separate criteria would need to be established at each air void level.

For this work, a NJDOT 9.5M64E 0% RAP asphalt mixture was used since it is commonly used throughout New Jersey and can be easily replicated in the laboratory. The resultant test data was evaluated using the t-Test to determine whether or not the results are statistically equal at a 95% confidence interval.

Table 4 summarizes the testing parameters and ranges used in the Ruggedness Study.

Table 4 – Proposed Ruggedness Testing for SCB Test Parameters

Test Name/Standard	Specimen Geometry	Ruggedness Testing Variables	Standard Factor	High Level	Low Level	Tolerance
LTRC SCB (Monotonic Test)	Dia. = 150 mm T = 25 mm ND. = 25.4, 31.8, 38.1 mm	1. Specimen Thickness (T) 2. Loading Rate (LR) 3. Test Temperature (t) 4. Notch Depth (ND) 5. Air Voids (AV)	57 mm 0.5 mm/min 25°C 25.4, 31.8, 38.1 mm 4%, 7%	+ 5 mm + 25% + 2.5°C + 5 mm + 0.5%	- 5 mm - 25% - 2.5°C - 5 mm - 0.5%	+/- 2 mm +/- 5% +/- 0.5°C +/- 1 mm +/- 0.25%
SCB Flexibility Index (FI)	Dia. = 150 mm T = 50 mm ND = 15 mm	1. Specimen Thickness (T) 2. Loading Rate (LR) 3. Test Temperature (t) 4. Notch Depth (ND) 5. Air Voids (AV)	50 mm 50 mm/min 25°C 15 mm 4%, 7%	+ 5 mm + 10% + 2.5°C + 5 mm + 0.5%	- 5 mm - 10% - 2.5°C - 5 mm - 0.5%	+/- 2 mm +/- 5% +/- 0.5°C +/- 1 mm +/- 0.25%

SCB Flexibility Index – Ruggedness Evaluation

The SCB Flexibility Index test procedure was conducted in accordance with AASHTO TP124. Each parameter type was tested in triplicate and averaged for presentation. As discussed earlier, two separate air void levels were used to determine if the parameters were significant or insignificant at different air void magnitudes that could potentially be used for different versions of specification implementation.

Specimen Thickness

The SCB Flexibility Index specimen thickness was varied by 10% from the standard 50 mm thick test specimen. The measured results for the Specimen Thickness are shown in Tables 5 and 6. Important to note in the tables were the consistency of the physical parameters (i.e. – air voids, thickness, ligament length) of the specimens for each of the parameters evaluated.

Table 5 – SCB Flexibility Index Results for Specimen Thickness @ 4% Air Voids

Specimen ID	Air Voids (%)	Thickness (mm)	Ligament Length (mm)	Max Load (kN)	Fracture Energy, G_f	Slope (kN/mm)	Flexibility Index (FI)
4% AV - Thickness (-5mm)	3.5	45.4	57.7	5.1	3523.3	-4.9	7.24
	3.6	46.2	57.3	5.4	3826.0	-5.2	7.34
	3.6	46.5	57.6	5.1	3718.1	-5.0	7.51
	3.6	**46.0**	**57.5**	**5.2**	**3689.1**	**-5.0**	**7.36**
4% AV - Thickness (50mm)	4.2	51.6	58.3	5.9	3579.5	-6.4	5.63
	4.2	51.4	56.9	6.0	3673.3	-5.9	6.23
	4	51.4	58.2	6.2	3641.0	-7.8	4.67
	4.1	**51.4**	**57.8**	**6.0**	**3631.3**	**-6.7**	**5.51**
4% AV - Thickness (+5mm)	4.4	55.1	57.4	5.8	3185.1	-6.3	5.06
	4.4	55.2	58.0	6.1	3616.7	-5.9	6.10
	4	55.0	57.8	6.6	3951.8	-6.3	6.28
	4.3	**55.1**	**57.7**	**6.2**	**3584.5**	**-6.2**	**5.81**

Table 6 - SCB Flexibility Index Results for Specimen Thickness @ 7% Air Voids

Specimen ID	Air Voids (%)	Thickness (mm)	Ligament Length (mm)	Max Load (kN)	Fracture Energy, G_f	Slope (kN/mm)	Flexibility Index (FI)
7% AV - Thickness (-5mm)	6.4	44.8	56.8	4.5	3307.3	-5.0	6.67
	6.4	44.7	59.0	4.3	3305.6	-3.8	8.72
	6.8	46.3	59.0	4.2	3091.2	-4.5	6.95
	6.5	**45.3**	**58.3**	**4.3**	**3234.7**	**-4.4**	**7.45**
7% AV - Thickness (50mm)	6.8	49.2	57.9	4.6	2925.4	-4.8	6.1
	6.8	49.0	58.8	4.8	2851.6	-5.1	5.6
	7	51.4	57.2	4.5	2670.9	-4.7	5.7
	6.9	**49.9**	**58.0**	**4.6**	**2816.0**	**-4.9**	**5.79**
7% AV - Thickness (+5mm)	7.4	56.2	56.4	4.6	2687.1	-4.4	6.16
	6.9	56.6	57.0	5.3	3142.0	-5.9	5.31
	6.9	56.4	58.0	4.7	2600.7	-4.7	5.57
	7.1	**56.4**	**57.1**	**4.9**	**2809.9**	**-5.0**	**5.68**

Tables 7 and 8 show the results of the t-Test to determine if the results are statistically equal at a 95% confidence interval. The tables show the p-value from the statistical analysis. When the p-value is less than 0.05, then the test results are statistically NOT equal. The results of the testing shows that when the thickness of the SCB specimen is 45 mm thick, the test results are NOT statistically equal or fairly close to being NOT statistically equal, while when the thickness was greater than the standard 50 mm, the results were statistically equal. This would clearly indicate that test specimens should not be cut thinner than the 50 mm standard thickness. This would also indicate that the testing of field cores may be an issue if the lift thickness is less than 2.0 inches.

Table 7 – t-Test Results for Specimen Thickness @ 4% Air Voids

Thickness	-5 mm	Standard	+5 mm
-5 mm			
Standard	0.016		
+5 mm		0.634	

Table 8 – t-Test Results for Specimen Thickness @ 7% Air Voids

Thickness	-5 mm	Standard	+5 mm
-5 mm			
Standard	0.066		
+5 mm		0.730	

Comparing the test results to the statistically equal and not equal results, it appears that the change in specimen thickness directly influences the maximum load and the post-peak slope of the load – deformation curve. The steeper or greater the magnitude of the slope, the more brittle the failure response of the asphalt mixture, resulting in a lower SCB Flexibility value.

Notch Depth

The influence of the notch depth of the SCB test specimens were evaluated by increasing/decreasing the notch depth by 5.0 mm over the standard 15 mm notch depth. The test results are shown in Tables 9 and 10. The test results do appear to be somewhat sensitive to the notch depth, as maximum load, fracture energy and the post-peak slope all decreased with increasing notch depth.

Table 9 - SCB Flexibility Index Results for Notch Depth Evaluation @ 4% Air Voids

Specimen ID	Air Voids (%)	Thickness (mm)	Ligament Length (mm)	Max Load (kN)	Fracture Energy, G_f	Slope (kN/mm)	Flexibility Index (FI)
4% AV - Notch (-5mm)	3.7	49.9	63.2	7.3	4203.4	-8.06	5.22
	3.7	51.3	63.0	7.4	4298	-7.79	5.52
	3.7	51.0	63.0	7.1	4099	-6.83	6.00
	3.7	**50.8**	**63.1**	**7.3**	**4200.1**	**-7.6**	**5.58**
4% AV - Notch (15mm)	4.2	51.6	58.3	5.9	3579.5	-6.4	5.63
	4.2	51.4	56.9	6.0	3673.3	-5.9	6.23
	4	51.4	58.2	6.2	3641.0	-7.8	4.67
	4.1	**51.4**	**57.8**	**6.0**	**3631.3**	**-6.7**	**5.51**
4% AV - Notch (+5mm)	3.9	49.6	51.8	4.5	3058	-4.86	6.30
	3.9	49.6	53.1	4.6	2903.2	-4.79	6.07
	3.8	49.8	51.5	4.4	2681.8	-4.34	6.18
	3.9	**49.7**	**52.1**	**4.5**	**2881.0**	**-4.7**	**6.18**

Table 10 - SCB Flexibility Index Results for Notch Depth Evaluation @ 7% Air Voids

Specimen ID	Air Voids (%)	Thickness (mm)	Ligament Length (mm)	Max Load (kN)	Fracture Energy, G_f	Slope (kN/mm)	Flexibility Index (FI)
7% AV - Notch (-5mm)	6.8	49.2	63.5	5.7	3538.2	-5.87	6.03
	6.6	49.9	63.2	5.7	3261.9	-5.17	6.31
	6.6	50.4	62.8	5.4	3346.9	-5.77	5.81
	6.7	**49.8**	**63.2**	**5.6**	**3382.3**	**-5.6**	**6.05**
7% AV - Notch (15mm)	6.8	49.2	57.9	4.6	2925.4	-4.8	6.1
	6.8	49.0	58.8	4.8	2851.6	-5.1	5.6
	7	51.4	57.2	4.5	2670.9	-4.7	5.7
	6.9	**49.9**	**58.0**	**4.6**	**2816.0**	**-4.9**	**5.79**
7% AV - Notch (+5mm)	6.5	50.9	53.4	4.0	3153.4	-3.35	9.41
	6.5	50.9	51.5	3.8	2754	-3.25	8.46
	6.7	50.0	52.0	3.3	2173.8	-2.78	7.83
	6.6	**50.6**	**52.3**	**3.7**	**2693.7**	**-3.1**	**8.57**

The t-Test statistical analysis for the notch depth variation is shown in Tables 11 and 12. The results show definitely at 7% air voids that too large a notch depth results in statistically different results over the standard notch depth. At 4% air voids, the difference between the standard notch depth and +5.0 mm are starting to show some statistical difference, but not at a 95% confidence level. The results of the notch depth would suggest that a shorter notch depth would not be a significant factor to change the SCB Flexibility Index value. However, too large a notch depth cut may result in artificially reducing the SCB Flexibility Index value.

Table 11 - t-Test Results for Notch Depth @ 4% Air Voids

Notch Depth	-5 mm	Standard	+5 mm
-5 mm			
Standard	0.897		
+5 mm		0.216	

Table 12 - t-Test Results for Notch Depth @ 7% Air Voids

Notch Depth	-5 mm	Standard	+5 mm
-5 mm			
Standard	0.311		
+5 mm		0.005	

Loading Rate

The influence of the loading rate of the SCB test was evaluated by modifying the deformation rate by 5 mm/min, slower and faster, than the standard 50 mm/min. The test results are shown in Tables 13 and 14. A quick review of the data clearly shows that the loading rate was effecting the post-peak slope of the load – deformation curve, as well as having influence on the maximum load.

Tables 15 and 16 summarize the statistical results of the t-Test analysis. The results clearly show that the loading rate has a significant influence on the SCB Flexibility Index results when compared to the standard rate of 50 mm/min.

Table 13 - SCB Flexibility Index Results for Loading Rate Evaluation @ 4% Air Voids

Specimen ID	Air Voids (%)	Thickness (mm)	Ligament Length (mm)	Max Load (kN)	Fracture Energy, G_f	Slope (kN/mm)	Flexibility Index (FI)
4% AV - Rate (45mm/min)	3.8	50.1	58.0	5.8	3777.5	-6.1	6.19
	3.8	50.2	57.3	5.2	3365.6	-3.91	8.61
	3.9	51.8	58.3	5.4	3091.2	-5.07	6.09
	3.8	**50.7**	**57.9**	**5.5**	**3411.4**	**-5.0**	**6.97**
4% AV - Rate (50mm/min)	4.2	51.6	58.3	5.9	3579.5	-6.4	5.63
	4.2	51.4	56.9	6.0	3673.3	-5.9	6.23
	4	51.4	58.2	6.2	3641.0	-7.8	4.67
	4.1	**51.4**	**57.8**	**6.0**	**3631.3**	**-6.7**	**5.51**
4% AV - Rate (55mm/min)	3.6	50.4	57.7	5.5	3577.7	-5.15	6.95
	4	49.3	58.0	5.1	3385.0	-4.59	7.37
	4	49.3	57.2	5.6	4064.2	-4.86	8.36
	3.9	**49.7**	**57.6**	**5.4**	**3675.6**	**-4.9**	**7.56**

Table 14 - SCB Flexibility Index Results for Loading Rate Evaluation @ 7% Air Voids

Specimen ID	Air Voids (%)	Thickness (mm)	Ligament Length (mm)	Max Load (kN)	Fracture Energy, G_f	Slope (kN/mm)	Flexibility Index (FI)
7% AV - Rate (45mm/min)	6.7	50.7	58.4	4.3	2947.4	-3.09	9.54
	6.4	49.9	57.8	4.8	3368.7	-4.31	7.83
	6.4	50.1	57.8	4.3	3232.3	-3.9	8.29
	6.5	**50.2**	**58.0**	**4.5**	**3182.8**	**-3.8**	**8.55**
7% AV - Rate (50mm/min)	6.8	49.2	57.9	4.6	2925.4	-4.8	6.1
	6.8	49.0	58.8	4.8	2851.6	-5.1	5.6
	7	51.4	57.2	4.5	2670.9	-4.7	5.7
	6.9	**49.9**	**58.0**	**4.6**	**2816.0**	**-4.9**	**5.79**
7% AV - Rate (55mm/min)	6.6	50.7	57.6	4.6	3399.4	-3.64	9.34
	6.4	49.3	57.6	4.6	3111.5	-4.41	7.05
	6.4	49.4	58.4	4.6	3261.1	-4.49	7.27
	6.5	**49.8**	**57.9**	**4.6**	**3257.3**	**-4.2**	**7.89**

Table 15 - t-Test Results for Loading Rate @ 4% Air Voids

Deformation Rate	-5 mm/min	Standard	+5 mm/min
-5 mm/min			
Standard	0.196		
+5 mm/min		0.029	

Table 16 - t-Test Results for Loading Rate @ 7% Air Voids

Deformation Rate	-5 mm/min	Standard	+5 mm/min
-5 mm/min			
Standard	0.007		
+5 mm/min		0.049	

Testing Temperature

The influence of testing temperature was evaluated within the ruggedness testing by increasing and decreasing the testing temperature by 2.5ºC from the standard 25ºC. The test results for the temperature influence evaluation are shown in Table 17 and 18. The results show that the maximum load, fracture energy and slope all increase when the temperature decreases, indicating that the asphalt mixture is becoming stiffer. This is expected knowing simply how asphalt materials perform due to temperature change. However, based on the flexibility index calculations, the t-Test showed that the SCB Flexibility Index is not as sensitive to the temperature change imposed in the study as the other test parameters evaluated (Tables 19 and 20). This is somewhat contradicting the information published by others and may have simply been an isolated situation with this particular asphalt mixture.

Table 17 - SCB Flexibility Index Results for Temperature Evaluation @ 4% Air Voids

Specimen ID	Air Voids (%)	Thickness (mm)	Ligament Length (mm)	Max Load (kN)	Fracture Energy, G_f	Slope (kN/mm)	Flexibility Index (FI)
4% AV - Temp (22.5C)	3.8	49.5	57.6	6.9	3577.9	-8.32	4.30
	4.1	50.6	58.6	8.1	4432.7	-10.49	4.22
	4.1	50.5	57.6	7.1	3594.4	-9.31	3.86
	4.0	**50.2**	**57.9**	**7.3**	**3868.3**	**-9.4**	**4.13**
4% AV - Temp (25C)	4.2	51.6	58.3	5.9	3579.5	-6.4	5.63
	4.2	51.4	56.9	6.0	3673.3	-5.9	6.23
	4	51.4	58.2	6.2	3641.0	-7.8	4.67
	4.1	**51.4**	**57.8**	**6.0**	**3631.3**	**-6.7**	**5.51**
4% AV - temp (27.5C)	3.8	50.5	56.6	4.9	3135.8	-4.55	6.89
	3.8	50.7	58.2	5.4	3446.4	-5.29	6.52
	3.8	51.0	56.5	5.2	2993.2	-5.35	5.59
	3.8	**50.7**	**57.1**	**5.2**	**3191.8**	**-5.1**	**6.33**

Table 18 - SCB Flexibility Index Results for Temperature Evaluation @ 7% Air Voids

Specimen ID	Air Voids (%)	Thickness (mm)	Ligament Length (mm)	Max Load (kN)	Fracture Energy, G_f	Slope (kN/mm)	Flexibility Index (FI)
7% AV - Temp (22.5C)	6.3	50.9	58.4	6.7	3977.3	-7.27	5.47
	6.7	51.0	57.1	6.1	3788.1	-5.89	6.43
	6.7	50.7	57.6	5.8	3424.4	-5.48	6.25
	6.6	**50.9**	**57.7**	**6.2**	**3729.9**	**-6.2**	**6.05**
7% AV - Temp (25C)	6.8	49.2	57.9	4.6	2925.4	-4.8	6.12
	6.8	49.0	58.8	4.8	2851.6	-5.1	5.57
	7	51.4	57.2	4.5	2670.9	-4.7	5.68
	6.9	**49.9**	**58.0**	**4.6**	**2816.0**	**-4.9**	**5.79**
7% AV - temp (27.5C)	6.7	50.4	57.0	4.2	2608.6	-4.88	5.35
	6.6	50.4	56.7	4.2	2479	-4.3	5.77
	6.6	50.5	57.7	4.1	2674.2	-3.6	7.43
	6.6	**50.4**	**57.1**	**4.1**	**2587.3**	**-4.3**	**6.18**

Table 19 - t-Test Results for Temperature @ 4% Air Voids

Temperature	-2.5C	Standard	+2.5C
-2.5C			
Standard	0.043		
+2.5C		0.238	

Table 20 - t-Test Results for Temperature @ 7% Air Voids

Temperature	-2.5C	Standard	+2.5C
-2.5C			
Standard	0.486		
+2.5C		0.583	

Notch Thickness

The influence on the SCB Flexibility Index due to differences in the notch thickness was evaluated. The notch thickness was considered since some laboratories may attempt to use a conventional wet saw blade thickness (test standard of 1.5mm vs wet saw blade of 3.2 mm) instead of the specified notch thickness generally required to be cut by a tile saw. Tables 21 and 22 show results of the testing. In general, the thinner the width of the notch, the larger the maximum load, fracture energy, and slope of the post-peak load vs deformation curve. The t-Test analysis indicated that the notch thickness was a significant factor with respect to measuring the SCB Flexibility Index.

