NCAT Report 17-09

EFFECTS OF LOADING RATE AND MIX REHEATING ON INDIRECT TENSILE N_{FLEX} FACTOR AND SEMI-CIRCULAR BEND J-INTEGRAL TEST RESULTS TO ASSESS THE CRACKING RESISTANCE OF ASPHALT MIXTURES

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1. INTRODUCTION

Implementation of the Superpave mix design method began over 20 years ago. Although its initial vision was to include mixture performance tests for higher risk projects, the cost and complexity of the recommended performance tests were too much for use in routine practice. Therefore, the Superpave mix design method relied upon improved asphalt binder characterization and aggregate criteria based on specific traffic and climate requirements but continued the use of volumetric properties to determine the optimum asphalt binder content. Over the past two decades, several refinements have been made to the Superpave standards, and individual state Departments of Transportation (DOTs) have made additional changes to the method and criteria. Still, some aspects of the Superpave mix design method are widely questioned and the resulting designed mixtures in many states are viewed to be lacking durability. Recently, several highway agencies began to explore the use of mixture cracking tests and criteria for some mix categories.

There are currently over a dozen different asphalt mixture cracking tests available in American Association of State Highway and Transportation Officials (AASHTO) and American Society for Testing and Materials (ASTM) standards or as draft procedures developed by different researchers. Some of these tests are better suited for routine use in mix design and quality assurance testing, while others are better suited for use in modeling pavement responses and may ultimately provide a means for predicting cracking over time. However, most of these tests are not ready for implementation into routine practice due to complexity. Therefore, this study was undertaken to explore two relatively simple laboratory tests, indirect tensile (IDT) N_{flex} Factor test and semi-circular bend (SCB) J-integral test, for evaluating the cracking resistance of asphalt mixtures for mix design and quality assurance.

2. OBJECTIVE

The objective of this study was to evaluate the effects of mix reheating and loading rate on the results of IDT N_{flex} Factor test and SCB J-integral test. Analysis was also performed to assess the effects of asphalt mixtures with different components and production parameters on the results of these two tests.

3. EXPERIMENTAL DESIGN

3.1 Research Methodology

Figure 1 presents the research methodology employed in this study. Seven asphalt mixtures from three field projects were tested in the IDT N_{flex} Factor and SCB J-integral tests to characterize their cracking resistance. For each project, the loose mix was sampled during plant production and was used to fabricate on-site specimens and off-site specimens. The on-site specimens were compacted at the plant without reheating the loose mix, while the off-site specimens were fabricated by compacting the loose mix after significant reheating. For the sake of expediting implementation of these tests during mix design and quality assurance, both on-site and off-site specimens were compacted to N_{design} instead of to the target air void contents. Testing of existing N_{design} specimens fabricated for volumetric measurements greatly reduces the sample preparation time, and therefore makes the cracking tests easier to implement. For both cracking tests, two different loading rates of 0.5 and 50 mm/min were investigated to determine whether they would yield different test results. Finally, the IDT N_{flex} Factor and SCB J-integral results were analyzed to discriminate the cracking potential of asphalt mixtures with different combinations of reclaimed asphalt pavement (RAP), recycled asphalt shingles (RAS), rejuvenators, and warm mix asphalt (WMA) technologies.

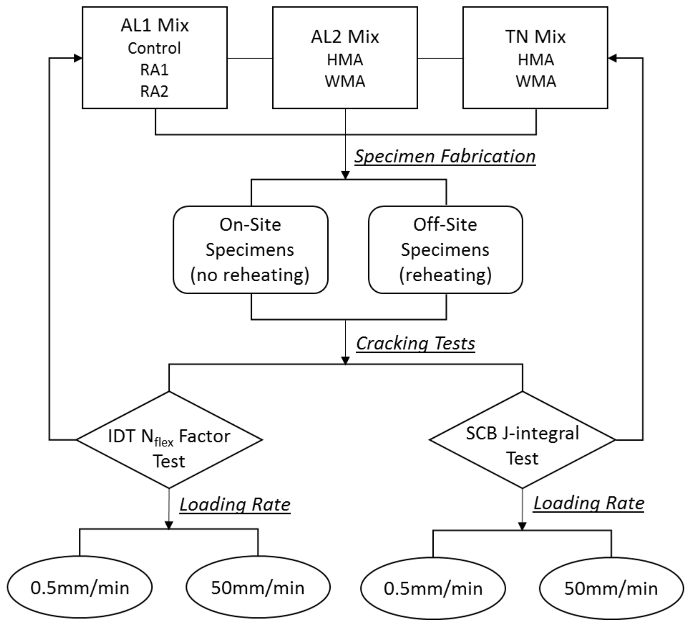


Figure 1. Research Methodology

3.2 Materials and Specimen Fabrication

Materials evaluated in this study were obtained from two field projects in Alabama and one project in Tennessee. The first project in Alabama (AL1), located on U.S. Highway 31 in Autauga County, included three asphalt mixtures with various RAP and RAS contents. All three mixtures were paved as a 2-inch overlay over an existing asphalt pavement. Rejuvenators were used in two of these mixtures, which had 25% RAP and 5% RAS. The other mixture had 20% RAP, no RAS, and no rejuvenators; thus, it was considered as the control mix. The job mix formula (JMF) for all three mixtures consisted of a 12.5 mm nominal maximum aggregate size (NMAS) Superpave mixture with an N_{design} of 60 gyrations. A PG 67-22 virgin binder was used in the mix design as the base binder. The two rejuvenators evaluated in this project are referred to as RA1 and RA2. The dosage of the rejuvenators was determined based on the recommendations from the contractor and the suppliers. Table 1 summarizes the mixture components and volumetric parameters of the three AL1 mixtures.

The second field project in Alabama (AL2), located on U.S. Highway 84 in Coffee County, included a WMA mixture and a hot mix asphalt (HMA) control mixture. Both mixtures contained 15% RAP and 5% RAS and used a PG 67-22 virgin binder. The WMA mixture was produced by a Gencor plant foamer using 1.5% foaming water content by weight of the binder. The JMF for both mixtures consisted of a 12.5 mm NMAS Superpave mixture with an N_{design} of 60 gyrations. The total binder content was 5.1%, with 3.4% contributed from the virgin binder and 1.7% from the recycled materials. A liquid anti-stripping additive manufactured by ArrMaz Custom Chemicals was included in both mixtures at 0.5% by weight of the total binder. The two mixtures were used as the surface lift of a new construction pavement with a target thickness of 1.5 inches. Table 2 summarizes the mixture components and volumetric parameters of the two AL2 mixtures.

The field project in Tennessee (TN), located on Raccoon Valley Drive (SR 170) in Anderson and Roane Counties, also included a WMA mixture and a HMA control mixture. Both mixtures contained 10% RAP and 3% RAS and used a PG 64-22 virgin binder. For the WMA mixture, Evotherm 3G was added at a rate of 0.5% by weight of the total asphalt binder. The JMF for both mixtures consisted of a 12.5 mm NMAS Marshall mixture with 75 blows. During plant production, a correlation was established between Marshall 75 blows and Superpave 25 gyrations to yield specimens with similar air voids contents, and thus, an N_{design} of 25 gyrations was selected. For both mixtures, a liquid anti-stripping additive manufactured by ArrMaz Custom Chemicals was added at 0.5% by weight of the total binder. The two mixtures were paved as a 1.5-inch overlay over an existing asphalt pavement. Table 3 summarizes the mixture components and volumetric parameters of the two TN mixtures.

Table 1. Mixture Components and Volumetric Parameters of AL1 Mixes

Mixture Components and Volumetric Parameters	Control Mix	RA1 Mix	RA2 Mix
#78 LMS, %	20	25	25
#8910 LMS, %	10	5	5
Coarse Sand, %	15	15	15
Shot Gravel, %	17	17	17
Crushed Gravel, %	17	7	7
Baghouse Fine, %	1	1	1
RAP/RAS, %	20/0	25/5	25/5
Rejuvenator, %*	-	4.5	8
WMA, %*	-	0.3 (Evotherm 3G)	-
Virgin Binder (PG 67-22) , %	4.1	2.95	2.95
AC from RAP, %	1.0	1.25	1.25
AC from RAS, %	0	0.9	0.9
Total AC, %	5.1	5.1	5.1
Mix Extracted Binder PG	88-10	94-10	94-10
N_{design}	60	60	60
Air Voids, %	4.3	2.0	2.4
G_{mm}	2.470	2.447	2.461
VMA, %	15.9	15.5	15.1
D/A Ratio	0.91	0.95	0.97
Compaction Temperature, °F	275	240	240

*Note: * by weight of the total binder*

Table 2. Mixture Components and Volumetric Parameters of AL2 Mixes

Mixture Components and Volumetric Parameters	HMA Mix	WMA Mix
CR Gravel, %	39	39
Short Gravel, %	11	11
# 78LMS, %	7	7
LMS SCRN's, %	7	7
Natural Sand, %	15	15
RAP/RAS, %	15/5	15/5
WMA, %*	-	1.5% (Foaming)
Anti-Stripping, %*	0.5	0.5
Virgin Binder (PG 67-22) , %	3.4	3.4
AC from RAP, %	0.7	0.7
AC from RAS, %	1.0	1.0
Total AC, %	5.1	5.1
Mix Extracted Binder PG	88-10	88-10
N_{design}	60	60
Air Voids, %	3.0	2.5
G_{mm}	2.480	2.476
VMA, %	13.3	13.3
D/A Ratio	1.05	1.16
Compaction Temperature, °F	305	280

