NCAT REPORT 23-01

June 2023

National Center for Asphalt Technology
NCAT
at AUBURN UNIVERSITY

Summary of Four Balanced Mix Design Case Studies for CRH Americas Materials Companies

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June 2023

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DISCLAIMER

ACKNOWLEDGMENTS

The authors gratefully acknowledge the following members of the NCAT Applications Steering Committee for their review of this technical report: Tanya Nash, Cheng Ling, Robert Rea, Parnian Ghasemi, and Carl Johnson.

1 BACKGROUND

Asphalt mixture design is a critical step in achieving long lasting asphalt pavement performance. An asphalt pavement should possess adequate stability (i.e., resistance to permanent deformation/rutting) and durability (i.e., resistance to cracking) for the intended design application. In recent years, there have been reports of mixture durability (cracking) related performance issues. In response, state Departments of Transportation (DOTs) have implemented a variety of specification changes, including establishing minimum binder contents, decreasing design gyration levels, and decreasing allowable recycled content (Tran, et al, 2019).

In addition, substantial interest has been shown in the concept of balanced mix design. Balanced mix design (BMD) was defined by the FHWA Expert Task Group (ETG) on Mixtures and Construction as “asphalt mixture design using performance tests on appropriately conditioned specimens that address multiple modes of distress taking into consideration mixture aging, traffic, climate and location within the pavement structure (West et al, 2018).” In simple terms, it means designing the right mixture for the right job.

Balanced mix design can be completed using four main approaches (NAPA, 2022a). The most conservative approach, Volumetric Design with Performance Verification, is to conduct a traditional volumetric mixture design and then evaluate mixture performance. Volumetric Design with Performance Optimization is a second option that begins with a volumetric mixture design but allows for small changes in asphalt content to meet performance testing criteria. Performance-Modified Volumetric Design is a third approach and starts with a mix design selection that it is intended to pass performance testing criteria with relaxed or eliminated volumetric requirements. The final conceptual approach, Performance Design, is to utilize performance testing with minimal traditional design requirements to design the mixture for the intended project application. This approach maximizes the innovation and value potential.

2 NEED

While owner agencies are aware of BMD approaches, hesitancy exists to electively pursue and evaluate the approaches. Active conversations and involvement between industry and agency personnel must occur to successfully move these concepts forward. One significant need is to generate detailed supporting data that illustrate how a Performance Design BMD approach can be used to develop optimized, performance-based mixtures.

3 OBJECTIVES

The objectives of this testing program are twofold. First, it is to determine the laboratory performance of currently produced asphalt mixtures at multiple CRH Americas Materials locations. Second, it is to illustrate how these mixtures can be designed to provide equal to or better performance via a BMD (Performance Design) approach. Each of the four case studies sought to accomplish these goals with different materials, BMD tests, and criteria.

4 METHODS

4.1 Specimen Fabrication

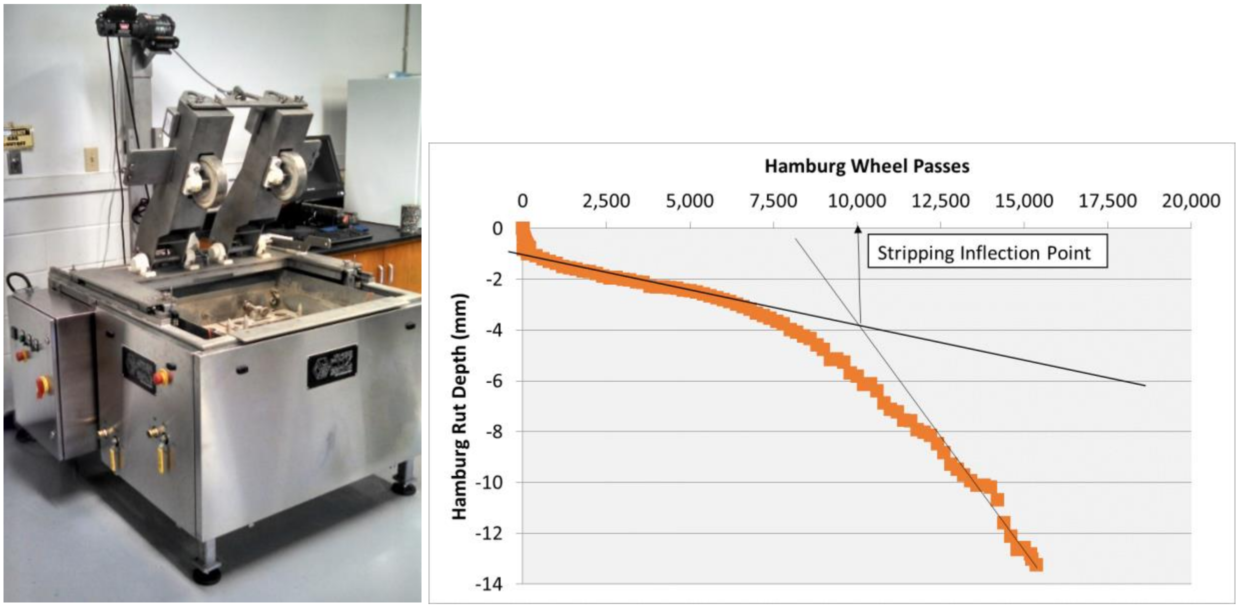
All specimens prepared for this study were lab-mixed lab-compacted (LMLC) specimens fabricated from raw materials (aggregate, RAP, binder) provided to NCAT by the participating contractors. Unless otherwise specified, all performance test specimens for this study were compacted to a target air void level of 7.0 ± 0.5 percent (after saw trimming, if required). Rejuvenator dosages were converted to by weight of virgin binder and were added to the hot virgin binder before mixing for all four case studies presented in this report. All performance tests were short-term oven aged (STOA) for four hours at 275°F per the *Short-Term Conditioning for Mixture Mechanical Property Testing* procedure documented in AASHTO R30-02 (2015). For the cracking test specimens, it was desired to test some mixes at a long-term aged condition that would be more representative of the pavement after a few years of service in the field. For this study, the aging procedure developed for use during the 2015 NCAT Test Track top-down cracking group experiment was selected (Chen et al., 2018). This procedure requires aging loose mix on large pans in a thin layer (<3/4" thick) for eight hours at 275°F prior to compaction (Figure 1). This aging procedure is termed critical aging (CA), as it is designed to simulate three to five years of field aging in the southeastern U.S. All critical aging for this study was performed on mix that had already been short-term oven aged.

Figure 1. Mix in a Thin Layer for Critical Oven Aging

4.2 Hamburg Wheel Tracking Test

The Hamburg Wheel Tracking Test (HWTT) (Figure 2) was conducted per AASHTO T324-17 to evaluate asphalt mixture rutting resistance and moisture susceptibility. Specimens were loaded for a maximum of 20,000 passes while submerged in heated water. AASHTO T324 does not specify a testing temperature so the temperature was selected individually for each project. Hamburg specimens were compacted to 62 mm tall with a target air voids of 7.0 ± 0.5 percent after short-term oven aging. In the Hamburg, two specimens are trimmed and loaded together as a single replicate. For each mixture in the study, a minimum of two replicates (four total specimens) were tested.

Several states have available HWTT criteria (West et al., 2018). The majority of states specify a minimum number of passes (such as 10,000 or 20,000) in the HWTT to reach a defined failure threshold (commonly 12.5 mm) based on factors such as the grade of the virgin binder or traffic level. A few states also require their mixtures to reach a defined number of passes without exhibiting a stripping inflection point (SIP). An example of the rut depth versus wheel passes data collected by the HWTT, including an example SIP, is also shown in Figure 2.



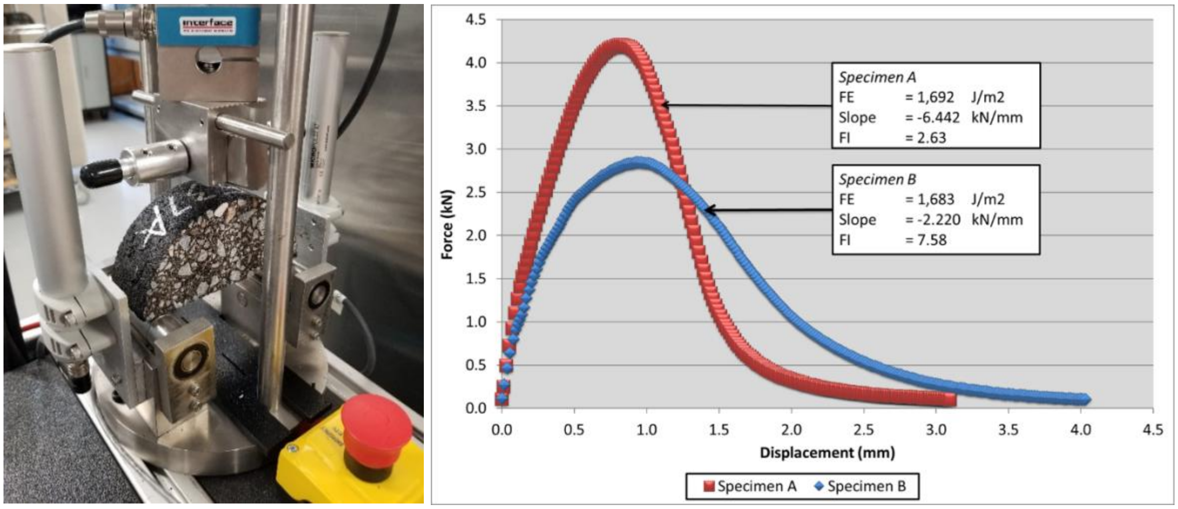
(a) (b)

Figure 2. (a) HWTT Machine and (b) Example Data

4.3 Illinois Flexibility Index Test

The Illinois Flexibility Index Test (I-FIT) was conducted to evaluate mixture resistance to intermediate temperature cracking. Testing was performed per AASHTO TP 124-18. This specification was adopted as AASHTSO T393 in 2021. A minimum of six replicates with an air void level of 7.0 ± 0.5 percent (after saw trimming) were prepared for each mixture. For each semi-circular specimen, a notch was cut at a depth of 15 ± 1.0 mm and a width of 1.5 ± 0.5 mm using a modified tile saw. The specimens were conditioned in an environmental chamber for two hours at 25°C prior to testing. The specimens were loaded monotonically at a rate of 50 mm/min until fracture to generate a plot of specimen load versus displacement. The test setup as well as example raw data are shown in Figure 3.

Flexibility index (FI) is a parameter used as a relative measure of mixture cracking resistance. The FI is essentially the area under the load-displacement curve (fracture energy) divided by the slope at the curve inflection point post-peak. A higher fracture energy would yield a higher FI while a higher (steeper) post-peak slope would yield a lower FI. Mixtures with a higher FI are considered more cracking resistant than mixtures with a lower FI. Figure 3 shows an example of how two different I-FIT specimens may have almost equal fracture energies but may have very different FI values due to the difference in their post-peak slope values. The FI calculation is shown as Equation 1. At the time of this work, the Illinois DOT recommended a minimum FI criteria of 8 for AC surface mixes (Al-Qadi et al., 2017) (West et al., 2018). However, state specific FI criteria are likely needed to be more representative of mixtures in different climates.



(a) **(b)**

Figure 3. (a) I-FIT Test Setup and (b) Example Raw Data (right)

$$FI = \frac{G_f}{|m|} \, x \, A \qquad (1)$$

Where:

G_f = Fracture Energy (J/m^2),
W_f = Work of Fracture (J),
A_{lig} = Ligament Area (mm^2) = (Radius – Notch Length) x Specimen Width,
FI = Flexibility Index,
m = Post-Peak Slope (kN/mm), and
A = Scaling Factor (0.01 for gyratory specimens).

4.4 Indirect Tensile Asphalt Cracking Test

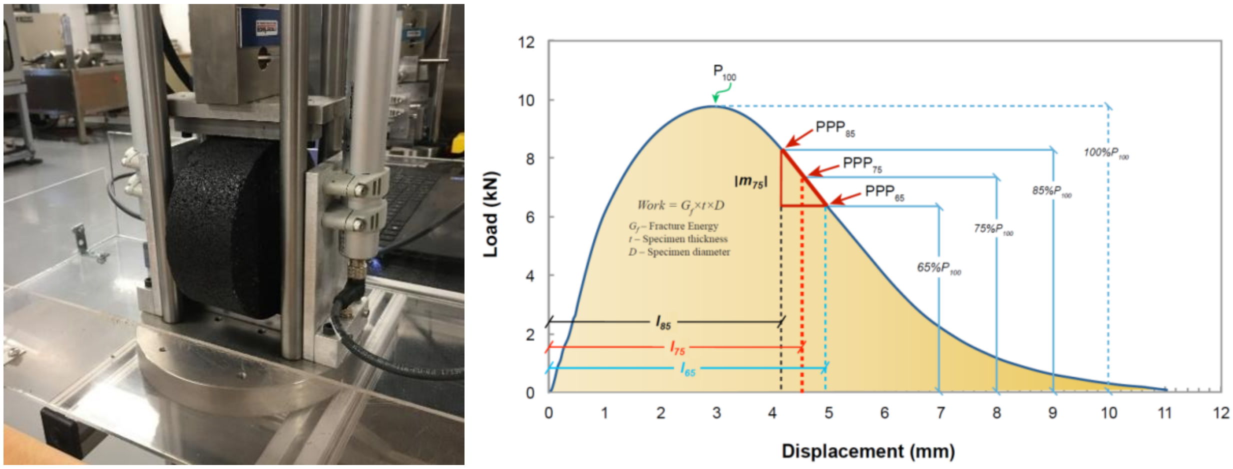
The Indirect Tensile Asphalt Cracking Test (IDEAL-CT) was conducted to evaluate mixture resistance to intermediate temperature cracking. Testing was performed per ASTM D8225-19. The test is relatively simple in that it does not require additional sample preparation beyond sample compaction itself. For this test, a minimum of four 62 mm tall gyratory specimens were prepared to a target air void level of 7.0 ± 0.5 percent. Specimens were loaded monotonically in indirect tension at a rate of 50 mm/min until failure while load line displacement (LLD) was recorded. Testing was performed using a device capable of sampling load and displacement data at a rapid rate (40 Hz), and a plot of load versus LLD was generated for each specimen. This plot was then analyzed to determine the CT_{Index} (Figure 4).

The CT_{Index} equation from ASTM D8225-19 is shown as Equation 2 below. Three major parameters factor into the calculation of the CT_{Index}. Similar to the I-FIT, the area under the load-displacement curve (G_f) and the post-peak slope $|m_{75}|$ factor into the results. The major difference from the I-FIT, in terms of the slope calculation, is that the I-FIT slope is determined at the post-peak inflection point of the load-displacement curve while this value is fixed at 75% of the peak load after the peak for the CT_{Index}. Additionally, the CT_{Index} calculation also includes the l_{75} parameter. The l_{75} is the displacement of the specimen at 75% of the peak load after the peak. A higher G_f and l_{75} would increase the CT_{Index} while a higher $|m_{75}|$ would lower the CT_{Index}. A higher CT_{Index} is generally representative of increased mixture cracking resistance. The Virginia DOT is currently proposing to use a minimum CT_{Index} of 70 for the design of surface mixes using BMD (VDOT, 2019).

$$\mathrm{CT}_{\mathrm{Index}} = \frac{t}{62} x \frac{l_{75}}{D} x \frac{\mathrm{G_f}}{|m_{75}|} \mathrm{x}\ 10^6 \tag{2}$$

Where:

CT_{Index} = cracking tolerance index,
G_f = fracture energy (J/m^2),
$|m_{75}|$ = absolute value of the post-peak slope m_{75} (N/m),
L_{75} = displacement at 75% of the peak load after the peak (mm),
D = specimen diameter (mm), and
t = specimen thickness (mm).



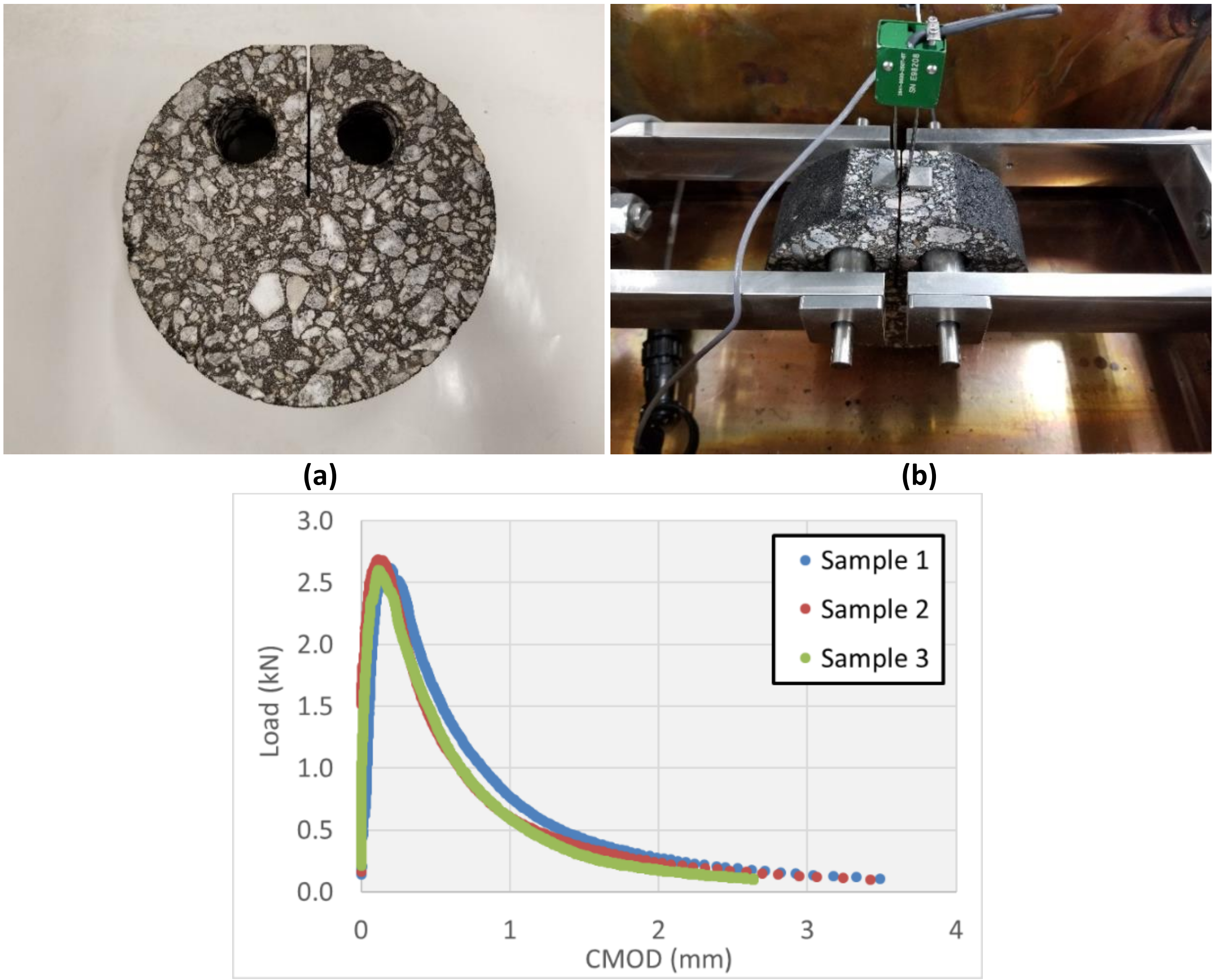
(a) **(b)**

Figure 4. (a) IDEAL-CT Test Setup and (b) Plot of Load vs. LLD (Zhou et al., 2017)

4.5 Disk Shaped Compact Tension (DCT) Test

The Disk-Shaped Compact Tension (DCT) test was used to assess the low temperature cracking susceptibility of the mixtures. Testing was performed per ASTM D7313-13 at a test temperature of -12°C. Lab-produced mix samples were re-heated and compacted to a height of 160 mm, and two DCT replicates were then cut from each larger specimen. Six replicates of each mix were prepared to a target air void level of 6.5 ± 0.5 percent for testing. Figure 5 shows a DCT specimen as well as the test setup utilized at NCAT.

The DCT specimen is loaded so that the notch at the top of the specimen (shown in Figure 5) is pulled apart in tension at the uniform rate of 0.017 mm/sec (approximately 1 mm per minute). The clip gage instrumented over the notch is referred to as the crack mouth opening displacement (CMOD) gage and serves as the control mechanism for the test. A plot of specimen load versus CMOD displacement is generated for each specimen (example shown in Figure 5). The area under this curve is the fracture energy (FE), and a higher value is generally indicative of a mixture with better low temperature cracking resistance. Table 1 shows the DCT Fracture Energy criteria that were developed as part of a national low temperature cracking pooled-fund study (Marasteanu et al., 2012).



(a)

(b)

(c)

Figure 5. (a) DCT Specimen, (b) Test Setup, and (c) Example Data

Table 1. Recommended DCT Fracture Energy (G_f) Criteria (Marasteanu et al., 2012)

Criteria	Project Criticality/Traffic Level		
	High >30M ESALs	**Moderate 10-30M ESALs**	**Low <10M ESALs**
Fracture Energy, minimum (J/m2), Low PG +10°C	690	460	400

4.6 Performance Space Diagrams

A performance space diagram is a useful tool for illustrating the interaction between rutting and cracking performance in balanced mix design (West et al., 2018). These diagrams are separated into four quadrants with the dividing lines being set performance testing thresholds. Four quadrants are then drawn on the diagram based on these thresholds: passing both rutting and cracking tests, failing the rutting test but passing the cracking test, passing the rutting test but failing the cracking test, and failing both rutting and cracking tests. An example of a performance diagram with the labeled mix performance quadrants is shown in Figure 6 for illustration purposes. It should be noted that different criteria exist for these performance tests (particularly the Hamburg) and that these performance criteria may need to be locally calibrated to effectively differentiate good and poor performing mixtures in a given climate and/or traffic condition.

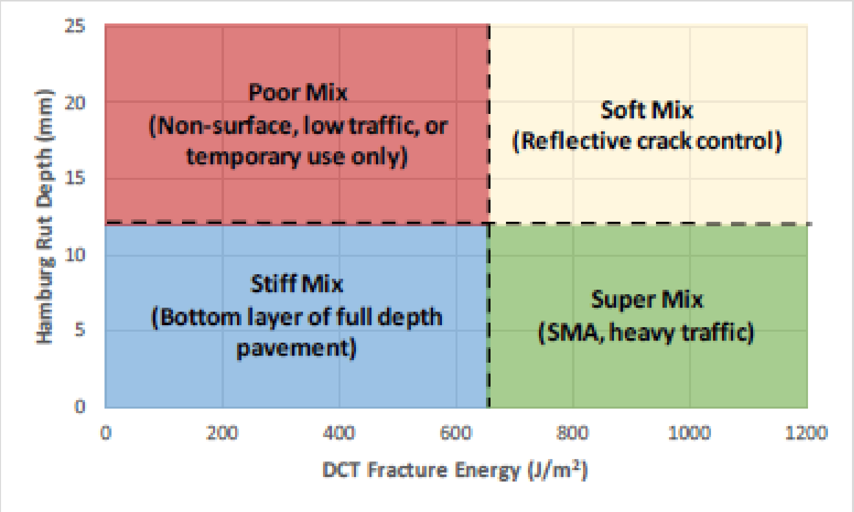


Figure 6. Example Performance Space Diagram (West et al., 2018)

5 Case Study 1: Pennsy Supply – Harrisburg, PA

5.1 Mixes and Workplan

NCAT received materials from Pennsy Supply and began initial laboratory work for this project in January 2018. Three mixes were used for this project. The control mix was a typical surface mix design (provided by Pennsy) and had 15% RAP. Two additional 35% RAP designs that had not been produced before were provided to NCAT for laboratory performance testing. These two designs had not yet been produced to determine their volumetric properties. They were the same mix design except one included a rejuvenator and the other did not. The overall purpose of this testing was to determine if equivalent performance could be achieved to a conventional surface mix after increasing the RAP content by 20%, and adding a rejuvenator to the binder. Both 35% RAP mix designs were trialed and verified by NCAT before performance testing. However, volumetric specifications were not rigidly adhered to or controlled with these mixtures since the emphasis was on establishing and meeting threshold criteria using the mixture performance tests. The gradations (provided by Pennsy) and volumetrics for the mixes are shown in Table 2. The 35% RAP mixes were only slightly coarser than the 15% RAP mix. The mixes had an Ndes of 75 gyrations.

