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Evaluation of Stripping Potential Tests for Bituminous Concrete

[1]Bijay K-C, [2]Ali Khorasani, [3]Ehsan Ghazanfari

[1]Graduate Research Assistant, Department of Civil and Environmental Engineering, The University of Vermont, Burlington, Vermont, 05405 (E-mail: bkc@uvm.edu)

[2]Former Graduate Student, Department of Civil and Environmental Engineering, The University of Vermont, Burlington, Vermont, 05405 (E-mail: Ali.khorasani@uvm.edu)

[3]Associate Professor, Department of Civil and Environmental Engineering, The University of Vermont, Burlington, Vermont, 05405 (E-mail: Ehsan.ghazanfari@uvm.edu)

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16. Abstract

Pavement stripping due to loss in adhesion/binding between asphalt binder and aggregate in presence of moisture is a common and challenging pavement distress in wet climates such as Vermont. Although Vermont Agency of Transportation (VTrans) requires Hamburg Wheel Tracking Test (AASHTO T 324) during mix design approval, MRD-10 is required daily if the source aggregate is known to be prone to stripping. MRD-10 test is usually conducted on aggregates retained on US No. 4 Sieve, excluding fine aggregates present in the asphalt concrete making this test unreliable. Thus, in this study, the effectiveness of ASTM D3625 (i.e. boiling water test), a more common test in other state DOTs is evaluated.

The stripping potential of the field mixed Hot Mix Aggregate (HMA) mixture used in roadway projects in Vermont and laboratory produced HMA mixture with different aggregates (i.e. prone and non-prone to stripping) was evaluated using ASTM D3625. In addition, the effect of extra RAP on the moisture susceptibility of HMA mixture and sensitivity of ASTM D3625 to ASA present in the HMA was evaluated. Further, an attempt to quantify the ASTM D3625 test procedure was made in this study.

AASHTO T283 was used to evaluate the moisture susceptibility of HMA mixtures used in four different roadway projects in Vermont using the compacted asphalt concrete cores retrieved from the field. In particular, the effect of additional cycle of Lottman conditioning on the Tensile Strength Ratio (TSR) of the asphalt cores was investigated. The TSR values indicated that all the regular as well as joint cores from these projects passed the specification. However, the joint cores exhibited lower compaction and indirect tensile strength compared to the regular cores.

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ORGANIZATION OF THE REPORT

This report is structured as follows: Chapter 1 provides an introduction about the stripping potential tests. Chapter 2 includes the research methodology and testing procedures used at different phases of the project. The results of all the tests are presented and discussed in Chapter 3. The conclusions of this research project are provided in Chapter 4. Finally, Chapter 5 provides recommendations.

CHAPTER 1. INTRODUCTION AND BACKGROUND

One of the prevalent failure modes of Hot Mix Asphalt (HMA) is disintegration of aggregates over time due to loss of adhesion/binding between asphalt binder and aggregate, as can be seen in Figure 1. This phenomenon, referred to as “stripping”, and in broader terms is addressed as moisture-induced damage in HMA (e.g. Xiao and Amirkhanian, 2009; Christensen et al., 2015; Ali et al., 2019). The deteriorating effect of moisture on HMA is progressive disruption of the integrity of the mix due to action of water by removing or “stripping” the asphalt binder from the surface of aggregate (e.g. Sebaaly et al., 2001; Anastasio, 2015). This complex process can have both chemical (due to formation of water/asphalt emulsion) and mechanical (traffic effect) components (e.g. Thileepan, 2010; Anastasio, 2015). The aggregate type, binder chemistry, aggregate gradation, traffic level, amount of rainfall and number of freeze-thaw cycles are among factors that can affect moisture damage in HMA (e.g. Thileepan, 2010).

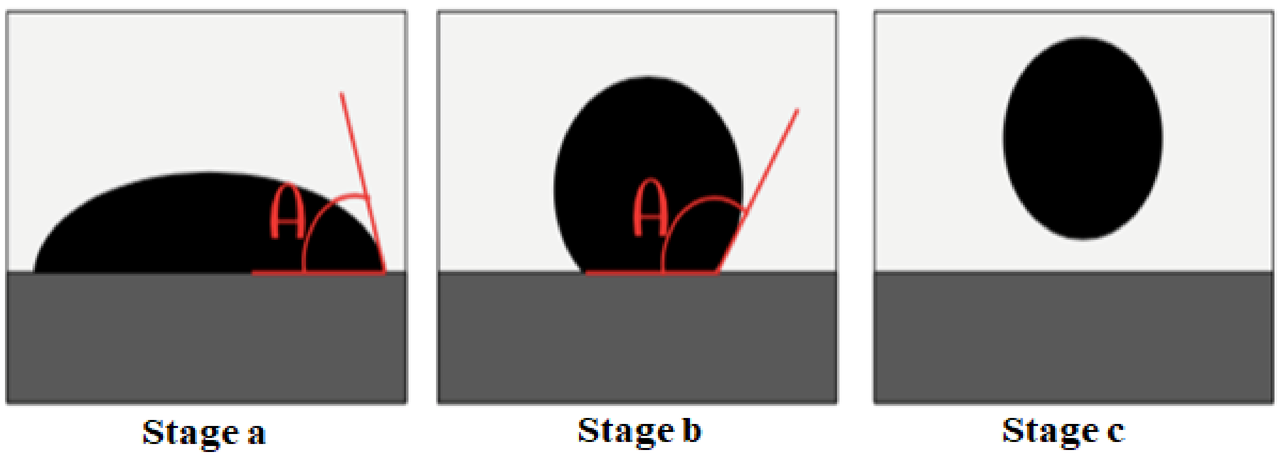
Source: Veeraragavan (2020) (a) Source: Pavement Interactive (2022a) (b) Source: Williams (2010) (c) Source: Colorado Pavement Solution 2019 (d)