*Note: * by weight of the total binder*

Table 3. Mixture Components and Volumetric Parameters of TN Mixes

Mixture Components and Volumetric Parameters	HMA Mix	WMA Mix
Hard LMS, %	42	42
Coarse Slag, %	20	20
Soft LMS #10, %	20	20
Natural Sand, %	25	25
RAP/RAS, %	10/3	10/3
WMA, %*	-	0.5 (Evotherm 3G)
Anti-Stripping, %*	0.5	0.5
Virgin AC (PG 64-22), %	4.4	4.4
AC from RAP, %	0.65	0.65
AC from RAS, %	0.65	0.65
Total AC, %	5.7	5.7
Mix Extracted Binder PG	82-10	76-16
N_{design}	25	25
Air Voids, %	6.2	5.3
G_{mm}	2.596	2.570
VMA, %	16.1	16.7
D/A Ratio	1.26	1.03
Compaction Temperature, °F	290	240

*Note: * by weight of the total binder*

For all three projects, during production loose mix samples were taken from the end-dump trucks before leaving the plant. For each of the mixtures sampled, a set of specimens was compacted on-site in the National Center for Asphalt Technology (NCAT) mobile laboratory without significant reheating. The loose mix was placed in an oven for approximately 30 minutes to account for the temperature loss that occurred between sampling and splitting. Once the desired compaction temperature was achieved and stabilized, the mix was compacted to N_{design} in the Superpave gyratory compactor (SGC). All specimens compacted on-site without reheating in the NCAT mobile laboratory are herein referred to as hot production specimens.

In the NCAT main laboratory, off-site specimens were fabricated using the reheated loose mix sampled from the plant, referred to as reheated specimens in this study. For the reheating process, the bucket with loose mix was first placed in an oven at the desired compaction temperature for approximately two hours. The loose mix was then batched into individual sample sizes using the quartering method described in AASHTO R 76-16 and was placed back in the oven for further reheating. A dial thermometer was used to continuously monitor the temperature of the mix. Once the desired compaction temperature was achieved, the loose mix was compacted in the SGC to N_{design}. The total reheating process took approximately four hours. Table 4 summarizes the air voids results of both hot production and reheated specimens. In most cases, the difference in the average air voids between the two sets of specimens was no greater than 0.5%, which was considered practically insignificant.

Table 4. Summary of Average Air Voids Results of Hot Production and Reheated Specimens

Mix Type	IDT Specimens (AV %)		SCB Specimens (AV %)	
	Hot Production	Reheated	Hot Production	Reheated
AL1 Control Mix 2	4.5	4.1	5.0	4.6
AL1 RA1 Mix	2.6	3.6	2.7	3.1
AL1 RA2 Mix	2.1	2.6	2.7	4.2
AL2 HMA	2.6	2.2	3.1	3.2
AL2 WMA	2.3	2.1	2.6	2.9
TN HMA	5.9	5.4	6.1	6.0
TN WMA	5.2	4.7	5.5	5.3

3.3 Preliminary Field Performance

A field performance evaluation was conducted for the AL1 project in August 2016, approximately two years after construction. Pavement cracking was inspected and rated in accordance with the Alabama Department of Transportation (ALDOT) Condition Assessments Data Collection Manual (ALDOT 2015). Table 5 summarizes the field cracking inspection results of the three test sections. In general, the control mixture showed the best cracking performance, followed by the RA1 mixture and then the RA2 mixture, respectively. Only 37 feet of low-severity longitudinal cracking was observed for the control mixture, but a significantly greater amount of alligator and longitudinal cracks was observed for the other two mixtures containing RAS and rejuvenators. Considering that the condition of the underlying pavement before resurfacing was similar for the three sections, the difference in their cracking performance was primarily due to the cracking potential of the overlay mixtures.

Table 5. AL1 Project Field Cracking Inspection Results

Test Sections	Alligator Cracking (ft^2)		Longitudinal Cracking (ft.)		Transverse Cracking (crack count)	
	Level 1	Level 2	Hair to 1/8”	1/8” to 1/4"	Hair to 1/8”	1/8” to 1/4"
Control	0	0	37	0	0	0
RA1	985	10	12	0	2	0
RA2	560	0	723	16	9	1

(a) Control Section **(b) RA1 Section** **(c) RA2 Section**

Figure 2. AL1 Project Field Performance Monitoring

For the AL2 project, field performance monitoring was conducted on November 19, 2015 and November 16, 2016 after approximately 17 and 29 months of traffic had been applied to the pavement sections, respectively. As shown in Figure 3, both sections have performed well in the first couple of years without any cracking observed during either inspection.

(a) HMA Section **(b) WMA Section**

Figure 3. AL2 Project Field Performance Monitoring

Field performance of the TN project was evaluated on November 11, 2015 and November 11, 2016 after approximately 13 and 25 months of traffic, respectively. No cracking was observed for either test section during the first inspection. At the time of the 25-month inspection, one low-severity transverse crack was observed in the WMA section; however, it was not determined whether the crack was a thermal crack or a reflective crack. Figure 4 shows photographs of the TN project. In general, both sections have performed well through the first two years; no difference in cracking performance was observed for the HMA versus the WMA sections.

(a) HMA Section **(b) WMA Section**

Figure 4. TN Project Field Performance Monitoring

3.4 Laboratory Tests

3.4.1 Indirect Tensile (IDT) N_{flex} Factor Test

The IDT test was originally developed in Japan (Akazawa 1953) and Brazil (Carniero and Barcellos 1953) for determining the strength of concrete. The IDT loading arrangement is now well known in the asphalt pavement industry for use in evaluating moisture damage susceptibility of asphalt mixtures per AASHTO T 283. Several other standard tests use the same loading arrangement with variations in loading rates, test temperatures, and specimen dimensions. For this study, loading rates of 0.5 and 50 mm/min were applied by a simple load frame that digitally captured load and vertical deformation data during the test. The test was performed at 25°C using approximately 50 mm thick specimens that were cut from 150-mm diameter SGC samples. Figure 5 presents the IDT test setup and specimen configuration.

Figure 5. IDT Test Setup and Specimen Configuration

For data analysis, a new parameter termed N_{flex} Factor was used to evaluate the cracking resistance of different asphalt mixtures (West et al. 2017). The determination of N_{flex} Factor was inspired by a similar method used in the flexibility index test developed at the University of Illinois (Al-Qadi et al. 2015). As expressed in Equations 1 to 4 and schematically illustrated in Figure 6, N_{flex} Factor was calculated as the specimen toughness divided by the slope of the post peak stress-strain curve at the inflection point. For data analysis, a sixth-degree polynomial function was used to fit the stress-estimated strain data, and the critical point on the curve where the second derivative of the polynomial function equaled zero was determined as the inflection point. Since no strain gauge was used during the test, the IDT strain of the specimen was estimated by multiplying the vertical deformation by an assumed Poisson's ratio of 0.35 and dividing by the specimen diameter. A high N_{flex} Factor value is considered to indicate better cracking resistance.

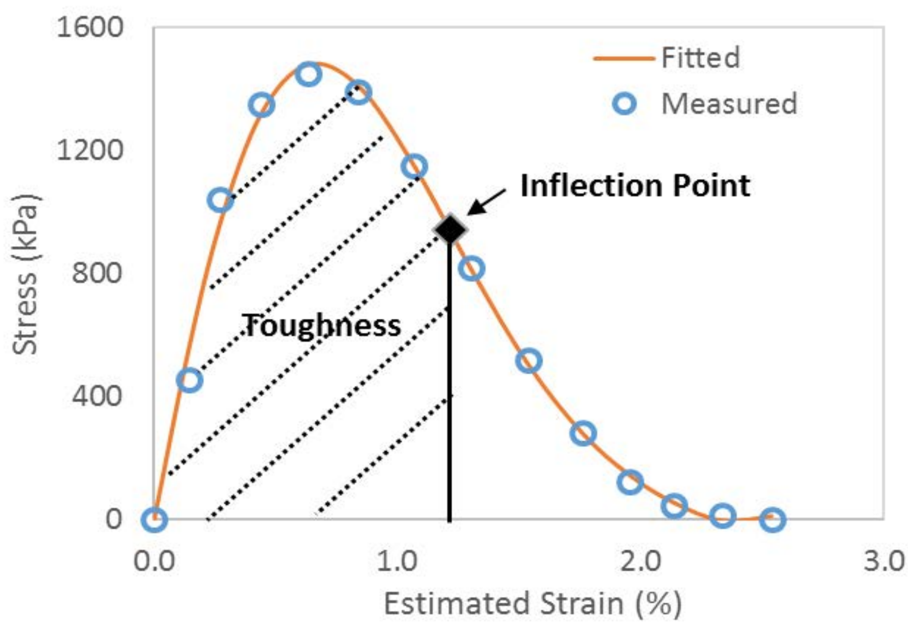


Figure 6. Determination of IDT N_{flex} Factor

$$\sigma = \frac{2000P}{\pi t D} \tag{1}$$

where

σ = IDT stress (kPa);
P = vertical load (N);
t = specimen thickness (mm); and
D = specimen diameter (mm).

$$\varepsilon = \frac{\Delta}{D}\nu \tag{2}$$

where

ε = estimated IDT strain (%);
v = Poisson's ratio, assumed to be 0.35 at 25°C; and
Δ = vertical deformation (mm).

$$T_{\text{inf}} = \int_{0}^{\varepsilon_{inf}} \sigma(d\varepsilon) \tag{3}$$

where

T_{inf} = toughness up to the inflection point on the post peak stress-strain curve (kPa).

$$N_{flex}\ Factor = \frac{T_{\text{inf}}}{|s|} \tag{4}$$

where

$|s|$ = slope of the post peak stress-strain curve at the inflection point (kPa).