Table 2. Pennsy Mix Designs

% Passing	Mix 1 (15% RAP)	Mix 2 (35% RAP No Rejuvenator)	Mix 3 (35% RAP With Rejuvenator)
3/4"	100	100	100
1/2"	100	100	100
3/8"	95.1	95.0	95.0
# 4	64.2	62.4	62.4
# 8	42.8	40.7	40.7
# 16	27.1	26.0	26.0
# 30	17.2	16.7	16.7
# 50	11.5	11.4	11.4
#100	8.5	8.4	8.4
#200	7.02	7.05	7.05
AC%, Total	5.7	5.6	5.6
AC%, Virgin	5.0	4.0	4.0
AC% from RAP	0.7	1.6	1.6
RBR	12%	28%	28%
Rejuvenator Dosage*	0%	0%	8%
Va, %	4.1	3.5	N/A
VMA, %	16.8	14.9	
VFA, %	76.3	77.1	
DP	1.27	1.42	
Gmm	2.487	2.489	
Gmb	2.384	2.402	

*By weight of RAP binder

The rejuvenator used for this project was dosed at 8% by weight of RAP binder. The binder used was a PG 64-22 and was modified with 0.25% liquid anti-strip agent by weight of total binder. All of the aggregates and RAP were shipped from Pennsy Supply to NCAT in barrels and were subsequently dried and processed.

The work plan included rutting and cracking tests for all three mixes. Rutting susceptibility was determined using the Hamburg Wheel Tracking Test at 50°C per AASHTO 324-17. Two cracking tests, the I-FIT (AASHTO TP 124-18) and IDEAL-CT (ASTM D8225-19) were used at 25°C to investigate the cracking resistance of the proposed mixes. The I-FIT was conducted at various densities, aging conditions, and loading rates. A detailed breakdown of the work plan is shown in Table 3. The binder contents used were the optimum binder contents from Table 2 with ±0.5% AC to show the effects of low and high binder contents. The binder contents are labeled in the following manner: optimum binder (asphalt) content = OAC, optimum binder – 0.5% AC (low asphalt content) = LAC, optimum binder + 0.5% AC (high asphalt content) = HAC. This labeling system will be used for the entirety of this report.

Two separate I-FIT procedures were used to evaluate these mixes. The first was the standard AASHTO test method and the second was a modified version from Pennsylvania State

University (PSU). The main differences between the AASHTO procedure and the modified PSU procedure (Penn State University, 2017) used in this particular project are summarized in Table 4.

Pennsy was interested in assessing the difference between the two procedures as PennDOT was considering implementing the PSU modified test procedure at that time. An additional set of I-FIT specimens was compacted at the lower air voids and aged for a shortened amount of time according to the PSU procedure, and tested at 25 °C and 50 mm/min, per AASHTO TP124-18. Finally, I-FIT testing was conducted at the optimum asphalt contents of Mix 1 and Mix 3 after additional aging for eight hours at 275°F beyond short term oven aging (STOA).

Table 3. Pennsy Work Plan

Mix	Test	AC%	Aging Condition
Mix 1 (15% RAP)	Hamburg	LAC, OAC, HAC	STOA - 4 hr @ 275°F
	IDEAL-CT	LAC, OAC, HAC	STOA - 4 hr @ 275°F
	I-FIT (TP 124-18, Va= 7%)	LAC, OAC, HAC	STOA - 4 hr @ 275°F
	I-FIT (PSU)	LAC, OAC, HAC	STOA - 2 hr @ 275°F
	I-FIT (TP 124/PSU), Va = 5%)	LAC, OAC, HAC	STOA - 2 hr @ 275°F
Mix 2 (35% RAP)	Hamburg	OAC	STOA - 4 hr @ 275°F
	IDEAL-CT	OAC	STOA - 4 hr @ 275°F
	I-FIT (TP 124, Va= 7%)	OAC	STOA - 4 hr @ 275°F
Mix 3 (35% RAP With Rejuvenator)	Hamburg	LAC, OAC, HAC	STOA - 4 hr @ 275°F
	IDEAL-CT	LAC, OAC, HAC	STOA - 4 hr @ 275°F
	I-FIT (TP 124, Va= 7%)	LAC, OAC, HAC	STOA - 4 hr @ 275°F

Table 4. I-FIT Test Method Differences

Testing Parameter	AASHTO TP-124	Modified PSU
Aging Temperature and Time	4 Hours @ 275°F	2 Hours @ 275°F
Sample Density	7% Air Voids	5% Air Voids
Testing Rate	50 mm/min	5 mm/min
Testing Temperature	25°C	20°C

5.2 Results

Table 5 includes a summary of the HWTT results from all three mixes. Some of the test replicates failed to reach 20,000 passes before exceeding 12.5 mm of rutting. The HWTT device stops recording data after both replicates exceed the input threshold rutting value. Thus, it is possible for one sample to reach 12.5 mm before 20,000 passes occurs while the opposite sample fails to reach the threshold before the test is concluded. When this occurs, one sample would have a known result for passes to 12.5 mm rutting and the other would be designated as greater than 20,000 passes to failure. In these cases, a true average of passes to failure is impossible to determine exactly. The averages reported for replicates where this occurred are designated as greater than the average of the known number of passes and 20,000 passes since that is the minimum possible result.

Table 5. Pennsy HWTT Results

Mix	AC Content (%)	Replicates	Air Voids (%)	Rut Depth at 10,000 passes (mm)	Rut Depth at 20,000 passes (mm)	Passes to 12.5 mm Rut Depth	Stripping Inflection Point (Passes)
			Average	Average	Average	Average	Average
Mix 1 (15% RAP)	LAC	6	7.1	6.8	*>12.5	15,100	8,900
	OAC - 0.15%	2	6.9	8.7	*>12.5	12,600	6,200
	OAC	2	7.3	5.0	13.1	**>18,500	12,100
	HAC	2	7.0	8.7	*>12.5	14,100	10,750
Mix 2 (35% RAP)	OAC	2	7.1	3.5	6.3	>20,000	>20,000
Mix 3 (35% RAP with rejuvenator)	LAC	2	6.7	2.9	5.1	>20,000	>20,000
	OAC	2	7.2	3.9	7.3	>20,000	>20,000
	HAC	2	6.6	5.8	12.3	**>19,600	>20,000

* Both replicates were terminated due to exceeding 12.5 mm of rutting prior to 20,000 passes

** Only one replicate exceeded 12.5 mm of rutting prior to 20,000 passes

Table 5 shows that all of the Mix 1 Hamburg samples (15% RAP) exhibited some form of stripping, while none was present in the Mix 2 or Mix 3 samples (35% RAP). Figure 7 shows the HWTT results of only Mix 1 to illustrate the stripping behavior. The plots represent the maximum rut depth after each pass. Only one replicate from all of the Mix 1 tests reached 20,000 passes without exceeding 12.5 mm. Interestingly, the best performers were at the optimum asphalt content. Both the HAC and LAC had more rutting than the optimum AC%. Additional testing was performed for Mix 1 due to unexpected poor rutting performance at the lowest asphalt content. Typically, lower asphalt contents will yield lower rutting values in the HWTT.

An additional AC%, OAC - 0.15%, was tested to verify the rutting performance between LAC and OAC since the LAC had worse performance than the OAC, despite the lower AC%. This AC% was selected to provide a measurement between LAC and OAC since the LAC results failed much sooner than the OAC test. The LAC set was retested twice to confirm the unexpected results and all three tests exhibited similar behavior. The results are shown in Figure 7 along with the other sets from Mix 1. Compared to the LAC results, the performance of the OAC – 0.15% mix was even worse. This was unexpected. The LAC data shown in Figure 7 represent the first two replicates tested out of the six total. The HWTT results at the optimum AC% were the best of all the sets. It is possible that below the OAC the mix was not viable due binder content being too low.

The HWTT results from Mix 2 and 3 are shown in Figure 8. The 35% RAP mixes exhibited notably less rutting than the 15% RAP mixes, as expected. Furthermore, the Pennsy mixes followed expected trends regarding the effect of increasing asphalt and the addition of a rejuvenator. Both of these modifications increased the overall rut depths, though not to the common failure threshold of 12.5 mm.

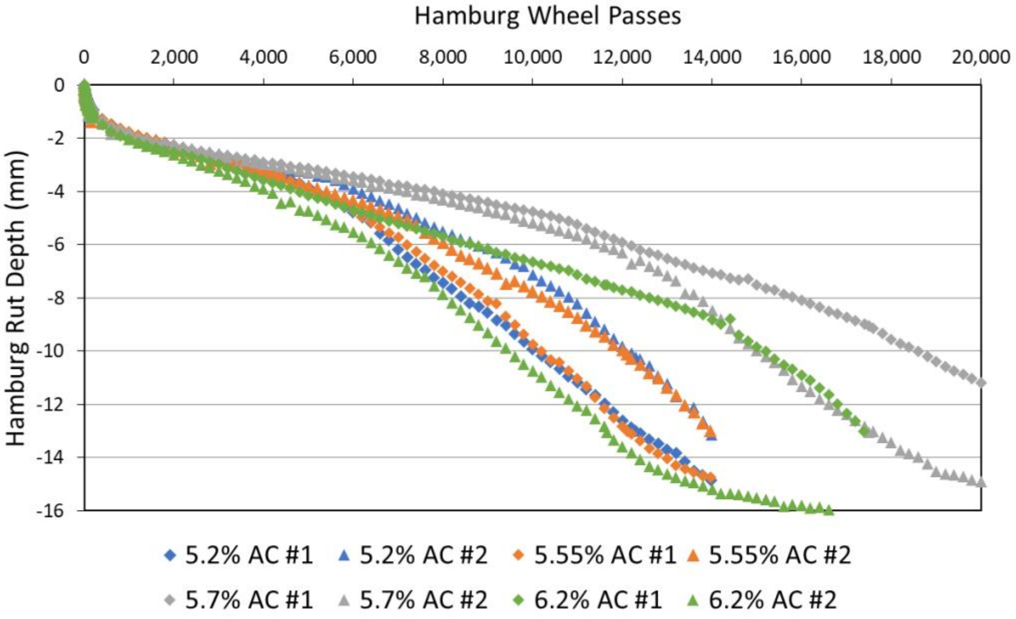


Figure 7 Pennsy HWTT Results: Mix 1 Individual Replicate Curves

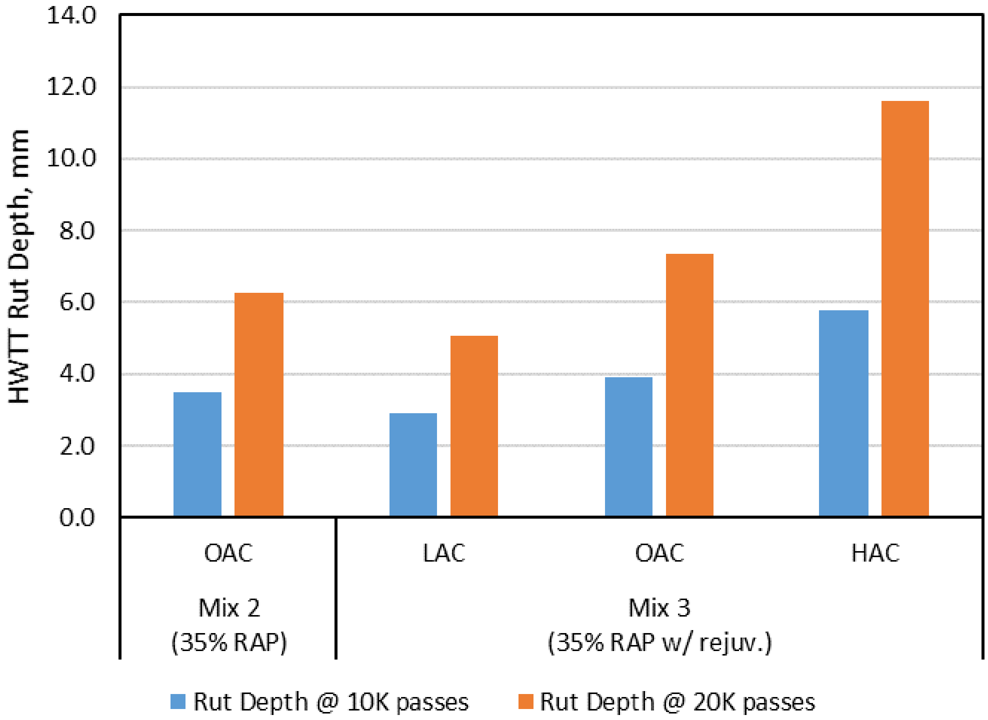


Figure 8. Mix 2 and 3 HWTT Results

All Pennsy I-FIT results are summarized in Table 6. Figure 9 shows the results of the standard STOA AASHTO TP-124-18 I-FIT testing for all three mixes. Mixes 1 and 3 were tested at three asphalt contents while Mix 2 was only tested at the optimum AC%. A set of critically aged I-FIT tests were conducted at the optimum asphalt contents for Mixes 1 and 3.

Table 6. Pennsy I-FIT Results

Mix	Load Rate (mm/min)	Target Air Voids (%)	Temp., °C	AC Content (%)	Aging Condition	Replicates	Flexibility Index		
							Average	St. Dev.	CV (%)
Mix 1	5	5	20	LAC	STOA (2hr)	7	7.4	2.0	26.6
	5	5	20	OAC	STOA (2hr)	6	8.4	2.5	30.1
	5	5	20	HAC	STOA (2hr)	7	17.9	5.5	30.9
	50	5	25	LAC	STOA (2hr)	8	5.2	1.0	19.4
	50	5	25	OAC	STOA (2hr)	6	7.9	1.0	12.8
	50	5	25	HAC	STOA (2hr)	5	9.1	1.1	12.2
	50	7	25	LAC	STOA (4hr)	8	5.7	1.1	19.0
	50	7	25	OAC	STOA (4hr)	6	7.3	0.7	9.2
	50	7	25	OAC	STOA + CA	7	5.1	1.2	24.6
	50	7	25	HAC	STOA (4hr)	8	13.9	2.7	19.2
Mix 2	50	7	25	OAC	STOA (4hr)	6	4.2	1.4	32.9
Mix 3	50	7	25	LAC	STOA (4hr)	5	6.3	1.5	23.7
	50	7	25	OAC	STOA (4hr)	7	8.4	2.3	27.6
	50	7	25	OAC	STOA + CA	5	7.7	1.1	14.6
	50	7	25	HAC	STOA (4hr)	6	13.7	3.2	23.6

Note: Mix 1 – 15% RAP, Mix 2 – 35% RAP, Mix 3 – 35% RAP with rejuvenator

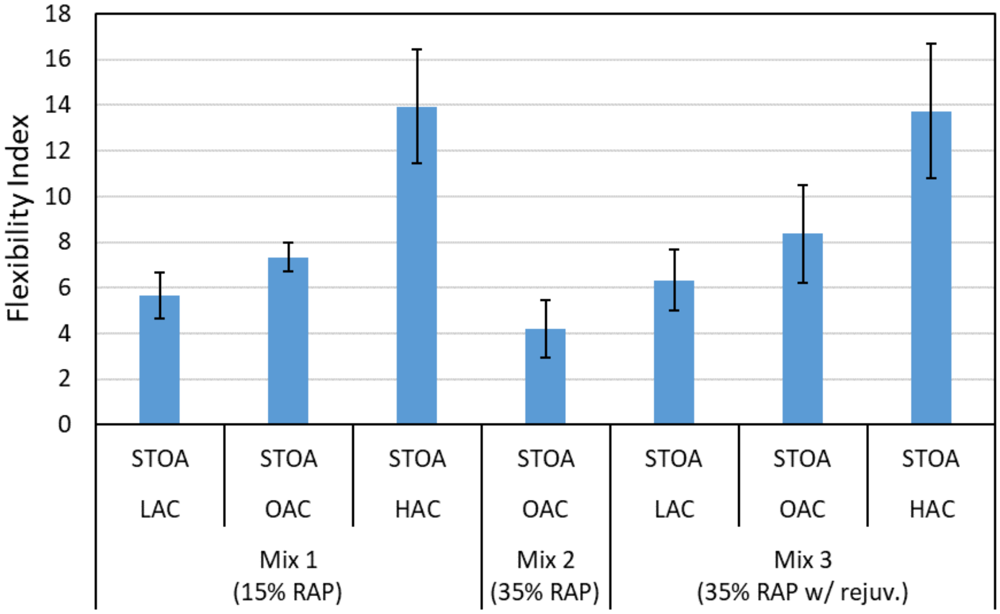


Figure 9. Pennsy I-FIT Results: AASHTO TP-124-18

The results from I-FIT testing at AASHTO TP 124-18 parameters yielded results that followed expected trends. The Flexibility index (FI) increased for both Mixes 1 and 3 as asphalt content increased. Increasing RAP content from Mix 1 to Mix 2 without adding a rejuvenator decreased FI at optimum asphalt contents. Using a rejuvenator improved the results from Mix 2 to Mix 3 at the optimum asphalt content. Finally, critically aging the mixes decreased the flexibility index at optimum AC% for Mix 1 and Mix 3. At all asphalt contents, the results of Mix 3 (with 20% more RAP and added rejuvenator) were either equal or better than the results of Mix 1.

Figure 10 shows the results of the PSU modified I-FIT testing for Mix 1 alongside the AASHTO TP 124-18 results of the 5% air voids set and the typical 7% air voids specimens. The PSU version of the I-FIT was conducted to assess the differences between the two test methods when compared to the standard method. The PSU method (left set of bars) increased the FI for all three binder contents versus the standard method (right set of bars). However, as shown in Figure 11, these two methods are highly correlated (r=0.99) with three data points and indicate the same trend but on a slightly different scale. The hybrid approach (middle set of bars) to the specification yielded results that were only subtly different from both test methods at the low and middle asphalt contents, while the high asphalt content results were much lower compared to the PSU method and the AASHTO method.

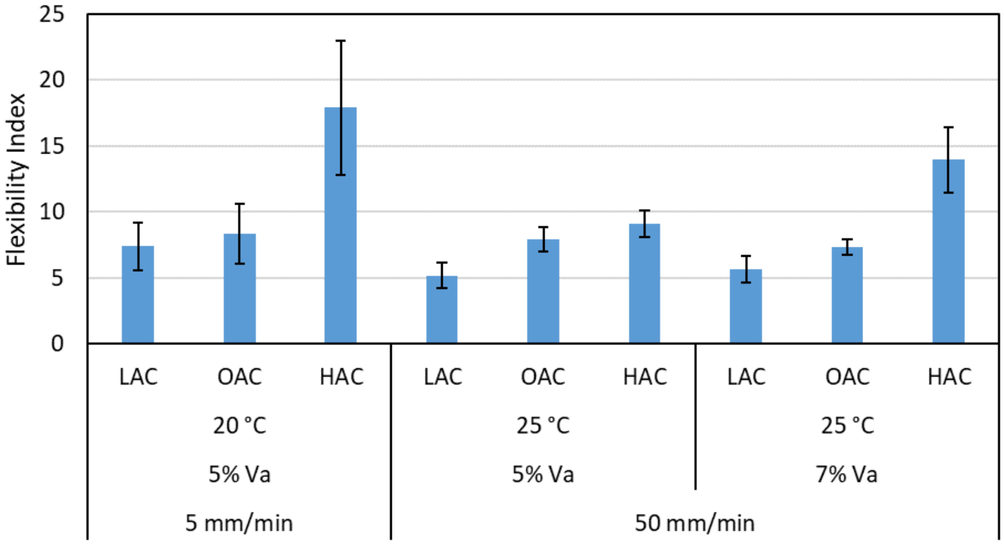


Figure 10. Comparison of PSU Modified and AASHTO I-FIT Results: Mix 1(15% RAP) Only

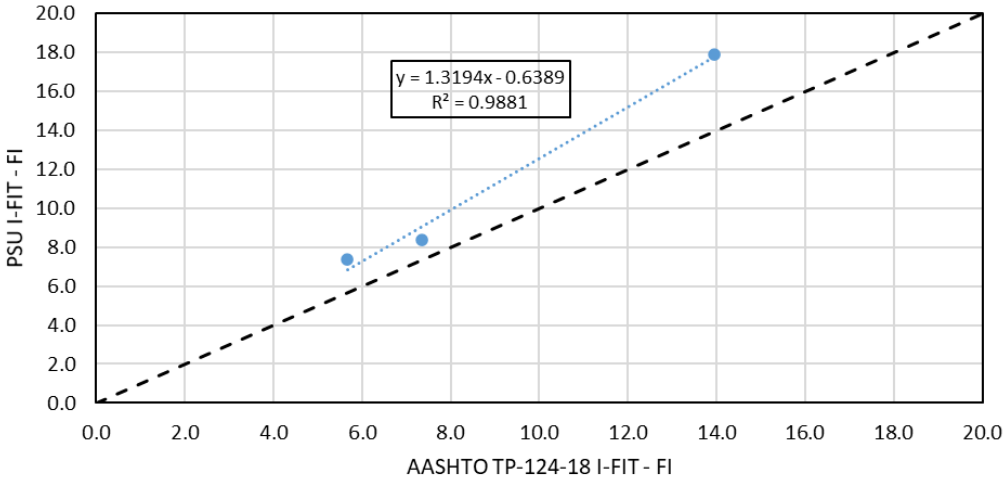


Figure 11. TP 124 vs. PSU I-FIT Method Comparison

IDEAL-CT results from all three mixes are shown in Figure 12 and the summary statistics are in Table 7. Increasing asphalt content significantly improved the CT_{Index} results of Mixes 1 and 3 while the increased RAP content from Mix 1 to Mix 2 decreased the CT_{Index} at the optimum binder content. Comparing the low asphalt content results indicates that the rejuvenator did not compensate for the increased RAP content at LAC binder content. At the OAC and HAC, the rejuvenator improved the CT_{Index} of Mix 3 to a result similar to Mix 1 but with 20% more RAP. All of the mixes, except Mix 3 at LAC, produced CT_{Index} values of greater than 100.