Table 21 - SCB Flexibility Index Results for Notch Thickness Evaluation @ 4% Air Voids

Specimen ID	Air Voids (%)	Thickness (mm)	Ligament Length (mm)	Max Load (kN)	Fracture Energy, G_f	Slope (kN/mm)	Flexibility Index (FI)
4% AV - Notch Width (1.5 mm)	4.2	51.6	58.3	5.9	3579.5	-6.4	5.63
	4.2	51.4	56.9	6.0	3673.3	-5.9	6.23
	4	51.4	58.2	6.2	3641.0	-7.8	4.67
	4.1	**51.4**	**57.8**	**6.0**	**3631.3**	**-6.7**	**5.51**
4% AV - Notch Width (3.2 mm)	4.1	51.3	57.2	6.0	3428.2	-6.6	5.23
	3.9	50.5	59.3	6.2	3822.7	-5.5	6.91
	3.9	50.6	57.2	5.7	3746.7	-5.5	6.78
	6.6	**50.4**	**57.1**	**4.1**	**2587.3**	**-4.3**	**6.31**

Table 22 - SCB Flexibility Index Results for Notch Thickness Evaluation @ 7% Air Voids

Specimen ID	Air Voids (%)	Thickness (mm)	Ligament Length (mm)	Max Load (kN)	Fracture Energy, G_f	Slope (kN/mm)	Flexibility Index (FI)
7% AV - Notch Width (1.5 mm)	6.8	49.2	57.9	4.6	2925.4	-4.8	6.12
	6.8	49.0	58.8	4.8	2851.6	-5.1	5.57
	7	51.4	57.2	4.5	2670.9	-4.7	5.68
	6.9	**49.9**	**58.0**	**4.6**	**2816.0**	**-4.9**	**5.79**
7% AV - Notch Width (3.2 mm)	6.6	51.1	57.2	5.1	3612.4	-4.26	8.48
	6.6	51.1	58.0	4.6	3221	-3.99	8.06
	6.9	51.3	57.7	5.2	3754.9	-4.17	9.01
	6.6	**50.4**	**57.1**	**4.1**	**2587.3**	**-4.3**	**8.52**

Summary of Modified Ruggedness Testing for SCB Flexibility Index

A summary of the SCB Flexibility Index laboratory testing is shown in Figures 22 and 23. The test results, combined with the t-Test statistical analysis, showed that the following parameters are critical with respect to influencing the final SCB Flexibility Index value:

1. Loading Rate
2. Temperature
3. Notch Width

Although the temperature influence testing conducted in this study showed conflicting information, others have shown that temperature as different at 1% air voids can have a significant effect on the final SCB Flexibility Index (Zhou et al., 2019). Therefore, this parameter was included.

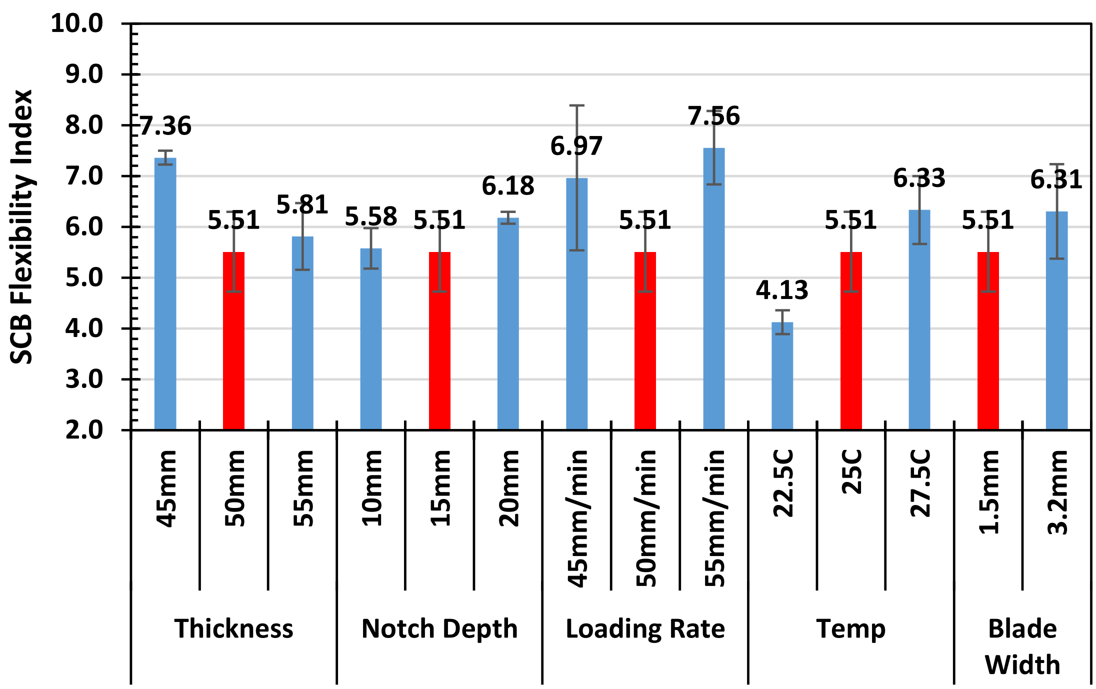


Figure 22 – SCB Flexibility Test Results for 4% Air Voids (Red = Standard; Blue = Modified Parameter)

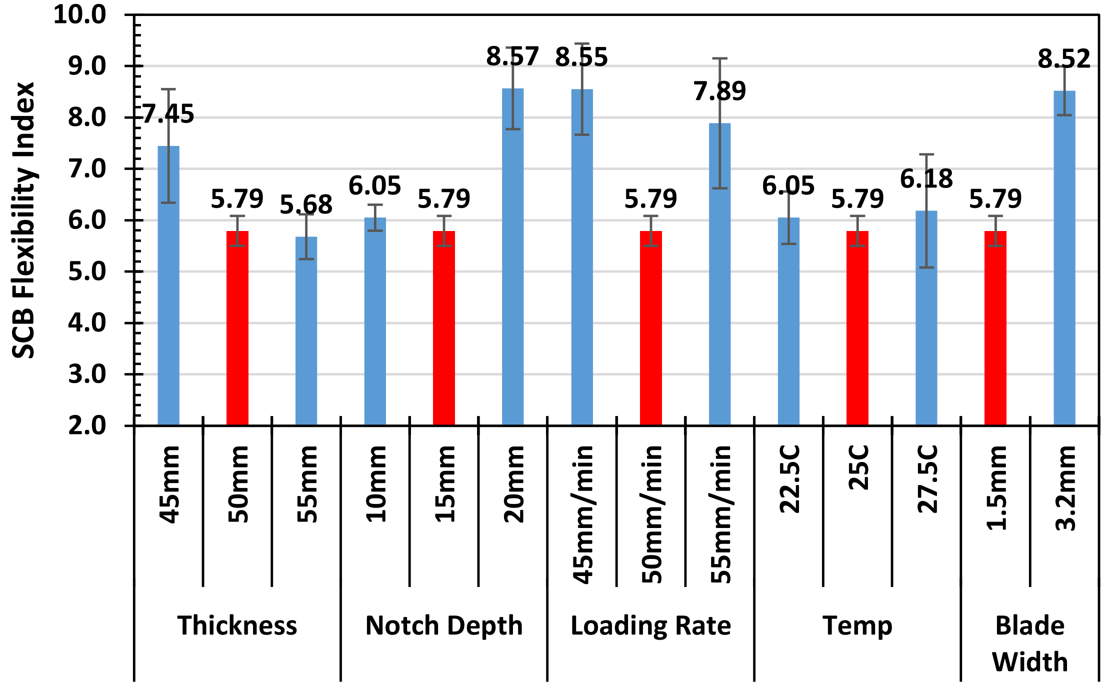


Figure 23 - SCB Flexibility Test Results for 7% Air Voids (Red = Standard; Blue = Modified Parameter)

In addition to the temperature, loading rate, and notch width, the compacted air voids has a significant effect on the SCB Flexibility Index. However, unlike the typical asphalt mixture performance where an increase in air voids is detrimental to performance, the SCB Flexibility Index actually increases as the air voids increase. Figures 24 through 26 show the change in SCB Flexibility Index due to the change in air voids as approximately 1.5 to 3.5 per 1% change in air voids. Although this may contradict general behavior, it is simply an indication that the material is capable of “bending” or “flexing” more when it is not as solid and stiff. Therefore, it is important that state agencies understand this and that specification tolerances be chosen appropriately.

Based on the work conducted for the SCB Flexibility Index, parameters that need special attention and should not deviate from the specification are:

1. Test Temperature
2. Loading Rate
3. Notch Width
4. Specimen Air Voids

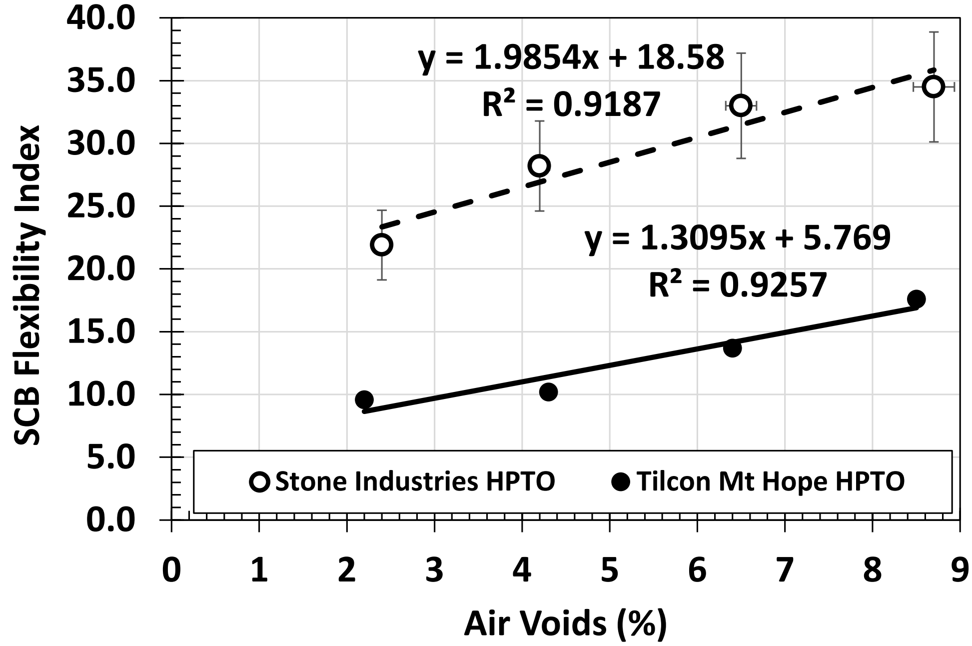


Figure 24 – Impact of Compacted Air Voids on Measured SCB Flexibility Index (HPTO Asphalt Mixture)

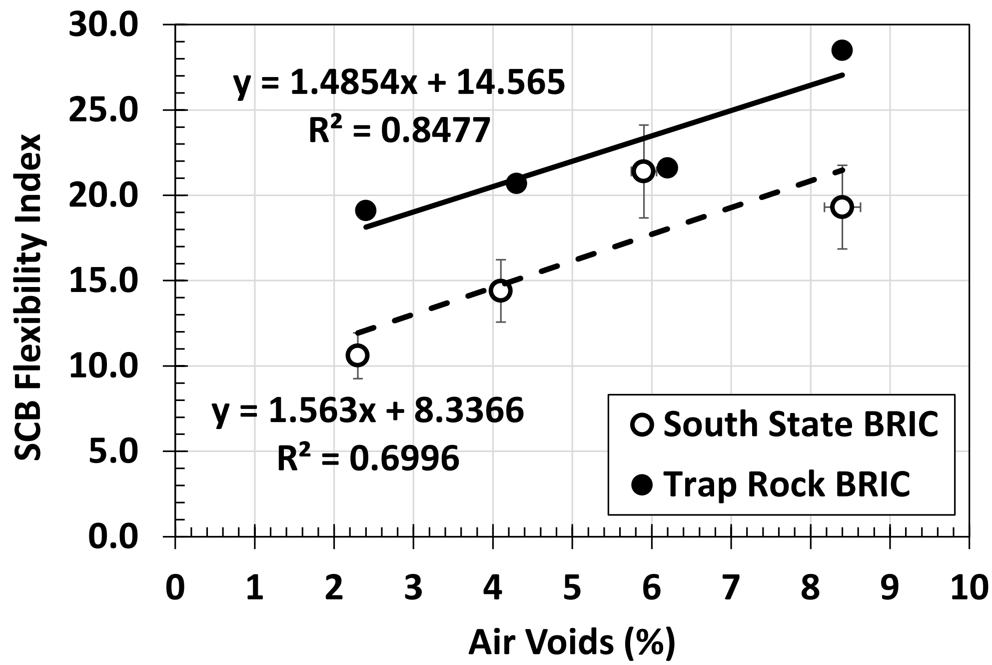


Figure 25 – Impact of Compacted Air Voids on Measured SCB Flexibility Index (BRIC Asphalt Mixture)

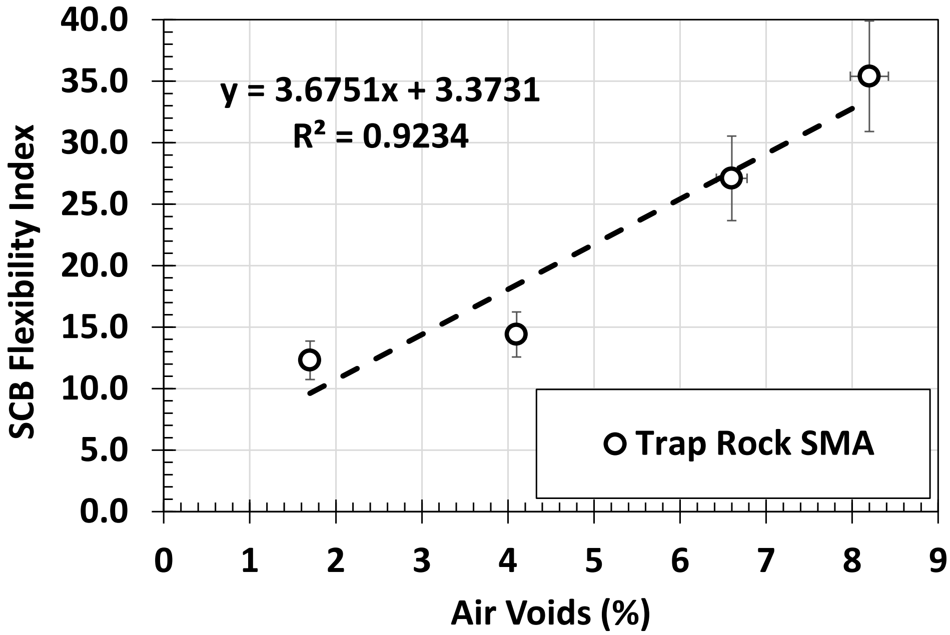


Figure 26 - Impact of Compacted Air Voids on Measured SCB Flexibility Index (SMA Asphalt Mixture)

LTRC SCB – Ruggedness Evaluation

The LTRC SCB test procedure was conducted in accordance with ASTM D8044, *Standard Test Method for Evaluation of Asphalt Mixture Cracking Resistance using the Semi-Circular Bend Test (SCB) at Intermediate Temperatures*. The test procedure requires the testing of asphalt specimens with three different notch depths, resulting in three times the number of test specimens as for the SCB Flexibility Index to determine the Critical Energy Release (Jc) parameter one single time. Therefore, to expedite the testing, two test specimens per notch depth were used and only a single Jc parameter was measured per "parameter" that was to be evaluated in the ruggedness study. This resulted in not being able to utilize the t-Test to evaluate the statistical difference of the test results. Therefore, the reported coefficient of variation (COV) of 20% was used to compare the test results (Mohammed et al., 2016). The 20% COV was applied to the "Standard" test specimens, and when the parameter result fell outside the 20% COV, it was determined that the parameter had a significant influence on the testing. This would result in the following Critical Strain Release (Jc) parameter ranges:

- For 4% air voids - being outside of 0.6414 and 0.9620 range being classified as being significant; and
- For 7% air voids - being outside of 0.3774 and 0.5660 range being classified as being significant.

As discussed earlier, two separate air void levels were used to determine if the parameters were significant or insignificant at different air void magnitudes that could potentially be used for different versions of specification implementation.

Specimen Thickness

The specimen thickness was evaluated as a parameter which may be influential with respect to measuring the Critical Strain Release (Jc) parameter from the LTRC SCB test. The results are shown in Tables 23 and 24. Using the COV as a means of comparing the test results, Tables 23 and 24 show that deviating by +/- 5.0 mm on the specimen thickness does not heavily influence the measurement of the LTRC SCB Jc parameter at the 4% air void level, but there was a significant difference at the 7% air void level.

Notch Depth

The LTRC SCB procedure utilizes three different notch depths, and for each notch depth, the Strain Energy is calculated and eventually used to determine Rate of Strain Change and Critical Strain Release (Jc). For the notch depth analysis, the specified notch depth was changed +/- 0.5 mm from the standard depth in an effort to evaluate its influence. Tables 25 and 26 show that for both air void levels, when the notch depth is too low, there is a significant difference in the results. However, the same was not true when the notch depth was +0.5 mm from the standard.