3.4.2 Semi-circular Bend (SCB) J-integral Test

The SCB test was originally developed to characterize the fracture mechanisms of rocks (Chong and Kuruppu 1988) and has recently been used to characterize the fracture and fatigue properties of asphalt mixtures (Li and Marasteanu 2004; Arabani and Ferdowsi 2009; Huang et al. 2009; Kim et al. 2012). The SCB test was conducted in accordance with ASTM D 8044-16 in most regards. This method has been championed by the Louisiana Transportation Research Center. The test utilized notched half-moon shaped specimens cut from SGC cylinders with three notch depths of 25.4, 31.8, and 38.1 mm. Figure 7 shows SCB test setup and specimen configuration. During the test, a SCB specimen is supported by two bars on a flat surface and a monotonic load is applied to the curved surface above the notch. The ASTM standard specifies a vertical displacement rate of 0.5 mm/min. For this study, tests were conducted with two rates of 0.5 and 50 mm/min. For data analysis, strain energy to failure was first calculated for each notch depth as the area under the load versus displacement data, and a linear regression was determined based on the strain energy versus notch depth results (Figure 8). Finally, the cracking parameter J-integral (J_c) was calculated by dividing the slope of the regression line by the specimen thickness, as expressed in Equation 5. Asphalt mixtures with higher J_c values are expected to have better resistance to intermediate temperature cracking than those with lower J_c values. It should be noted that there is another SCB test available termed Illinois Flexibility Index (I-FIT) test that takes into consideration both the fracture energy and post-peak load-displacement behavior of the mixture under loading. Although the I-FIT test had also been found promising for evaluating the cracking resistance of asphalt mixtures during mix design and quality assurance (Al-Qadi et al, 2015), it was not included in the experimental test plan of this study.

$$J_c = -\frac{1}{b}\frac{dU}{da} \tag{5}$$

where

- *b* = specimen thickness (m);
- *a* = notch depth (m); and
- *U* = strain energy to failure (*kJ*).

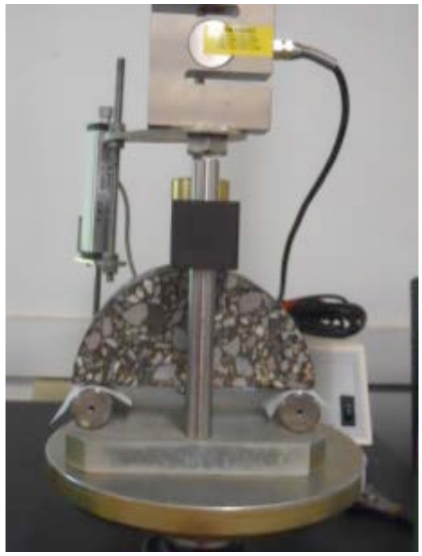


Figure 7. SCB Test Setup and Specimen Configuration

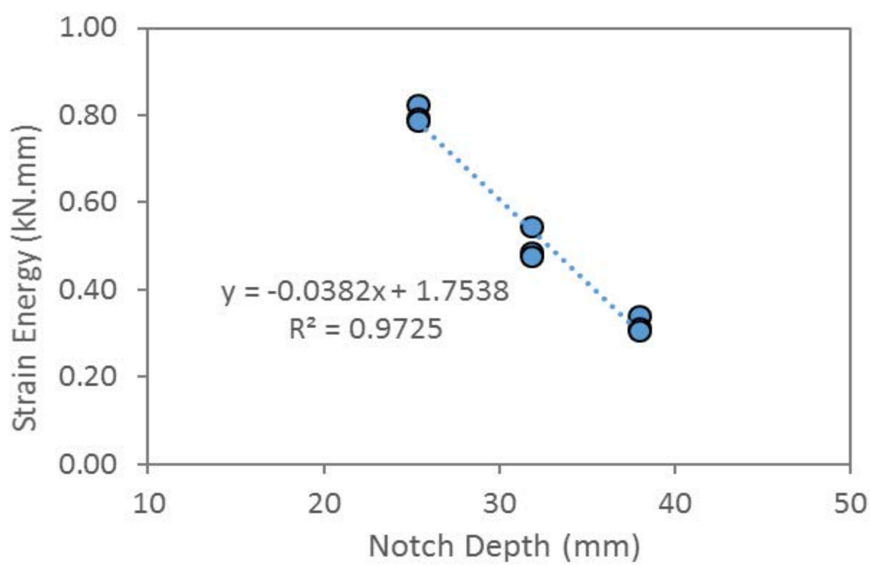


Figure 8. SCB Notch Depth versus Strain Energy Plot

4. TEST RESULTS AND DATA ANALYSIS

This section presents the IDT N_{flex} Factor and SCB J-integral results obtained in this study. Data analysis was performed to identify the effects of mix reheating and loading rate on the IDT and SCB test results. In addition, the cracking resistance of asphalt mixtures with various combinations of RAP, RAS, rejuvenator, and WMA technologies was compared.

4.1 IDT N_{flex} Factor Test Results

Figure 9 presents an example of the load-displacement curves obtained from the IDT N_{flex} Factor test using a loading rate of 50 mm/min. As illustrated, the mixtures with different components showed significantly different behaviors during the test. In general, the two TN mixtures had lower peak loads and higher displacements as compared to the other mixtures, indicating a more ductile behavior. As compared to the AL1 control mixture, the two mixtures with rejuvenators showed higher peak loads, which was likely due to the inclusion of a higher content of recycled materials, especially the RAS with heavily aged and very stiff asphalt binder.

Table 6 summarizes the IDT N_{flex} Factor test results; a reasonably good repeatability is observed with an average coefficient of variation (COV) of approximately 13%. It should be noted that not enough hot production specimens were available from the AL2 project to conduct the IDT N_{flex} Factor test.

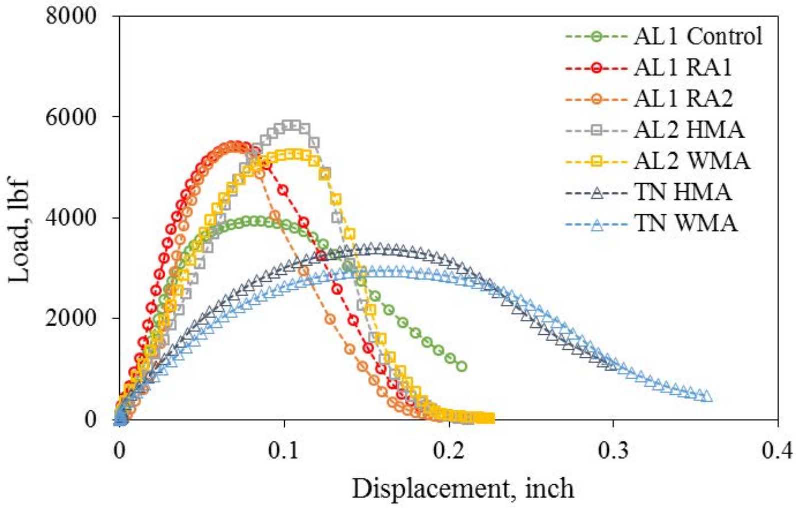
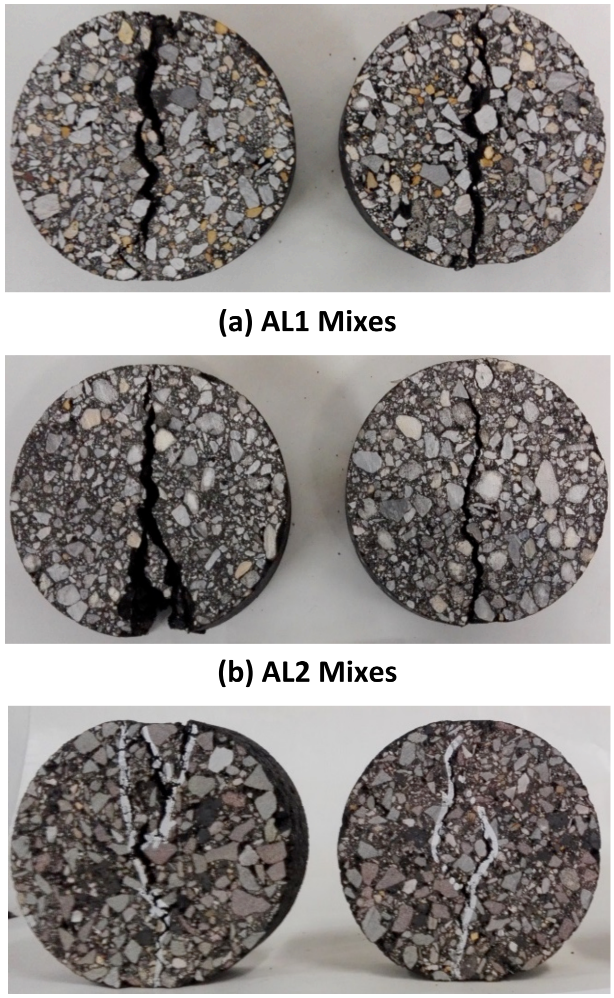


Figure 9. Example of the Load-Displacement Curves from the IDT Test (Reheated Specimens; Loading Rate of 50mm/min)

During the IDT test, it was observed that cracking generally developed from two locations: 1) near the loading strips and 2) near the center of the specimen, as shown in Figure 10. Failure initiating from the center of the specimen is the desired location, as this is where the maximum indirect tensile stress occurs based on principles of mechanics, whereas cracking initiating near the loading strips is primarily due to localized shear stress (Hudson and Kennedy 1968). Due to the limited test results, the two failure modes observed in the IDT test were not investigated in this study but need to be addressed by future research.