Table 7. Pennsy CT_{Index} Results

Mix	AC Content (%)	Replicates	CT Index		
			Average	St. Dev.	CV (%)
Mix 1 (15% RAP)	LAC	10	136.7	38.0	27.8
	OAC	6	170.3	33.2	19.5
	HAC	6	240.0	73.2	30.5
Mix 2 (35% RAP)	OAC	6	128.8	37.9	29.4
Mix 3 (35% RAP With Rejuvenator)	LAC	6	87.7	17.7	20.2
	OAC	6	158.8	7.8	4.9
	HAC	6	210.0	15.9	7.6

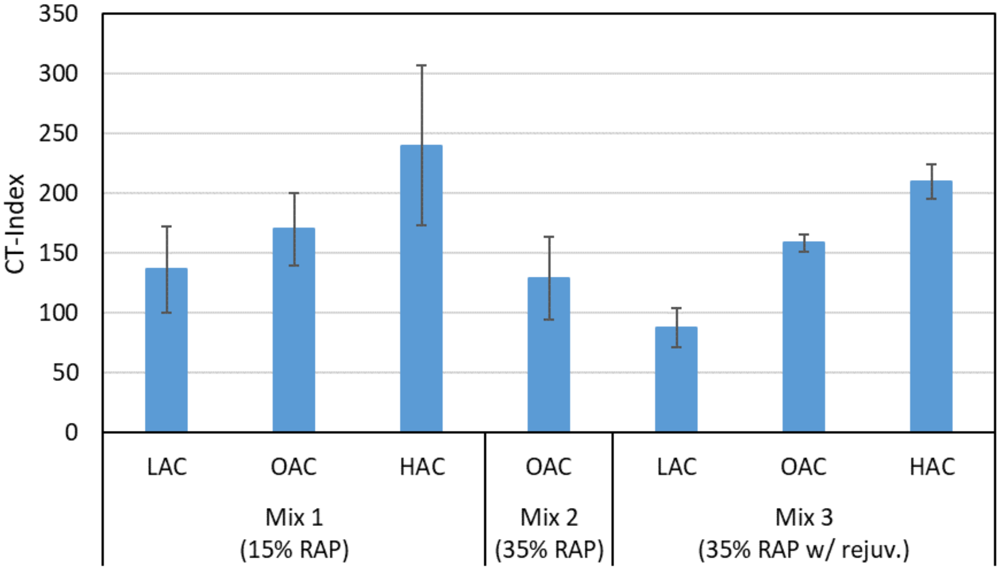


Figure 12. Pennsy IDEAL-CT Results

5.3 Performance Space Diagrams

Two performance space diagrams are shown for the Pennsy project: HWTT vs. I-FIT (Figure 13) and HWTT vs. IDEAL-CT (Figure 14). The threshold values selected for the performance space diagrams are as follows: Maximum 12.5 mm rut depth at 10,000 wheel passes (NCHRP Report 646), a minimum I-FIT FI of 8 (West et al., 2018), and a minimum IDEAL-CT CT_{Index} of 70 (VDOT BMD Specification, 2019). The rut depth at 10,000 passes was selected for the HWTT because the mixture was produced with a neat binder of PG 64-22. This criterion was used by other states (OK, TX, WI) at the time of this testing (West et al., 2018) and has also been adopted as PennDOT's preliminary performance test (NAPA ,2022b). Each data point on the performance space diagram represents the test results of an individual mix. The shorthand label for each data point includes the RAP content, presence or absence of rejuvenator (RA or no RA), and AC content relative to optimum (LAC, OAC, HAC).

Based on the threshold criteria selected, all seven mixes for this study were acceptable with regard to the HWTT and the IDEAL-CT. The I-FIT criteria were more aggressive, with four mixes falling below the selected minimum FI of 8. For the I-FIT performance space diagram, the three mixes that fell in the desired quadrant were as follows: 15% RAP with no RA at HAC, 35% RAP with RA at OAC, and 35% RAP with RA at HAC. The data points for each mix design (15% RAP and 35% RAP) would shift to the right on the performance space diagram as additional AC or rejuvenator was added to the mix. The addition of RA had very little impact on the rutting resistance of the 35% RAP mix. Increasing binder content shifted the points slightly up, indicating a slight decrease in rutting resistance. However, the magnitudes of the HWTT rut depths were well below the designated thresholds. This trend is appropriate and indicates improved cracking resistance and reduced rutting resistance as additional binder or rejuvenator are added to the mix.

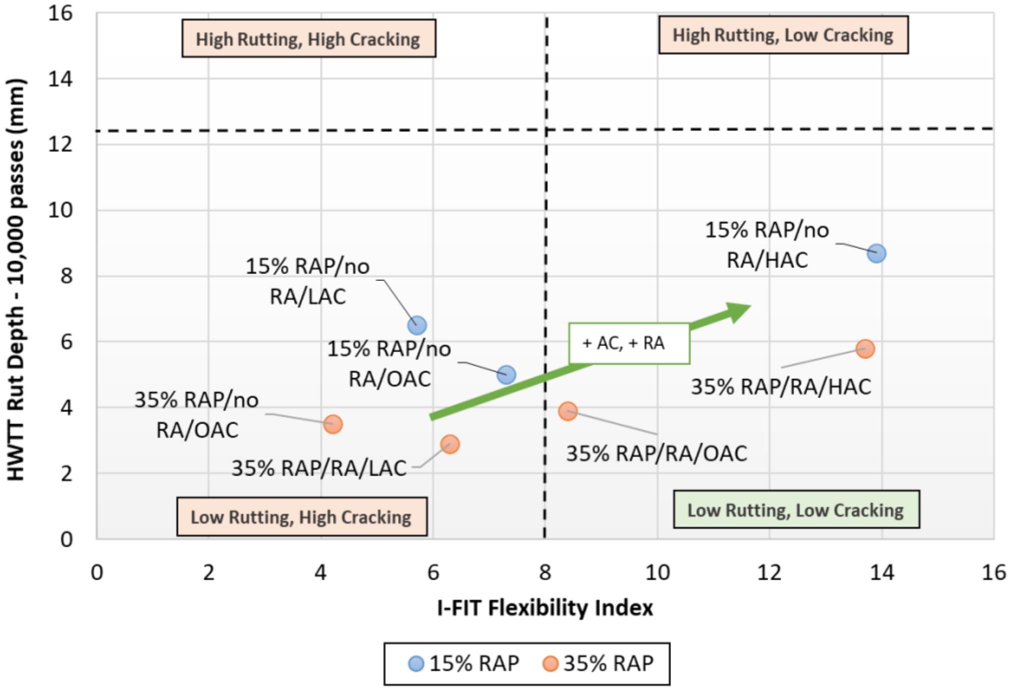


Figure 13. Performance Space Diagram: Pennsy HWTT Rut Depth (10,000 passes) vs. I-FIT FI

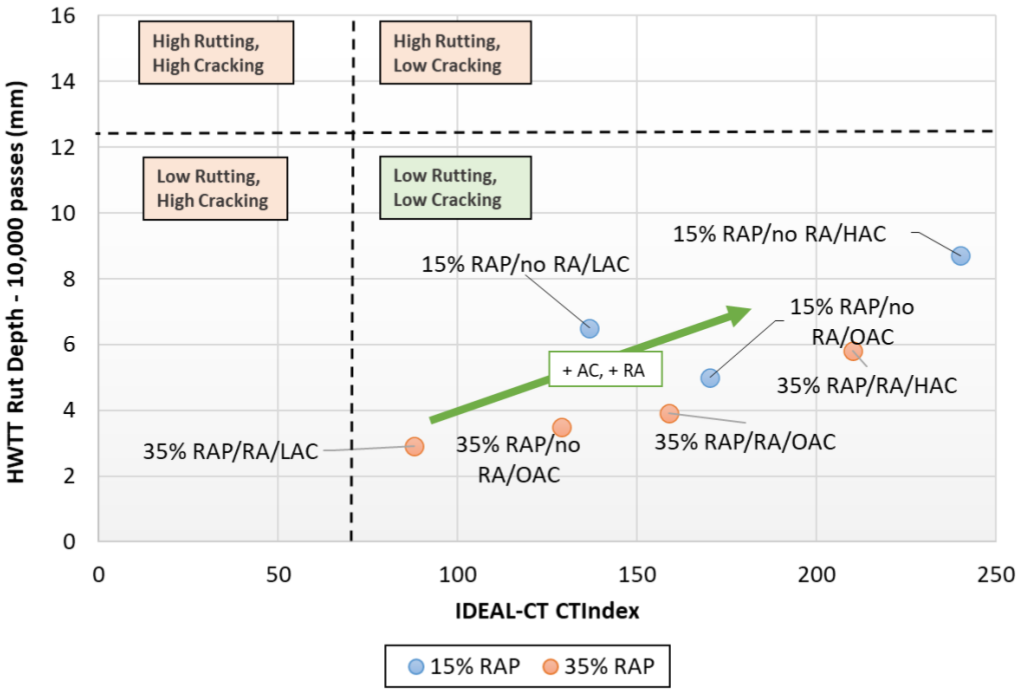


Figure 14. Performance Space Diagram: Pennsy HWTT Rut Depth (10,000 passes) vs. CT_{Index}

5.4 Summary of Pennsy Testing

With the exception of the rutting performance of Mix 1 in the HWTT, the Pennsy mix testing produced results consistent with expectations. Increasing asphalt content and adding rejuvenator improved cracking resistance and decreased rutting resistance, and increasing RAP content without any rejuvenator stiffened the mix. Finally, although the HWTT from Mix 1 resulted in every sample exhibiting stripping, it seems that the lower asphalt content specimens stripped sooner than the samples with more asphalt. If stripping was prevented, it is expected that the rutting results would be much lower. Increasing asphalt content and adding rejuvenator increased the cracking resistance parameters and the addition of more RAP decreased them. In the case of the IDEAL-CT results, the addition of rejuvenator did not compensate for the increased 20% RAP from Mix 1 to Mix 3 at the lower AC%. However, at the OAC and HAC the 35% RAP with rejuvenator showed similar results to the 15% RAP without rejuvenator. As this was the first of four case studies completed in this project, it provided confirmation that the selected BMD tests followed expected trends and were sensitive to various mixture modifications.

6 Case Study 2: Staker Parson Materials & Construction – Draper, Utah

6.1 Mixes and Workplan

NCAT received materials from Staker Parson and began work in March 2018. Three mixes were tested for this project. The control mix had 25% RAP and used a PG 64-34 polymer-modified binder. Two additional mix designs were proposed by Staker Parson and were verified at NCAT. These mixes had 35% RAP and 45% RAP, respectively, and PG 64-34 polymer-modified binder, which was modified with the rejuvenator at a rate of 8% by weight of RAP binder. The objective of this particular project was to investigate the effect of increasing RAP content in a performance-based design framework. Thus, the binder contents were set to be the same for each mix and the volumetric results were reasonably close to each other. The gradations, AC%, and volumetric information for the three mixes are provided in Table 8.

Table 8. Staker Parson Mix Designs

% Passing	Mix 1 (25% RAP)	Mix 2 (35% RAP With Rejuvenator)	Mix 3 (45% RAP With Rejuvenator)
3/4"	100	100	100
1/2"	93.3	91.3	91.5
3/8"	80.0	76.2	75.2
# 4	50.5	48.1	47.4
# 8	32.2	31.2	31.4
# 16	22.1	21.9	22.6
# 50	12.6	12.8	13.5
#200	6.69	6.40	6.53
AC%, Total	4.8	4.8	4.8
AC%, Virgin	3.6	3.2	2.7
AC% from RAP	1.2	1.6	2.1
RBR	25%	34%	44%
Rejuvenator Dosage*	0%	8%	8%
Va, %	3.5	3.7	3.2
VMA, %	14.2	13.8	13.1
VFA, %	75.1	73.7	76.1
DP	1.51	1.50	1.57
Gmm	2.572	2.571	2.568
Gmb	2.480	2.478	2.485

*By weight of RAP binder

The work plan, detailed in Table 9, included the Hamburg Wheel Tracking Test (HWTT) (AASHTO T324-17) to assess rutting resistance and the I-FIT (AASHTO TP 124-18) and IDEAL-CT (ASTM D8225-19) to assess cracking resistance. Each mix was tested at the optimum asphalt content (OAC) and at ± 0.5% AC% from the optimum (low asphalt content = LAC, high asphalt content = HAC). All mixes were short-term oven-aged (STOA) for four hours at 275°F before compaction. Additional I-FIT samples at the optimum binder contents only were prepared and critically aged (CA) for an additional eight hours at 275°F before compaction. I-FIT testing for Mix 3 was performed at 8% and 12% rejuvenator at all three binder contents for the STOA samples and at the optimum binder content for the CA samples. The 12% rejuvenator dosage was added to assess the effect of additional rejuvenator after the 8% rejuvenator dosage testing was completed.

Table 9. Staker Parson Workplan

Mix	Test	AC%	Aging Condition	Rejuvenator Dosage by Weight of RAP Binder
Mix 1 (25% RAP)	Hamburg	LAC, OAC, HAC	STOA Only	0%
	IDEAL-CT		STOA Only	0%
	I-FIT		STOA & CA	0%
Mix 2 (35% RAP With Rejuvenator)	Hamburg	LAC, OAC, HAC	STOA Only	8%
	IDEAL-CT		STOA Only	8%
	I-FIT		STOA & CA	8%
Mix 3 (45% RAP With Rejuvenator)	Hamburg	LAC, OAC, HAC	STOA Only	8%
	IDEAL-CT		STOA Only	8%
	I-FIT		STOA & CA	8% and 12%

6.2 Results

Table 10 shows the summary of HWTT at 50°C for the three Staker Parson mixes. None of the replicates exceeded the common HWTT failure threshold of 12.5 mm of rutting at 20,000 passes; all of the average rut depths of all the mixes tested were less than 5.0 mm. Despite the high rutting resistance, the results follow the expected trends for varying asphalt contents. This is graphically illustrated in Figure 15 as the rut depths increase with increasing asphalt.

Table 10. Staker Parson Average HWTT Results

Mix ID	AC Content (%)	Replicates	Rut Depth at 10,000 Passes (mm)	Rut Depth at 20,000 Passes (mm)
			Average	Average
Mix 1 (25% RAP)	LAC	2	2.0	2.4
	OAC	2	2.3	2.6
	HAC	2	3.4	4.2
Mix 2 (35% RAP With Rejuvenator)	LAC	2	2.5	3.0
	OAC	2	3.2	4.0
	HAC	2	3.7	4.7
Mix 3 (45% RAP With Rejuvenator)	LAC	2	1.9	2.4
	OAC	2	2.7	3.2
	HAC	2	3.2	3.8

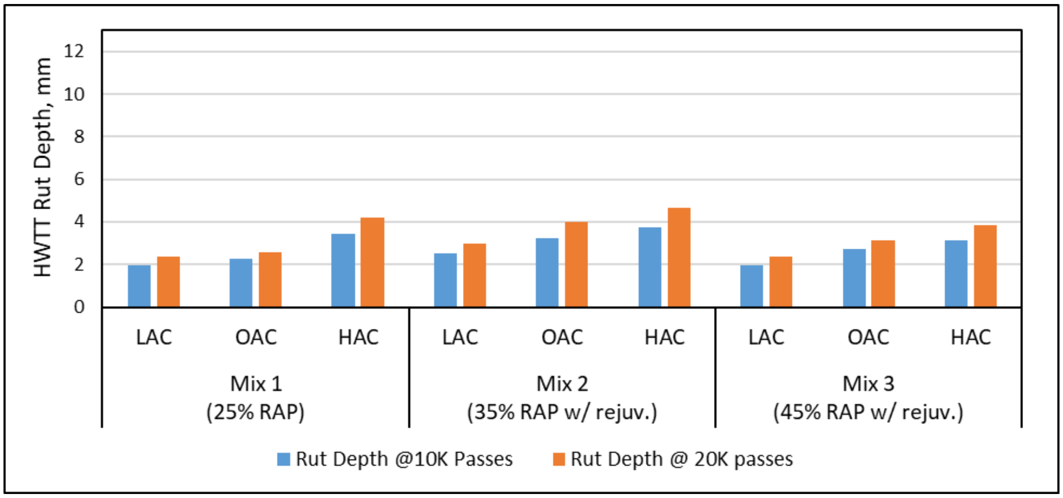


Figure 15. Staker Parson HWTT Results

I-FIT Flexibility Index (FI) results for the three mixes and additional testing for Mix 3 at 12% rejuvenator are summarized in Table 11. Figures 16-18 show the I-FIT results from the Staker Parson mixes highlighting specific variables. Figure 16 shows the effects of increasing AC%. The results follow the expected trend of FI increasing with increased binder content. Interestingly, the magnitude of the variability also seems to increase with the additional AC%. The effects of aging are shown in Figure 17. The results did not universally follow the generally expected trend that additional aging should decrease cracking resistance in laboratory testing. Mix 1 and Mix 2 did follow that trend to varying degrees. Mix 2 saw a decrease of approximately 30% after aging from STOA at optimum binder content to critically aging while the FI of Mix 1 decreased approximately 10% under the same conditions. Mix 3 did not exhibit any significant decrease in flexibility index after aging at 8% rejuvenator content. It is possible that the presence of rejuvenator dampened the effect of aging for this mix. Finally, Figure 18 shows the additional rejuvenator (12% by weight of RAP binder) in Mix 3 did not have much effect on the flexibility index, especially at the low and high binder contents nor after aging. The FI values after aging for Mix 3 at both rejuvenator contents were essentially equal.

Table 11. Staker Parson I-FIT Results

Mix	AC Content (%)	Aging Condition	Replicates	Air Voids (%)	Flexibility Index		
				Average	Average	St. Dev.	CV (%)
Mix 1 (25% RAP)	LAC	STOA	6	7.2	3.9	1.0	25.5
	OAC	STOA	7	7.1	7.2	2.0	27.5
	OAC	STOA + CA	7	7.0	6.6	1.8	26.8
	HAC	STOA	8	7.0	14.6	5.6	38.2
Mix 2 (35% RAP With Rejuvenator)	LAC	STOA	7	7.2	4.4	0.8	18.3
	OAC	STOA	7	7.4	8.3	1.5	18.4
	OAC	STOA + CA	7	6.8	5.9	1.2	20.0
	HAC	STOA	6	7.2	17.7	4.1	23.2
Mix 3 (45% RAP With Rejuvenator)	LAC	STOA	6	6.8	3.7	0.9	25.8
	OAC	STOA	5	7.0	5.2	1.2	23.8
	OAC	STOA + CA	6	6.8	5.2	1.7	33.6
	HAC	STOA	6	7.0	10.1	3.2	32.2
Mix 3 (12% Rejuvenator)	LAC	STOA	5	6.9	3.5	0.4	11.4
	OAC	STOA	6	6.9	7.2	1.3	17.8
	OAC	STOA + CA	6	6.7	5.2	1.3	25.2
	HAC	STOA	4	7.1	8.9	0.7	7.6

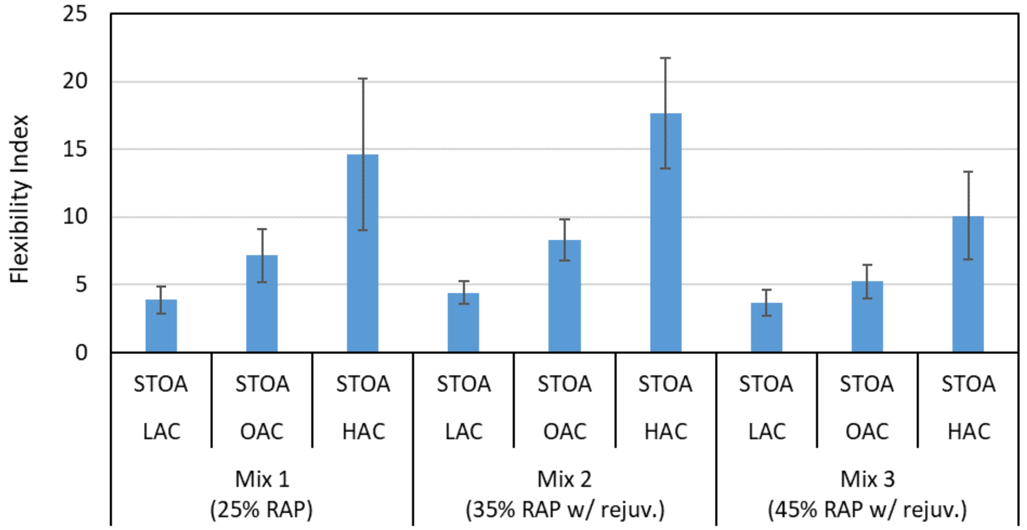


Figure 16. Staker Parson I-FIT Results: Varying AC%

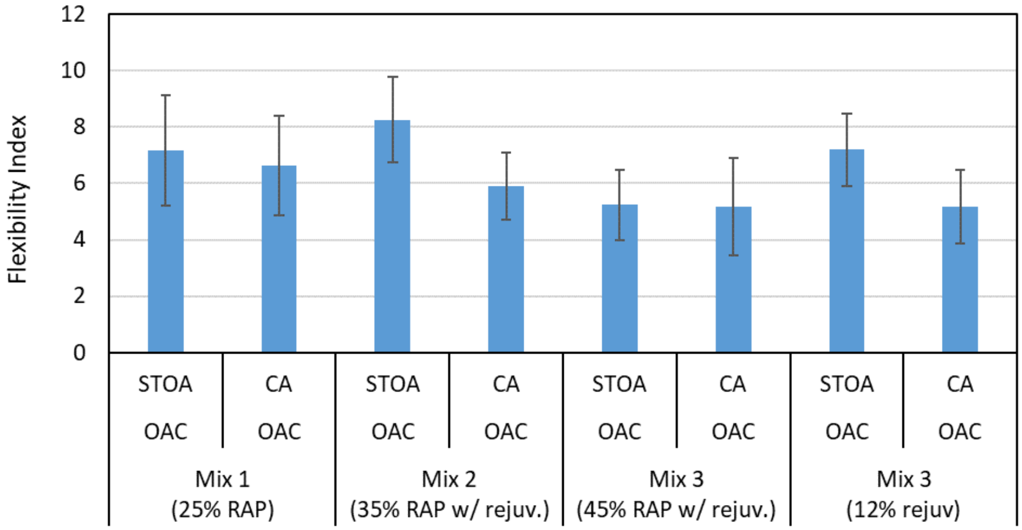


Figure 17. Staker Parson I-FIT Results: Aging Effects at Opt AC%

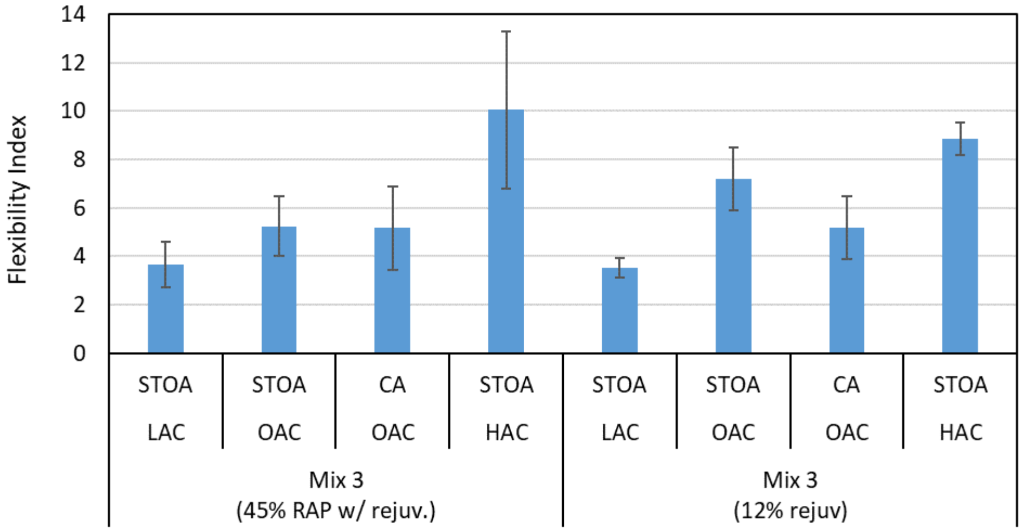


Figure 18. Staker Parson I-FIT Results: Rejuvenator Effects

IDEAL-CT testing was performed only on short-term oven aged specimens for these mixes. The CT_{Index} results followed the expectation that CT_{Index} results increase with increased asphalt content. The 0.5% increase in binder from the LAC to the OAC specimens yielded increases of 58%, 72%, and 100% for Mixes 1, 2, and 3, respectively. When 0.5% more asphalt was added to achieve the HAC binder contents, the CT_{Index} values were 97%, 138%, and 104% of the values at the optimum binder contents for Mixes 1, 2, and 3, respectively. These values were calculated from the data listed in Table 12 and the data are presented graphically in Figure 19.