Table 23 – LTRC SCB Jc Parameter Results for Specimen Thickness @ 4% Air Voids

Specimen ID	Target Notch Depth (mm)	Actual Notch Depth (mm)	Air Voids (%)	Thickness (mm)	Max Load (kN)	Strain Energy (kJ)	Rate of Strain Change	Jc
4% AV - Thickness (-5mm)	25.4	25.6	3.8	52.4	1.29	0.001226	-0.0404	0.779
		25.5	3.8	52.2	1.04	0.000931		
	31.8	31.8	3.9	51.3	0.87	0.000728		
		31.8	3.9	51.6	0.89	0.000699		
	38.1	37.2	3.8	51.9	0.74	0.000639		
		38.1	3.8	51.5	0.59	0.000505		
4% AV - Thickness (57mm)	25.4	25.7	4.2	57.1	1.11	0.001067	-0.0461	0.802
			4.2					
	31.8	31.1	3.6	57.8	0.85	0.000883		
		32.1	3.6	57.8	1.00	0.000800		
	38.1	38.0	3.9	57.2	0.51	0.000512		
		37.3	3.9	57.5	0.66	0.000546		
4% AV - Thickness (+5mm)	25.4	25.7	4.1	63.0	1.29	0.001221	-0.0435	0.697
			4.1		1.04			
	31.8	32.3	3.8	62.9	0.87	0.000765		
		32.1	3.8	62.2	0.89	0.000983		
	38.1	38.0	3.9	61.9	0.74	0.000679		
		38.0	3.9	62.0	0.59	0.000673		

Table 24 – LTRC SCB Jc Parameter Results for Specimen Thickness @ 7% Air Voids

Specimen ID	Target Notch Depth (mm)	Actual Notch Depth (mm)	Air Voids (%)	Thickness (mm)	Max Load (kN)	Strain Energy (kJ)	Rate of Strain Change	Jc
7% AV - Thickness (-5mm)	25.4	25.9	7.1	52.2	0.76	0.000826	-0.038	0.729
		25.8	7.1	52.4	0.94	0.001073		
	31.8	31.5	6.2	51.7	0.81	0.000769		
		31.9	6.2	51.9	0.59	0.000524		
	38.1	37.5	6.7	52.3	0.50	0.000494		
		38.3	6.7	52.4	0.42	0.000492		
7% AV - Thickness (57mm)	25.4	25.8	6.9	57.6	0.96	0.000934	-0.0272	0.472
		25.8	6.9	57.5	0.94	0.000805		
	31.8	31.3	6.7	57.7	0.74	0.000651		
		32.2	6.7	57.8	0.74	0.000815		
	38.1	38.3	6.6	57.6	0.46	0.000417		
		37.8	6.6	57.8	0.69	0.000654		
7% AV - Thickness (+5mm)	25.4	25.3	6.5	62.4	1.07	0.001135	-0.04701	0.757
		25.7	6.5	62.2	1.17	0.001066		
	31.8	32.2	6.5	62.5	0.89	0.000920		
		31.0	6.5					
	38.1	38.2	7	61.8	0.47	0.000520		
		37.4	7.0	61.8	0.56	0.000516		

Table 25 - LTRC SCB Jc Parameter Results for Notch Depth @ 4% Air Voids

Specimen ID	Target Notch Depth (mm)	Actual Notch Depth (mm)	Air Voids (%)	Thickness (mm)	Max Load (kN)	Strain Energy (kJ)	Rate of Strain Change	Jc
4% AV - Notch Depth (-5mm)	20.4	20.3	4	57.8	1.62	0.001460388	-0.06443	1.118
		19.8	4	57.9	1.68	0.001684952		
	26.8	26.8	3.9	57.9	1.27	0.00107843		
		27.4	3.9	57.7	1.00	0.000892732		
	33.1	32.9	4	57.2	0.91	0.000631504		
		33.2	4.0	57.2	0.97	0.000863274		
4% AV - Notch Depth (Spec)	25.4	25.7	4.2	57.1	1.11	0.001067	-0.0461	0.802
			4.2					
	31.8	31.1	3.6	57.8	0.85	0.000883		
		32.1	3.6	57.8	1.00	0.000800		
	38.1	38.0	3.9	57.2	0.51	0.000512		
		37.3	3.9	57.5	0.66	0.000546		
4% AV - Notch Depth (+5mm)	30.4	30.6	3.8	57.9	1.11	0.00093115	-0.04057	0.703
		60.8	3.8	57.8	1.15	0.001002357		
	36.8	36.9	3.7	57.8	0.83	0.000627494		
		36.8	3.7	58.0	0.73	0.00065917		
	43.1	43.2	3.6	57.4	0.51	0.000605942		
		43.0	3.6	57.5	0.38	0.000314632		

Table 26 - LTRC SCB Jc Parameter Results for Notch Depth @ 7% Air Voids

Specimen ID	Target Notch Depth (mm)	Actual Notch Depth (mm)	Air Voids (%)	Thickness (mm)	Max Load (kN)	Strain Energy (kJ)	Rate of Strain Change	Jc
7% AV - Notch Depth (-5mm)	20.4	20.2	6.3	57.6	1.23	0.001205	-0.04829	0.836
		20.5	6.3	57.8	1.19	0.001289		
	26.8	27.5	6.5	57.6	0.78	0.000728		
		27.5	6.5	57.7	0.82	0.000941		
	33.1	32.9	6.6	58.0	0.66	0.000632		
		32.7	6.6	58.0	0.66	0.000673		
7% AV - Notch Depth (Spec)	25.4	25.8	6.9	57.6	0.96	0.000934	-0.0272	0.472
		25.8	6.9	57.5	0.94	0.000805		
	31.8	31.3	6.7	57.7	0.74	0.000651		
		32.2	6.7	57.8	0.74	0.000815		
	38.1	38.3	6.6	57.6	0.46	0.000417		
		37.8	6.6	57.8	0.69	0.000654		
7% AV - Notch Depth (+5mm)	30.4	30.6	6.5	57.7	0.73	0.000601	-0.02844	0.493
		30.6	6.5	57.9	0.92	0.000894		
	36.8	36.9	6.4	58.0	0.54	0.000538		
		36.8	6.4	58.0	0.58	0.000517		
	43.1	43.2	6.6	57.2	0.35	0.000378		
		43.3	6.6	57.5	0.38	0.000396		

Loading Rate

The loading rate of the LTRC SCB test procedure is 100 times slower than the SCB Flexibility Index. At a rate of 0.5 mm/min, the test method can be quite slow when considering it recommends testing a minimum of 6 test specimens with 9 test specimens suggested. The loading rate was varied +/- 0.125 mm/min with all of the required test parameters measured. The final results are shown in Table 27 and 28. The results suggest that at the slow loading rate of 0.5 mm/min, the variance of +/- 0.125 mm/min does not significantly influence the test results.

Table 27 - LTRC SCB Jc Parameter Results for Loading Rate @ 4% Air Voids

Specimen ID	Target Notch Depth (mm)	Actual Notch Depth (mm)	Air Voids (%)	Thickness (mm)	Max Load (kN)	Strain Energy (kJ)	Rate of Strain Change	Jc
4% AV - Loading Rate (0.375 mm/min)	25.4	25.1	4.1	57.4	1.22	0.001066	-0.04498	0.797
		25.7	4.1	57.3	1.17	0.001104493		
	31.8	31.6	4.1	56.2	0.93	0.000686		
		31.1	4.1	56.1	0.88	0.000626		
	38.1	38.0	3.8	55.9	0.69	0.000487		
		38.0	3.8	56.0	0.68	0.000537		
4% AV - Loading Rate (0.5 mm/min)	25.4	25.7	4.2	57.1	1.11	0.001067	-0.0461	0.802
			4.2					
	31.8	31.1	3.6	57.8	0.85	0.000883		
		32.1	3.6	57.8	1.00	0.000800		
	38.1	38.0	3.9	57.2	0.51	0.000512		
		37.3	3.9	57.5	0.66	0.000546		
4% AV - Loading Rate (0.625 mm/min)	25.4	25.4	4.4	56.0	1.42	0.001193	-0.04937	0.867
		25.6	4.4	56.1	1.29	0.000984		
	31.8	31.9	4	57.5	1.04	0.000926		
		31.6	4	57.4	0.85	0.000629		
	38.1	37.8	3.8	57.3	0.68	0.000516		
		37.8	3.8	57.3	0.64	0.000438		

Table 28 - LTRC SCB Jc Parameter Results for Loading Rate @ 7% Air Voids

Specimen ID	Target Notch Depth (mm)	Actual Notch Depth (mm)	Air Voids (%)	Thickness (mm)	Max Load (kN)	Strain Energy (kJ)	Rate of Strain Change	Jc
7% AV - Loading Rate (0.375 mm/min)	25.4	25.2	7	57.4	0.88	0.000902	-0.03095	0.545
		25.4	7	57.3	0.85	0.000816		
	31.8	31.7	6.6	56.2	0.59	0.000628		
		31.5	6.6	56.2	0.69	0.000781		
	38.1	38.3	6.7	56.7	0.52	0.000533		
		37.5	6.7	56.9	0.43	0.000399		
7% AV - Loading Rate (0.5 mm/min)	25.4	25.8	6.9	57.6	0.96	0.000934	-0.0272	0.472
		25.8	6.9	57.5	0.94	0.000805		
	31.8	31.3	6.7	57.7	0.74	0.000651		
		32.2	6.7	57.8	0.74	0.000815		
	38.1	38.3	6.6	57.6	0.46	0.000417		
		37.8	6.6	57.8	0.69	0.000654		
7% AV - Loading Rate (0.625 mm/min)	25.4	25.1	6.6	57.1	1.16	0.001174	-0.02999	0.523
		25.9	6.6	57.1	0.94	0.000905		
	31.8	32.0	7.1	57.1	0.76	0.000685		
		32.1	7.1	57.2	0.69	0.000680		
	38.1	38.4	6.9	57.5	0.41	0.000571		
		38.1	6.9	57.8	0.58	0.000767		

Test Temperature

The standard test temperature for the LTRC SCB test procedure is 25ºC, identical to the SCB Flexibility Index. In general, it would be expected that as test temperature increases, the asphalt mixture becomes "softer" and more resistant to cracking. In contrast, the colder the test temperature, the more brittle. The test temperature was varied +/- 2.5ºC (10%) to assess the influence of test temperature on the LTRC SCB Jc parameter. The results are shown in Tables 29 and 30. As expected for both air void levels, there is a significant influence on the measured Jc parameter when the test temperature is varied by 2.5ºC.

Table 29 - LTRC SCB Jc Parameter Results for Test Temperature @ 4% Air Voids

Specimen ID	Target Notch Depth (mm)	Actual Notch Depth (mm)	Air Voids (%)	Thickness (mm)	Max Load (kN)	Strain Energy (kJ)	Rate of Strain Change	Jc
4% AV - Temperature (22.5C)	25.4	25.7	3.8	56.5	1.84	0.001575	-0.06914	1.213
		25.9	3.8	56.5	1.71	0.001441		
	31.8	32.3	3.7	57.2	1.32	0.000996		
		32.9	3.7	57.4	1.35	0.000954		
	38.1	38.1	5.3	57.2	0.84	0.000719		
		38.0	5.3	57.1	0.75	0.000617		
4% AV - Temperature (25C)	25.4	25.7	4.2	57.1	1.11	0.001067	-0.0461	0.802
			4.2					
	31.8	31.1	3.6	57.8	0.85	0.000883		
		32.1	3.6	57.8	1.00	0.000800		
	38.1	38.0	3.9	57.2	0.51	0.000512		
		37.3	3.9	57.5	0.66	0.000546		
4% AV - Temperature (27.5C)	25.4	25.6	3.7	56.8	1.11	0.001051	-0.04226	0.742
		25.9	3.7	56.5	1.13	0.000993		
	31.8	32.7	4.2	57.6	0.82	0.000753		
		32.8	4.2	57.7	0.76	0.000668		
	38.1	38.3	4.1	56.7	0.55	0.000544		
		38.1	4.1	56.5	0.62	0.000454		

Table 30 - LTRC SCB Jc Parameter Results for Test Temperature @ 7% Air Voids

Specimen ID	Target Notch Depth (mm)	Actual Notch Depth (mm)	Air Voids (%)	Thickness (mm)	Max Load (kN)	Strain Energy (kJ)	Rate of Strain Change	Jc
7% AV - Temperature (22.5C)	25.4	25.4	6.8	56.5	1.19	0.001104	-0.0177	0.311
		25.5	6.8	56.5	1.06	0.000919		
	31.8	32.5	6.4	57.4	0.91	0.000844		
		32.5	6.4	57.3	0.85	0.001030		
	38.1	38.1	6.4	57.1	0.69	0.000759		
		38.4	6.4	57.0	0.70	0.000806		
7% AV - Temperature (25C)	25.4	25.8	6.9	57.6	0.96	0.000934	-0.0272	0.472
		25.8	6.9	57.5	0.94	0.000805		
	31.8	31.3	6.7	57.7	0.74	0.000651		
		32.2	6.7	57.8	0.74	0.000815		
	38.1	38.3	6.6	57.6	0.46	0.000417		
		37.8	6.6	57.8	0.69	0.000654		
7% AV - Temperature (27.5C)	25.4	25.4	6.5	57.3	0.91	0.000939	-0.03901	0.684
		26.1	6.5	57.2	0.79	0.000829		
	31.8	32.2	6.6	56.4	0.62	0.000589		
		32.6	6.6	56.5	0.57	0.000590		
	38.1	38.4	6.6	57.4	0.38	0.000384		
		38.2	6.6	57.3	0.37	0.000414		

Air Voids

The influence of compacted air voids was evaluated by comparing the measured air voids for the different test parameters and applying the 20% COV to determine if the difference in the measured LTRC SCB Jc parameter was significant. Figure 27 shows that 7 of the 10 comparisons were outside the 20% COV. This clearly indicates that the compacted air void level has a significant impact on the measured Jc parameter. In general, as the air voids decrease, the Critical Strain Release (Jc) increases (i.e. – increases in cracking resistance).

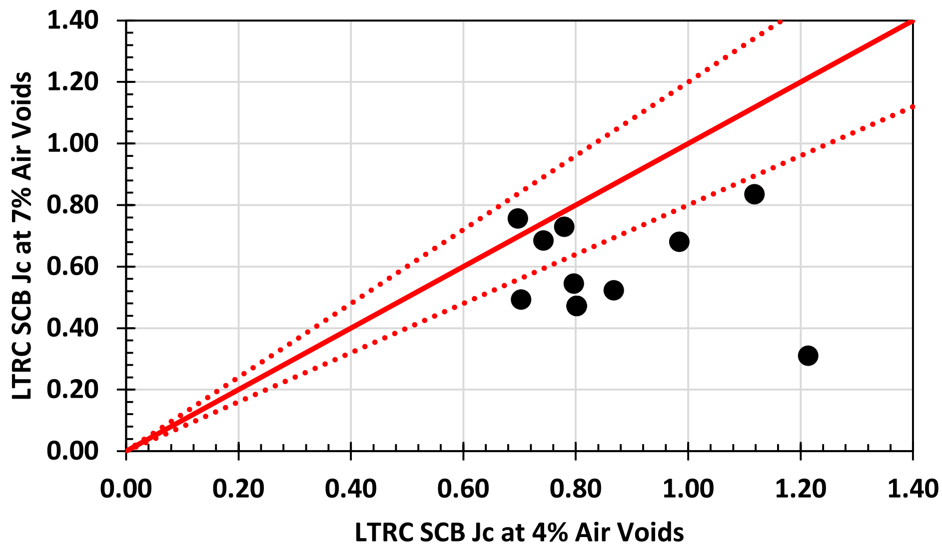


Figure 27 – Comparison of Compacted Air Voids on Impact of Critical Strain Release (Jc) Parameter

Summary of Modified Ruggedness Testing for LTRC SCB Critical Strain Release (Jc) Parameter

A modified ruggedness study was conducted using the LTRC SCB test procedure to determine the Critical Strain Release (Jc) parameter. As reported in the literature and noted earlier in the report, as the Jc parameter increases, the potential for fatigue cracking is supposed to decrease. A number of test parameters were evaluated to assess their respective impact on measuring the Jc parameter with their average values shown in Figures 28 and 29. Overall, it was found that the following parameters had a significant impact:

1. Specimen thickness;
2. Notch Depth;
3. Test Temperature; and
4. Specimen Air Voids

It is highly recommended that the above test parameters be rigorously enforced and followed when conducting the ASTM D8044 test method.