Table 6. Summary of IDT N_{flex} Factor Results

Specimen Type	Loading Rate	Mix ID	N_{flex} Factor (4 replicates)		
			Average	Stdev	COV
Hot Production Specimens	0.5 mm/min	AL1 Control	0.573	0.044	8%
		AL1 RA1	0.483	0.040	8%
		AL1 RA2	0.432	0.082	19%
		AL2 HMA		n/a	
		AL2 WMA		n/a	
		TN HMA	0.941	0.088	9%
		TN WMA	1.300	0.108	8%
	50 mm/min	AL1 Control	0.545	0.065	12%
		AL1 RA1	0.513	0.076	15%
		AL1 RA2	0.517	0.044	9%
		AL2 HMA		n/a	
		AL2 WMA		n/a	
		TN HMA	1.037	0.103	10%
		TN WMA	1.386	0.202	15%
Reheated Specimens	0.5 mm/min	AL1 Control	0.556	0.049	9%
		AL1 RA1	0.257	0.069	27%
		AL1 RA2	0.112	0.015	13%
		AL2 HMA	0.181	0.016	9%
		AL2 WMA	0.312	0.043	14%
		TN HMA	0.765	0.055	7%
		TN WMA	1.493	0.016	1%
	50 mm/min	AL1 Control	0.453	0.055	12%
		AL1 RA1	0.389	0.099	25%
		AL1 RA2	0.220	0.048	22%
		AL2 HMA	0.168	0.039	23%
		AL2 WMA	0.237	0.023	10%
		TN HMA	0.841	0.121	14%
		TN WMA	1.112	0.097	9%



(a) AL1 Mixes

(b) AL2 Mixes

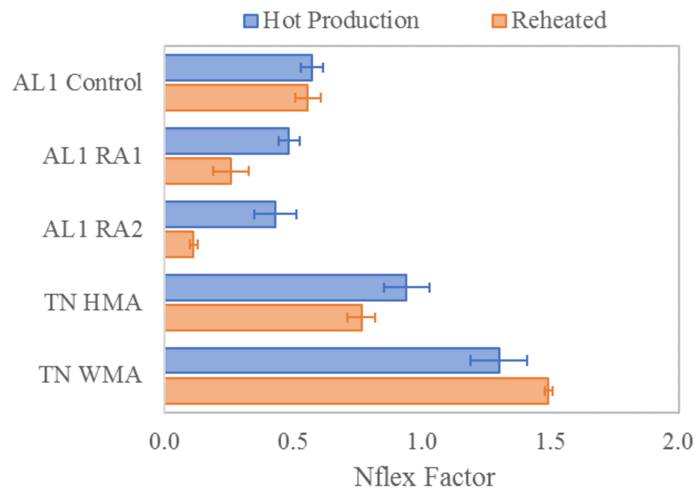
(c) TN Mixes

Figure 10. Fractured IDT Test Specimens

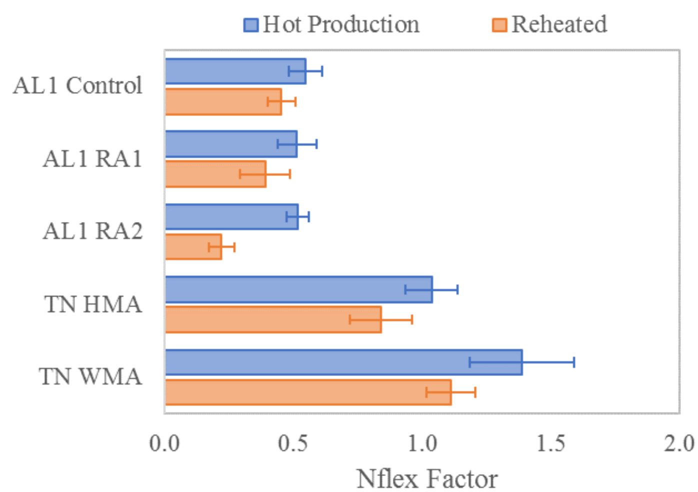
4.1.1 Effect of Mix Reheating

Figure 11 presents the comparison of the N_{flex} Factor results for reheated versus hot production specimens of AL1 and TN mixtures. The test was not performed on the hot-production specimens for AL2 mixtures due to lack of available material. As shown in Figure 11, for most of the mixtures, the reheated specimens exhibited lower N_{flex} Factor values as compared to the hot production specimens, indicating reduced cracking resistance. The only exception was the TN WMA mixture, which showed a higher N_{flex} Factor value with a loading rate of 0.5 mm/min after mix reheating. As compared to the AL1 control mixture, the two mixtures with rejuvenators (especially the RA2 mixture) showed more substantial reductions in N_{flex} Factor for reheated versus hot production specimens. To consider the test variability in discriminating the properties of reheated versus hot production specimens, the analysis of variance (ANOVA) generalized linear model (GLM) was used to analyze the N_{flex} Factor and the corresponding COV results. The ANOVA test was selected over the two-sample t-test because it was able to account for the two-way interaction between the two factors of 'Specimen Type' and 'Loading Rate'. ANOVA GLM analysis showed that the factor of 'Specimen Type' had a p-value of 0.026 for the

N_{flex} Factor results and a p-value of 0.329 for the corresponding COV results. These results indicated that mix reheating had a statistically significant effect on the IDT N_{flex} Factor results but had no effect on the variability of test results.



(a) Loading Rate of 0.5 mm/min

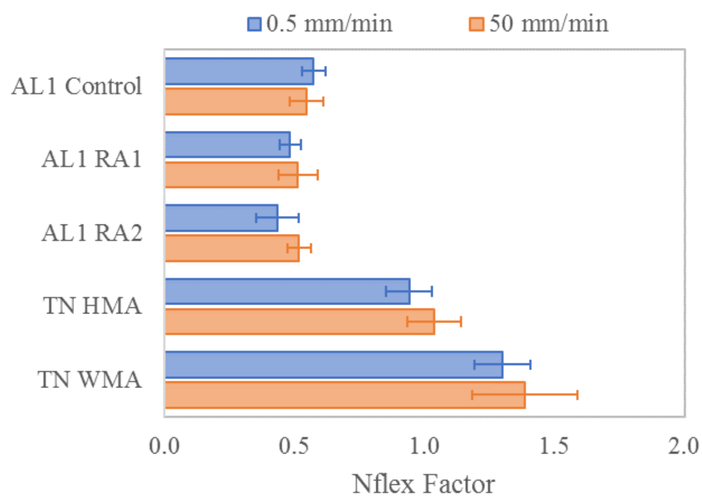


(b) Loading Rate of 50mm/min

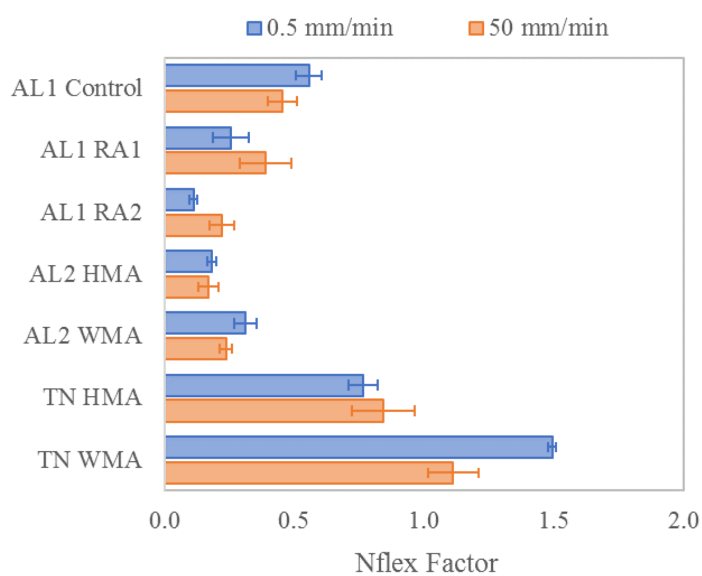
Figure 11. Effect of Mix Reheating on IDT N_{flex} Factor

4.1.2 Effect of Loading Rate

Figure 12 presents the comparison of IDT N_{flex} Factor results for two different loading rates of 0.5 and 50 mm/min. Overall, no consistent trend was observed; some mixtures showed higher N_{flex} Factor values at a higher loading rate while others showed the opposite trend. However, the differences might not be significant considering the test variability as denoted by the error whiskers. Figure 13 and Figure 14 present the IDT toughness and post-peak slope results that were used to determine the N_{flex} Factor. As illustrated, all mixtures exhibited significantly higher toughness and post-peak slopes when tested with the higher loading rate of 50 mm/min than the slower rate of 0.5 mm/min. Further investigations indicated that the effect of loading rate on IDT toughness was proportional to that of post-peak slopes. As shown in Table 7, the ratios of both IDT parameters at 50 mm/min over those at 0.5 mm/min were in the range of 2.0 to 3.0 for most of the mixtures. Since IDT N_{flex} Factor was determined as specimen toughness divided by the post-peak slope (Equation 4), the effect of loading rate on N_{flex} Factor was cancelled out. The same statistical analysis method introduced previously was used to identify the effect of loading rate on the IDT N_{flex} Factor results as well as the test variability. The results confirmed that the effect of loading rate on IDT N_{flex} Factor was not statistically significant, as indicated by a p-value of 0.476 for the N_{flex} Factor results and a p-value of 0.249 for the corresponding COV. Considering that a shorter testing time is desired during mix design and quality assurance, the faster loading rate of 50 mm/min is recommended for implementation in the IDT N_{flex} Factor test to assess the cracking performance of asphalt mixtures.