Table 12. Staker Parson IDEAL-CT Results

Binder Type	AC Content (%)	Aging Condition	Rejuvenator Dosage, %*	Replicates	CT Index		
					Average	St. Dev.	CV (%)
Mix 1 (25% RAP)	LAC	STOA	0%	6	51.5	9.5	18.5
	OAC	STOA	0%	5	81.5	7.8	9.6
	HAC	STOA	0%	6	160.3	39.4	24.6
Mix 2 (35% RAP With Rejuvenator)	LAC	STOA	8%	5	50.2	16.9	33.6
	OAC	STOA	8%	6	86.2	18.8	21.8
	HAC	STOA	8%	6	205.3	38.8	18.9
Mix 3 (45% RAP With Rejuvenator)	LAC	STOA	8%	5	35.0	11.7	33.4
	OAC	STOA	8%	6	69.9	33.6	48.1
	HAC	STOA	8%	5	142.8	50.7	35.5

*By weight of RAP binder

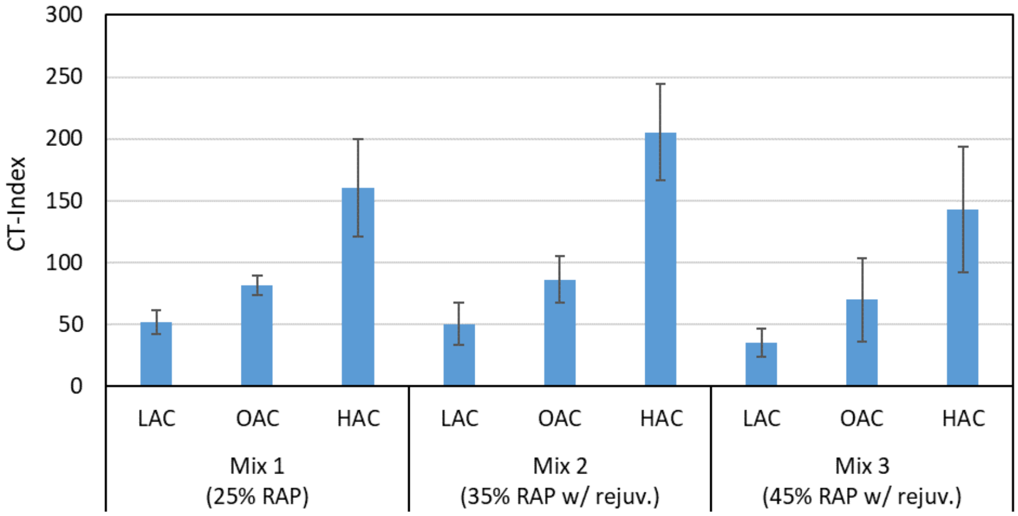


Figure 19. Staker Parson IDEAL-CT Results

6.3 Mixture Performance Space Diagrams

Two performance space diagrams are shown for the Staker Parson project: HWTT vs. I-FIT (Figure 20) and HWTT vs. IDEAL-CT (Figure 21). The threshold values selected for the performance space diagrams are as follows: maximum 12.5 rut depth at 20,000 wheel passes (NCHRP Report 646), a minimum I-FIT FI of 8 (West et al., 2018), and a minimum IDEAL-CT CT_{Index} of 70 (VDOT BMD Spec, 2019). The rut depth at 20,000 passes was selected for the HWTT because this mixture was produced with a polymer modified PG 64-34 binder.

All Staker Parson mixes were acceptable for rutting resistance in the HWTT. Four of the nine mixes passed the FI criteria of 8 while five of the nine mixes had a CT_{Index} above 70. None of the LAC mixes (25% RAP with no RA, 35% RAP with RA, or 45% RAP with RA) passed the cracking index thresholds. For both I-FIT and IDEAL-CT, the HAC mixes (25% RAP with no RA, 35% RAP with RA, and 45% RAP with RA) were the top performers for cracking resistance. All three mixes (25% RAP, 35% RAP, and 45% RAP) followed expected trends with respect to changing AC content and adding rejuvenator. The 45% RAP mix with 12% RA is not included in Figures 20-21.

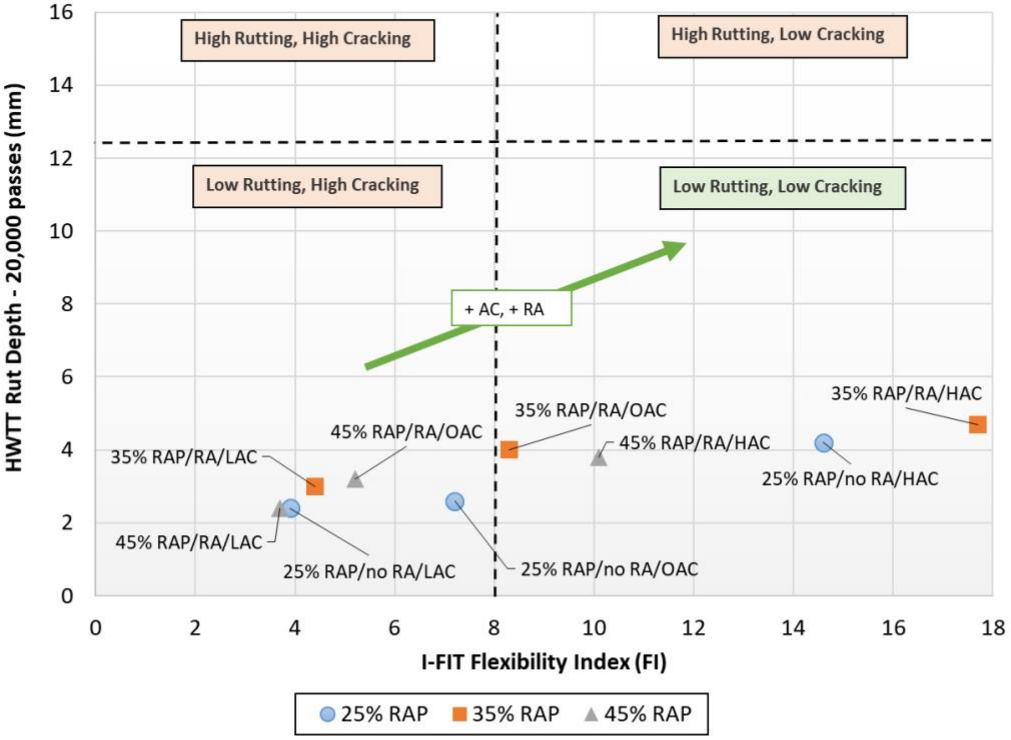


Figure 20. Staker Parson Performance Space Diagram: I-FIT and HWTT

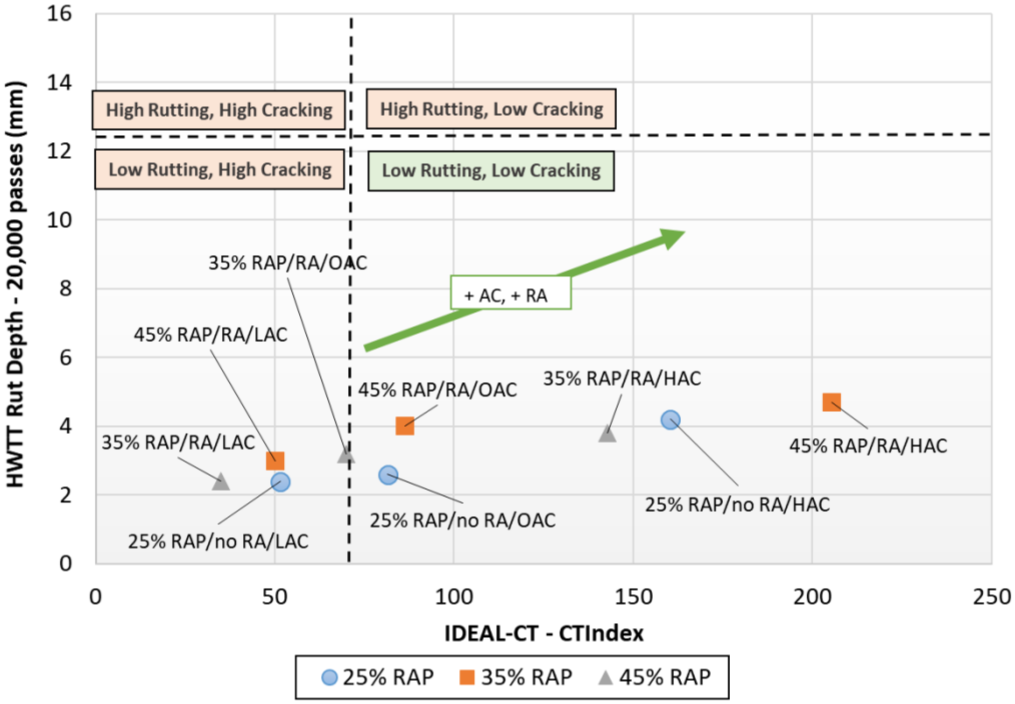


Figure 21. Staker Parson Performance Space Diagram: IDEAL-CT and HWTT

6.4 Summary of Staker Parson Testing

The results from the two cracking tests conducted for the Staker Parson mixes were as expected with regard to varying asphalt contents. The addition of binder significantly improved the FI and CT_{Index} results for all mixes. Additional aging decreased the FI results for each mix, although the magnitudes of the reductions were varied. Two mixes only experienced a minor change after an additional eight hours of aging and the other two mixes had FI decreases by over 20%. Interestingly, Mix 3 with 8% rejuvenator yielded a lower decrease after aging than the same mix with 12% rejuvenator. The mixes were not critically aged for IDEAL-CT testing. The rutting magnitudes for these mixes were low, though they did exhibit the trend of showing more rutting with increasing asphalt content

7 Case Study 3: Dufferin Construction Company – Oakville, Ontario

7.1 Mixes and Workplan

NCAT received raw materials from Dufferin Construction Company and began BMD optimization work in Fall 2018. Three aggregate blends were tested for this project: a virgin mix (0% RAP), 15% RAP, and a 30% RAP mix. The main binder utilized in this study was a PG 70-28 XJ binder. According to representatives from Dufferin, the “XJ” indicated some kind of modification that improved the quality of the modified binder over a PG 70-28 binder. The exact modification of the binder was not shared with NCAT. For the mixture description in the figures below, ‘XJ’ represents a mix produced with the PG 70-28 XJ binder while ‘Reg’ represents the mix produced with the regular PG 70-28 binder.

The 15% RAP blend was used for two mixes: one with 70-28 XJ binder and one with normal 70-28 binder. Thus, a total of four mixes were included in this study. A rejuvenator was added to the binders for some of the performance tests on the RAP mixes. The objective of this experiment was to determine if mixes with lower asphalt contents could utilize rejuvenators to produce similar cracking performance to mixes with 0.5% more binder but no rejuvenator. The mix designs were provided by Dufferin and were verified at NCAT before the experiment. The optimum asphalt content of the two RAP blends was slightly adjusted from the JMF. The gradations, AC%, and volumetric information for the three mixes are provided in Table 13.

Table 13. Dufferin Mix Designs

% Passing	Blend 1 (0% RAP)	Blend 2 (15% RAP)	Blend 3 (30% RAP)
3/4"	100	100	100
1/2"	96.0	96.3	97.0
3/8"	82.8	84.6	86.7
# 4	54.8	54.8	59.0
# 8	40.8	40.8	44.3
# 16	27.0	27.8	31.2
# 30	19.7	20.4	23.1
# 50	12.6	14.7	15.4
# 100	6.7	6.9	8.3
#200	3.4	3.3	4.2
AC%, Total	5.0	4.7	4.8
AC%, Virgin	5.0	4.0	3.4
AC% from RAP	N/A	0.7	1.4
RBR	N/A	15.0%	29.4%
Rejuvenator Dosage*	0%	8% (When Applicable)	8% (When Applicable)
Va, %	4.0	4.0	4.0
VMA, %	15.2	14.6	14.3
VFA, %	74.5	72.5	72.1
DP	0.71	0.69	0.98
Gmm	2.526	2.569	2.585
Gmb	2.428	2.466	2.482

*By weight of RAP binder

The work plan for this project is shown in Table 14. Rutting resistance was assessed using the Hamburg Wheel Tracking Test (HWTT) (AASHTO T324-17), thermal cracking resistance was evaluated using the Disc-shaped Compact Tension Test (DCT) (ASTM D7313-13), and intermediate temperature cracking resistance was determined using both the IDEAL-CT (ASTM D8225-19) and the I-FIT (AASHTO TP 124-18).

The virgin mix was only tested at the optimum binder content and had no rejuvenator. The mixes with RAP were tested at the optimum binder content from Table 13 in addition to ±0.5% binder from optimum, except for the IDEAL-CT test which was performed at the OAC and HAC only. Rejuvenator was added to the mixes with RAP at the low binder content (LAC) and at the OAC by weight of RAP binder. An OAC set without rejuvenator was also tested for Mixes 2, 3, and 4, as shown in Table 14. The mixes with high binder content (HAC) did not include rejuvenator. Finally, the three cracking tests were conducted on short-term oven-aged samples (STOA) and critically aged (CA) samples for all four mixes. These aging procedures were described previously in this report.

Table 14. Dufferin Testing Plan

Mix	Test	AC%	Aging Condition	Rejuvenator Dosage, % by Weight of RAP Binder
Mix 1 Virgin 70-28 XJ	Hamburg	OAC	STOA	0%
	DCT		STOA & CA	
	I-FIT		STOA & CA	
	IDEAL-CT		STOA & CA	
Mix 2 15% RAP 70-28 XJ	Hamburg	LAC, OAC, HAC	STOA	8% When Applicable
	DCT		STOA & CA	
	I-FIT		STOA & CA	
	IDEAL-CT	OAC, HAC	STOA & CA	
Mix 3 15% RAP 70-28	Hamburg	LAC, OAC, HAC	STOA	8% When Applicable
	DCT		STOA & CA	
	I-FIT		STOA & CA	
	IDEAL-CT	OAC, HAC	STOA & CA	
Mix 4 30% RAP 70-28 XJ	Hamburg	LAC, OAC, HAC	STOA	8% When Applicable
	DCT		STOA & CA	
	I-FIT		STOA & CA	
	IDEAL-CT	OAC, HAC	STOA & CA	

7.2 Results

Table 15 includes a summary of the average HWTT results at 50°C for the four Dufferin mixes. None of the samples failed the typical criteria of 12.5 mm of rutting after 20,000 passes. Furthermore, no stripping was present in any of the samples. Figures 22-24 show the effects of mixture variables on HWTT results.

Table 15. Dufferin HWTT Results

Mix ID	AC Content (%)	Rejuvenator Dosage, % by Weight of RAP Binder	Rut Depth at 10,000 Passes (mm)	Rut Depth at 20,000 Passes (mm)
			Average	Average
Mix 1 Virgin	OAC	0%	2.6	5.6
Mix 2 15% RAP 70-28 XJ	LAC	8%	1.8	2.3
	OAC	0%	2.2	3.0
	OAC	8%	2.8	3.7
	HAC	0%	3.2	4.3
Mix 3 15% RAP 70-28	LAC	8%	2.0	2.4
	OAC	0%	1.9	2.2
	OAC	8%	2.3	3.0
	HAC	0%	3.3	6.5
Mix 4 30% RAP 70-28 XJ	LAC	8%	1.4	1.7
	OAC	0%	1.7	2.1
	OAC	8%	2.1	3.1
	HAC	0%	2.8	4.4

Figure 22 demonstrates the effect of increasing the RAP content. The four mixes shown represent the optimum asphalt content with no rejuvenator. The effect is best recognized by assessing rutting after 20,000 passes. There was a relatively large decrease in rutting when the RAP content increased from 0% to 15%. Between Mix 2 and Mix 4 (two mixes having the same binder type), a slight drop in rutting was seen when RAP content was increased from 15% to 30%. This is consistent with existing evidence that increasing RAP will improve rutting resistance. The magnitude of the increase will vary for each unique mix depending on a variety of mix design factors.

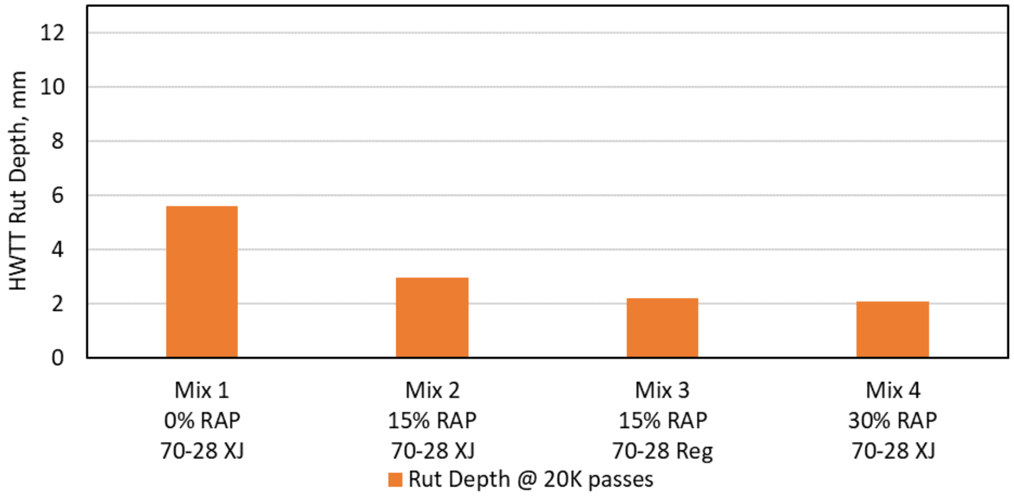


Figure 22. Dufferin HWTT Results: Increasing RAP Content

Figure 23 and Figure 24 combine to show the effects of softening a mix, either by increasing asphalt content or adding rejuvenator (to the LAC mixes only), respectively. Comparing the lower AC% to optimum AC% results, shown in Figure 23, show very similar rut depths. The usage of a rejuvenator seemed to soften the mixes with lower binder content to the same level as the mixes with optimum binder content. Each of the three cases involving increasing AC% beyond optimum resulted in noticeably higher rut depths in Hamburg testing. Figure 24 shows the results from adding rejuvenator to mixes at optimum binder content. In all three mixes, the rejuvenator caused a slight increase in rutting, which is attributed to the mix softening. However, the rut depths for these mixes were all less than 4 mm, which is significantly below the typical failure criteria.

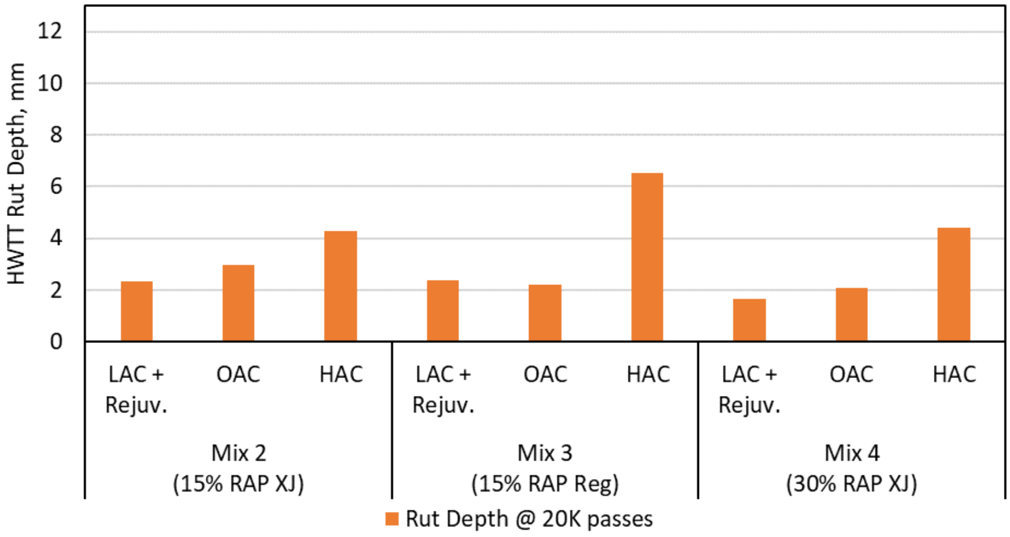


Figure 23. Dufferin HWTT Results: Varying AC%

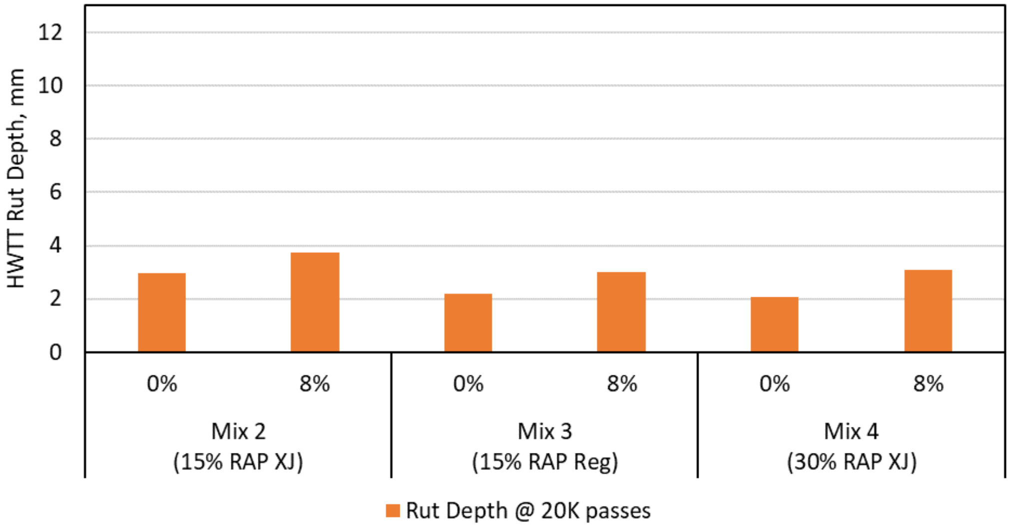


Figure 24. Dufferin HWTT Results: Added Rejuvenator at OAC

Table 16 includes the average results from I-FIT testing. The effects of RAP content, asphalt content, and rejuvenator are illustrated in Figures 25-28. Aging had a significant effect on the FI results for each mix at the optimum binder content both with and without rejuvenator. The reduction in the flexibility index after aging was near threefold for Mix 1, Mix 2, and Mix 3, and double for Mix 4. This is consistent with the expected trends.