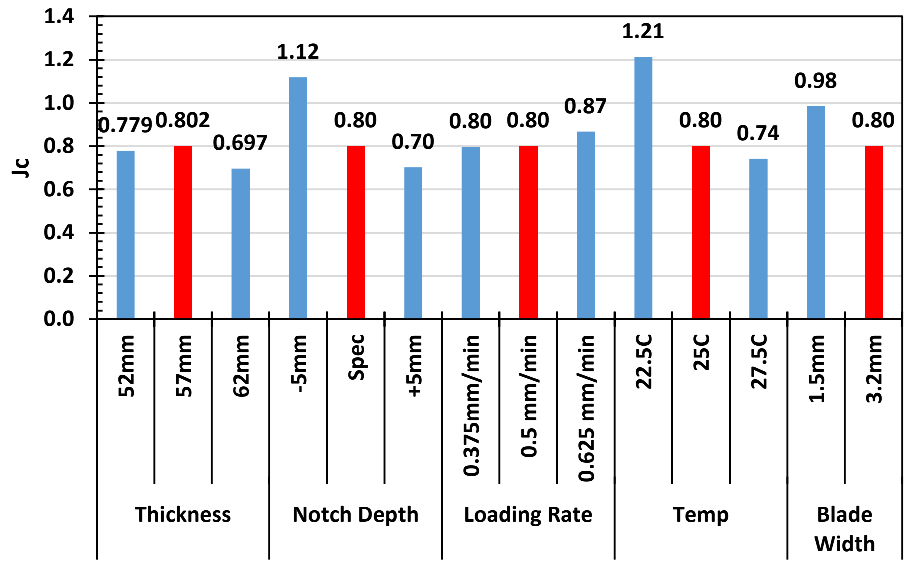


Figure 28 – Average Results for LTRC SCB Critical Strain Release (Jc) Parameter @ 4% Air Voids

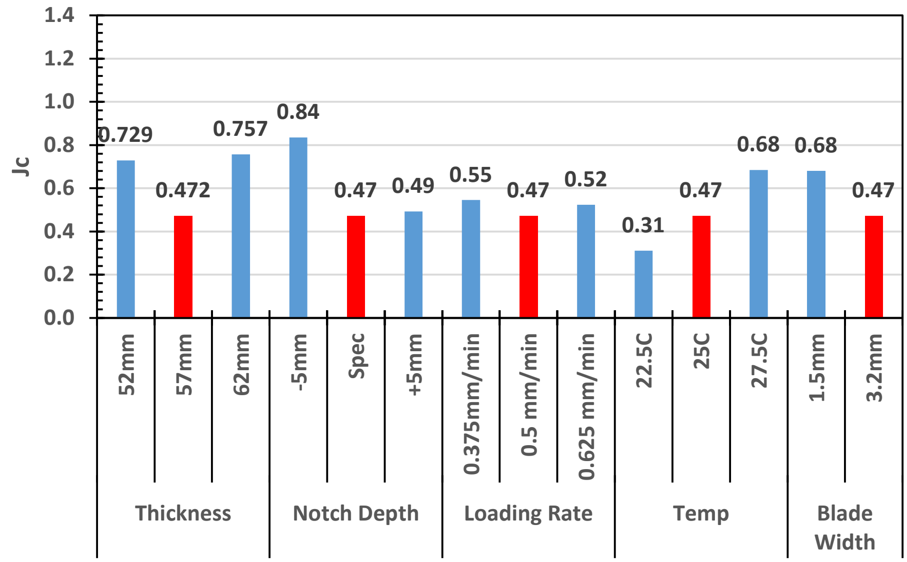


Figure 29 - Average Results for LTRC SCB Critical Strain Release (Jc) Parameter @ 7% Air Voids

TASK 2 – SCB FLEXIBILITY INDEX CORRELATION TO THE OVERLAY TESTER AND SIGNIFICANCE OF ASPHALT MATERIAL PARAMETERS

In the Literature Review and Task 1, the SCB Flexibility Index (AASHTO TP124) and the LTRC SCB (ASTM D8044) were compared to one another regarding general use, correlation to field performance and sensitivity to test parameters. Based on discussions with the NJDOT Materials Bureau, the LTRC SCB test procedure was no longer evaluated in the study due to the slower testing time, larger number of required test specimens, and conflicting performance reported in the literature. Therefore, the remainder of the research study and report focuses solely on the SCB Flexibility Index (AASHTO TP124).

SCB Flexibility Index Correlation to the Overlay Tester

A database of SCB Flexibility Index (AASHTO TP124) and Overlay Tester (NJDOT B-10) was developed during the length of this research study. Companion SCB and Overlay Tester specimens were compacted to the same air void level for each asphalt mixture evaluated. In total, there were 98 sets of companion samples of the identical asphalt mixture using triplicate testing for averaging purposes. Figure 30 shows the results of the comparison testing. The correlation coefficient (R^2) was found to be 0.78, which indicates a good relationship between the two intermediate temperature fatigue cracking test procedures.

With the goal of the task to develop a tentative performance criteria using the SCB Flexibility Index, a 20% “factor of safety” was applied to the trendline to take into consideration the reported coefficient of variation within the test method. The resulting increase is graphically shown in Figure 31 along with the original trendline shown earlier. Now that the coefficient of variation was applied to the trendline, the relationship shown in Figure 31 was used to develop equivalent SCB Flexibility Index criteria that matches the current Overlay Tester. Table 31 shows the existing Overlay Tester criteria and the resultant SCB Flexibility Index criteria. The results show that a minimum SCB Flexibility Index for any asphalt mixture designed for NJDOT should be 6.0. Meanwhile, the minimum SCB Flexibility Index for any asphalt mixture placed on the roadway surface should be 9.0. Both the HPTO and BRIC asphalt mixtures show a much higher requirement for the SCB Flexibility Index with minimum design values of 15.0 and 16.0, respectively.

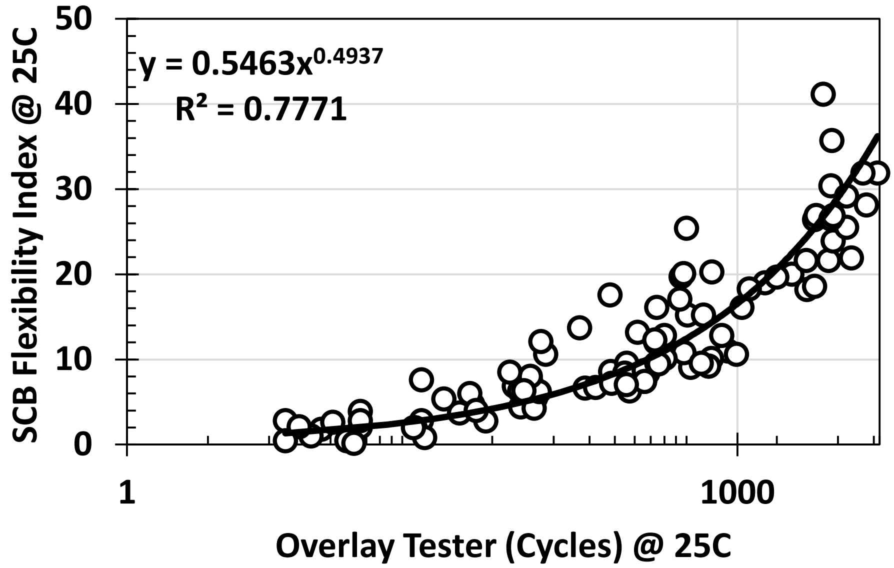


Figure 30 – Relationship Between SCB Flexibility Index (AASHTO TP124) and Overlay Tester (NDOT B-10)

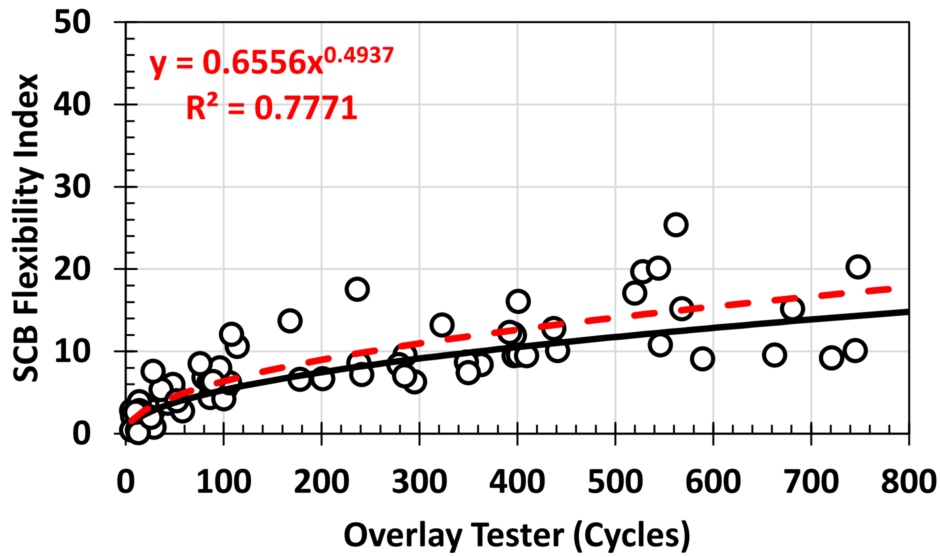


Figure 31 – Overlay Tester and SCB Flexibility Index Relationship with Proposed Specification

Table 31 – Fatigue Cracking Specifications for NJDOT Specialty Mixes

<table>
<tr><th colspan="3">Mixture Type</th><th>Min. Cycles in Overlay Tester</th><th>Min. SCB Flexibility Index (Rounded)</th></tr>
<tr><td rowspan="4">HRAP</td><td rowspan="2">Surface</td><td>76-22</td><td>275</td><td>10.0</td></tr>
<tr><td>64-22</td><td>200</td><td>9.0</td></tr>
<tr><td rowspan="2">Intermediate/ Base</td><td>76-22</td><td>150</td><td>8.0</td></tr>
<tr><td>64-22</td><td>100</td><td>6.0</td></tr>
<tr><td rowspan="2">BRIC</td><td colspan="2">Mixture Design</td><td>700</td><td>17.0</td></tr>
<tr><td colspan="2">Production</td><td>650</td><td>16.0</td></tr>
<tr><td rowspan="2">HPTO</td><td colspan="2">Mixture Design</td><td rowspan="2">600</td><td rowspan="2">15.0</td></tr>
<tr><td colspan="2">Production</td></tr>
</table>

Significance of Asphalt Material Parameters on SCB Flexibility Index

Selected asphalt mixtures that were collected during the study were utilized to evaluate the importance of various asphalt material properties on the SCB Flexibility Index. A total of 36 different asphalt mixtures were in the analysis and include:

- 17 different dense graded asphalt mixture from various asphalt suppliers using different asphalt binder grades and sources;
- 3 HPTO asphalt mixture from three different asphalt suppliers;
- 7 different HRAP asphalt mixtures from four different asphalt suppliers;
- 5 different BRIC asphalt mixtures from four different asphalt suppliers; and
- 4 different SMA asphalt mixtures from three different asphalt suppliers (4 different asphalt plants).

Table 32 shows the list of asphalt mixtures, their resultant SCB Flexibility Index and their respective asphalt mixture and binder properties evaluated.

The Regression tool in Microsoft Excel© was utilized to determine which asphalt mixture and binder properties were statistically significant to the SCB Flexibility Index at a 95% confidence level. The results of the analysis are shown in Table 33. Based on the database used, the following properties were found to have the most significant influence on the SCB Flexibility Index:

1. BBR Stiffness (S) after 40 Hr PAV Conditioning;
2. Intermediate Temperature PG Grade;
3. BBR Stiffness (S) after 20 Hr PAV Conditioning;
4. Total Asphalt Content;
5. Effective Asphalt Content by Volume; and
6. % Recovery from the MSCR test @ 64C.

Table 32 – Database of SCB Flexibility Index Values and Material Parameters

Mix Type	Supplier/Mix Description	SCB	QC AC%	Eff AC by Vol	HT	Int	20 Hr, S	20 Hr, m	20 Hr, ΔTc	Jnr	%Rec	40 Hr, S	40 Hr, m	40 Hr, ΔTc
DGA	I-5	8.6	5.92	13.6	82.9	23.4	-26.8	-26.7	-0.1	0.124	58.1	-25.6	-21.4	-4.2
	I-4	9.6	5.42	12.2	71.7	21.7	-28.4	-28.7	0.3	1.45	9.95	-26.9	-24.6	-2.3
	FAA #2	7.5	5.14	12.2	89	22.4	-27.4	-28	0.6	0.054	74.9	-25.7	-21.5	-4.2
	I-4A	7.4	4.57	11.1	83.5	22.6	-28.8	-32.4	3.6	0.135	61.7	-25.7	-20.1	-5.6
	I-4A	6.6	4.85	11.2	82.3	23.5	-26.4	-26.3	-0.1	0.179	58.4	-26.1	-19.4	-6.7
	FAA #2	12.1	5.46	12.2	71.5	22.5	-28.5	-26.9	-1.6	1.57	3.76	-26.4	-23.3	-3.1
	I-5A	20.3	6.46	13.6	82.6	22.8	-26.8	-25.9	-0.9	0.177	57.1	-26.5	-22.2	-4.3
	FAA #2	9.1	5.37	12.4	79.4	22.6	-27.2	-26.3	-0.9	0.322	47.7	-25.8	-21.7	-4.1
	PA-4	11.0	5.58	12.2	79.5	23	-28.1	-26.6	-1.5	0.301	48.1	-26.8	-22.1	-4.7
	12.5M64 Stone Industries	13.8	5.39	12	74.4	21.9	-27	-23.3	-3.7	0.987	6.8			
	12.5M64 TRI Keasby	9.5	4.6	11.5	69.6	22.5	-25.2	-25.4	0.2	1.980	0.8			
	12.5ME TRI Keasby	6.4	5.19	11.4	83.1	22.9	-26.3	-26.4	0.1	0.199	52.4			
	Winslow 12.5ME	5.3	4.61	10.1	83.4	23.3	-26.4	-23.5	-2.9	0.2049	45.9			
	12.5ME Hybrid AE Stone	7.3	5.32	12.5	87.5	23.9	-26.4	-22.4	-4	0.09	63.7	-24.7	-10	-14.7
	12.5ME AE Stone	9.1	5.37	11.8	85.9	24.8	-26.2	-23.7	-2.5	0.119	60.5	-24.7	-18.6	-6.1
	South State 9.5M64R15	16.9	5.29	11.1	70.1	22.9	-25.8	-25.9	0.1	2.066	1			
	FAA #3 with Vestoplast	6.9	5.71	12.9	71.8	23.5	-24.1	-22.3	-1.8	1.503	4.921	-23.2	-19.1	-4.1
HPTO	Stone Ind 2015	29.2	7.15	18	85.1	22.7	-28.3	-22	-6.3	0.054	86.6	-26.4	-18.7	-7.7
	South State Downer HPTO	15.8	7.33	15.7	86.6	21.6	-28.5	-25.5	-3.0	0.083	70.1			
	Til Mt Hope 2015	10.1	7.11	15	89.3	25.9	-25.2	-22.1	-3.1	0.048	74.2	-24.8	-14.9	-9.9
HRAP	Pierson 9.5M 20%	0.4	5.69	13	100.3	36.1	-20.6	-14.1	-6.5	0.013	74.4	-20	-6.3	-13.7
	Pierson 12.5M 30%	8.4	5.6	12.9	76.6	25.8	-25.7	-23.4	-2.3	0.664	10	-24.9	-20.1	-4.8
	Pierson 12.5M 40%	7.2	5.74	11.5	76.8	23	-26.4	-25.2	-1.2	0.717	7.1	-25.8	-21.1	-4.7
	Stavola 50%	2.0	4.56	9.9	81.4	24.6	-26.5	-21.9	-4.6	0.338	18.4	-24.6	-16.3	-8.3
	Stone Industries 30%	6.7	5.96	12.8	80.6	25.8	-25.5	-23.3	-2.2	0.400	14.2	-24.5	-18.2	-6.3
	Mt. Hope 9.5M 30%	0.2	5.05	12.3	83.1	29.3	-24	-22.7	-1.3	0.270	15.8	-23.6	-15.8	-7.8
	Mt. Hope 12.5M 40%	0.8	5.47	11.6	82.5	29.5	-21.8	-19	-2.8	0.301	13.8	-21.2	-14.3	-6.9
BRIC	South State 2013	9.2	7.01	17.8	87.6	22.8	-27.3	-27.5	0.2	0.048	81.8	-26.5	-21	-5.5
	Stavola 2014	18.2	8.35	16.9	88.4	21.3	-27.3	-27.3	0	0.038	86.5	-26.9	-20.2	-6.7
	Til North Berg 2012	7.1	7.19	14.1	90.1	24.8	-27.4	-23.9	-3.5	0.018	83.3	-27.1	-15	-12.1
	Trap Rock 2018	20.7	7.55	17.8	81.6	19.2	-28.9	-28.3	-0.6	0.090	81.3			
	Trap Rock 2015	13.3	8.51	20.1	89.1	20.6	-28.6	-25.3	-3.3	0.035	83.4	-27.8	-16.4	-11.4
SMA	AE Stone	14.9	5.8	12.3	87	22.9	-28	-23.8	-4.2	0.064	73.6	-26.6	-17.9	-8.7
	TRI WMA SMA	23.2	6.14	12.4	83.3	22.3	-27.8	-25	-2.8	0.127	66.8			
	Stone Industries	11.3	5.98	12.8	81.8	23.6	-27.7	-24.7	-3.0	0.150	69.1			
	TRI Mt. Holly	21.1	5.84	12.3	81.2	21.3	-26.8	-28.5	1.7	0.227	55.6			

Table 33 – Statistical Analysis of Asphalt Material Parameters and Significance to SCB Flexibility Index Value

Asphalt Mixture/Binder Parameter	Pierson Correlation Coefficient	P-value	Statistical Significance (95% Confidence)
BBR Stiffness (S), 40 Hr PAV	**0.6224**	**0.0007**	**Significant[2]**
Intermediate Temperature PG Grade	**0.6108**	**0.0001**	**Significant[1]**
BBR Stiffness (S), 20 Hr PAV	**0.5793**	**0.0002**	**Significant[1]**
Total Asphalt Content	**0.5205**	**0.0011**	**Significant[1]**
Effective Asphalt Content by Volume	**0.4800**	**0.0031**	**Significant[1]**
MSCR % Recovery at 64C	**0.3484**	**0.0373**	**Significant[1]**
BBR m-value (m), 20 Hr PAV	**0.3452**	**0.0392**	**Significant[1]**
BBR m-value (m), 40 Hr PAV	**0.3960**	**0.0452**	**Significant[2]**
BBR ΔTc, 40 Hr PAV	0.1567	0.4447	Not Significant
MSCR Jnr Value @ 64C	0.0229	0.8948	Not Significant
High Temperature PG Grade	0.0919	0.5938	Not Significant
BBR ΔTc, 20 Hr PAV	0.0124	0.9426	Not Significant