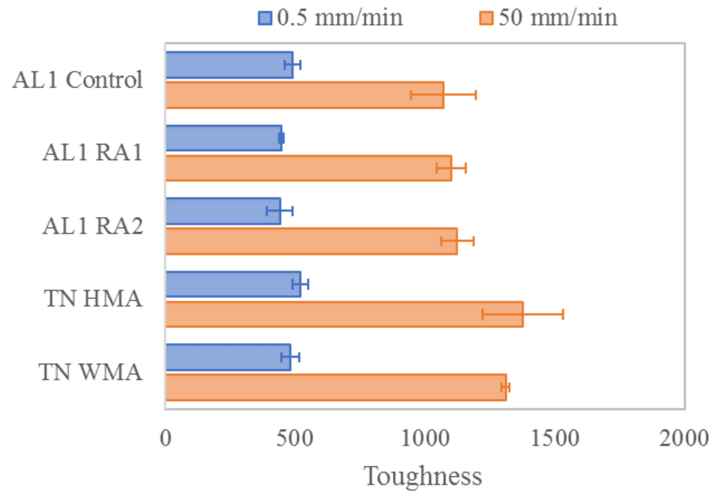


(a) Hot Production Specimens

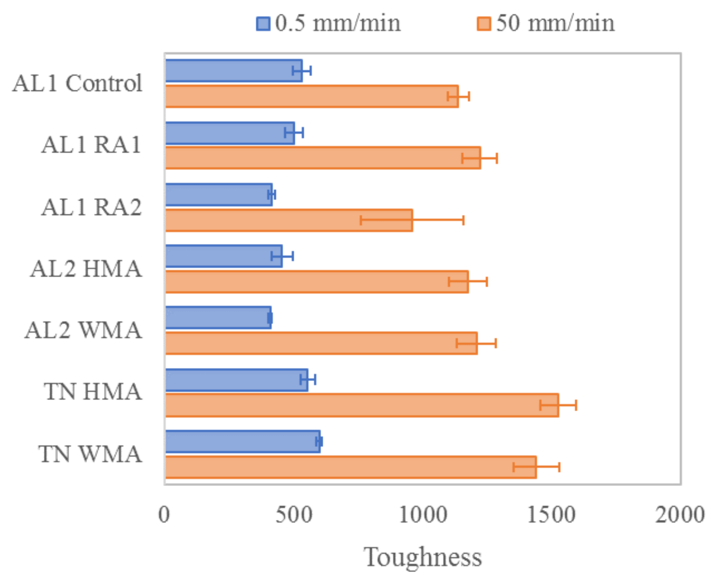


(b) Reheated Specimens

Figure 12. Effect of Loading Rate on IDT N_{flex} Factor

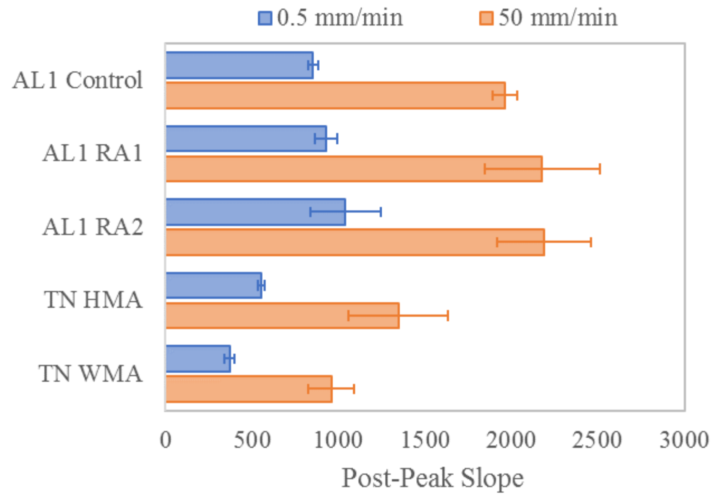


(a) Hot Production Specimens

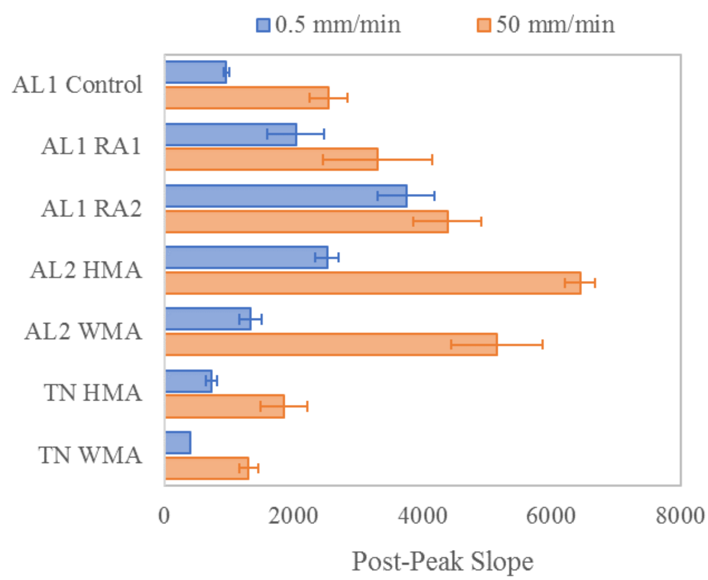


(b) Reheated Specimens

Figure 13. Effect of Loading Rate on IDT Toughness



(a) Hot Production Specimens



(b) Reheated Specimens

Figure 14. Effect of Loading Rate on IDT Post-Peak Slope

Table 7. IDT Toughness and Post-Peak Slope Ratio Results

Specimen Type	Mix ID	Toughness Ratio (50mm/min / 0.5mm/min)	Post-Peak Slope Ratio (50mm/min / 0.5mm/min)
Hot Production Specimens	AL1 Control	2.19	2.30
	AL1 RA1	2.46	2.35
	AL1 RA2	2.55	2.10
	AL2 HMA	n/a	
	AL2 WMA		
	TN HMA	2.65	2.43
	TN WMA	2.73	2.59
Reheated Specimens	AL1 Control	2.14	2.65
	AL1 RA1	2.44	1.62
	AL1 RA2	2.31	1.17
	AL2 HMA	2.58	2.55
	AL2 WMA	2.95	3.88
	TN HMA	2.75	2.54
	TN WMA	2.40	3.24

4.1.3 Comparison of Different Mixtures

Figure 15 presents the comparison of IDT N_{flex} Factor results for the AL1 mixtures. The hot production specimens of all three mixtures showed similar N_{flex} Factor values regardless of the loading rate. Considering that the two rejuvenated mixtures had a higher RAP content plus RAS than the control mixture, the rejuvenators seemed effective in restoring the properties of recycled materials. However, after mix reheating, the N_{flex} Factor of both the RA1 and RA2 mixtures decreased substantially. These results are consistent with findings by Yin et al. (2017), which showed that the effectiveness of rejuvenators on the properties of recycled materials reduced with aging. In addition, the ANOVA results in Table 8 indicated that, for the reheated specimens, the control mixture had the highest IDT N_{flex} Factor value and thus, the best cracking resistance, followed by the RA1 mixture and RA2 mixture, respectively. These results are in agreement with the ranking of these mixtures based on their two-year pavement cracking performance (Table 5).

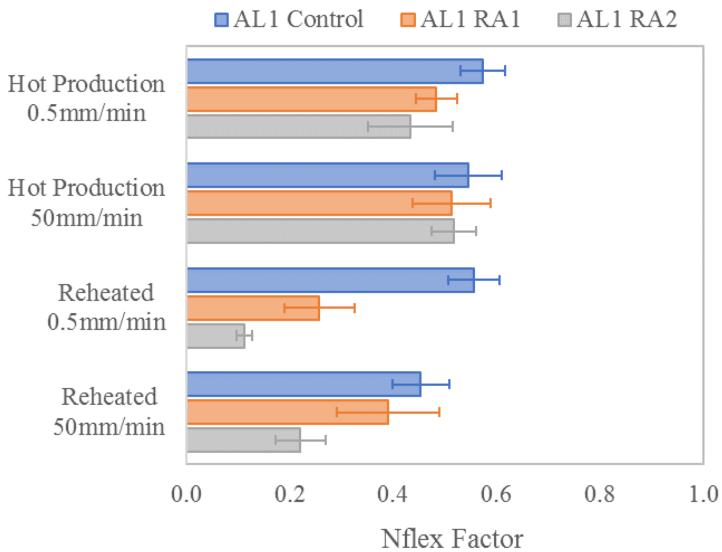


Figure 15. Comparison of IDT N_{flex} Factor Results for AL1 Mixes

Table 8. Statistical Comparison of IDT N_{flex} Factor Test Results

Field Project	Mixture Type	Hot Production Specimen	Reheated Specimen
AL1*	Control	A	A
	RA1	A	B
	RA2	A	C
AL2#	HMA	N/A	WMA > HMA
	WMA		
TN#	HMA	WMA > HMA	WMA > HMA
	WMA		
Notes	* *comparisons made based on ANOVA and Tukey's HSD test* # *comparisons made based on two-sample t-test*		

Figure 16 presents the comparison of IDT N_{flex} Factor results for the AL2 mixtures. The WMA mixture had higher N_{flex} Factor values than the HMA mixture for both loading rates evaluated in this study. The better cracking resistance of the WMA mixture was likely due to greater flexibility resulting from the lower temperature (280°F versus 305°F) during plant production and laboratory reheating process. The two-sample t-test results in Table 8 also confirmed that the WMA mixture had significantly better cracking resistance than the HMA mixture in the IDT N_{flex} Factor test. A similar trend was also observed for the IDT N_{flex} Factor results of TN mixtures (Figure 17), where the WMA mixture had statistically higher N_{flex} Factor values than the HMA mixture for both hot production and reheated specimens.