Table 16. Dufferin I-FIT Results

Mix ID	AC Content	Rejuvenator Dosage, % by Weight of RAP Binder	Aging Condition	Flexibility Index		
				Average	St. Dev.	CV (%)
Mix 1 (Virgin)	OAC	0%	STOA	16.3	3.1	19.1
	OAC	0%	STOA + CA	5.2	1.3	25.6
Mix 2 (15% RAP XJ)	LAC	8%	STOA	6.9	2.6	38.2
	OAC	0%	STOA	9.3	2.4	25.3
	OAC	0%	STOA + CA	3.0	0.7	24.5
	OAC	8%	STOA	9.6	2.1	21.8
	OAC	8%	STOA + CA	2.9	1.1	38.1
	HAC	0%	STOA	13.1	0.9	6.8
Mix 3 (15% RAP Reg)	LAC	8%	STOA	4.0	0.6	14.5
	OAC	0%	STOA	5.4	0.5	9.5
	OAC	0%	STOA + CA	1.8	0.5	26.9
	OAC	8%	STOA	7.7	2.0	26.1
	OAC	8%	STOA + CA	2.9	0.4	14.2
	HAC	0%	STOA	11.8	3.3	28.1
Mix 4 (30% RAP XJ)	LAC	8%	STOA	3.6	0.7	18.3
	OAC	0%	STOA	3.4	0.5	14.5
	OAC	0%	STOA + CA	1.7	0.5	32.6
	OAC	8%	STOA	6.1	1.2	19.8
	OAC	8%	STOA + CA	2.8	0.6	21.4
	HAC	0%	STOA	7.1	0.2	3.4

Figure 25 shows the FI of the mixes as RAP content is increased. These results are from specimens at optimum binder content with no rejuvenator. It is clear that increasing RAP decreased the cracking resistance of the mixes. Also noteworthy is that the only difference between Mix 2 and Mix 3 is the binder type. The PG 70-28 XJ binder resulted in better cracking resistance in I-FIT testing than the regular PG 70-28 binder. The same behavior is also seen when comparing the FI results at the low asphalt content for Mix 2 and Mix 3 in Figure 26.

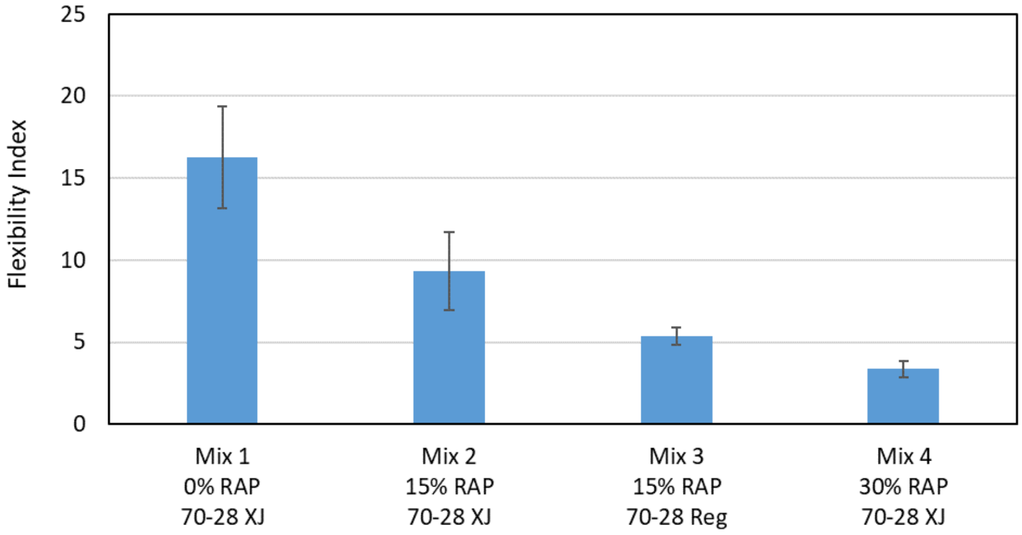


Figure 25. Dufferin I-FIT Results: Increasing RAP Content

The effect of binder content is demonstrated in Figure 26. As was the case with the HWTT results, the low asphalt content specimens also had 8% rejuvenator by weight of RAP binder. One objective of this experiment was to determine if mixes with lower asphalt contents could utilize rejuvenators to produce similar cracking performance to mixes with 0.5% more binder but no rejuvenator. The results were mixed in this case study. In the case of Mix 2, there was a difference of approximately two FI units between the LAC with rejuvenator and OAC samples. The magnitude of the difference between the LAC and OAC samples for Mix 3, with the regular PG 70-28 binder grade, was approximately half that of Mix 2. Finally, the mix with LAC and rejuvenator outperformed the mix at OAC for Mix 4. Unsurprisingly, the results of the HAC samples for the three mixes were significantly higher than the LAC and OAC samples.

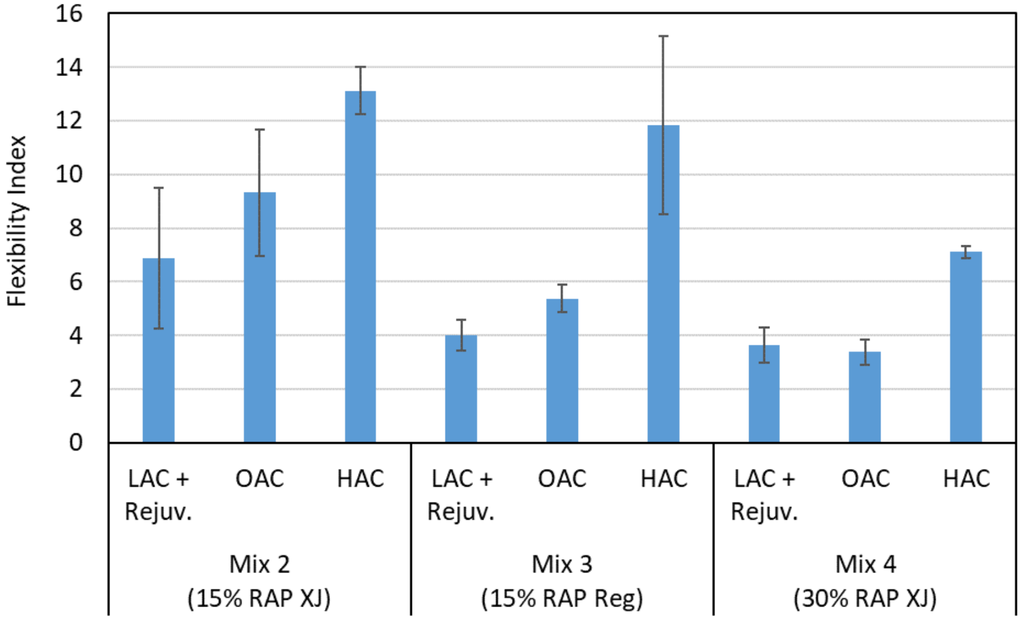


Figure 26. Dufferin I-FIT Results: Varying AC% on STOA Specimens

Figure 27 and Figure 28 show the effects of adding rejuvenator to I-FIT specimens at the optimum binder content for STOA and CA mixes, respectively. In both cases of mixture aging, the added rejuvenator had no effect on the magnitude of the FI for Mix 2 but improved the results for Mixes 3 and 4. It is possible that the rejuvenator had a muted effect on Mix 2 because it only had 15% RAP and a higher quality binder compared to Mix 3, with the “regular” binder, and Mix 4, with 30% RAP.

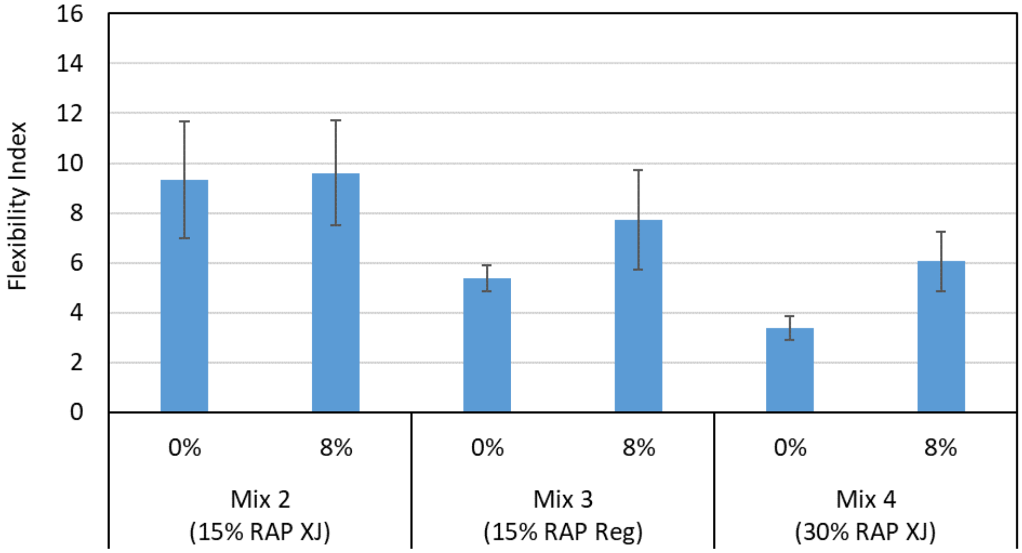


Figure 27. Dufferin I-FIT Results: Added Rejuvenator STOA at OAC Specimens

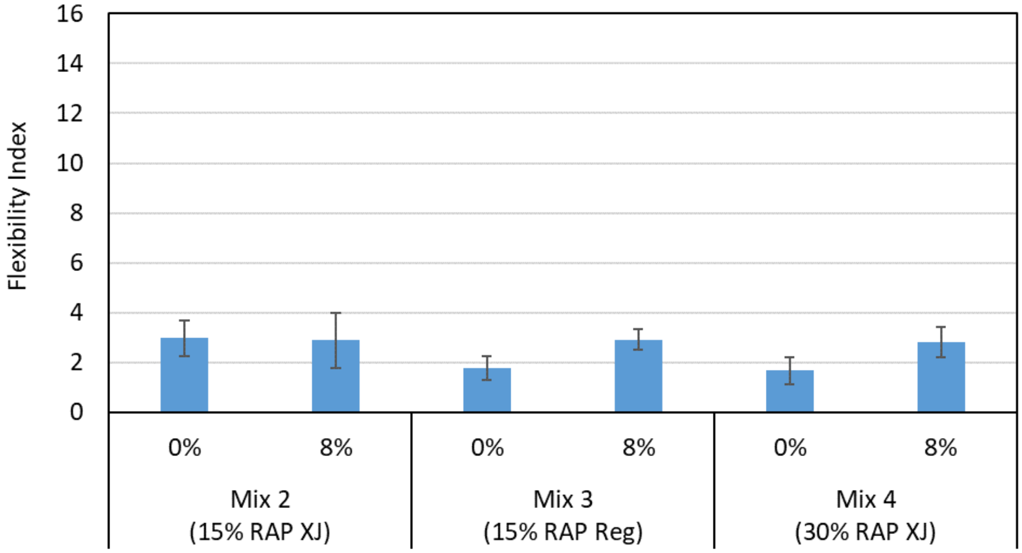


Figure 28. Dufferin I-FIT Results: Added Rejuvenator on CA at OAC Specimens

The summary of IDEAL-CT results is presented in Table 17. Note that IDEAL testing was only conducted at the optimum binder content for all four mixes. The effects of aging are not shown graphically, but the reduction in the CT_{Index} after aging was near threefold for Mix 1, Mix 2, and Mix 3, and double for Mix 4. This is consistent with the expected trends.

Table 17. Dufferin IDEAL-CT Results

Mix ID	AC Content (%)	Rejuvenator Dosage, % by Weight of RAP Binder	Aging Condition	CT Index		
				Average	St. Dev.	CV (%)
Mix 1 (Virgin)	OAC	0%	STOA	124	27.2	22.0
	OAC	0%	STOA + CA	38	4.5	11.9
Mix 2 (15% RAP XJ)	OAC	0%	STOA	77	20.2	26.4
	OAC	0%	STOA + CA	23	4.7	20.3
	OAC	8%	STOA	55	7.2	13.1
	OAC	8%	STOA + CA	23	1.4	6.1
Mix 3 (15% RAP Reg)	OAC	0%	STOA	56	11.9	21.1
	OAC	0%	STOA + CA	18	3.2	18.2
	OAC	8%	STOA	58	11.9	20.4
	OAC	8%	STOA + CA	22	3.5	16.0
Mix 4 (30% RAP XJ)	OAC	0%	STOA	37	4.7	12.8
	OAC	0%	STOA + CA	18	3.1	17.5
	OAC	8%	STOA	40	9.5	23.4
	OAC	8%	STOA + CA	23	2.8	12.0

The effect of adding RAP on CT_{Index} specimens is shown in Figure 29. These mixes had no rejuvenator and were produced at the optimum binder content. The same behavior observed between Mix 2 and Mix 3 in the I-FIT testing is also shown. Mix 2, with the modified XJ binder, outperformed Mix 3 (with regular PG 70-28 binder) at the same RAP and binder amounts. This illustrates that the IDEAL-CT test can be influenced by binder modification in some cases.

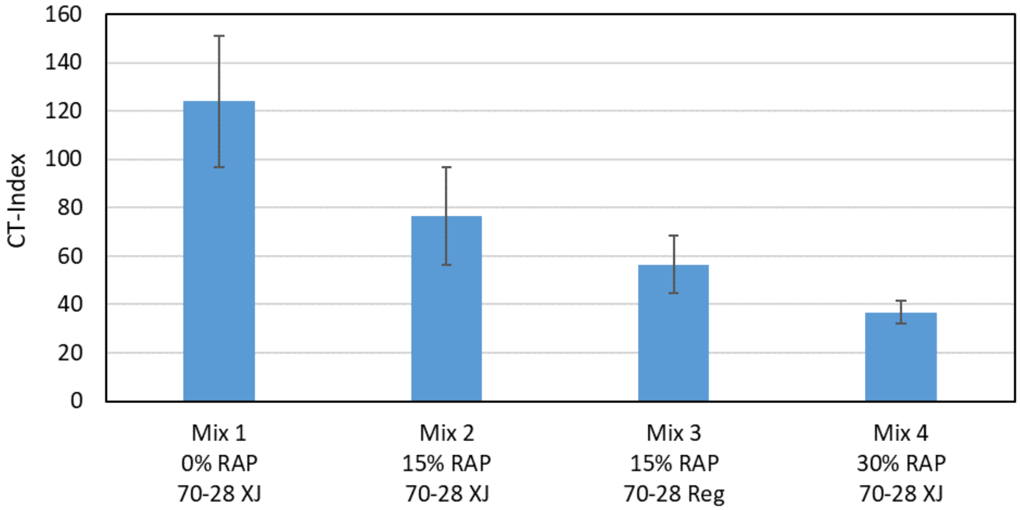


Figure 29. Dufferin IDEAL-CT Results: Increasing RAP Content

Figures 30-31 display the effects that rejuvenator had on the IDEAL-CT results for these mixes at both STOA and CA conditions. In the STOA cases, the addition of rejuvenator decreased the CT_{Index} for Mix 2 and had little to no effect relative to the overall magnitude for Mixes 3 and 4. In the CA cases, Mix 2 resulted in almost no effect after aging for the rejuvenator while Mixes 3 and 4 saw a small improvement. This result was unexpected. It is possible that the rejuvenator was replacing asphalt binder, dropping the amount of actual binder in the mix, but this is improbable. The increase in the CT_{Index} for Mix 2 and Mix 3 was larger relative to the magnitude of the actual CT_{Index} for the CA mixes than for the STOA mixes.

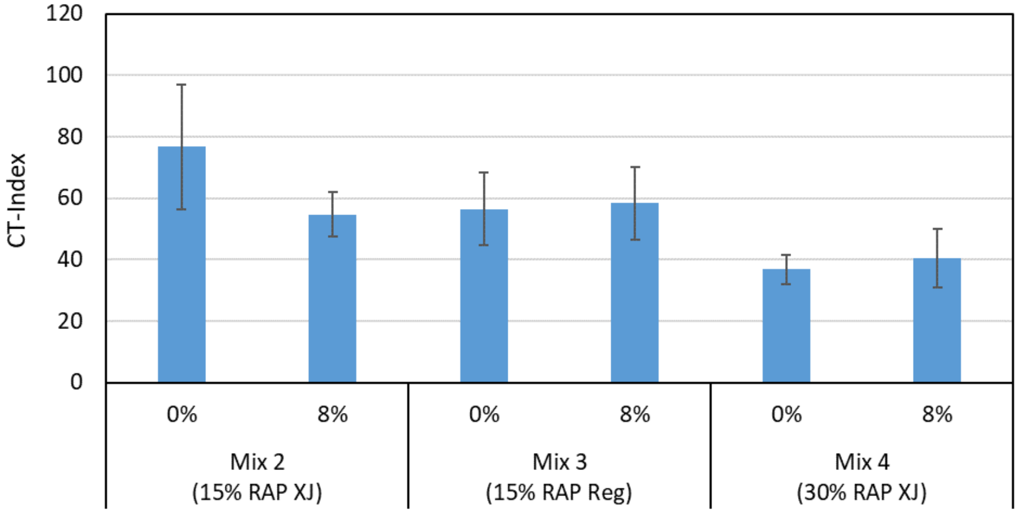


Figure 30. Dufferin IDEAL-CT Results: Added Rejuvenator on STOA at OAC Specimens

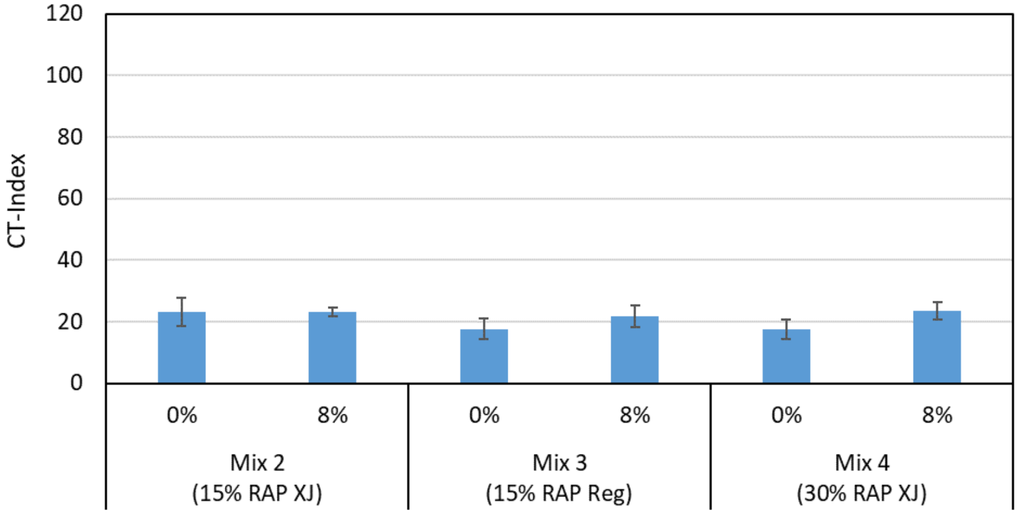


Figure 31. Dufferin IDEAL-CT Results: Added Rejuvenator on CA at OAC Specimens

Table 18 includes the average fracture energy results from DCT testing for the Dufferin mixes. Figure 32 and Figure 33 display the effects of RAP content, aging, asphalt content, and rejuvenator on the DCT results from the Dufferin mixes.

Table 18. Dufferin DCT Results

Mix ID	AC Content (%)	Rejuvenator Dosage, % by Weight of RAP Binder	Aging Condition	Fracture Energy, J/m²		
				Average	St. Dev.	CV (%)
Mix 1 (Virgin)	OAC	0%	STOA	938	93	9.9
	OAC	0%	STOA + CA	647	8	1.2
Mix 2 (15% RAP XJ)	LAC	8%	STOA	762	65	8.5
	OAC	0%	STOA	719	85	11.8
	OAC	0%	STOA + CA	636	73	11.4
	OAC	8%	STOA	793	126	15.9
	OAC	8%	STOA + CA	641	54	8.4
	HAC	0%	STOA	706	13	1.8
Mix 3 (15% RAP Reg)	LAC	8%	STOA	756	120	15.8
	OAC	0%	STOA	675	81	12.0
	OAC	0%	STOA + CA	549	13	2.4
	OAC	8%	STOA	834	36	4.4
	OAC	8%	STOA + CA	617	86	13.9
	HAC	0%	STOA	724	50	6.9
Mix 4 (30% RAP XJ)	LAC	8%	STOA	682	96	14.0
	OAC	0%	STOA	537	58	10.8
	OAC	0%	STOA + CA	526	92	17.4
	OAC	8%	STOA	739	121	16.4
	OAC	8%	STOA + CA	651	19	2.9
	HAC	0%	STOA	740	75	10.1

Figure 32 shows the effect of increasing RAP content for these mixes. The decrease in fracture energy as more brittle material is added is consistent with the expected trend for this test. The difference between the fracture energy from Mix 2 (XJ binder) to Mix 3 (PG 70-28), both with 15% RAP, was less than 10%.

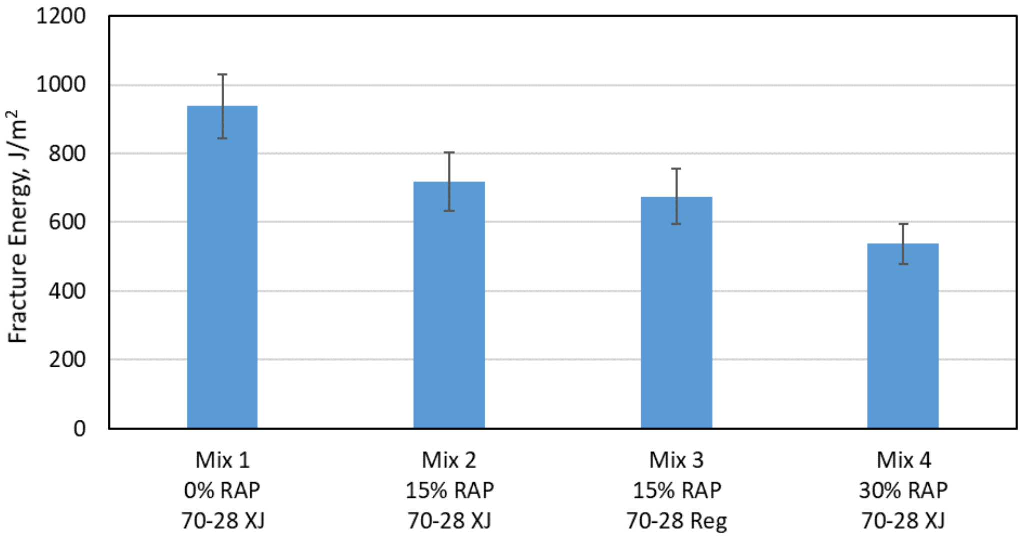


Figure 32. Dufferin DCT Results: Increasing RAP Content

Compared to the previous test results, aging the mixes did not have the same magnitude of effect on the fracture energy. The other two index tests demonstrated reductions in cracking resistance as high as threefold. This is not surprising given the fact that both the I-FIT and IDEAL-CT include a measurement of the post-peak slope in their output. As mixes become more brittle (i.e. after aging), the post-peak slope steepens which causes those two parameters to decrease dramatically. The DCT only measures fracture energy, which should decrease after aging but it should not decrease in the same order as the other two previously discussed tests. To illustrate this fact, Figure 33 shows the results of critical aging on the sets from each mix at optimum binder and no rejuvenator.