[1] Data set of n = 36
[2] Data set of n = 26

The above asphalt mixture and binder properties found to be statistically significant were used to develop a predictive equation for the SCB Flexibility Index parameter. Equation 1 and Figure 32 show the resultant regression equation. Overall, there is a fairly good agreement between the measured and predicted SCB Flexibility Index. The average difference between the measured and predicted SCB Flexibility Index is 2.3 using Equation 1.

$$SCB\ FI = 42.905 + (5.0406 \cdot AC\%) + (-1.7889 \cdot EACV) + (36.7813 \cdot Int\ PG) + (-0.0283 \cdot LT_m) + \left[-1.7077 \cdot \left(\frac{Z}{100}\right)^2\right] \quad (1)$$

Where,

SCB FI = SCB Flexibility Index
AC% = Total Asphalt Content by Mass of Mixture (%)
EACV = Effective Asphalt Content by Volume (%)
Int PG = Continuous Intermediate Temperature PG Grade (^{o}C)
LT_m = Continuous Low Temperature PG Grade Determined Using the BBR m-value (^{o}C)
Z = Difference Between the Measured MSCR % Recovery and the MSCR Elastomer Line

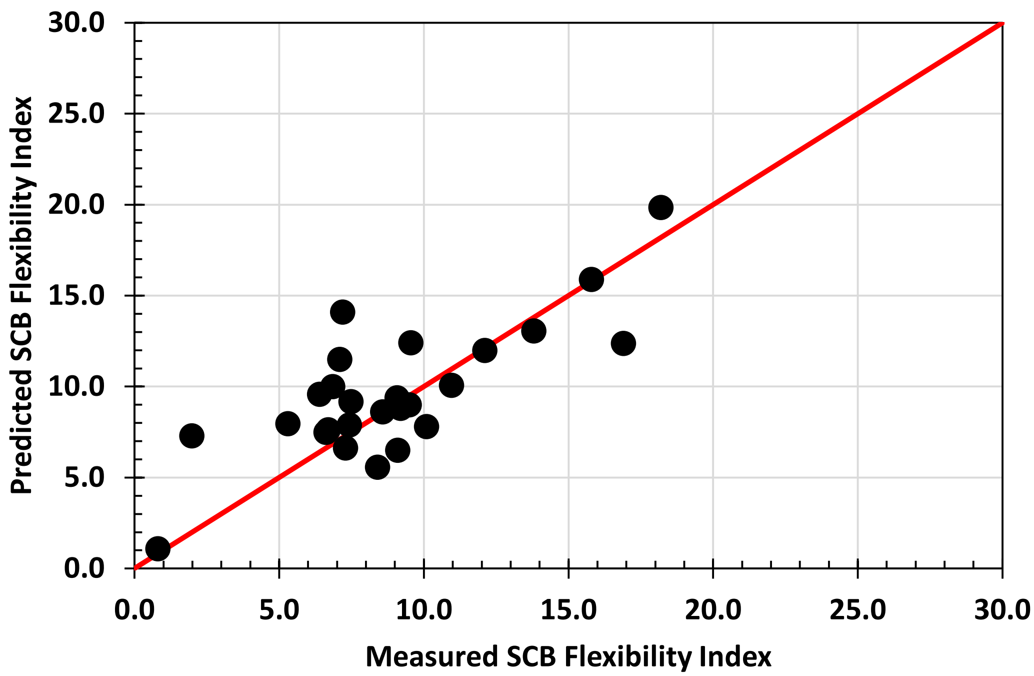


Figure 32 – Predicted SCB Flexibility Index Values Based on Asphalt Mixture and Binder Properties

TASK 3 – FLEXIBILITY INDEX ROUND ROBIN STUDY

In an effort to evaluate the potential multiple user variability of the SCB Flexibility Index test procedure, laboratories were requested to conduct the testing of three different asphalt mixtures, produced to achieve various levels of SCB Flexibility Index values. Five different laboratories were provided three compacted gyratory samples for each of the three asphalt mixtures evaluated. Each laboratory was asked to cut and trim two test specimens from the middle of each gyratory specimen, while testing four of the resultant specimens and keeping the remaining two in case there were issues with specimen fabrication and testing. The five testing laboratories involved in the round robin were:

1. Rutgers Asphalt Pavement Laboratory
2. John J. Hughes FAA Technical Center in Atlantic City, NJ
3. Trap Rock Industries, Kingston, NJ
4. Port Authority of NY/NJ
5. Texas Transportation Institute (TTI)

Round Robin Asphalt Mixtures' Gradation and Volumetric Properties

Two different plant produced asphalt mixtures were used in the study: 1) High Performance Thin Overlay (HPTO) from Tilcon Mt. Hope and 2) 12.5ME from Trap Rock Industries. Plant produced asphalt mixtures were used to simulate the collecting and reheating process that would be followed if the SCB Flexibility Index test were to be included in the NJDOT specifications.

The asphalt mixtures were reheated at compaction temperature for two hours prior to specimen compaction. The 12.5ME test specimens were targeted for air void levels of 6.0% +/- 0.5% when measured prior to cutting. Meanwhile, the HPTO test specimens were targeted for air void levels of 5.0% +/- 0.5%. The HPTO asphalt mixture was also long term aged to provide a 3rd "different" asphalt mixture for evaluation. The HPTO asphalt mixture was loose mix conditioned for 24 hours at a temperature of 135^{o}C. After the conditioning process was completed, the long term conditioned loose mix was compacted into gyratory specimens targeting the same air voids as noted earlier. All laboratories were asked to determine the bulk specific gravity of each of the test specimens prior to testing.

During sample fabrication, every 5th gyratory specimen compacted was used for quality control testing. Asphalt content, gradation, and maximum specific gravity were measured to evaluate the consistency of the asphalt material. Since the asphalt mixtures were plant produced, it was important that the asphalt mixture did not change over the time of production and therefore potentially influence the SCB Flexibility Index values.

To determine the material properties, the gyratory specimens batched out for the 5th specimen was not compacted, just simply allowed to cool after the oven conditioning period had concluded. Once cooled, the specimen was split to provide a maximum specific gravity (AASHTO T209) sample and an ignition oven sample (AASHTO T308). The recovered aggregates from the ignition oven sample was then used to determine the aggregate gradation of the asphalt mixture. Loose mix samples were randomly selected for SCB specimens and QC specimens in an attempt to minimize any bias.

Maximum Specific Gravity (Gmm)

The QC test results for the asphalt content are shown in Figure 33. The test results indicate good consistency with the different asphalt mixtures tested in the study. Mix A had an average asphalt content of 4.9% with a standard deviation of 0.11%. Meanwhile, Mix B and C had asphalt contents of 7.27% and 7.19%, with both mixtures showing the same standard deviation of 0.09%.

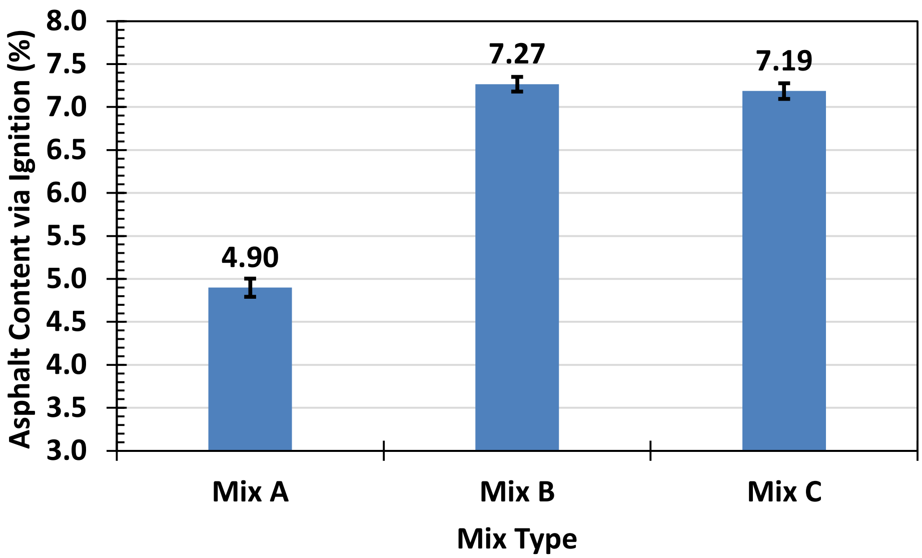


Figure 33 – Asphalt Content of SCB Flexibility Index Asphalt Mixtures

Maximum Specific Gravity, Gmm (AASHTO T209)

The results of the maximum specific gravity (Gmm) QC testing are shown in Figure 34. The testing shows the Mix A had the largest Gmm value of 2.746 while the HPTO asphalt mixture was found to be 2.413. The trend in results were expected as Mix A had the lowest asphalt content compared to the HPTO (Mix B and C). The standard deviation of the Gmm results were very low, 0.050 for Mix A and Mix C and 0.080 for Mix B, showing the mixtures were produced with good consistency.

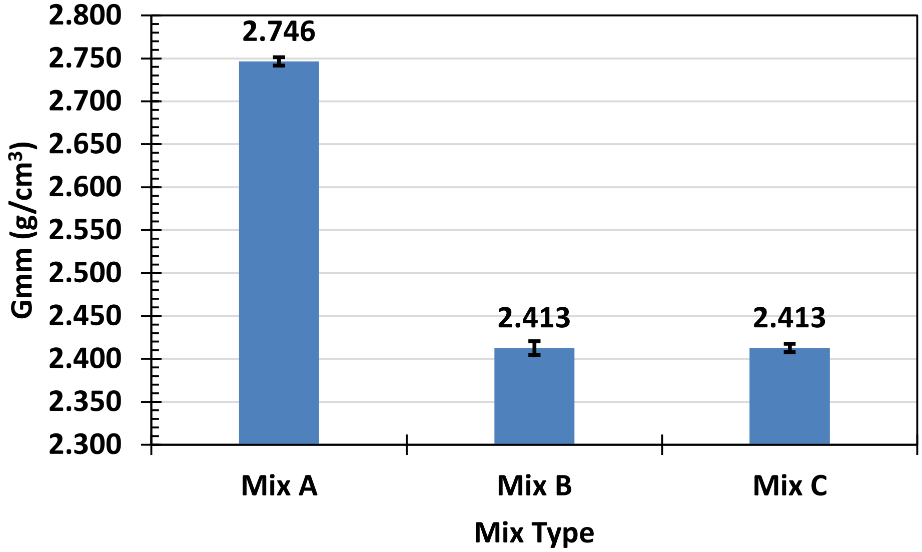


Figure 34 – Maximum Specific Gravity (Gmm) Results from SCB Flexibility QC Testing

Aggregate Gradations of Round Robin Mixtures

The aggregates recovered from the ignition oven tests were tested in accordance with AASHTO T30, *Standard Method of Test for Mechanical Analysis of Extracted Aggregate*. The test results are shown in Tables 34 to 36 for Mix A, Mix B, and Mix C, respectively. The test results showed relatively good consistency with some higher variability found on the #4 sieves for all three mixtures, as well as the 9.5 mm sieve for Mix A.

Table 34 – Summary of Mixture Aggregate Gradation for SCB Mixture A

Sieve Opening (mm)	Percent Passing (%)					Average	Std Dev
50.0	100.0	100.0	100.0	100.0	100.0	100.0	0.00
37.5	100.0	100.0	100.0	100.0	100.0	100.0	0.00
25.0	100.0	100.0	100.0	100.0	100.0	100.0	0.00
19.0	100.0	100.0	100.0	100.0	100.0	100.0	0.00
12.5	93.2	92.4	93.6	96.0	95.2	94.1	1.45
9.5	79.5	80.3	79.9	82.5	84.8	81.4	2.23
4.8	58.5	57.7	57.9	59.9	62.8	59.4	2.11
2.4	45.6	45.2	44.9	46.6	48.5	46.2	1.48
1.2	33.5	33.2	33.2	34.2	35.3	33.9	0.92
0.6	24.8	24.6	24.6	25.2	26.2	25.1	0.67
0.3	18.0	17.9	17.9	18.2	19.0	18.2	0.48
0.15	12.4	12.3	12.2	12.4	13.0	12.5	0.34
0.075	7.5	7.4	7.4	7.4	7.9	7.5	0.22

Table 35 – Summary of Mixture Aggregate Gradation for SCB Mixture B

Sieve Opening (mm)	Percent Passing (%)					Average	Std Dev
50.0	100.0	100.0	100.0	100.0	100.0	100.0	0
37.5	100.0	100.0	100.0	100.0	100.0	100.0	0
25.0	100.0	100.0	100.0	100.0	100.0	100.0	0
19.0	100.0	100.0	100.0	100.0	100.0	100.0	0
12.5	100.0	100.0	100.0	100.0	100.0	100.0	0
9.5	100.0	100.0	99.6	100.0	100.0	99.9	0.17
4.8	70.5	75.9	73.2	70.2	74.5	72.9	2.50
2.4	37.1	40.4	38.8	37.4	39.4	38.6	1.37
1.2	26.3	28.2	27.7	26.2	28.2	27.3	1.00
0.6	19.0	20.1	20.3	18.7	20.7	19.8	0.87
0.3	13.4	13.8	14.5	13.0	14.9	13.9	0.80
0.15	8.7	8.8	9.7	8.3	10.0	9.1	0.70
0.075	5.2	5.3	6.0	4.9	6.2	5.6	0.56

Table 36 – Summary of Mixture Aggregate Gradation for SCB Mixture C

Sieve Opening (mm)	Percent Passing (%)					Average	Std Dev
50.0	100.0	100.0	100.0	100.0	100.0	100.0	0
37.5	100.0	100.0	100.0	100.0	100.0	100.0	0
25.0	100.0	100.0	100.0	100.0	100.0	100.0	0
19.0	100.0	100.0	100.0	100.0	100.0	100.0	0
12.5	100.0	100.0	100.0	100.0	100.0	100.0	0
9.5	100.0	99.9	99.8	99.8	99.8	99.9	0.10
4.8	77.5	77.6	76.5	76.4	70.7	75.7	2.88
2.4	41.8	42.1	40.1	41.0	39.3	40.9	1.16
1.2	29.2	29.6	28.1	28.8	27.7	28.7	0.76
0.6	20.9	21.2	20.3	20.7	19.7	20.5	0.59
0.3	14.5	14.8	14.2	14.4	13.6	14.3	0.45
0.15	9.3	9.5	9.1	9.2	8.7	9.1	0.32
0.075	5.6	5.9	5.5	5.6	5.2	5.6	0.23

Round Robin SCB Flexibility Index Results

As discussed earlier, gyratory compacted samples were randomly selected and provided to five different laboratories for SCB Flexibility Index testing. All testing was conducted in accordance with AASHTO TP124, *Standard Method of Test for Determining the Fracture Potential of Asphalt Mixtures Using Semicircular Bend Geometry (SCB) at Intermediate Temperature*, at a test temperature of 25^{o}C. Laboratories were requested to condition all test specimens for 4 to 6 hours at test temperature. Each laboratory was requested to determine the SCB Flexibility Index using the equations from AASHTO TP124.

The results of the SCB Flexibility Index testing for Mix A, B, and C are shown in Figures 35, 36, and 37, respectively. Included in the figures are the average value recorded, standard deviation of the four specimens measured, the average SCB Flexibility Index for all specimens tested of that mix and the resultant standard deviation for all specimens tested of that respective mix.

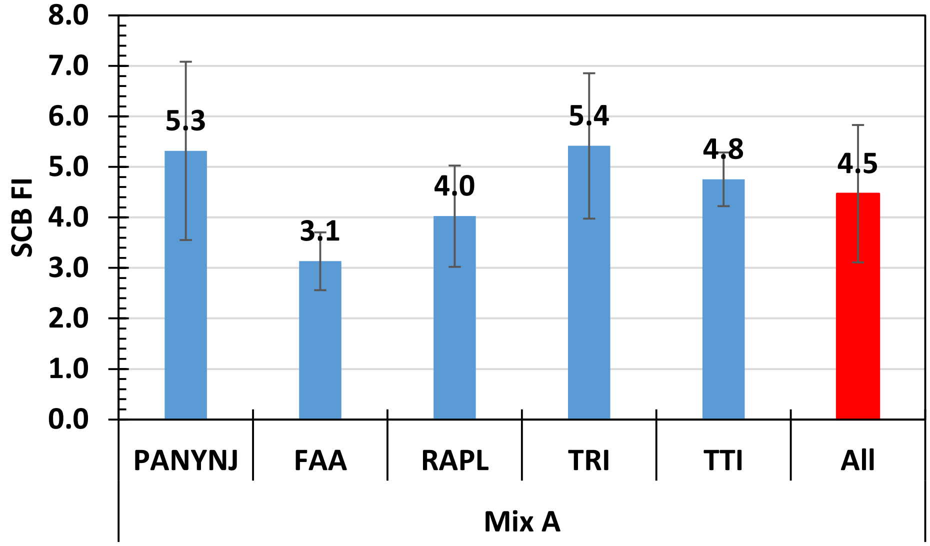


Figure 35 – SCB Flexibility Index Results for Mix A

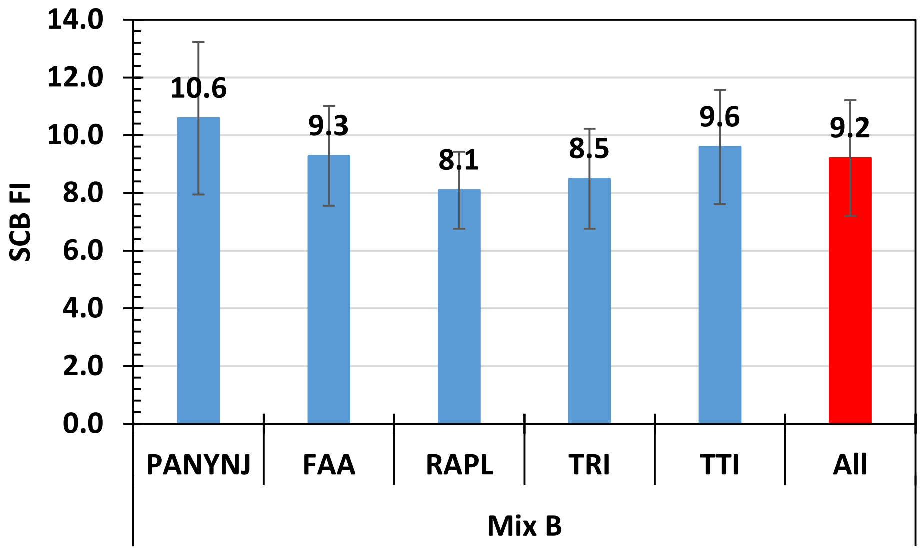


Figure 36 – SCB Flexibility Index Results for Mix B

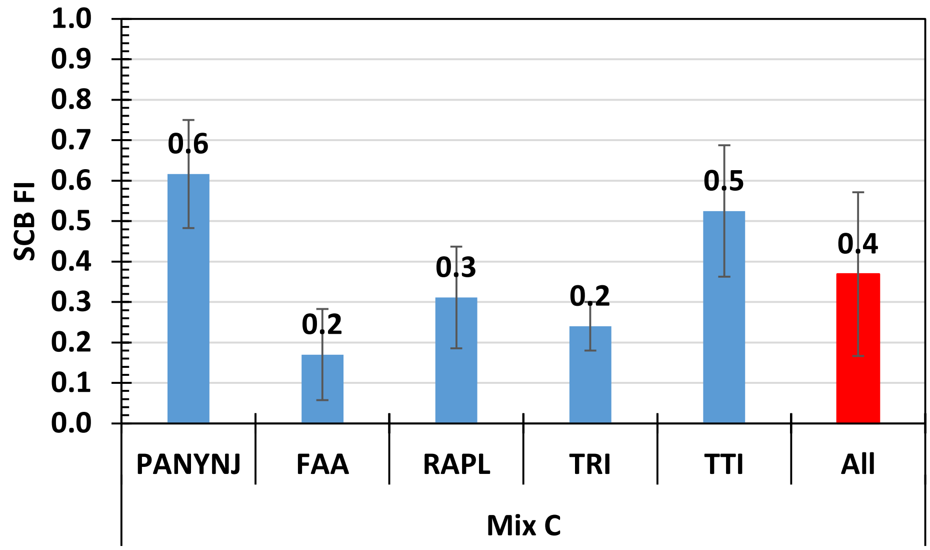


Figure 37 – SCB Flexibility Index Results for Mix C

The results of the round robin testing indicated that:

1. The average Single Operator coefficient of variation was 26.7%. However, Mix C had the largest variability due to its severe brittleness. If Mix C was taken out of the Single Operator analysis, the coefficient of variation would reduce to 21.5%.
2. The average Multiple Operator coefficient of variation was 35.7%. But once again, due to the high variability associated with the extremely low SCB Flexibility values of Mix C, if the Mix C values were ignored in the analysis, the Multiple Operator coefficient of variation would reduce to 26.1%.

The round robin testing highlights the potential issue with testing brittle or aged asphalt mixtures with the SCB Flexibility Index. The brittle and sudden failure of these materials during testing makes it difficult for accurately determining the post peak slope of the load-deformation curve.

Influence of Measured Air Voids on Round Robin SCB Flexibility Index

As discussed in Chapter 2, specimen air voids can have an influence on the measured SCB Flexibility Index. As the air voids increase, so does the SCB Flexibility Index. Therefore, it was of interest to determine if there was any correlation between the measured specimen air voids and the SCB Flexibility Index.

Figures 38 to 40 show the resultant relationship between the specimen air voids and the measured SCB Flexibility Index. It would appear that Mix A was the most affected by the specimen air voids with little to no relationship found with Mix B and Mix C. For Mix

A, the 12.5ME asphalt mixture, the trendline shows that within a 1% air void range (5.5 to 6.5%), the SCB Flexibility Index had a range of 1.7. The 1% air void range is already a very tight tolerance when considering to produce the specimen, you need to measure the outside air voids of a compacted gyratory sample and assume it is within the required specification tolerance.

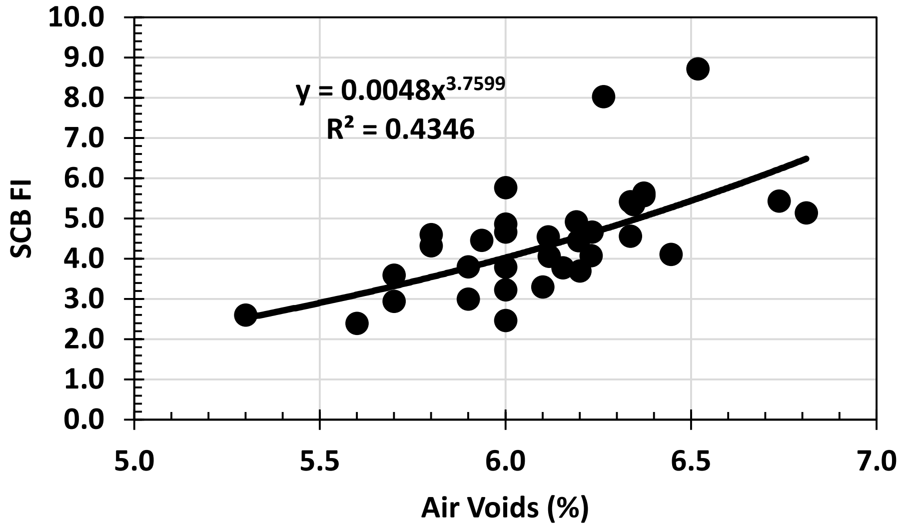


Figure 38 – Specimen Air Voids vs SCB Flexibility Index for Mix A

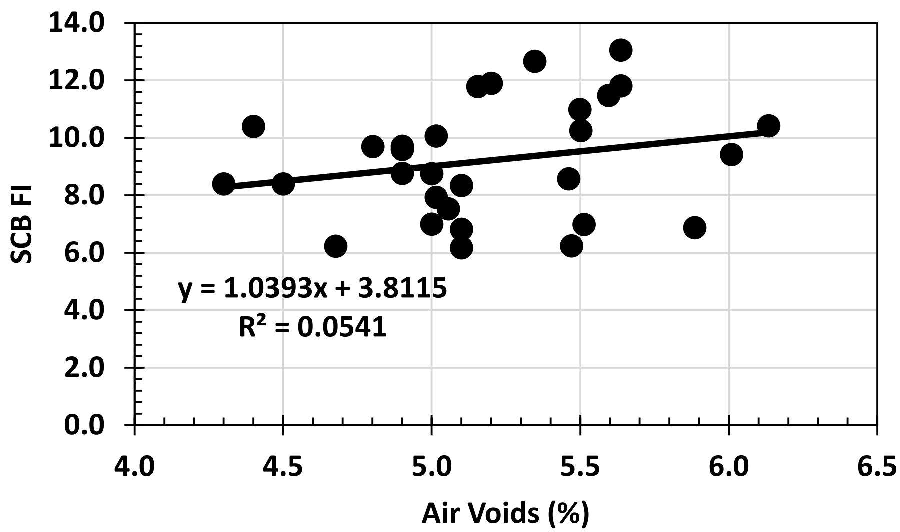


Figure 39 – Specimen Air Voids vs SCB Flexibility Index for Mix B

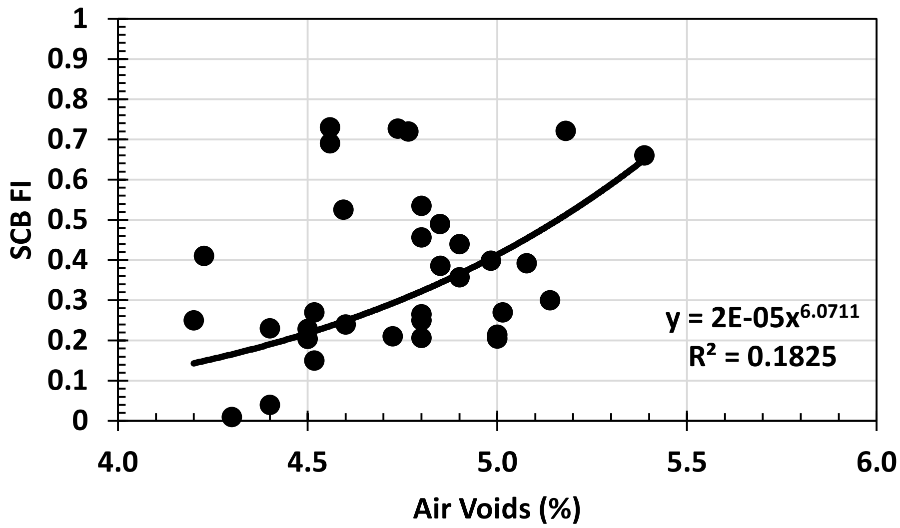


Figure 40 – Specimen Air Voids vs SCB Flexibility Index for Mix C

TASK 4 – EVALUATING SCB FLEXIBILITY INDEX WITH PAVEMENT-ME PAVEMENT PREDICTIONS

Background on Modeling of Reflective Cracking

The basic mechanism of reflection cracking is the propagation of cracks through the flexible overlay due to horizontal and vertical movements in the vicinity of cracks and joints in the underlying concrete pavement. These movements are caused by vehicular loading, temperature and moisture variations, or the combination of both, as shown in Figure 41. The initiation and propagation of reflective cracking are affected by the thickness of asphalt overlay and the load transfer efficiency at the joints and cracks. It is challenging to control reflective cracking because the inherent structure discontinuity at the joints and cracks magnifies the stress in the flexible overlay.

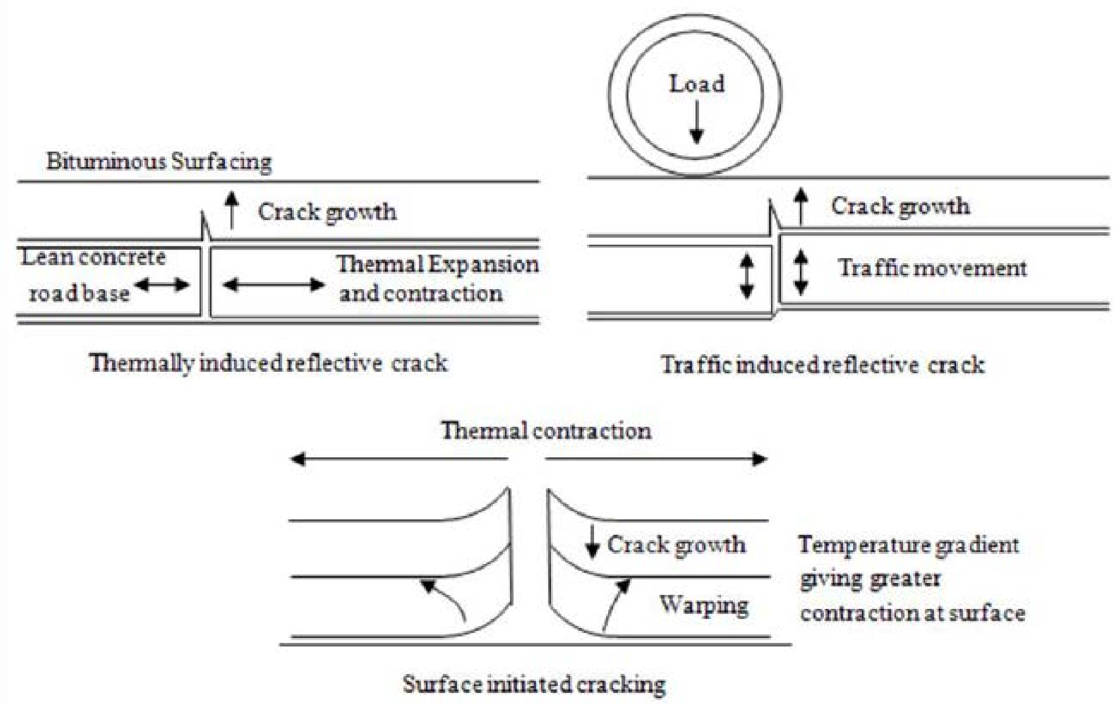


Figure 41 - Mechanisms of Reflective Cracking

Recently, pavement design has shifted from empirical methods to more rational approaches based upon mechanistic-empirical methods. Therefore, the performance of flexible overlay on composite pavements needs to be evaluated using theoretical modeling. Modeling analysis of pavement performance under vehicular loading can be based on either multilayer elastic theory (MLE) or finite element model (FEM). Although theoretical calculations using MLE are relatively inexpensive and simple, the reliability of the results is questionable due to the inability of simulating crack development. Thus, FEM approach that can consider the interaction between material, structure, loading and environment is considered more appropriate to improve the accuracy of pavement damage prediction. A number of studies have been performed to simulate the propagation of reflective cracking using three-dimensional (3-D) FE models, including the work published by the research team members (Ozer et al. 2013; Baek, et al. 2010).

The NCHRP 1-41 project "Models for Predicting Reflective Cracking of Hot Mix Asphalt Overlays" was completed and an improved mechanistic-empirical model was proposed to analyze the reflective cracking development for composite pavement design. The proposed design method has been integrated into the current AASHTOWare Pavement-ME Design software. Figure 42 illustrates the four modules for prediction of reflection cracking following mechanistic-empirical pavement design guideline (MEPDG) (Lytton et al. 2010).

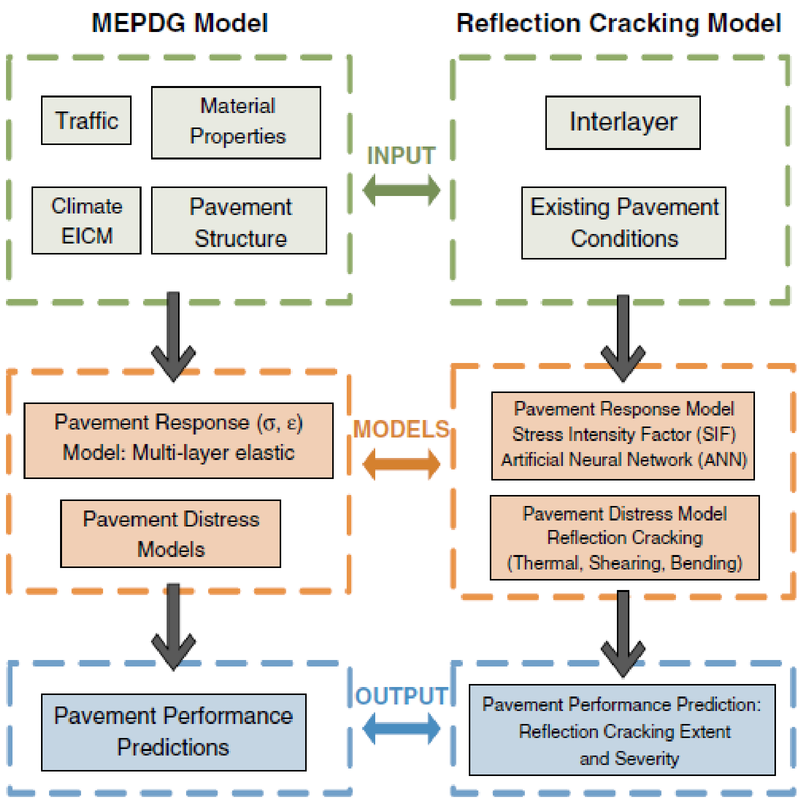


Figure 42 - Framework of Cracking Model in MEPDG for pavement design and performance analysis (Lytton et al. 2010)

The main components of the design methodology are the following:

- Input Module: Climatic data, traffic information, pavement structure, and material properties are required in this module. A tiered input strategy (Levels 1, 2, and 3) was proposed. The program is capable of handling mixture properties through binder properties using Witczak models and Artificial Neural Networks.
- Pavement Response Module: The module was used to calculate the response of pavement structure at the crack tip based on the parameters defined in the input module. The authors chose a 2-D finite element because of its computational

efficiency. The program can calculate stress intensity factors (SIFs) based on bending, shearing, and thermal loads. Viscoelasticity of asphalt mixtures was considered through amplification coefficients derived from stress wave patterns of axle loads. This module was coupled with Artificial Neural Networks to develop a computationally efficient prediction tool for stress intensity factors, which is the backbone of the model to predict cracking.

- Crack Propagation Prediction Module: The stress intensity factors produced in the previous step were used with a crack propagation model to calculate the amount of crack propagation for given loading and environmental conditions.
- Pavement Distress Prediction Module: The amount of crack length compared to the initial construction was used in a reflective cracking model that was calibrated using field data. This model is an exponential function with two coefficients that control the rate of crack growth for three severity levels (high, medium + high, low + medium + high).

Another M-E based reflecting model was developed in CalME at the University of California, Davis. The CalME model assumes that after composite pavement is open to traffic, the asphalt overlay and concrete pavement is quickly debonded and thus the asphalt overlay becomes a flexural beam under vehicular loading. In this case, the crack tip strain is assumed equal to the maximum bending strain at the bottom of the asphalt overlay. The reflection cracking model is based on regression models for crack tip strains based on a large factorial of cases (i.e. pavement systems and applied traffic loads) solved using the finite element method (Wu 2005). An incremental damage approach was used to characterize the modulus degradation of asphalt overlay. Compared to the NCHRP 1-41 model, the CalME model is simple and ease of implementation, but it does not account for thermal loads, load transfer at joints (i.e. doweling), or severity levels in cracking.

Prediction Models of Pavement Cracking in Pavement ME

Pavement Performance Models

The MEPDG uses mechanistic pavement analysis to determine critical responses of pavement under environmental and traffic loading, which is linked to pavement performance through empirical transfer functions. The simulation continues until the accumulated pavement distresses reach terminal thresholds, in which the service life of pavement is determined. AASHTOWare Pavement ME Design is the software that builds upon MEPDG for state-of-art pavement design. The performance models (transfer functions) used in Pavement ME software were summarized below, respectively, for fatigue cracking, transverse cracking, and reflective cracking. Both the default model parameters and the calibrated parameters (using LTPP sections in New Jersey) were presented in Tables 35 to 37.