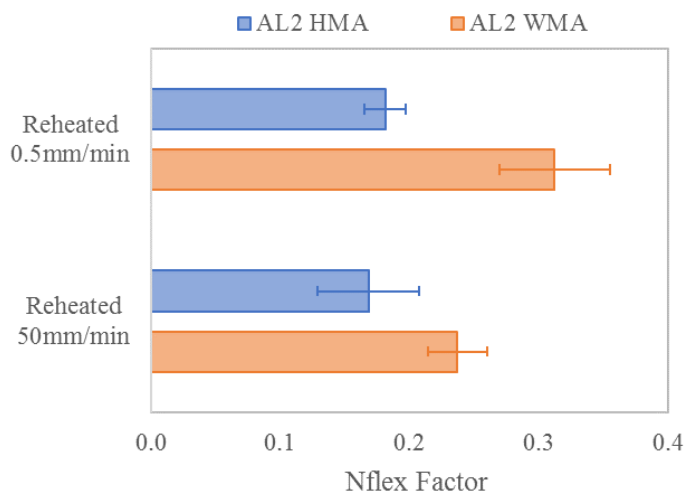


Figure 16. Comparison of IDT N_{flex} Factor Results for AL2 Mixes

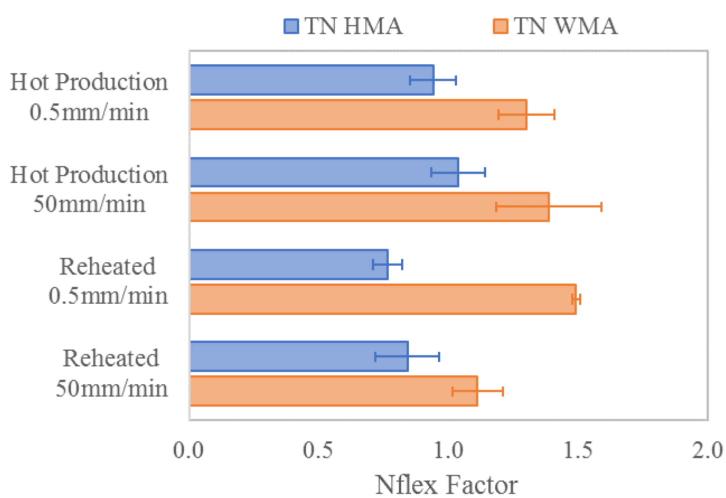


Figure 17. Comparison of IDT N_{flex} Factor Results for TN Mixes

4.2 SCB J-integral Test Results

Figure 18 presents an example of the load-displacement curves obtained from the SCB J-integral test with a loading rate of 0.5 mm/min. In general, the trends observed for different asphalt mixtures were consistent with those shown in the IDT N_{flex} Factor test (Figure 9). For example, the TN mixtures showed a more ductile behavior as compared to other mixtures, as indicated by lower peak loads, less steep post-peak load-displacement curves, and higher displacements. In addition, the two AL1 mixtures with rejuvenators and a higher RAP and RAS content were more brittle than the corresponding control mixture without rejuvenator. The SCB J-integral results are summarized in Table 9.

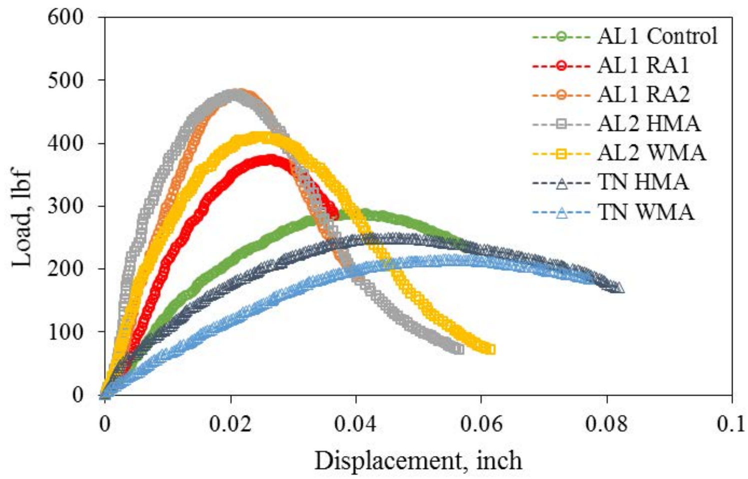


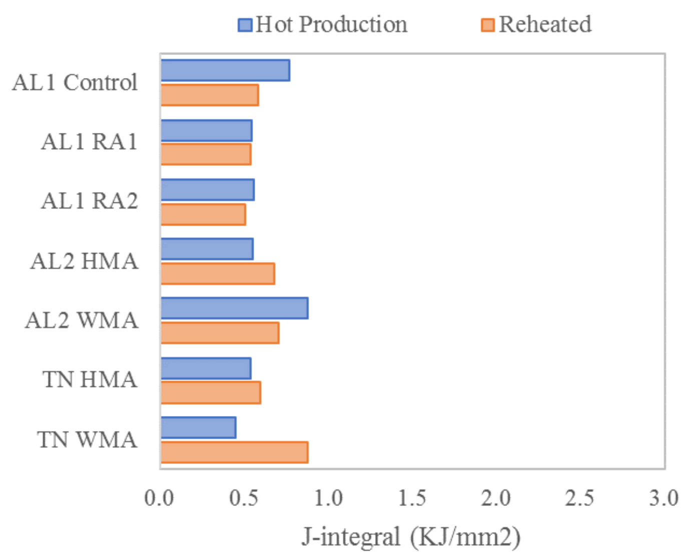
Figure 18. Example of the Load-Displacement Curves from the SCB Test (Reheated Specimens; Loading Rate of 0.5mm/min; 25.4 mm Notch Depth)

Table 9. Summary of SCB J-integral Results

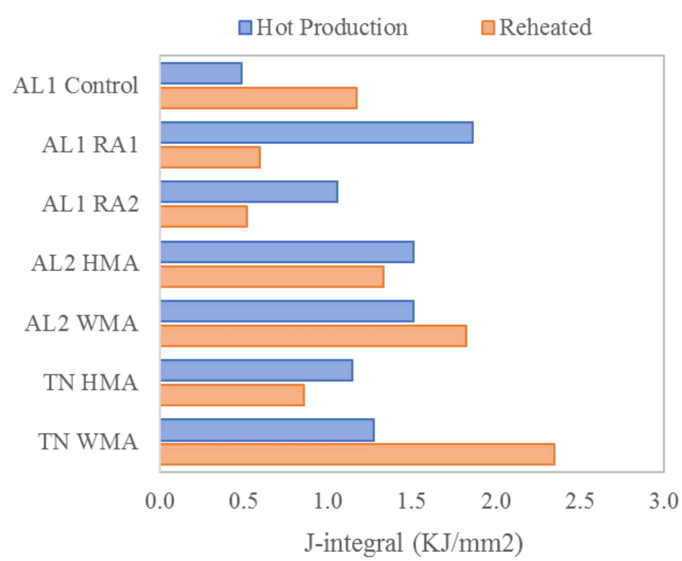
Specimen Type	Loading Rate	Mix ID	dU/da	J-integral (KJ/mm^2)
Hot Production Specimens	0.5 mm/min	AL1 Control	-0.044	0.771
		AL1 RA1	-0.031	0.544
		AL1 RA2	-0.031	0.556
		AL2 HMA	-0.031	0.554
		AL2 WMA	-0.049	0.881
		TN HMA	-0.030	0.538
		TN WMA	-0.025	0.451
	50 mm/min	AL1 Control	-0.028	0.485
		AL1 RA1	-0.106	1.858
		AL1 RA2	-0.060	1.056
		AL2 HMA	-0.085	1.506
		AL2 WMA	-0.084	1.506
		TN HMA	-0.065	1.145
		TN WMA	-0.073	1.270
Reheated Specimens	0.5 mm/min	AL1 Control	-0.033	0.584
		AL1 RA1	-0.030	0.537
		AL1 RA2	-0.029	0.508
		AL2 HMA	-0.038	0.683
		AL2 WMA	-0.040	0.707
		TN HMA	-0.034	0.598
		TN WMA	-0.050	0.880
	50 mm/min	AL1 Control	-0.067	1.172
		AL1 RA1	-0.034	0.591
		AL1 RA2	-0.030	0.519
		AL2 HMA	-0.075	1.329
		AL2 WMA	-0.102	1.820
		TN HMA	-0.048	0.854
		TN WMA	-0.133	2.348

4.2.1 Effect of Mix Reheating

Figure 19 presents the comparison of SCB J-integral results for reheated versus hot production specimens. As illustrated in Figure 19(a), when the test was conducted with a loading rate of 0.5 mm/min, the reheated and hot production specimens showed similar J-integral values in most cases. However, there were substantial differences in J-integral results for reheated versus hot production specimens when the test was performed at a higher loading rate of 50 mm/min. Considering the SCB test provides a single J-integral value (no replication of the result), evaluation of the test variability was not available. The ANOVA GLM analysis showed that the p-value for the factor 'Specimen Type' was higher than the specified significance level of 0.05, indicating an insignificant effect from mix reheating on the SCB J-integral results.