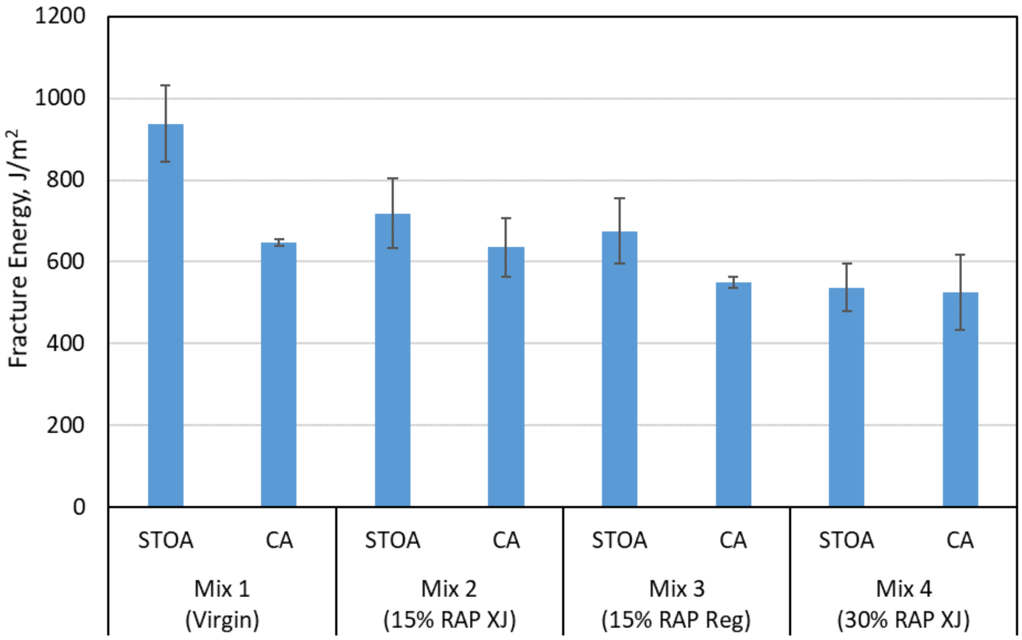


Figure 33. Dufferin DCT Results: Critically Aged Mixes at OAC With No Rejuvenator

The effect of varying asphalt content on fracture energy is shown in Figure 34. The results do not match the expectation of improved cracking resistance with increased binder. This is illustrated in the drop in fracture energy for Mix 3 and Mix 4 from the LAC with rejuvenator to OAC without rejuvenator. More subtly, Mix 2 saw a slight but steady decrease in fracture energy as the binder content was increased from LAC to OAC and then from OAC to HAC. The fracture energy parameter struggled to consistently recognize the effects of additional binder for this set of mixes.

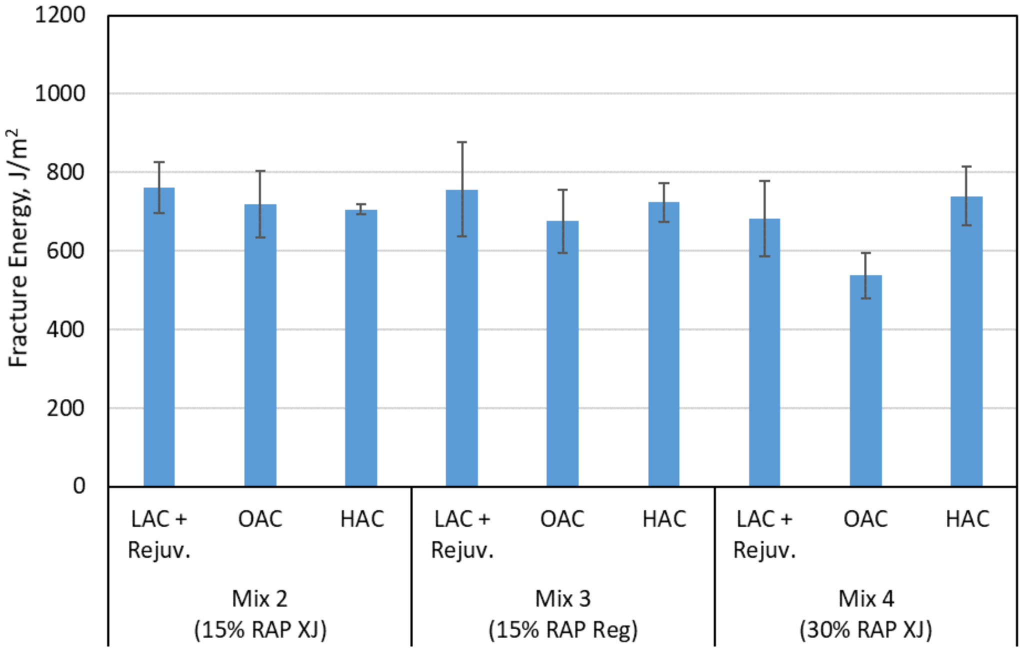


Figure 34. Dufferin DCT Results: Varying AC% on STOA Specimens

Finally, Figures 35-36 show the effect of rejuvenator on the fracture energy of DCT specimens for the Dufferin mixes for STOA and CA mixes, respectively. The addition of rejuvenator had a positive effect on the cracking resistance for all the mixtures. Although the increases do not all appear to be statistically different, there is a consistent trend that the rejuvenator marginally improved the fracture energy for each mix.

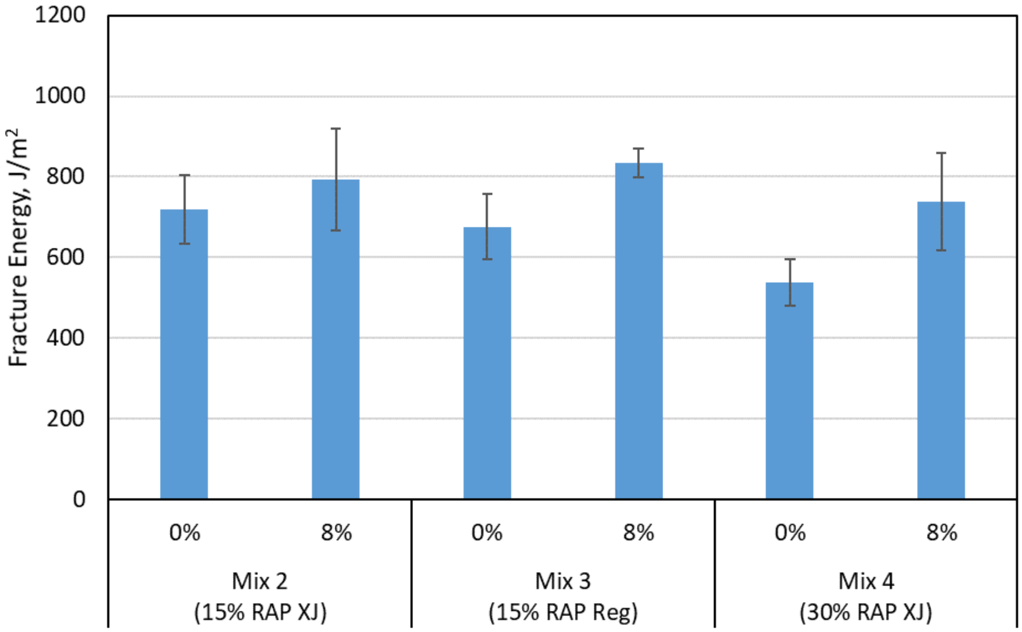


Figure 35. Dufferin DCT Results: Added Rejuvenator on STOA at OAC Specimens

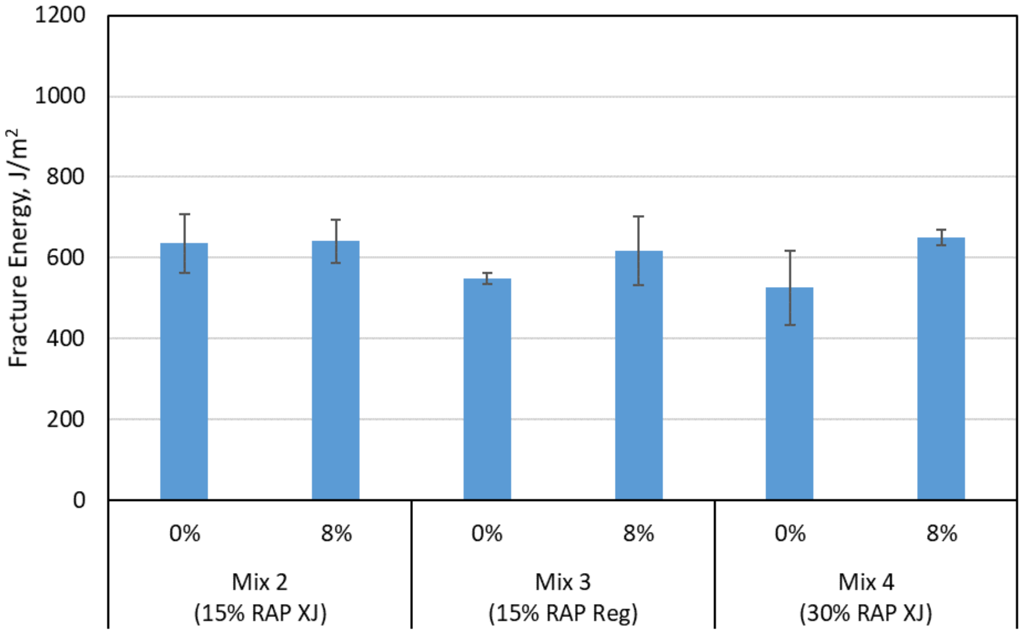


Figure 36. Dufferin DCT Results: Added Rejuvenator on CA at OAC Specimens

7.3 Mixture Performance Space Diagrams

Three performance space diagrams are shown for the Dufferin project: HWTT vs. I-FIT (Figure 37), HWTT vs. IDEAL-CT (Figure 38), and HWTT vs. DCT (Figure 39). The threshold values selected for the performance space diagrams are as follows: Maximum 12.5 rut depth at 20,000 wheel passes (NCHRP Report 646), a minimum I-FIT FI of 8 (West et al., 2018), a minimum IDEAL-CT CT_{Index} of 70 (VDOT BMD Spec, 2019), and a minimum DCT FE of 460 J/m^2 per the 'moderate traffic' criteria from Marasteanu et al., 2012. The rut depth at 20,000 passes was selected for the HWTT because this mixture was produced with a polymer modified PG 70-28 binder.

All of the Dufferin mixes were acceptable for rutting resistance in the HWTT. Five of the thirteen mixes had an I-FIT FI above the threshold value of 8. The virgin mix was the top performer with regard to I-FIT, while none of the 30% RAP mixes had an FI above 8. With regards to the 15% RAP mixes, three of the four mixes with the 'XJ' performance binder had an I-FIT FI above 8 while only one of the four mixes with the PG 70-28 'Regular' binder had an FI meet this threshold. The only mix with the 'XJ' binder not to pass the FI threshold was the mix at the low asphalt content (LAC) while the only mix with the PG 70-28 'Regular' binder to pass was the mix at the high asphalt content (HAC).

The IDEAL-CT was only performed on mixes at the optimum asphalt content (OAC) for this project. Of these seven mixes, only two had a CT_{Index} above 70 – the virgin mix and the 15% RAP mix with the 'XJ' binder and no RA. Neither of the 30% RAP mixes nor the 15% RAP mixes with the PG 70-28 'regular' binder met the CT_{Index} threshold of 70. All of the DCT FE values for the Dufferin project were above the selected threshold of 460 J/m^2. All but three of the 13 mixes meet the 'high' traffic minimum DCT FE criteria of 690 J/m2 from Marasteanu et al. (2012).

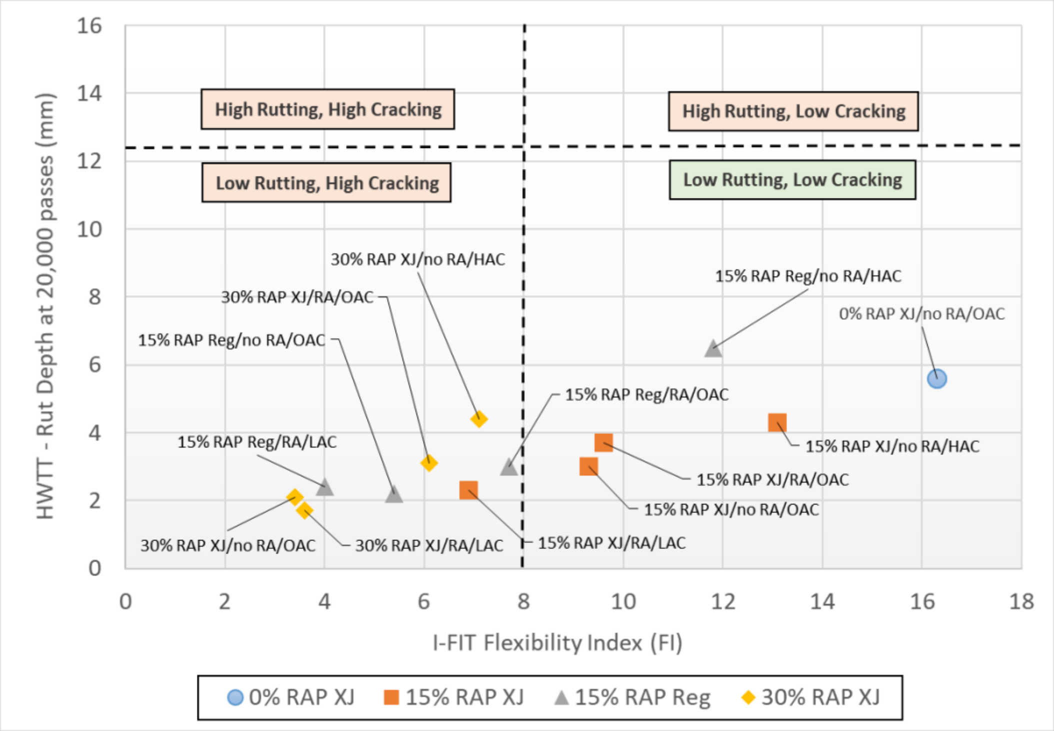


Figure 37. Dufferin Performance Space Diagram: HWTT Rut Depth (20,000 passes) vs. I-FIT FI

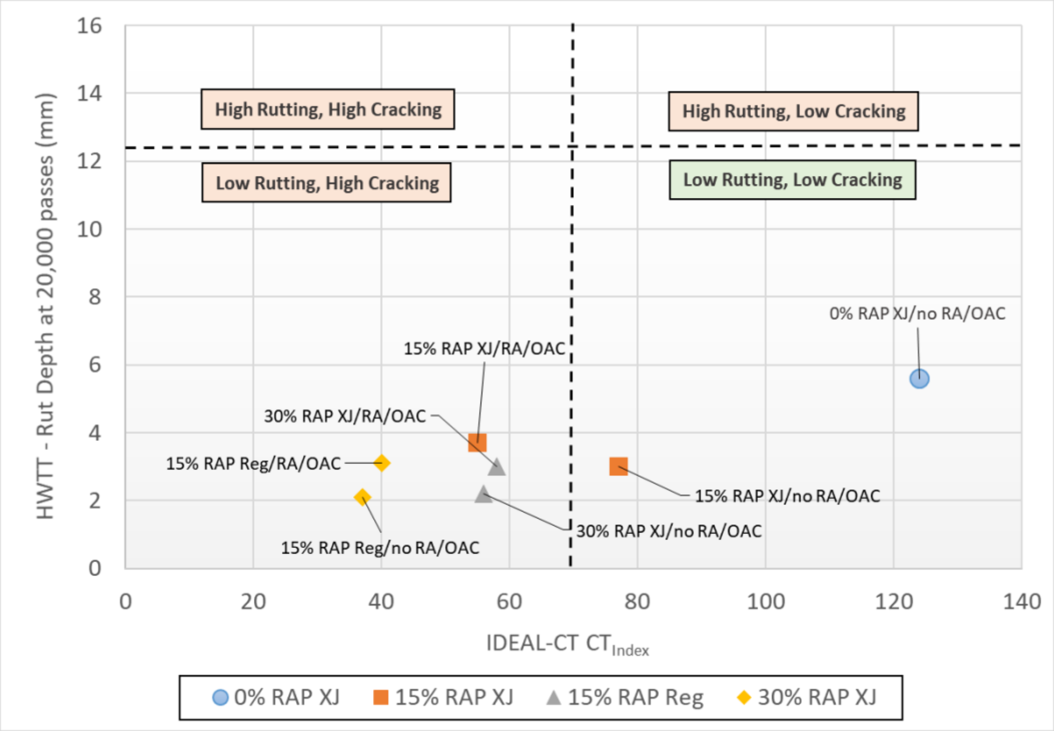


Figure 38. Dufferin Performance Space Diagram: HWTT Rut Depth (20,000 passes) vs. OAC CT$_{Index}$

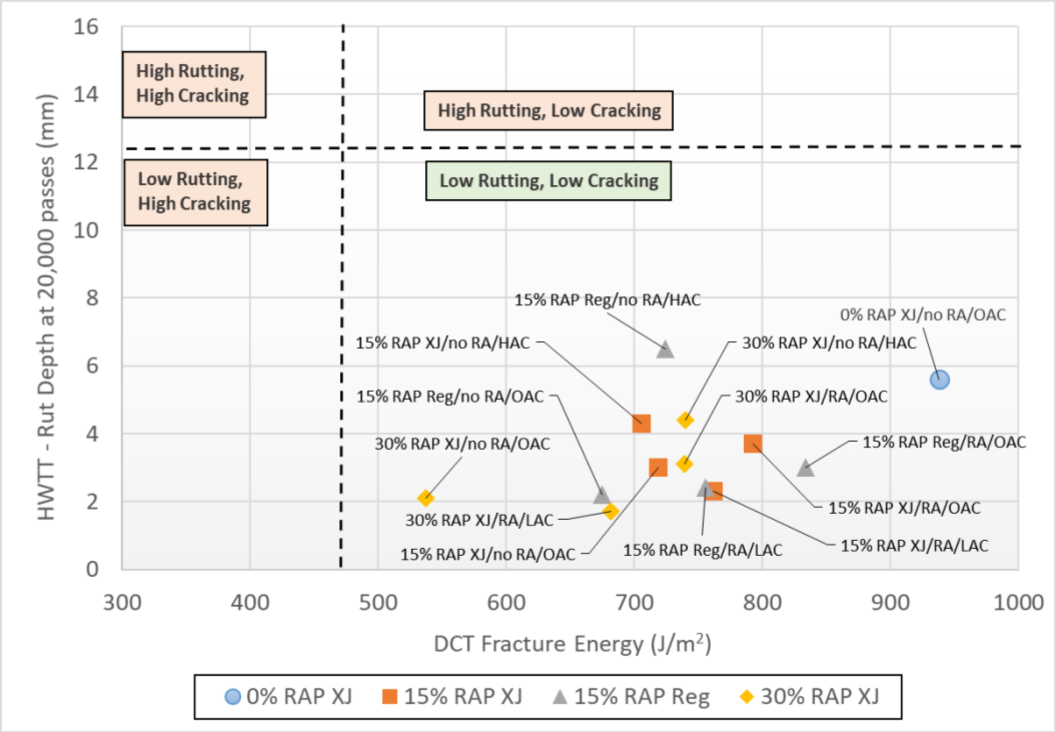


Figure 39. Dufferin Performance Space Diagram: HWTT Rut Depth (20,000 passes) vs. DCT FE

7.4 Summary of Dufferin Testing

The results from the HWTT for the Dufferin mixes were as expected. The addition of RAP decreased rutting and the addition of more asphalt or rejuvenator increased the rut depths. Comparing the rutting results for Mix 3 at LAC and OAC shows a slight improvement in the rut depths with the additional binder, which is the opposite of the expected trend. However, the rut depths were so low (<2.5mm) that the difference is considered practically insignificant. Adding asphalt to the mixes improved FI results in almost every instance. The Dufferin case study provided a noteworthy example of the possibility of finding reduced laboratory cracking results when rejuvenator is used. Adding rejuvenator to the I-FIT specimens at least slightly improved the FI of the STOA mixes and two of the three CA mixes. The other CA mix resulted in minimal change in the FI after rejuvenator was added. Adding rejuvenator to the IDEAL-CT specimens yielded mixed effects for the STOA specimens. The CT_{Index} results for Mix 2 worsened after rejuvenator was added and exhibited only marginal improvement for Mixes 3 and 4. Adding rejuvenator to the mixes improved the DCT fracture energy results for all three mixes in both the STOA and CA aging conditions. Finally, additional asphalt did not always improve the DCT fracture energy results. Fracture energy decreased in Mix 2 with each additional 0.5% AC and the fracture energy in mixes 3 and 4 decreased from LAC to OAC before increasing again at the highest binder content.

8 Case Study 4: Hardrives, Inc. – Rosemount, Minnesota

8.1 Mixes and Workplan

NCAT received raw materials from Hardrives, Inc. and began BMD optimization work in Spring 2019. There were four unique mixes included in this project. Each mix contained at least 19%

RAP. Two different aggregate sources (limestone and natural gravel) and two binder grades (PG 58-28 and 58-34) were used. Additionally, one mix contained RAS as well as a rejuvenator, ANOVA®, supplied by Cargill. The mix designs were provided by Hardrives and Mix 1 was the only one that had been produced prior to this study. The rest were theoretical blends containing varied raw materials. The mixes were produced in the lab and were approved to proceed with BMD testing even though the volumetric results did not pass traditional Superpave criteria. The mix design information for the four mixes is provided in Table 19.