Fatigue Cracking

Fatigue cracking of asphalt pavement is related to the tensile strain at the bottom of asphalt layer. The prediction of fatigue cracking in Pavement ME are shown in the following equations.

$$N_f = k_t \left[\beta_{f1} k_1 C \left(\varepsilon_t\right)^{-\beta_{f2} k_2} \left(E\right)^{-\beta_{f3} k_3} \right]$$

Where,

Nf = number of repetitions of a given load to failure;
kt = thickness correction factor;
$\beta_{f1}, \beta_{f2}, \beta_{f3}$ = field calibration coefficients;
k1, *k2*, *k3* = material properties determined from regression analysis laboratory test data;
C = laboratory to field adjustment factor;
ε_t= tensile strain at the critical location within asphalt concrete layer; and
E = asphalt concrete stiffness at given temperature.

$$k_t = \frac{1}{0.000398 + \frac{0.003602}{1 + e^{11.02 - 3.49 h_{AC}}}}$$

Where,

h_{AC} = total AC thickness.

The laboratory-field adjustment factor is given by:

$$C = 10^M$$

$$M = 4.84 \left\{ \frac{V_{beff}}{V_a + V_{beff}} - 0.69 \right\}$$

Where,

Vbeff = effective binder content (% of volume); and
Va = air voids (%).

$$D = \sum_{i=1}^{T} \frac{n_i}{N_{fi}}$$

Where,

D = damage;
T = total number of seasonal periods;
n_i = actual traffic for period *i*; and
N_{fi} = traffic repetitions of a given load to cause failure at period *i*.

The last step is to convert damage into cracked area as follows:

$$FC = \left(\frac{C_4}{60\left(1 + e^{\left(C_1 C_1^{'} + C_2 C_2^{'} \log(100D)\right)}\right)} \right)$$

Where,

FC = fatigue cracking (% of lane area);
C1, *C2*, *C4* = Calibration factors;
D = damage.

Table 37 - Fatigue Model Parameters Before and After Calibration

Parameter	AC Thick.(in)	Default	After Calibration
βf1 Intercept	< 5	0.02054	Remain the same
	5 to 12	$\beta_{f1} = 0.5014(h_{AC})^{-3.416}$	
	> 12	0.001032	
Bf2 E Exponent	---	0.88	Remain the same
βf3 Strain Exponent	---	1.38	1.304
C2	< 5	2.1585	Remain the same
	5 to 12	$C_2 = 0.867 + 0.2583(h_{AC})$	
	> 12	3.9666	
C1	---	1.31	Remain the same

Transverse Cracking

Transverse cracking is related the tensile stress at the pavement surface that is caused by thermal loading. The transverse cracking is predicted in Pavement ME through the following equations.

$$C_f = 400 * N(\frac{logC/h_{ac}}{\sigma})$$

$$\Delta C = A * (\Delta K)^n$$

Where,

C_f = observed amount of thermal cracking, ft/500ft;
N () = standard normal distribution evaluated at ();
σ = standard deviation of the log of the depth of cracks in the pavement (0.769), inch;
C = crack depth, inch;
h_{ac}= thickness of asphalt layer, inch;
ΔC = change in the crack depth due to one cooling cycle;
ΔK = change in the stress intensity factor (SIF) due to a cooling cycle; and
A and n = Fracture parameters of asphalt mixture.

Reflective Cracking

Reflective cracking in an asphalt overlay is caused by the crack growth from existing crack or joint underneath the asphalt overlay. Reflective cracking is predicted in Pavement ME through the following equations:

$$\Delta C = k_1\,\Delta_{bending} + k_2\Delta_{sheering} + k_3\Delta_{thermal}$$

$$\Delta D = \frac{(C_1 k_1\,\Delta_{bending} + C_2 k_2\Delta_{sheering} + C_3 k_3\Delta_{thermal})}{h_{OL}}$$

$$\Delta_{bending} = A(SIF)_B^n$$
$$\Delta_{sheering} = A(SIF)_S^n$$
$$\Delta_{thermal} = A(SIF)_T^n$$
$$D = \sum_{i=1}^{N} \Delta D$$
$$RCR = \left(\frac{100}{C4 + e^{C5logD}}\right) * EX\_CRK$$

Where,

ΔC= crack length increment, inch;
ΔD= incremental damage ratio;
$k_1 k_2\ k_3\ C_1 C_2 C_3 C_4 C_5$= calibration factors;
$\Delta_{bending}, \Delta_{sheering}, \Delta_{thermal}$= crack length increments caused by bending, shearing, and thermal loading;
A, n= HMA material fracture properties;
N= total number of days;
$(SIF)_B$, $(SIF)_B$, $(SIF)_B$= stress intensity factors caused by bending, shearing, and thermal loading;
D = damage ratio;
h_{OL}= overlay thickness, inch;
RCR= cracks in the underlying layers reflected, %;
EX_CRK= transverse cracking in underlying pavement layers, ft/miles; alligator cracking in underlying pavement layers, % lane area.

Table 38 - Reflective Cracking Model Parameters Before and After Calibration

Pavement Type	Distress Type	k1	K2	K3	C1	C2	C3	C4	C5
Default									
AC/AC	Transverse	0.012	0.005	1	3.22	25.7	0.1	133.4	-72.4
AC/AC	Fatigue	0.012	0.005	1	0.38	1.66	2.72	105.4	-7.02
After calibration									
Pavement Type	Distress Type	k1	K2	K3	C1	C2	C3	C4	C5
AC/AC	Transverse	Remain the same						165	-111
AC/AC	Fatigue	Remain the same						160	-18

Determination of Fracture Parameters

In MEPDG, Paris law is generally used to simulate crack growth of asphalt concrete, as shown in Equation 1. In Paris' law, the stress intensity factor describes the stress state in the crack tip; while the two fracture parameters (A and n), are needed to predict crack propagation speed under repeated loading cycles.

$$\frac{dC}{dN} = A(\Delta K)^n$$

Where,

C = crack length;
N = number of load cycles;
ΔK = change of stress intensity factor (SIF); and
A and n = fracture parameters of asphalt mixture.

Empirical models have been developed to estimate the fracture parameters from the volumetric data of asphalt mixture (especially binder properties) or the other material properties of asphalt mixture. These empirical relationships are mainly developed from the limited dataset obtained from laboratory tests and thus requires local calibration to improve the accuracy of performance prediction. In the current version of Pavement ME, the two key fracture parameters (A and n) were determined based on the inputs of creep compliance and IDT tensile strength.

Based on Schapery's theory of crack propagation, the fracture parameters were directly correlated to the creep compliance and tensile strength of asphalt mixtures (Schapery 1973). Through experimental tests, the following equations were proposed for estimating the fracture parameters (Molenaar 1984).

$$\log A = 4.389 - 2.52 \log(E \cdot \sigma_m \cdot n)$$
$$\mathrm{n} = 0.8\ (1 + \frac{1}{\mathrm{m}})$$
$$D(t) = D_0 + D_1 t^m$$

Where,

E = stiffness (modulus) of apshalt mixture;
σ_m = undamaged tensile strength measured using Indirect Tensile test (IDT);
D = creep complianec of asphalt mixture; and
m = the slopeof the linear portion of creep compliance master curve of asphalt mixture.

The IDT tensile strengths are required inputs for level 1 and 2 designs. Level 3, is estimated from the binder PG and mixture volumetrics, as shown in the following equation.

$\sigma_m = 7416.712 - 114.016V_a - 0.304V_a^2$ - 122.592VFA + 0.704 VFA^2 + 405.71 log(Pen) – 2039.296 log(A_{RTFO})

Where,

V_a = air voids content (percent);
VFA = voids filled with asphalt (percent);
Pen = Penetration at 77°F; which is estimated from PG grade of binder and
A_{RTFO} = Intercept of viscosity-temperature relationship for RTFO-conditioned asphalt binder; which is estimated from PG grade of binder.

The mixture stiffness (modulus) actually varies with temperature due to its viscoelastic behavior. In Pavement ME, the stiffness value was set as a constant value and calibration paramter β was added to calculate the parameter A. The calibration parameter has been determined during the development of Pavement ME. The national (global) calibration process performed under the NCHRP 1-37 project provided three values of β, one for each hierarchical level of analysis. For local calibration, another parameter K was added as a multiplication factor of the global calibration parameter β, as shown in the following equation.

$$\log A = K\beta[4.389 - 2.52 \log(E \cdot \sigma_m \cdot n)]$$

Where,

β = global calibration parameter; and
K = local calibration parameter.

Table 39 - Transverse Cracking Model Parameters Before and After Calibration

	Default	After Calibration
Level 1 K	$(3 * 10^{-7} * MAAT^{4.0319}) * 1 + 0$	Remain the same
Level 2 K	$(3 * 10^{-7} * MAAT^{4.0319}) * 1 + 0$	Remain the same
Level 3 K	$(3 * 10^{-7} * MAAT^{4.0319}) * 1 + 0$	$(3 * 10^{-7} * MAAT^{4.0319}) * 1 + 4.5$

On the other hand, theoretical models have been developed to calculate the fracture parameters (A and n) based on Overlay Tester. Zhou et al. (2009) developed a simplified method to determine fracture parameters with stress intensity factor and crack growth function obtained from overlay test. During the analysis, asphalt mixtures were assumed to be quasi-elastic and the viscoelastic behavior is neglected. The crack length during Overlay Tester can be back calculated from the recorded load or displacements (Roque et al. 1999) or directly measured using digital image correlation (DIC) method (Seo et al. 2004). A two-dimensional (2-D) finite element (FE) program was used to determine stress intensity factor (SIF). Recently, Gu et al. (2015) proposed a new methodology to determine fracture parameters of asphalt mixtures using mechanical analysis of viscoelastic force equilibrium and finite element simulation of the Overlay Tester results. The modified Paris Law was used by replacing the SIF with the pseudo J-integral. However, it is noted that the current version of Pavement ME does not allow for the direct input of fracture parameters (A and n).

Pavement ME Analysis

Material Properties of Different Surface Mixtures

Seven asphalt mixtures were used in the analysis using Pavement ME, including two 12.5M64, two 12.5SMA, two HPTO, and one 12.5ME mixtures. These mixtures have different asphalt binder types and contents and mixture volumetrics. Three types of mixtures have two different producers for each.

These asphalt mixtures have different mechanical properties, including fracture properties, dynamic modulus, creep compliance, etc. The SCB Flexibility Index (FI) value of each asphalt mixture was measured from SCB FI test, as shown below:

1) 12.5M64 – Stone Industries – Haledon, FI= 13.8
2) 12.5 M64 – Trap Rock Industries – Keasby, FI= 9.5
3) 12.5 SMA – Stone Industries – Haledon, FI= 11.3
4) 12.5 SMA – Trap Rock - Mt Holly, FI= 21.1
5) HPTO – Tilcon Oxford, FI= 29.2
6) HPTO – Stone Industries, FI= 10.1
7) 12.5 ME – Trap Rock, FI= 6.4

The dynamic modulus and flexibility index of asphalt mixture was measured in the laboratory. The creep compliance was converted from the measured dynamic modulus and phase angles based on linear viscoelastic theory (Park and Kim 1999). Figure 43 compares dynamic modulus master curves of all asphalt mixtures. Figure 44 compares creep compliance master curves of all asphalt mixtures.

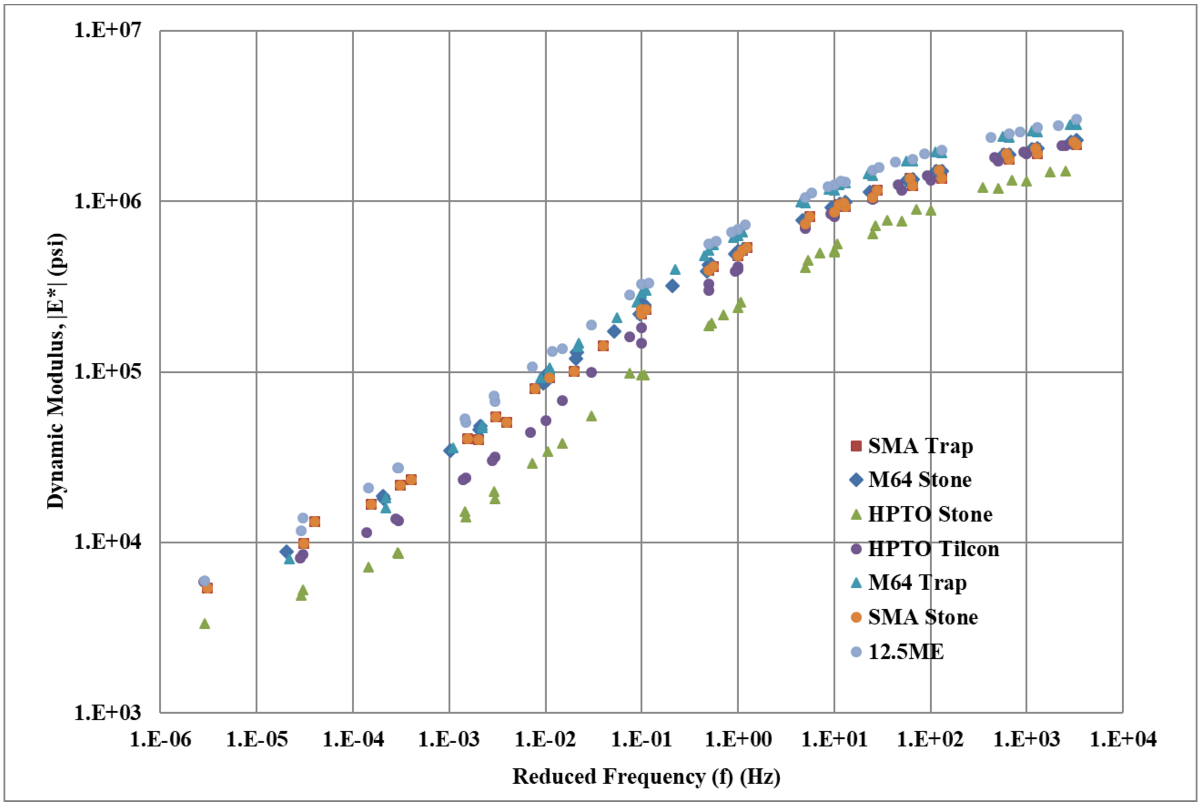


Figure 43 - Comparisons of Dynamic Moduli of All Asphalt Mixtures

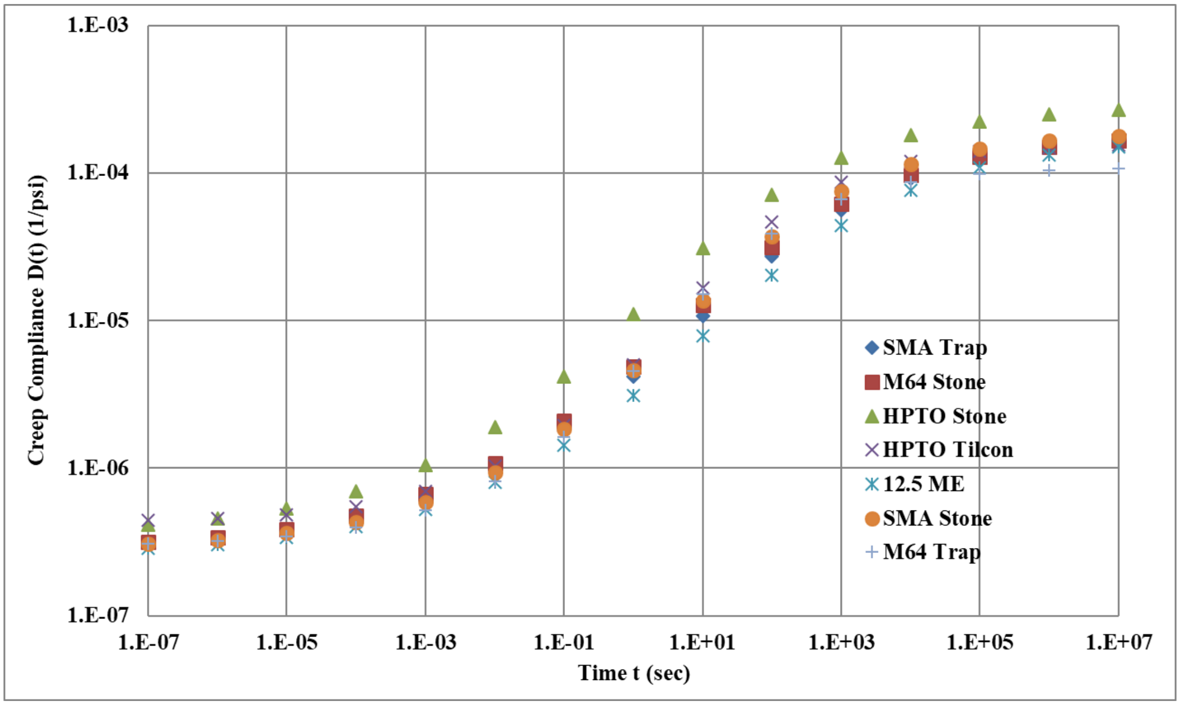


Figure 44 - Comparisons of Creep Compliance of All Asphalt Mixtures

Pavement Structures and Other Inputs

Two pavement overlay structures are considered in the analysis: the first is asphalt concrete overlay on existing asphalt pavement (AC over AC) and the second is asphalt concrete overlay on existing composite (AC over composite). The two pavement structures were selected from the pavement report submitted by the consultant to New Jersey DOT. Table 38 lists the details of two pavement structures.