(a) Loading Rate of 0.5 mm/min

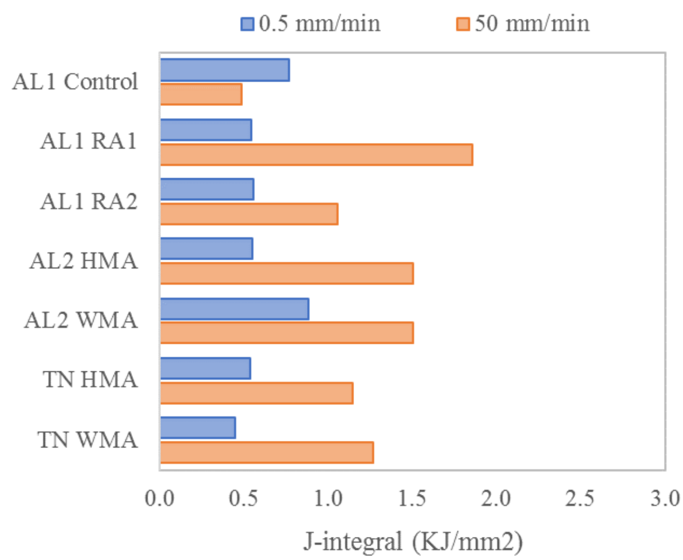


(b) Loading Rate of 50mm/min

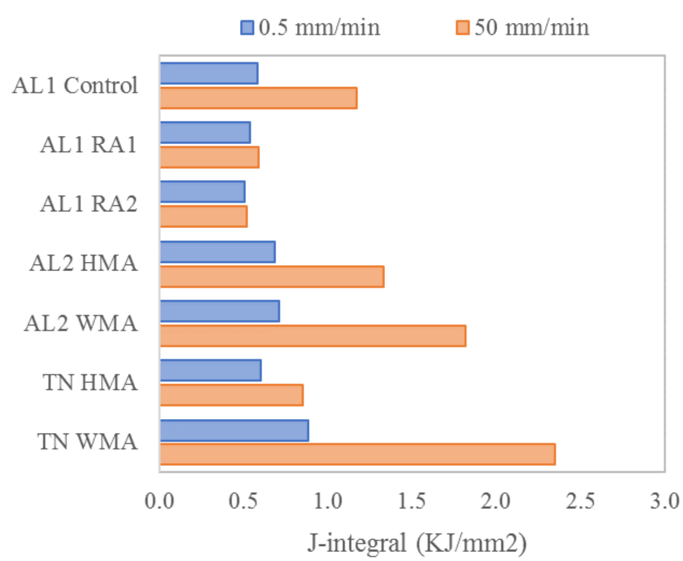
Figure 19. Effect of Mix Reheating on SCB J-integral

4.2.2 Effect of Loading Rate

Figure 20 presents the comparison of SCB J-integral results for the two different loading rates of 0.5 and 50 mm/min. In most cases, the higher loading rate resulted in a higher J-integral. The trend was confirmed by the ANOVA GLS analysis results; the factor of 'Loading Rate' had a p-value of 0.001, which was well below the significance level of 0.05. Therefore, loading rate had a significant effect on the SCB test results; specifically, mixtures tested with a higher loading rate of 50 mm/min showed higher J-integral values than those tested with a lower rate of 0.5 mm/min.



(a) Hot Production Specimens



(b) Reheated Specimens

Figure 20. Effect of Loading Rate on SCB J-integral

4.2.3 Comparison of Different Mixtures

Figure 21 presents the comparison of SCB J-integral results for the AL1 mixtures. When tested at a loading rate of 0.5 mm/min, the three mixtures exhibited similar J-integral values for both hot production and reheated specimens. However, no consistent trend was observed for the higher loading rate of 50 mm/min. For the hot production specimens, the RA1 mixture had the highest J-integral value followed by the RA2 mixture and then the control mixture; for the reheated specimens, the control mixture had a higher J-integral value than the two mixtures with rejuvenators.

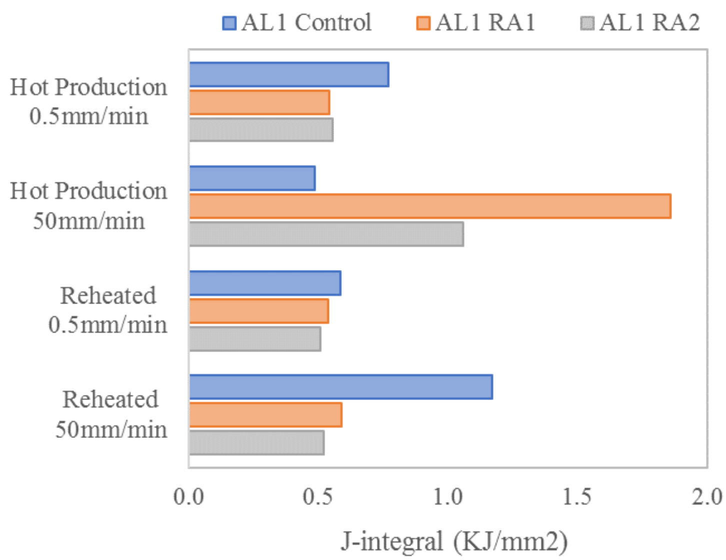


Figure 21. Comparison of SCB J-integral Test Results for AL1 Mixes

As previously discussed, since only one SCB J-integral value was determined for each mixture, statistical analysis for comparing the test results was not available. To overcome this issue, a practical comparison method developed by Moore (2016) was used to discriminate the J-integral results of different mixtures. For this method, the built-in regression function in Excel was first used to calculate the mean dU/da slope based on the strain energy versus notch depth results and the sum of squared residuals (SS_{Resid}) of the regression model. The standard deviation of the mean dU/da slope was then calculated by following Equations 6 through 8.

$$\sigma_e{}^2 \approx S_e{}^2 = \frac{SS_{Resid}}{n-2} \tag{6}$$

where

σ_e = standard deviation of regression model population total error;

S_e = estimated standard deviation of regression model total error;

SS_{Resid} = sum of squared residuals; and

n = sample size.

$$S_{xx} = \sum x_i^2 - \frac{\left(\sum x_i\right)^2}{n} \quad (7)$$

where
S_{xx} = sum of squared differences between notch depths; and
x_i = i[th] value of notch depth.

$$S_s = \frac{S_e}{\sqrt{S_{xx}}} \quad (8)$$

where
S_s = estimated standard deviation of the dU/da slope of the regression model.

Finally, the 95% confidence intervals of the dU/da slope for each mixture type were determined using Equation 9 and were used to statistically compare the cracking resistance of different mixtures.

$$CI = Slope \pm t * S_s \quad (9)$$

where
CI = 95% confidence interval of the dU/da slope of the regression model.

If the confidence intervals of two mixtures did not overlap, the results would be considered statistically different. It should be noted that the statistical comparison described herein was only performed on the significant factor of 'Loading Rate' as identified in the previous section. Table 10 summarizes the statistical comparison results; more detailed outputs are presented in the Appendix in Tables 10-12. As shown, no statistically significant difference was observed for the SCB J-integral test results among the three mixtures for both loading rates of 0.5 and 50 mm/min.

Table 10. Statistical Comparison of SCB J-integral Test Results

Field Project	Mixture Type	Loading Rate 0.5mm/min	Loading Rate 50mm/min
AL1	Control	Control = RA1 = RA2	Control = RA1 = RA2
	RA1		
	RA2		
AL2	HMA	WMA = HMA	WMA = HMA
	WMA		
TN	HMA	WMA = HMA	WMA = HMA
	WMA		

Figure 22 presents the comparison of SCB J-integral results for the AL2 mixtures. The WMA mixture had higher or similar SCB J-integral values than the HMA mixture, indicating better or equivalent cracking resistance. However, the difference was found to be statistically insignificant, as shown in Table 10. A similar trend was observed for the SCB J-integral results of TN mixtures in Figure 23.