Table 19. Hardrives Mix Designs

% Passing	Mix 1 (LMS 19% RAP)	Mix 2 (LMS 30% RAP)	Mix 3 (Nat. Gravel 19% RAP)	Mix 4 (LMS 20/5% RAP/RAS)
3/4"	100.0	100.0	100.0	100.0
1/2"	89.7	86.2	90.9	84.4
3/8"	82.3	77.8	85.3	75.5
# 4	63.9	62.3	60.6	61.5
# 8	49.0	49.2	46.7	49.4
# 16	36.5	37.7	36.1	36.7
# 30	25.4	26.7	25.1	25.6
# 50	12.7	13.3	12.6	13.4
# 100	6.8	6.5	6.5	7.5
#200	4.89	4.61	4.56	5.08
AC%, Total	5.3	4.9	5.3	5.0
AC%, Virgin	4.3	3.3	4.3	3.0
AC% from RAP/RAS	1.0	1.6	1.0	2.0
RBR	19.1%	32.7%	19.1%	37.0%
Rejuvenator Dosage*	N/A	N/A	N/A	4.9%
PG Grade	58-28	58-34	58-28	58-28
Aggregate	Limestone	Limestone	Natural Gravel	Limestone
Va, %	4.3	4.1	5.2	5.0
VMA, %	14.9	14.0	15.8	14.4
VFA, %	71.3	70.8	67.3	73.0
DP	1.1	0.94	1.02	1.14
Gmm	2.552	2.537	2.570	2.521
Gmb	2.443	2.433	2.438	2.422

*By weight of RAP binder

The work plan for this project is shown in Table 20. Rutting resistance was assessed using the Hamburg Wheel Tracking Test (HWTT) (AASHTO T324-17), thermal cracking resistance was evaluated using the disc-shaped compact tension test (DCT) (ASTM D7313-13), and intermediate temperature fatigue cracking resistance was determined using both the IDEAL-CT (ASTM D8225-19) and the I-FIT (AASHTO TP 124-18). All four mixes had the same testing plan. HWTT testing was performed on STOA mixes at the optimum asphalt content (OAC) and optimum plus 0.5% (HAC). The three cracking tests were conducted at the same binder contents on STOA mixes as the HWTT but were also tested on OAC mixes that had been critically aged (CA). These aging procedures were described previously in this report.

Table 20. Hardrives Testing Plan

Mix	Test	AC%	Aging Condition	Rejuvenator Dosage by Weight of RAP Binder
Mix 1 19% RAP (LMS) 58-28	Hamburg	OAC, HAC (STOA Only)	STOA	N/A
	DCT		STOA & CA	
	I-FIT		STOA & CA	
	IDEAL-CT		STOA & CA	
Mix 2 30% RAP (LMS) 58-34	Hamburg	OAC, HAC (STOA Only)	STOA	N/A
	DCT		STOA & CA	
	I-FIT		STOA & CA	
	IDEAL-CT		STOA & CA	
Mix 3 19% RAP (Natural Gravel) 58-28	Hamburg	OAC, HAC (STOA Only)	STOA	N/A
	DCT		STOA & CA	
	I-FIT		STOA & CA	
	IDEAL-CT		STOA & CA	
Mix 4 20% RAP/5% RAS With Rejuvenator 58-28	Hamburg	OAC, HAC (STOA Only)	STOA	4.9%
	DCT		STOA & CA	
	I-FIT		STOA & CA	
	IDEAL-CT		STOA & CA	

8.2 Results

HWTT testing was performed at 45°C, and Table 21 includes a summary of the average results for the four Hardrives mixes. Rut depths increased with the addition of 0.5% AC for each of the four mixes presented in Figure 40. Mix 1 performed well at the optimum binder content and rutting increased but did not exceed the 12.5 mm threshold when 0.5% more binder was added to the mix. Mix 2, with increased RAP but softer virgin binder than Mix 1, performed similarly to Mix 1 for the first 10,000 passes. However, at 20,000 passes, one replicate had a similar performance to Mix 1 and the other failed due to stripping. Rut depths were higher for Mix 2 at the HAC and ultimately reached the failure threshold around 15,000 passes after stripping. Mix 3 was a similar mix to Mix 1 but instead contained natural gravel. Mix 3 showed slightly higher rut depths after testing than Mix 1. Mix 4, with 20% RAP and 5% RAS, had very low rutting due to its increased stiffness. The results are shown graphically in Figure 40.

Table 21. Hardrives HWTT Results

Mix ID	AC Content (%)	Rut Depth at 10,000 passes (mm)	Rut Depth at 20,000 passes (mm)	Passes to 12.5 mm Rut Depth	Stripping Inflection Point (Passes)
		Average	Average	Average	Average
Mix 1 19% RAP LMS	OAC	3.0	4.7	>20,000	N/A
	HAC	3.9	7.1	>20,000	N/A
Mix 2 30% RAP	OAC	3.5	6.0*	16,400*	11,000*
	HAC	6.8	>12.5	15,300	12,000
Mix 3 19% RAP NG	OAC	2.8	4.1	>20,000	N/A
	HAC	4.5	8.7	>20,000	N/A
Mix 4 RAP/RAS with rejuvenator	OAC	2.1	3.3	>20,000	N/A
	HAC	2.9	3.7	>20,000	N/A

* One replicate exhibited stripping and failed before 20K passes. The other had 6 mm of rutting after 20K passes.

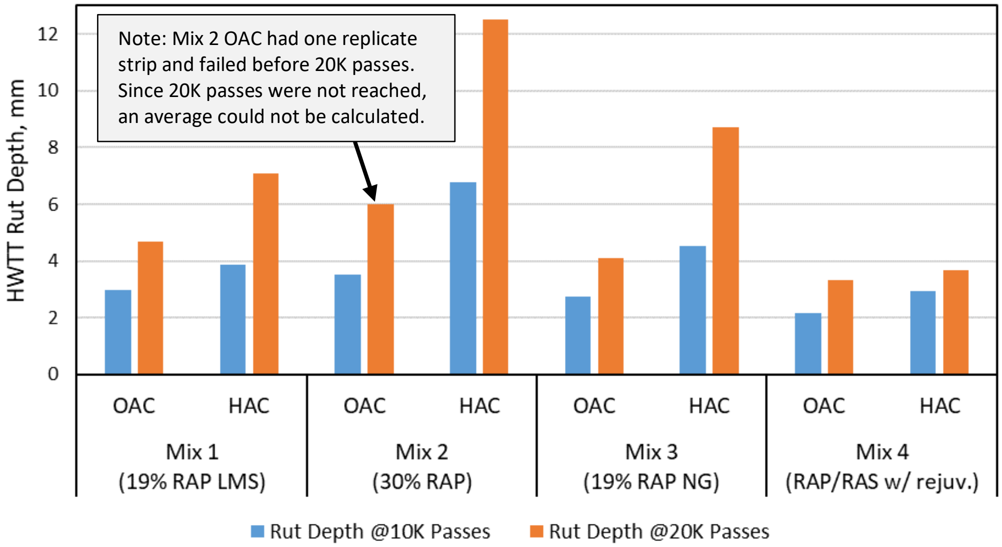

Note: Mix 2 OAC had one replicate strip and failed before 20K passes. Since 20K passes were not reached, an average could not be calculated.

Figure 40. Hardrives HWTT Results

Table 22 shows the I-FIT results for the four Hardrives mixes. STOA samples were tested at the OAC and at HAC. CA samples were tested only at the volumetric optimum binder content. The variability, indicated by the CV%, ranged from 12.4% to 38.0%. Figure 41 and Figure 42 show the effects of adding additional binder to the mix and of mix aging, respectively. Adding an additional 0.5% binder increased the Flexibility Index by a minimum of 43% for the four mixes. Critically aging reduced the Mix 1 and Mix 2 Flexibility Index to the same value, even though Mix 2 had a softer binder. Mix 3 had the highest FI after aging and Mix 4 had a result of less than 1.0. In the authors’ experience, this is typical for mixes containing RAS. Mix 3 outperformed Mix 1 in terms of Flexibility Index, indicating that the natural aggregate source has the potential to produce mixes more resistant to cracking than the limestone for the same asphalt content and gradation.

Table 22. Hardrives I-FIT Results

Mix ID	AC Content (%)	Binder Grade	Aggregate	Aging Condition	Flexibility Index		
					Average	St. Dev.	CV (%)
Mix 1 (19% RAP)	OAC	58-28	Limestone	STOA	7.4	1.6	22.1%
	HAC			STOA	13.9	4.8	34.8%
	OAC			CA	2.4	0.9	38.0%
Mix 2 (30% RAP)	OAC	58-34		STOA	10.5	2.8	26.5%
	HAC			STOA	18.3	5.0	27.6%
	OAC			CA	2.4	0.5	20.2%
Mix 3 (19% RAP NG)	OAC	58-28	Natural Agg	STOA	12.1	2.2	18.2%
	HAC			STOA	17.3	3.0	17.2%
	OAC			CA	4.3	1.0	22.4%
Mix 4 (RAP/RAS with rejuvenator)	OAC		Limestone	STOA	2.5	0.3	12.4%
	HAC			STOA	7.0	1.7	24.1%
	OAC			CA	0.6	0.2	27.9%

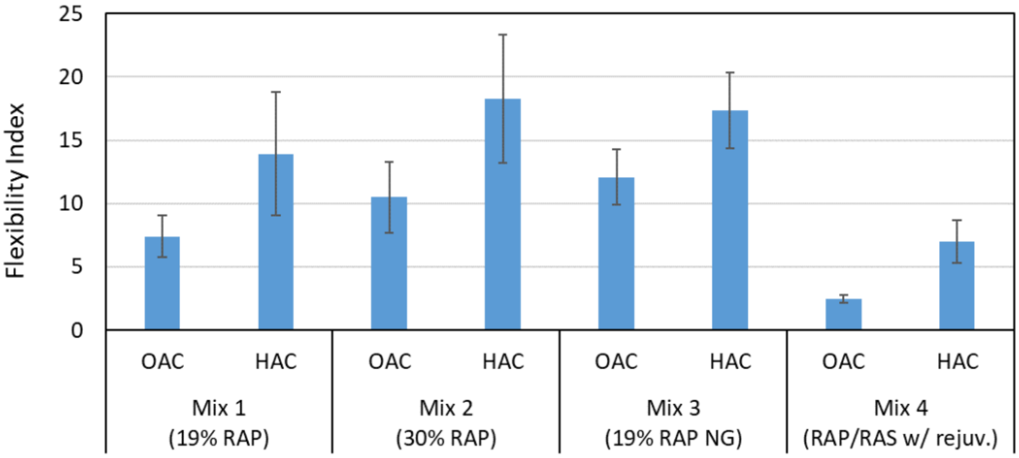


Figure 41. Hardrives I-FIT Results: Varying AC%

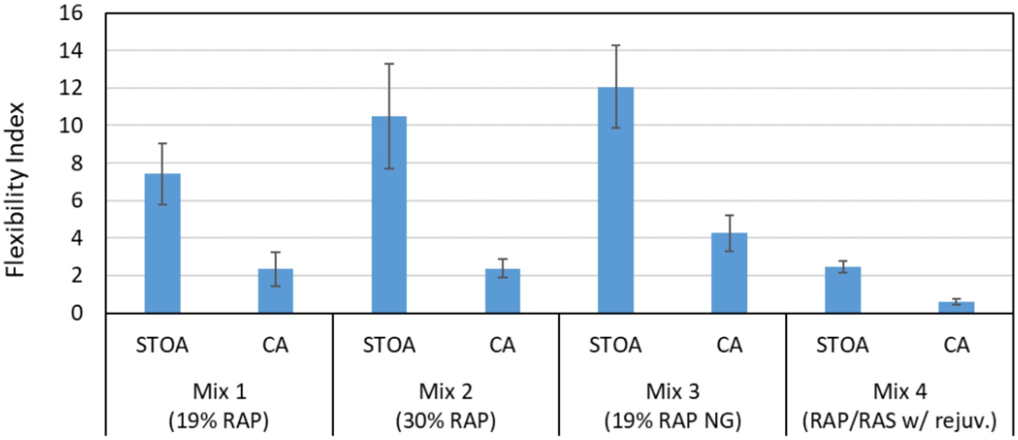


Figure 42. Hardrives I-FIT Results: Effect of Aging at OAC

Table 23 lists the IDEAL-CT results from the four Hardrives mixes. The results trended as expected with regard to asphalt content and aging. Figure 43 shows the results of additional binder on the CT-Index results. The addition of 0.5% AC increased the CT-Index of the mixes by at least 70%. Figure 44 shows the results of critically aging the mix on CT-Index. Critically aging resulted in a collapse in the CT-Index to dramatically lower than the results at the STOA condition. Mix 2 and Mix 3 had similar results after aging while Mix 1 had a lower CT-Index than Mix 3. This behavior was also present in the I-FIT FI and further indicates that the natural aggregate source may be the superior source of the two options tested in this project in terms of intermediate temperature cracking resistance. The effect of aggregate source is isolated because the gradation and AC% was the same between Mix 1 and Mix 3.

Table 23. Hardrives IDEAL-CT Results

Mix ID	AC Content (%)	Binder Grade	Aggregate	Aging Condition	CT-Index		
					Average	St. Dev.	CV (%)
Mix 1 (19% RAP)	OAC	58-28	Limestone	STOA	64	6.6	10.4%
	HAC			STOA	111	23.9	21.5%
	OAC			CA	21	2.8	13.6%
Mix 2 (30% RAP)	OAC	58-34	Limestone	STOA	68	14.7	21.5%
	HAC			STOA	157	54.9	35.0%
	OAC			CA	39	9.2	23.5%
Mix 3 (19% RAP NG)	OAC	58-28	Natural Agg	STOA	83	18.7	22.6%
	HAC			STOA	143	15.3	10.7%
	OAC			CA	33	13.8	41.3%
Mix 4 (RAP/RAS with rejuvenator)	OAC		Limestone	STOA	41	3.8	9.4%
	HAC			STOA	75	16.1	21.6%
	OAC			CA	15	2.6	17.7%

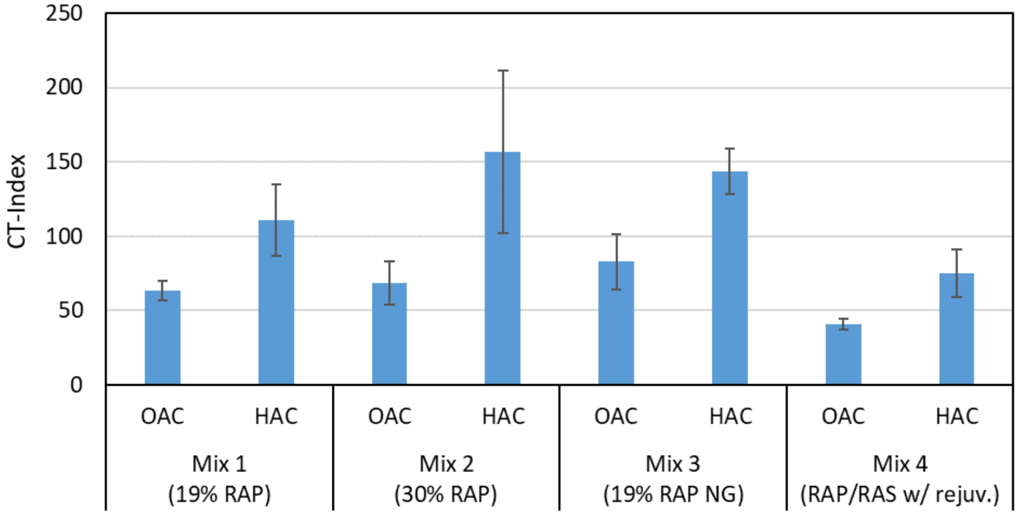


Figure 43. Hardrives IDEAL-CT Results: Varying AC%

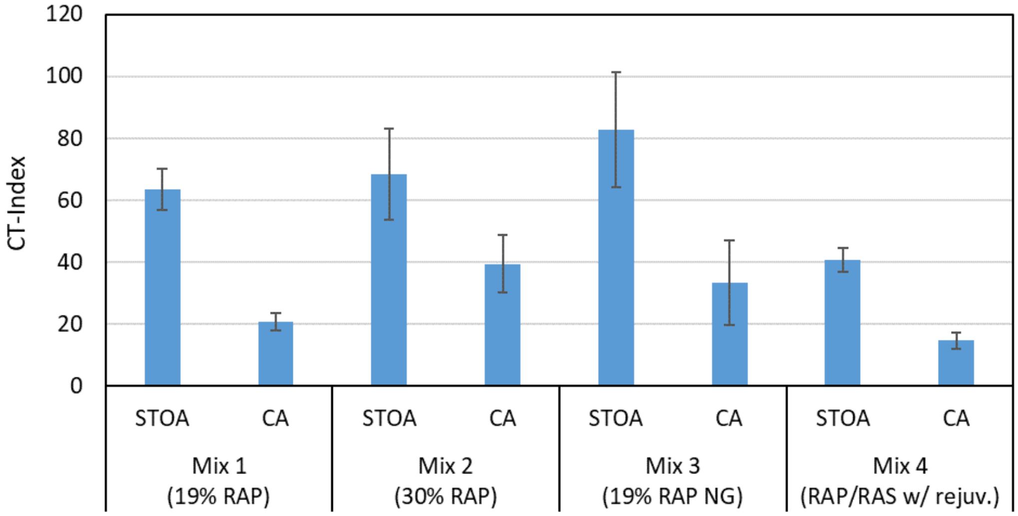


Figure 44. Hardrives IDEAL-CT Results: Effect of Aging at OAC

Table 24 includes the results of DCT testing at -20.1°C for the Hardrives mixes. According to MnDOT, this was the test temperature for Rosemount, Mn (Dave et al., 2019). The results do not consistently follow the expected trends with regards to the effects of additional binder and aging. For example, Figure 45 shows that the additional binder increased the fracture energy result for two mixes but reduced it for the other two. This behavior is not exhibited in the other tests used in this project. Furthermore, Figure 46 shows the fracture energy for Mix 1 increased after additional aging and the result for Mix 4 remained essentially the same after aging. This was unexpected given the RAS present in Mix 4. However, Mix 3 did outperform Mix 1, as was the case with the other cracking tests. It is notable that past research at NCAT has shown that the DCT is not extremely sensitive to changing asphalt content. A study for the Wisconsin DOT showed that for six mixes, average improvement in DCT FE when the mixture asphalt content was increased by 0.3% to 0.4% was only around 12% (West, Rodezno, Leiva, and Taylor 2018).

Table 24. Hardrives DCT Results (Tested at -20.1°C)

Mix ID	**AC Content (%)**	**Binder Grade**	**Aggregate**	**Aging Condition**	**Fracture Energy, J/m^2**		
					Average	**St. Dev.**	**CV (%)**
Mix 1 (19% RAP)	OAC	58-28	Limestone	STOA	361	35.6	9.9
	HAC			STOA	482	59.4	12.3
	OAC			CA	411	30.8	7.5
Mix 2 (30% RAP)	OAC	58-34		STOA	371	51.7	13.9
	HAC			STOA	350	23.5	6.7
	OAC			CA	340	32.7	9.6
Mix 3 (19% RAP NG)	OAC	58-28	Natural Agg	STOA	597	71.1	11.9
	HAC			STOA	450	33.5	7.4
	OAC			CA	468	23.9	5.1
Mix 4 (RAP/RAS with rejuvenator)	OAC		Limestone	STOA	325	31.8	9.8
	HAC			STOA	377	31.5	8.4
	OAC			CA	319	33.4	10.5

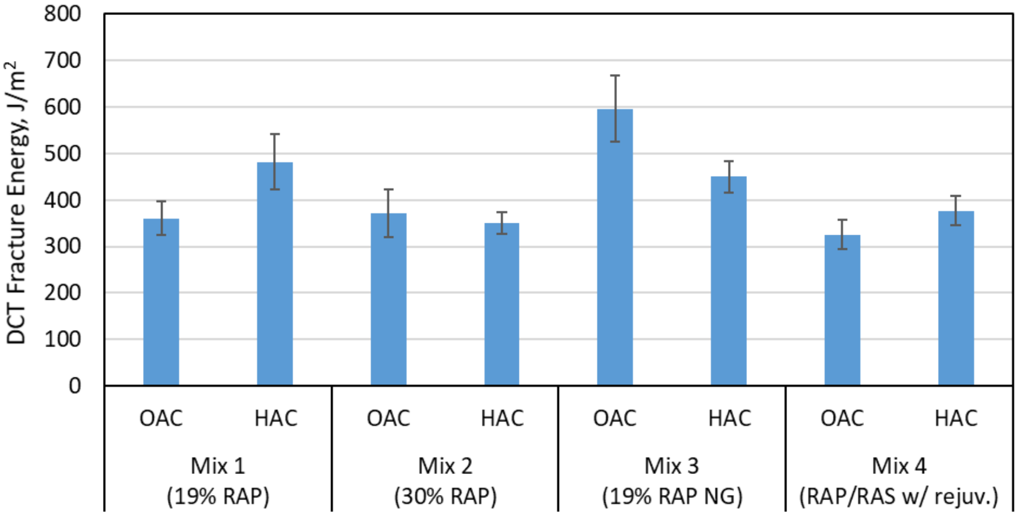


Figure 45. Hardrives DCT Results: Varying AC%

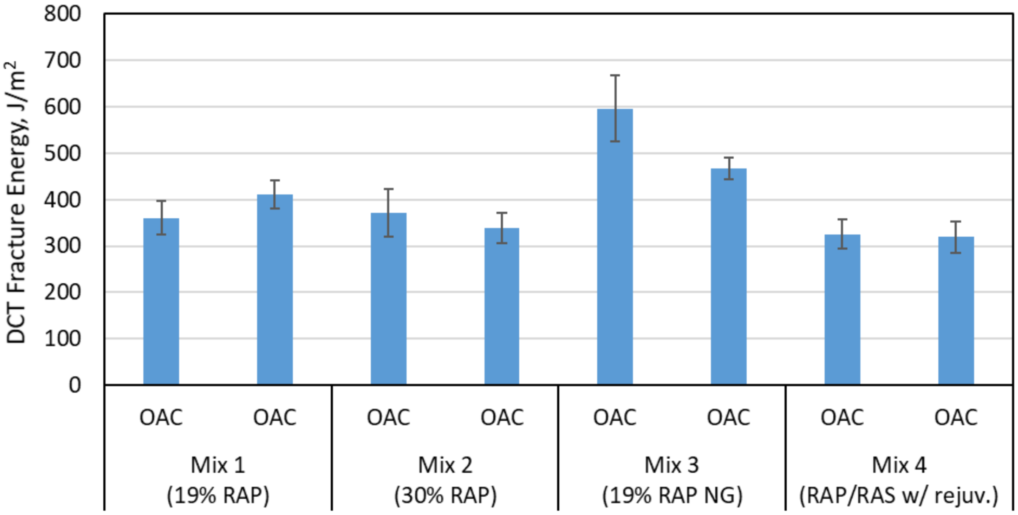


Figure 46. Hardrives DCT Results: Effect of Aging at OAC

8.3 Performance Space Diagrams

Three performance space diagrams are shown for the Hardrives project: HWTT vs. I-FIT (Figure 47), HWTT vs. IDEAL-CT (Figure 48), and HWTT vs. DCT (Figure 49). The threshold values selected for the performance space diagrams are as follows: maximum 12.5 rut depth at 10,000 wheel passes (NCHRP Report 646), a minimum I-FIT FI of 8 (West et al., 2018), a minimum IDEAL-CT CT_{Index} of 70 (VDOT BMD Spec, 2019), and a minimum DCT FE of 460 J/m^2 per the 'moderate traffic' criteria from Marasteanu et al., 2012. The rut depth at 10,000 passes was selected for the HWTT because this mixture was produced in a northern climate without a polymer modified binder. Each data point on the diagram represents a single mix and each mix is provided with a shorthand description. For example, mix '20/5, RA, 58-28, LMS, OAC' contains the following: 20% RAP and 5% RAS (20/5), a rejuvenating additive (RA), PG 58-28 base binder (58-28), Limestone (LMS), and produced at the optimum asphalt content (OAC).