Table 40 - Two Pavement Structures Considered in Analysis

Layer type	AC over AC	AC over Composite
	Thickness (in)	Thickness (in)
Asphalt overlay	3 or 5	3 or 5
Existing asphalt layer	10	7.5
Existing PCC layer	N/A	10
Aggregate base	20	14
Subgrade	Semi-infinite	Semi-infinite

For design of AC over composite pavement in Pavement ME, the option of AC over Semi-Rigid was used with one additional asphalt layer on a semi-rigid layer. In this case, the added asphalt layer can be treated as an existing layer and the semi-rigid layer represents the old PCC layer. The level 1 material inputs were used for asphalt overlay, while level 3 material inputs were used for all other pavement layers. The existing asphalt layer was assumed as PG64-22 mixture with fair condition for both pavement structures. Based on the definition in Pavement ME software, the fair condition indicates that the existing asphalt layer has moderate load and/or non-load related cracking, moderate rutting, moderate amounts of mixture-related distresses, and/or some roughness (IRI > 120 in./mi).

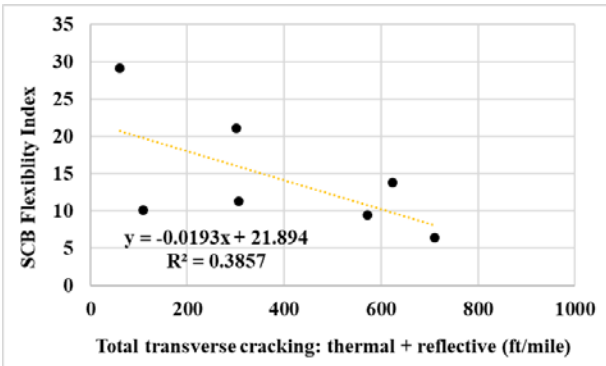
The traffic inputs used were based on the traffic cluster of “Urban Other Principal Arterial”. These included clustered traffic inputs in axle load spectra, vehicle class distribution, and number of axles per truck (Jasim et al. 2019). The two-way average annual daily truck traffic (AADTT) was assumed as 4000 to simulate high traffic volume conditions.

The climate condition was based on MERRA station 144170, which is located at Jackson Township, NJ and has latitude of 40.0583238 and Longitude of -74.4056612. The mean annual air temperature is 59.51°F and the mean annual precipitation is 53.27 inches. The freezing index is 90.95 °F-days and the average annual number of freeze/thaw cycles is 47.58.

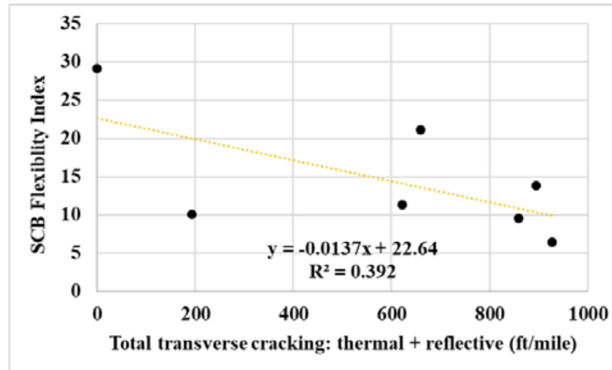
Results and Analysis

The pavement distress prediction results from Pavement ME were compared among the cases using different asphalt mixtures as asphalt overlay. The calibrated performance model parameters were used in Pavement ME for analysis. In particularly, the total transverse cracking (thermal + reflective) of asphalt pavement overlay was compared with the flexibility index (FI) of asphalt mixtures from SCB tests.

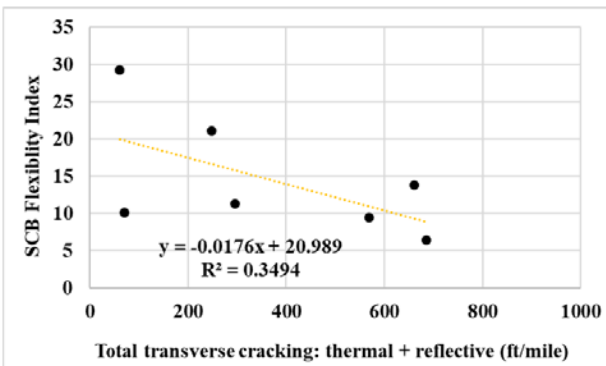
Figure 45 presents the relationship between SCB FI of asphalt mixtures and total transverse cracking in pavement overlays after two years pavement life, respectively, for (a) 3-inch AC over AC; (b) 5-inch AC over AC; (c) 3-inch AC over composite; and (d) 5-inch AC over composite pavemnets. Similarly, Figure 46 presents the similar relationship using the total transverse cracking after 10 years' pavement life. The results show that in general the higher value of SCB FI caused less transverse cracking in general. Although the level of correlation varied depending on pavement structure and pavement age, the general trends are consistent. As the pavement age increases, the correlation between the SCB FI and total transverse cracking becomes more significant.



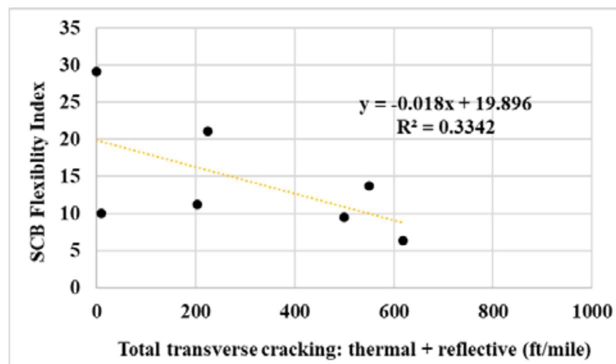
(a)



(b)



(c)



(d)

Figure 45 - Relationship Between SCB FI of Asphalt Mixtures and Total Transverse Cracking in Pavement Overlays after Two Years' Pavement Life for (a) 3-inch AC over AC; (b) 5-inch AC over AC; (c) 3-inch AC over composite; and (d) 5-inch AC over composite pavemnets

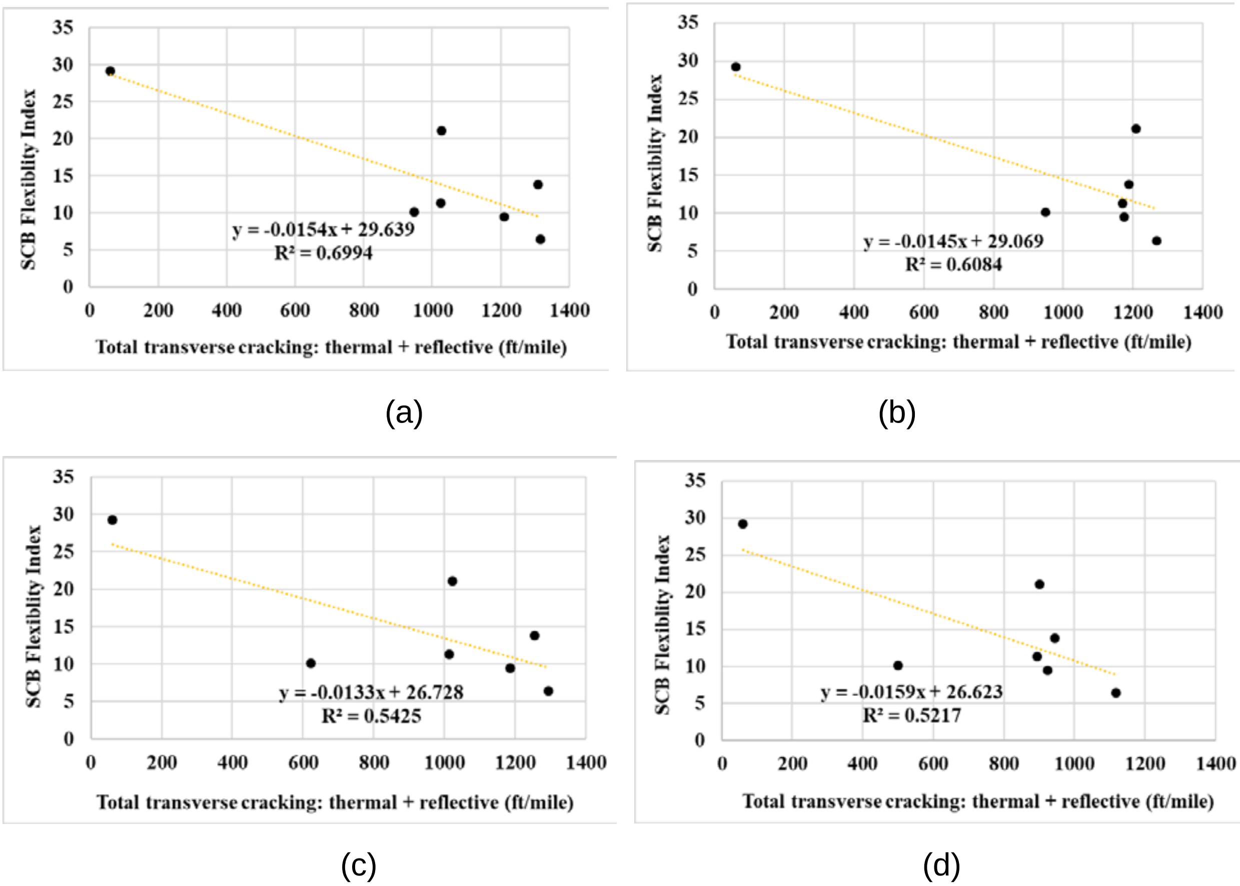


Figure 46 - Relationship Between SCB FI of Asphalt Mixtures and Total Transverse Cracking in Pavement Overlays after 10 years' Pavement Life for (a) 3-inch AC over AC; (b) 5-inch AC over AC; (c) 3-inch AC over composite; and (d) 5-inch AC over composite pavemnets

The analysis findings here are in agreement with the findings reported in the literature. Ozer et al. (2016) found that the SCB FI of asphalt mixtures had good correlations with the number of cycles to fatigue cracking failure obtained from accelerated pavement test sections, as shown in Figure 47. Another study conducted at Illinois found that the SCB FI of asphalt mixtures were consistent with the amount of transverse cracking observed from the field, respectively, for the thick and thin pavement families, as shown in Figure 48.

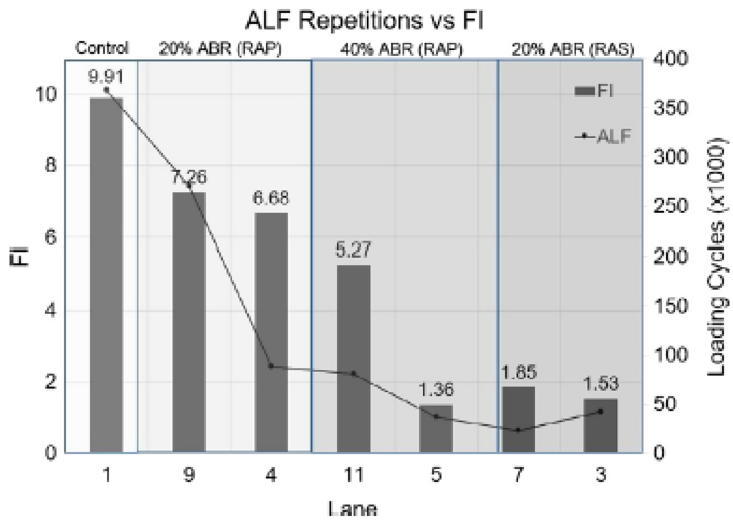


Figure 47 - Correlation of SCB FI with Fatigue Cracking Measurements after Accelerated Pavement Testing (Ozer et al. 2016)

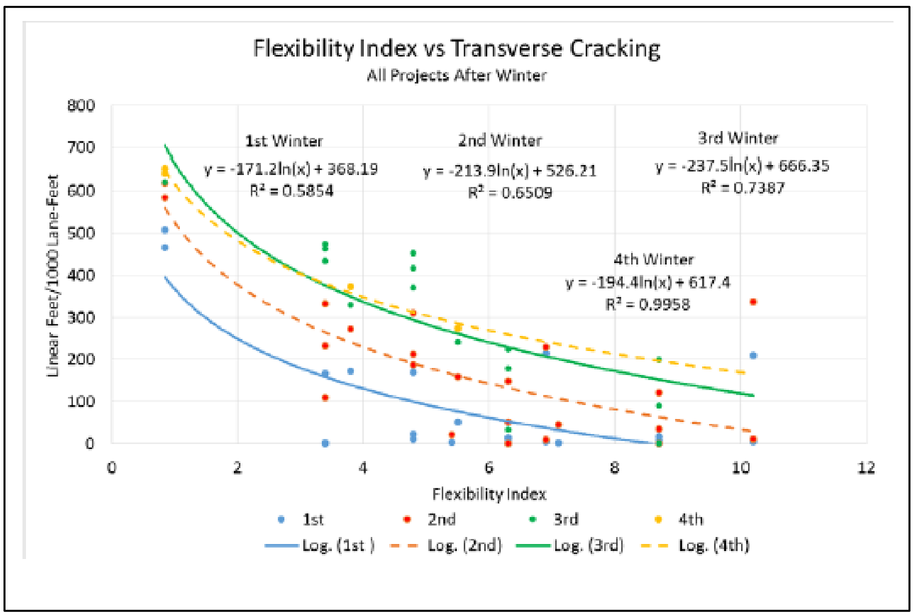


Figure 48 - Flexibility Index (FI) Relationship to Transverse Cracking on Field Projects (Al-Qadi et al. 2007)

The anlaysis results indicate that the SCB FI of asphalt mixture can be used as an indicator of cracking potential for asphalt pavement overlays, especially transverse cracking. The higher SCB FI value; the less transverse cracking in the pavement. Therefore, the semi-circular bending test shows the great potential of evaluating field cracking performance of different apshalt mixtures.

CONCLUSIONS

This research study was conducted to evaluate the SCB Flexibility Index as a potential test method that could be implemented by the NJDOT with their performance related specifications. The advantage of using the SCB Flexibility Index over the NJDOT's current test procedure, the Overlay Tester (NJDOT B-10), is the improvement in testing speed (from both sample preparation and actual testing to failure). This research study included: 1) a Literature Review to provide background information related to the SCB Flexibility Index; 2) a modified ruggedness study to assess critical testing parameters that affect the measurement and repeatability of the SCB Flexibility Index; 3) comparative testing of identical asphalt mixtures between the SCB Flexibility Index and the Overlay Tester; and 4) comparison of modeled pavement cracking performance to the SCB Flexibility Index value for the surface course asphalt mixture.

Based on the testing conducted in this study, the following conclusions can be drawn;

1. When utilizing the SCB geometry for measuring the fatigue cracking resistance of asphalt mixtures, the SCB Flexibility Index (FI) appears to have big advantages over the LTRC SCB method. First, the testing time required for the SCB FI is much quicker than the LTRC SCB. The LTRC SCB is conducted at a rate of 0.5 mm/min as compared to the 50 mm/min for the SCB FI. In addition, the LTRC SCB recommends testing 9 test specimens while the SCB FI only requires 3 test specimens. Lastly, based on the literature review conducted, it appears that there are conflicting results regarding how well the LTRC SCB procedure correlates to field performance. Meanwhile, the SCB FI was shown to relate well to field studies from various researchers.
2. The modified ruggedness study showed that there were a number of testing parameters that laboratory technicians need to be especially careful of. In particular: 1) compacted air voids; 2) testing temperature; 3) loading rate; and 4) notch width. It is important to note that when technicians are fabricating test specimens and conducting AASHTO TP124, it is imperative that the testing requirements and ranges be strictly followed to ensure representative and repeatable test results.
3. Approximately 100 sets of comparative tests were conducted between the Overlay Tester and the SCB Flexibility Index. The comparison of testing results was used to determine if a correlation exists between the two test methods, and if so, develop proposed performance criteria that uses the SCB Flexibility Index parameter to control mixture fatigue cracking. A R^2 value of 0.78 was found between the two test methods, which indicates a good correlation. Using this relationship, a series of criteria was developed and shown in the table following this conclusion. In addition, a statistical analysis was conducted to evaluate which asphalt mixture and binder properties most affected the SCB FI value. In particular, binder properties such as intermediate PG grade, low temperature PG

grade from the m-value and the MSCR Percent Recovery, and mixture properties such as asphalt binder content and effective asphalt content by volume, were found to highly influence the SCB FI performance.

Mixture Type			**Min. Cycles in Overlay Tester**	**Min. SCB Flexibility Index (Rounded)**
HRAP	Surface	76-22	275	10.0
		64-22	200	9.0
	Intermediate/ Base	76-22	150	8.0
		64-22	100	6.0
BRIC	Mixture Design		700	17.0
	Production		650	16.0
HPTO	Mixture Design		600	15.0
	Production			

4. Using the PAVEMENT-ME pavement distress model, it was shown that the SCB Flexibility Index correlated well with the predicted cracking in the analysis. This would indicate that the SCB FI could be utilized to help screen asphalt mixtures during the mixture design process, as well as help identify potential issues during plant production to help mitigate potential field performance issues.

RECOMMENDATIONS

Future work regarding the SCB Flexibility Index should concentrate on a few items:

1. Highly aged/stiff asphalt mixtures are difficult to test and analyze due the brittle failure of these mixtures. The quick post peak failure results in a severe slope with limited data points to use in the analysis. Future research may be needed to evaluate how the SCB FI test procedure can better handle this situation. Emphasis could be placed on slower loading rates or warmer test temperatures to aid in lessening the brittle failure.
2. The comparison to the PAVEMENT-ME results show that the SCB FI parameter had a general correlation to the predicted pavement distress. Future research could be attempted to use the SCB FI to help calibrate material specific model coefficients to incorporate in the PAVEMENT-ME that would improve the accuracy of the pavement distress predictions.
3. Lastly, whenever a project such as a new testing method is conducted, follow-up testing that includes field evaluation is necessary. Test methods should be provided to the industry for evaluation and potential adoption, and the SCB FI has this potential – as the Round Robin study showed with including one asphalt plant in the testing program.

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