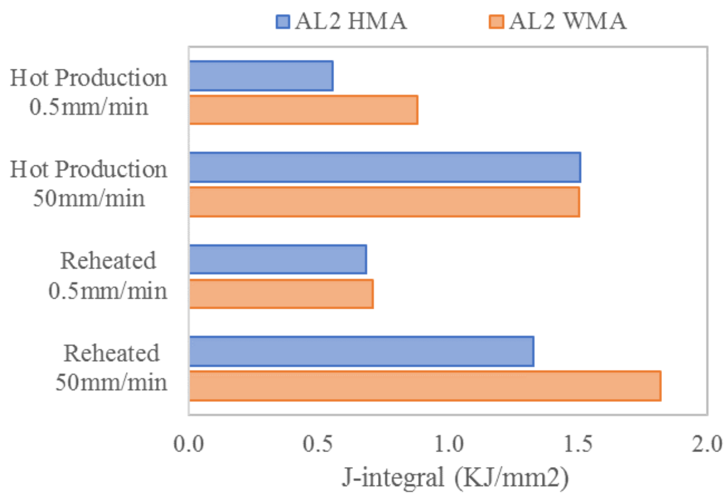


Figure 22. Comparison of SCB J-integral Test Results for AL2 Mixes

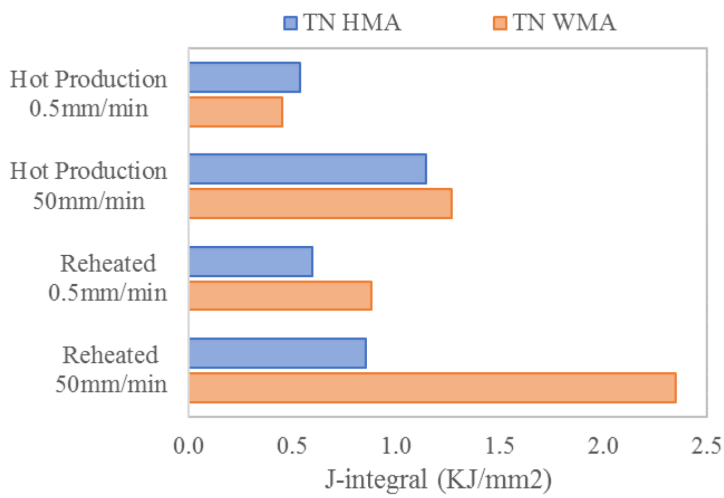
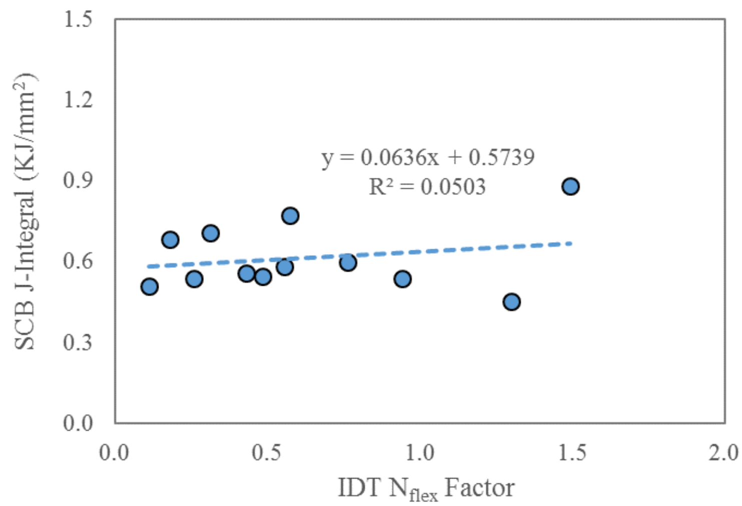


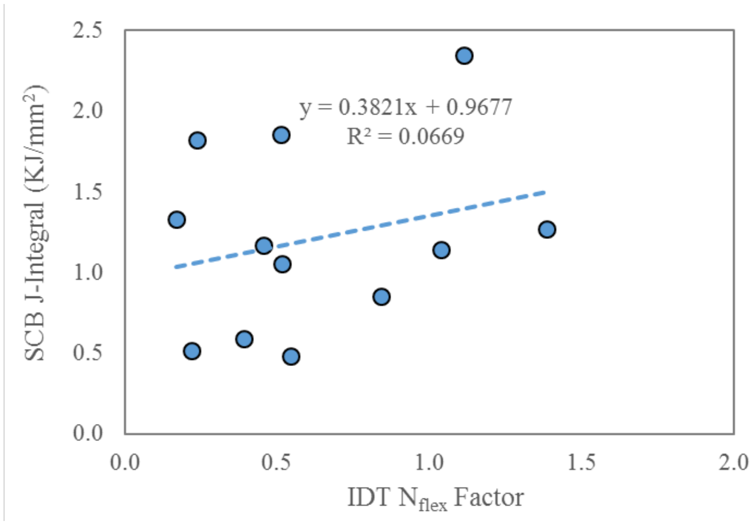
Figure 23. Comparison of SCB J-integral Test Results for TN Mixes

4.3 Correlation of IDT N_{flex} Factor and SCB J-integral Test Results

Figure 24 presents the correlation of IDT and SCB test results for all mixtures evaluated in this study. Each of the data points represents one mixture with a specific combination of specimen type (i.e., hot production and reheated specimens) and loading rate (i.e., 0.5 and 50 mm/min); the x-axis coordinate refers to the IDT N_{flex} Factor value, and the y-axis coordinate represents the corresponding SCB J-integral value. The dashed line is the best fitting linear regression relationship determined based on the least squares method. In general, no correlation was observed between the IDT and SCB test results (i.e., R^2 values of 0.0503 and 0.0669).



(a) Loading Rate of 0.5 mm/min



(b) Loading Rate of 50 mm/min

Figure 24. Correlation of IDT N_{flex} Factor and SCB J-integral Test Results

5. CONCLUSIONS AND RECOMMENDATIONS

This study evaluated the IDT N_{flex} Factor and SCB J-integral as potential parameters for assessing the cracking potential of asphalt mixtures for mix design and quality assurance. The experimental plan was designed to investigate the effects of mix reheating and loading rate on the results of these two tests. In addition, test results were analyzed to discriminate the cracking resistance of asphalt mixtures with different combinations of RAP, RAS, rejuvenators, and WMA technologies. Based on the results from this study, the following conclusions were obtained:

- Mix reheating showed a significant effect on the IDT N_{flex} Factor results; reheated specimens exhibited lower N_{flex} Factor values compared to hot production specimens. This suggests that the IDT N_{flex} Factor is sensitive to changes in mixture stiffness and embrittlement resulting from the reheating process.

- The effect of loading rate on the IDT N_{flex} Factor results was not statistically significant. The faster rate of 50 mm/min is recommended for use due to the shorter testing time and the broad availability of simple load frames to apply this rate.
- Mix reheating did not show an effect on the SCB J-integral results for tests conducted at the standard loading rate of 0.5 mm/min. However, results of reheated versus hot production mixtures were different for the loading rate of 50 mm/min, but there was not a consistent trend. Some reheated specimens had higher J-integral results than companion hot production specimens; other mixtures had lower J-integral results after reheating.
- Loading rate showed a significant effect on the SCB J-integral results; in most cases, the higher loading rate resulted in a higher J-integral value.
- The two rejuvenators used in the AL1 project seemed effective in restoring the properties of recycled materials, but their effectiveness was substantially reduced with mix reheating (aging). The IDT N_{flex} Factor results of reheated specimens matched the two-year pavement cracking performance.
- WMA mixtures from AL2 and TN projects exhibited better cracking resistance than the corresponding HMA mixtures in both IDT N_{flex} Factor and SCB J-integral tests, but no difference in the pavement cracking performance has been observed.
- No relationship was found between the IDT N_{flex} Factor and SCB J-integral results.

Further research is needed to monitor the field cracking performance of the projects over a longer period of time. In addition, the two modes of failure observed for the IDT test should be further explored. Finally, ruggedness and inter-laboratory evaluations are recommended for both cracking tests prior to being considered for implementation into routine practice.

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APPENDIX

Table 11. Detailed Statistical Comparison of SCB J-integral Test Results for AL1 Mixes

Loading Rate	Mix ID	dU/da Slope	Intercept	Jc (KJ/mm^2)	Absolute value of estimate of slope β (b)	Estimate of total model variance σ2 (s_e^2)	Estimate of total model deviation σ (s_e)	Estimate of deviation in slope only (s_s)	df	95% confidence interval of slope (lower)	95% confidence interval of slope (upper)
0.5	Control	-0.039	1.826	0.678	0.039	0.007	0.081	0.004	16	0.031	0.047
	RA1	-0.031	1.503	0.541	0.031	0.004	0.064	0.003	16	0.024	0.037
	RA2	-0.030	1.475	0.532	0.030	0.004	0.062	0.003	16	0.024	0.036
50	Control	-0.048	2.475	0.829	0.048	0.103	0.320	0.015	16	0.017	0.079
	RA1	-0.070	2.959	1.222	0.070	0.147	0.383	0.018	16	0.032	0.107
	RA2	-0.045	2.077	0.785	0.045	0.139	0.372	0.017	16	0.009	0.081

Table 12. Detailed Statistical Comparison of SCB J-integral Test Results for AL2 Mixes

Loading Rate	Mix ID	dU/da Slope	Intercept	Jc (KJ/mm^2)	Absolute value of estimate of slope β (b)	Estimate of total model variance σ2 (s_e^2)	Estimate of total model deviation σ (s_e)	Estimate of deviation in slope only (s_s)	df	95% confidence interval of slope (lower)	95% confidence interval of slope (upper)
0.5	HMA	-0.035	1.630	0.618	0.035	0.003	0.059	0.003	16	0.029	0.040
	WMA	-0.044	2.001	0.794	0.044	0.006	0.079	0.004	16	0.037	0.052
50	HMA	-0.080	3.790	1.418	0.080	0.054	0.232	0.011	16	0.057	0.102
	WMA	-0.093	4.414	1.663	0.093	0.053	0.230	0.011	16	0.070	0.115

Table 13. Detailed Statistical Comparison of SCB J-integral Test Results for TN Mixes

Loading Rate	Mix ID	dU/da Slope	Intercept	Jc (KJ/mm^2)	Absolute value of estimate of slope β (b)	Estimate of total model variance σ2 (s_e^2)	Estimate of total model deviation σ (s_e)	Estimate of deviation in slope only (s_s)	df	95% confidence interval of slope (lower)	95% confidence interval of slope (upper)
0.5	HMA	-0.032	1.749	0.568	0.032	0.011	0.106	0.005	16.000	0.022	0.042
	WMA	-0.037	1.967	0.666	0.037	0.044	0.210	0.010	16.000	0.017	0.058
50	HMA	-0.057	2.977	1.000	0.057	0.104	0.322	0.015	16.000	0.025	0.088
	WMA	-0.104	4.689	1.824	0.104	0.173	0.417	0.020	12.000	0.060	0.147