All eight of the study mixes passed the selected rut depth criteria of a maximum 12.5 mm of rutting at 10,000 passes. Only one mix (Mix 2 – 30/0, no RA, 58-34, LMS) did not meet this criteria at the more stringent criteria of 12.5 mm maximum rut depth at 20,000 passes. This is likely driven by the softer base asphalt (PG 58-34 relative to PG 58-28 for the other mixes). For the I-FIT test (Figure 47), five of the eight mixes passed the selected threshold (minimum FI of 8). Neither mix containing RAS (OAC or HAC) met the selected FI criteria. Additionally, the 19% RAP mix with PG 58-28 and LMS at the OAC did not meet the FI criteria. Increasing the asphalt content of this mix appreciably increased the FI. The mixtures with the PG 58-34 binder and the natural gravel both performed well in the I-FIT for this study.

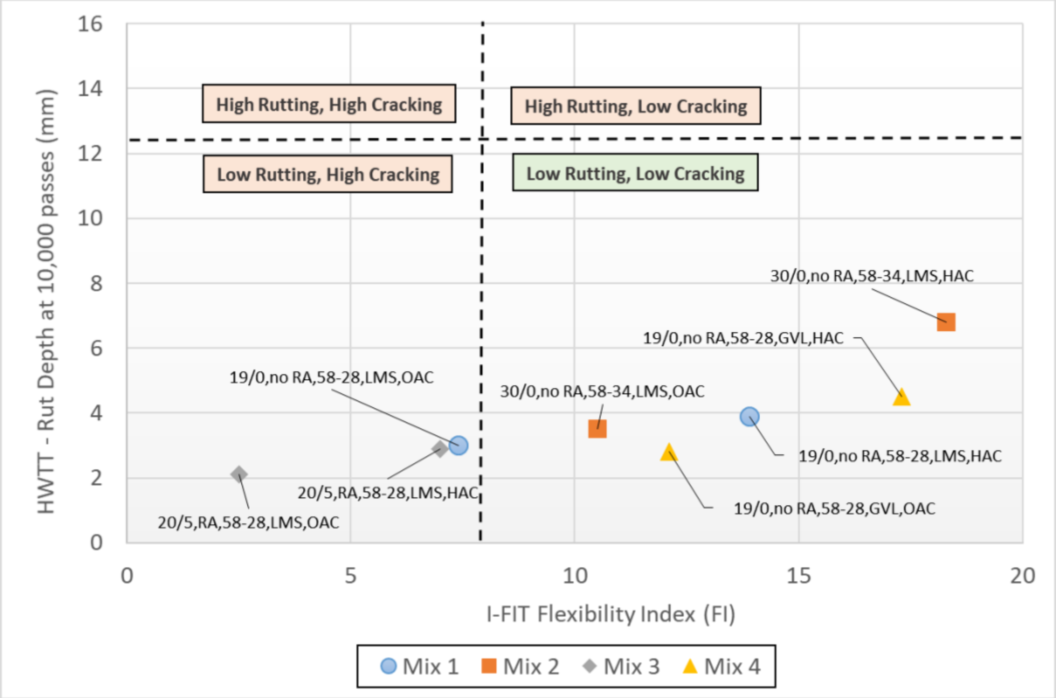


Figure 47. Hardrives Performance Space Diagram: HWTT Rut Depth (10,000 Passes) vs. I-FIT FI

For the IDEAL-CT (Figure 48), similar trends were observed in the results as for the I-FIT test. Five of the eight mixes passed the selected CT$_{\text{Index}}$ threshold minimum of 70. For the IDEAL-CT, the 20% RAP and 5% RAS mix with RA barely passed the minimum CT$_{\text{Index}}$ threshold whereas it barely failed for the I-FIT test. Conversely, the 30% RAP mix with PG 58-34 binder barely failed the selected CT$_{\text{Index}}$ threshold while it passed the I-FIT test.

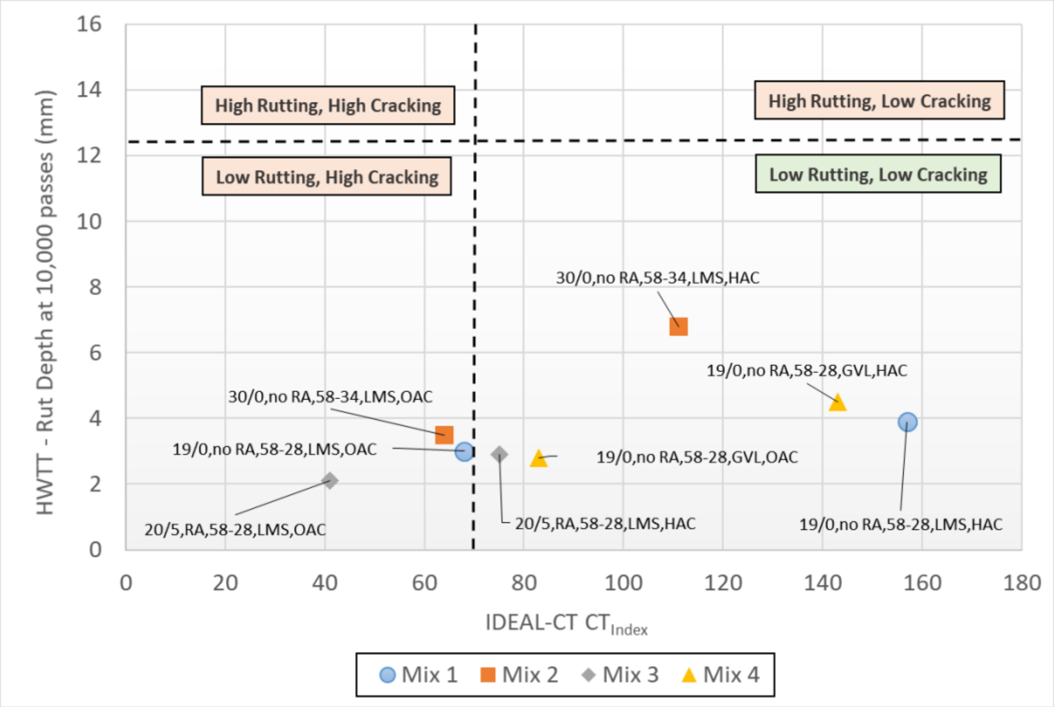


Figure 48. Hardrives Performance Space Diagram: HWTT Rut Depth (10,000 Passes) vs. CT_{Index}

For the DCT test (Figure 49), only two of the eight mixes passed the selected DCT FE minimum criteria of 460 J/m^2: the 19% RAP mix with limestone at the high asphalt content and the 19% RAP mix with natural gravel at the optimum asphalt content. The mix with 19% RAP and natural gravel did not trend as expected for asphalt content (OAC having significantly higher FE than the same mix at the high asphalt content) and seemed like an outlier relative to the overall dataset. However, a review of the raw data and specimen fabrication records yielded no notable concerns. Overall, different mix design modifications may be needed to help improve the performance of this mix in the DCT test.

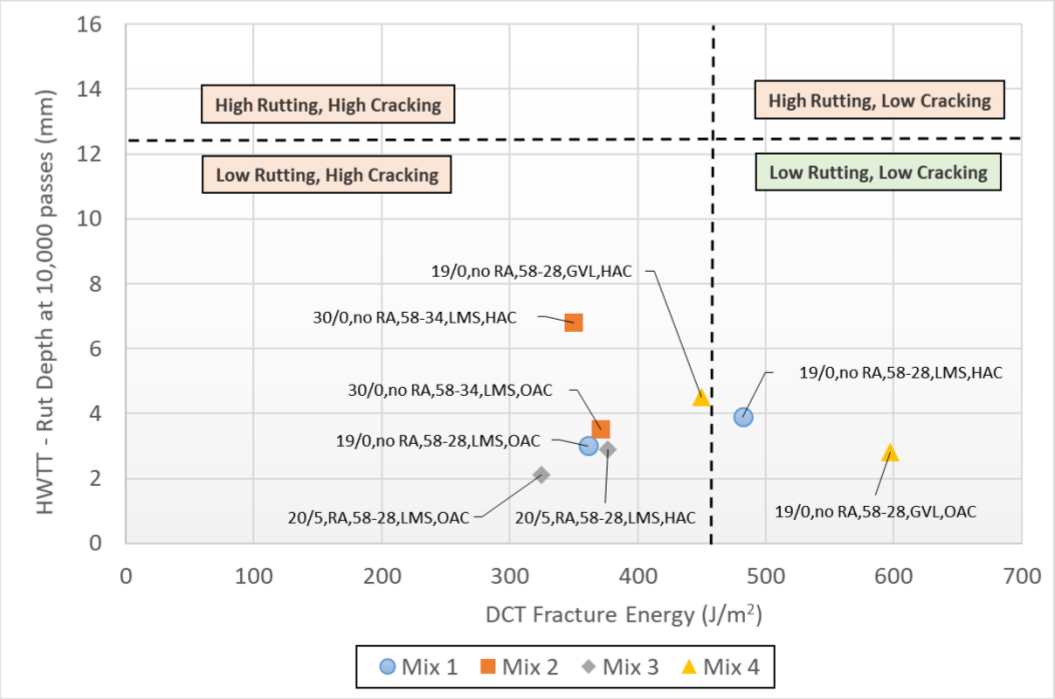


Figure 49. Hardrives Performance Space Diagram: HWTT Rut Depth (10,000 Passes) vs. DCT FE

8.4 Summary of Hardrives Testing

The results from the HWTT for the Hardrives mixes yielded results as expected concerning binder content, recycled material content, and binder grade. I-FIT and IDEAL-CT results increased for all of the Hardrives mixes when 0.5% AC was added, and the results for both tests decreased when the mixes were critically aged. Additional binder did not improve the DCT fracture energy results for all of the Hardrives mixes. Mix 1 experienced a significant increase in fracture energy when binder increased while Mix 3 resulted in a large decrease in fracture energy. Mixes 2 and 4 showed a marginal reduction and improvement in fracture energy, respectively. Finally, when the mixes were critically aged, only Mix 3 showed a large decrease in fracture energy, while Mix 1 increased fracture energy. There was a small reduction in fracture energy after aging for mixes 2 and 4.

9 SUMMARY OF ALL FOUR CASE STUDIES AND CONCLUSIONS

The four case studies provide an in-depth investigation into the effects of mix design variables such as RAP content, AC%, rejuvenator dosage, and aggregate type. These four studies do not constitute a factorial statistical design where each variable can be individually isolated and analyzed. However, when the results are combined, some themes can easily be extracted from the four studies. For example, every IDEAL-CT example presented in this report demonstrated the positive effect that additional AC% has on cracking resistance.

The effectiveness of mix design variables utilized in this report at improving cracking or rutting resistance are summarized in Table 25. Cells are marked with “increase” if the mixture laboratory performance increases when that particular mix design variable was used, and “decrease” marks the instances where the incorporation of the variable decreased the laboratory performance. For example, increasing asphalt content increased the cracking resistance of the mixes in IDEAL-CT and I-FIT testing but decreased their rutting resistance in Hamburg testing. The cells that are marked as “inconclusive” indicate that the variable could not be isolated in that case study and the singular effect cannot be known. For example, the Hardrives mixes had a mix that used higher RAP contents but also contained a softer binder. Cells that are marked as “varied” indicate that the variables sometimes improved performance and other times worsened it inside the same case study. For example, increasing the AC% for the Dufferin mixes did not always improve the DCT results. Finally, cells that are left blank indicate that this variable was not a part of the study for a particular performance test.

Table 25: Summary of Mix Design Variables

		IDEAL-CT		
Mix Design Variable	**Pennsy**	**Staker Parson**	**Dufferin**	**Hardrives**
Increasing AC%	Increase	Increase	Increase	Increase
Adding Rejuvenator	Increase	Increase	Varied	
Increasing RAP	Decrease	Decrease	Decrease	Inconclusive
Critically Aging			Decrease	Decrease
		I-FIT		
Mix Design Variable	**Pennsy**	**Staker Parson**	**Dufferin**	**Hardrives**
Increasing AC%	Increase	Increase	Increase	Increase
Adding Rejuvenator	Increase	Inconclusive	Increase	
Increasing RAP	Decrease	Decrease	Decrease	Inconclusive
Critically Aging	Decrease	Decrease	Decrease	Decrease
		Hamburg		
Mix Design Variable	**Pennsy**	**Staker Parson**	**Dufferin**	**Hardrives**
Increasing AC%	Decrease	Decrease	Decrease	Decrease
Adding Rejuvenator	Decrease	Inconclusive	Decrease	
Increasing RAP	Increase	Increase	Increase	Inconclusive
Critically Aging				
		DCT		
Mix Design Variable	**Pennsy**	**Staker Parson**	**Dufferin**	**Hardrives**
Increasing AC%			Varied	Varied
Adding Rejuvenator			Increase	
Increasing RAP			Decrease	Inconclusive
Critically Aging			Decrease	Varied

In summary, increasing asphalt content improved mixture cracking resistance for the two intermediate temperature cracking tests (i.e., I-FIT and IDEAL-CT). It is expected that the varied results shown in DCT testing are a result of the sensitivity of the test and do not accurately represent the increased resistance to thermal cracking that additional asphalt provided. Increased asphalt content also decreased rutting resistance for all four studies, as expected. Using more recycled material almost always provided a stiffer mix that was more resistant to rutting and less resistant to cracking. Although marked as inconclusive for the Hardrives mixes due to the mix that included both increased RAP and a softer binder grade, the Hardrives mix that used RAP and RAS combined with a rejuvenator exhibited worse performance than the mixes with only RAP. Rejuvenator had a positive effect a majority of the time but there were instances when mixture performance was worsened unexpectedly. This finding should be used to encourage mix producers to verify rejuvenator performance on an individual mix-by-mix basis in their labs before assuming good results will ensue from its use. Finally, increased aging worsened cracking resistance in all but one instance. This single instance is most likely an outlier. Note that this work was completed in 2018 when BMD specimen preparation best practices were still being developed. Thus, it was not uncommon to have higher variability than would be considered normal five years later.

9.1 IDEAL-CT and I-FIT Correlations

Immediately after the introduction of the IDEAL-CT to the asphalt industry, researchers began to consider the possibility that the I-FIT and the IDEAL-CT could correlate well with each other. The two methods use the same testing temperature and loading rate and extremely similar analysis methods. Shown below in Figure 50, the CT-Index is plotted against the Flexibility Index for all four case studies. In all four cases, the two test results correlate extremely well. The correlation coefficient, r, is the square root of R^2 and ranges from -1 to 1. A correlation coefficient of 1.0 indicates perfect positive correlation between two independent test results. A negative correlation coefficient indicates a negative (i.e. downward) trend. In general, correlation coefficients greater than 0.80 are considered high. Three of the four studies yielded correlations coefficients greater than 0.95. The correlation coefficient for the results from the Pennsy study was 0.88, which is still considered to be very good. These results indicate that these two tests can, and possibly often, correlate well with each other when only varying some mix components within the same mix. However, when the case studies are combined, the trend becomes less clear. This is shown in Figure 51. The combined correlation coefficient was 0.78. This is still fairly high, but it refutes the idea that there is a universal correlation between these two tests. This fact is further proven by observing the slopes of the individual lines for the case studies. The slopes in the four plots in Figure 50 range from 6.9 to 11.6, indicating that the CT-Index can be as low as 6.9 times higher than the FI for the Dufferin mixes and as high as 11.6 times the FI for the Pennsy mixes.

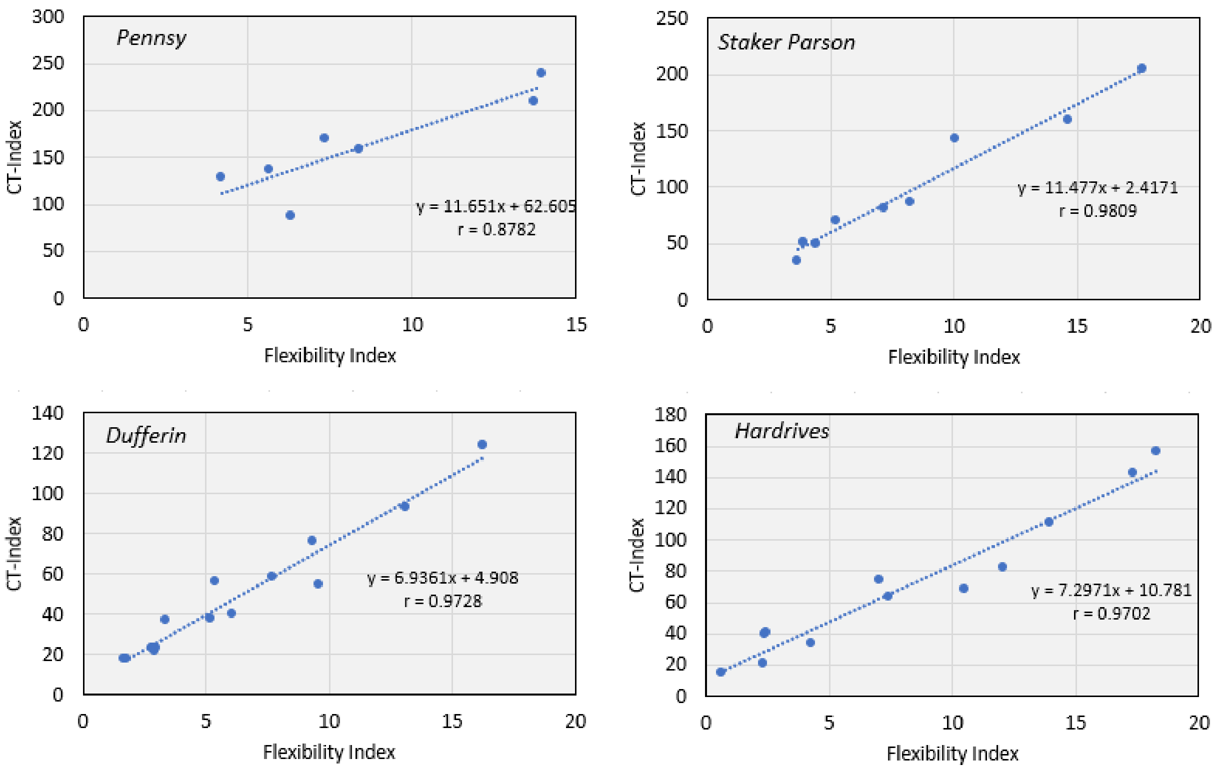


Figure 50. CT-Index vs. Flexibility Index Individual Correlations

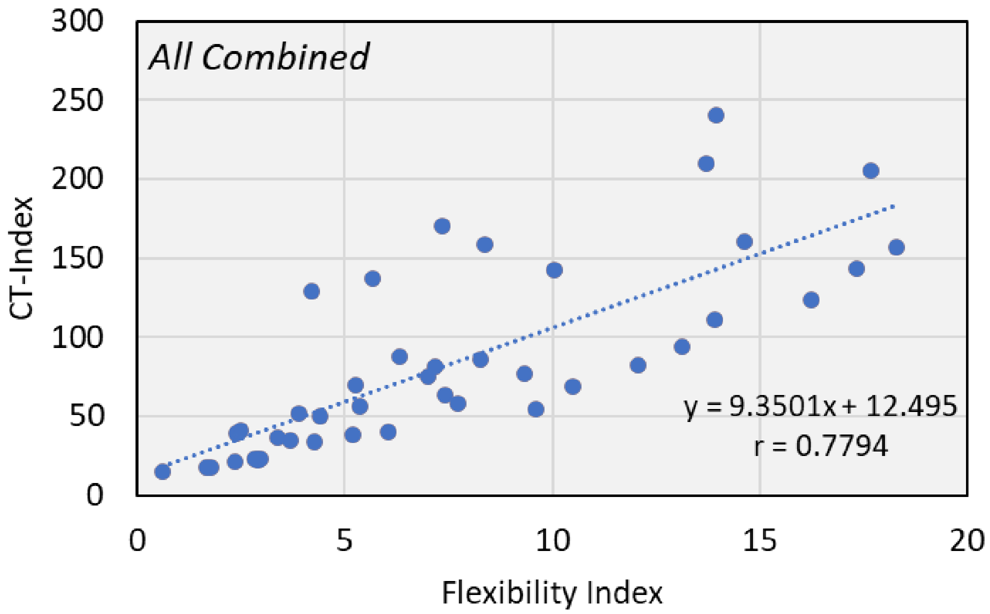


Figure 51: CT-Index vs. Flexibility Index Combined Correlation

10 REFERENCES

Al-Qadi, Imad L., D. L. Lippert, S. Wu, H. Ozer, G. Renshaw, I. M. Said, A. F. Espinoza Luque, et al. Utilizing Lab Tests to Predict Asphalt Concrete Overlay Performance. FHWA-ICT-17-020, Urbana, IL: Illinois Center for Transportation, 2017.

Bonaquist, R. NCHRP Report 673: A Manual for Design of Hot Mix Asphalt with Commentary. Washington, D.C., NCHRP, 2011.

Chen, C., Yin, F., Turner, P., West, R., & Tran, N. (2018). Selecting a Laboratory Loose Mix Aging Protocol for the NCAT Top-Down Cracking Experiment. *TRR Volume 2672(28)*, pp. 359-371.

Dave, E., Oshone, M., Schokker, A., & Bennett, C. (2019). Disc shaped compact tension (DCT) specifications development for asphalt pavement (Final Report MN/RC 2019-24; p. 135). Minnesota Department of Transportation. https://www.dot.state.mn.us/research/reports/2019/201924.pdf

Marasteanu, M., Buttlar, W., Bahia, H., Williams, C., & al., e. (2012). Investigation of Low Temperature Cracking in Asphalt Pavements National Pooled Fund Study - Phase II. Minneapolis, MN: University of Minnesota, Report No. MN/RC 2012-23.

NAPA (2022a). Balanced Mix Design Resource Guide (Website) – Balanced Mix Design Approaches, https://www.asphaltpavement.org/expertise/engineering/resources/bmd-resource-guide/balanced-mix-design-approaches

NAPA (2022b). Balanced Mix Design Resource Guide (Website) – PA-SOP03.2022, https://www.asphaltpavement.org/uploads/documents/ERT%20Related/BMD_Resource_Guide/PA-SOP_03.2022.pdf

Penn State University (2017*). Semi-circular Beam (SCB) Fatigue Test Procedure (September 11, 2017),* State College, PA: College of Engineering – Larson Transportation Institute

Tran, N., Yin, F., Leiva, F., Rodezno, C., Huber, G., & Pine, W. (2019). Adjustments to the Superpave Volumetric Mixture Design Procedure for Selecting Optimum Asphalt Content. NCHRP 20-07, Task 412. Washington, D.C.: National Cooperative Highway Research Program (NCHRP).

Virginia Department of Transportation (VDOT) Special Provision for Balanced Mix Design (BMD) Surface Mixtures Designed Using Performance Criteria. 2019.

West, R., Rodezno, C., Leiva, F., & Yin, F. (2018). Development of a Framework for Balanced Mix Design. Washington, D.C.: National Cooperative Highway Research Program (NCHRP).

West, R., Rodezno, C., Leiva, F., & Taylor, A. (2018). Regressing Air Voids for Balanced HMA Mix Design. Madison, WI: WHRP Report No. 0092-16-06.

Zhou, F., S. Im, L. Sun, and T. Scullion. Development of an IDEAL Cracking Test for Asphalt Mix Design and QC/QA. *Road Materials and Pavement Design*, Vol. 18, 2017, pp. 405-427.