Figure 1 - Photos of some typical moisture induced damages (a) longitudinal cracks, (b) stripping), (c) potholes, and (d) raveling

The strength and longevity of the bond between the aggregate and bitumen can be significantly influenced by presence of water and humidity, making it critical to address moisture susceptibility in the mix design. In addition, the moisture damage starting simply by presence of water can lead to acceleration of other pavement distress modes such as permanent deformation, fatigue and thermal cracking in the asphalt concrete (e.g. Sebaaly et al., 2001; Anastasio, 2015; Lu and Harvey, 2006).

The mechanisms of moisture-induced damages in the asphalt concrete mixes include loss of cohesion, loss of adhesion, pore pressure and hydraulic scouring caused by cyclic loading of the pavement (by traffic), and pH instability (e.g. Sebaaly et al., 2001; Anastasio, 2015; Lu and Harvey, 2006). Adhesive failure (see Figure 2(a)) occurs due to the damage at the interface between the mastic and the aggregate (i.e. debonding and complete separation at the interface), whereas cohesive failure occurs due to the damage within the mastic leaving both fracture surfaces coated with bitumen (e.g. Anastasio, 2015; Lu and Harvey, 2006). Loss of adhesion between aggregates and binder significantly contributes to stripping (e.g. Anastasio, 2015). Figure 2(b) illustrates different stages of stripping process, where an aggregate plate with a drop of bitumen is immersed in water. The contact angle between the bitumen drop and the aggregate is less than 90° at the beginning (i.e stage a), then the drop starts separating from the aggregate as the bonding is affected by water leading to increased contact angle (stage b), followed by complete loss of adhesion in stage c (e.g. Hicks, 1991; Anastasio, 2015).

(a)



(b)

Figure 2 - Schematics of (a) adhesive and cohesive failure in asphalt (adapted from Anastasio, 2015), and (b) different stages of stripping process (adapted from Hicks, 1991; Anastasio, 2015).

For HMA, the important underlying mechanisms contribution to stripping can be explained by different adhesion theories, as summarized in table 1. Utilizing Anti-Strip Additive (ASA) is one of the typical approaches to address the stripping phenomenon. The use of ASA, however, doesn't guarantee the moisture resistance of the pavement. Many ASAs are not compatible with all types of aggregate and care must be taken in selection of aggregate, binder, proper type of ASA as well the right amount of ASA (percentage) to be used. Therefore, it is necessary to determine the best mix design tailored to specific project's location and environmental conditions (e.g. Putman and Amirkhanian, 2006).

Table 1 - Relationships between stripping mechanisms and adhesion theories in HMA (adapted and modified from Kiggundu and Roberts, 1988).

		Theory								
		Mechanical interlock			Chemical reaction			Interfacial energy		
	Mode	P	C	P-C	P	C	P-C	P	C	P-C
Stripping Mechanism	Detachment	S						S	W	
	Displacement					S		S		
	Spontaneous emulsification				S	W				
	Film rupture	S								
	Pore pressure	S								
	Hydraulic scouring	S								
	pH instability					S				
Note: P: Physical; C: Chemical; P-C: Physical-Chemical; S: Primary contributor; W: Secondary contributor										

To evaluate and predict the moisture damage susceptibility of asphalt concrete mixes, several testing methods/procedures have been developed over the years, including: the modified Lottman procedure, the environmental conditioning system, the immersion-compression test (AASHTO T 165), the Hamburg Wheel Tracking (HWT) test (AASHTO T 324), boiling water test quick bottle test, the rolling bottle method, and the static immersion test (ASTM D1664). The boiling water (ASTM D3625) and modified Lottman procedure (AASHTO T 283) are prevalently used in the United States (e.g. Thileepan, 2010). The accuracy and suitability of several moisture resistance tests have been studied by several researchers (e.g. Vuorinen and Hartikainen, 2001; Dave and Koktan, 2011; Amirkhanian et al., 2018), with mixed results arguing for and against these tests. Moreover, the repeatability and correlation of the laboratory results with field performance of most of these tests is not satisfactory (e.g. Dave and Koktan, 2011; Amirkhanian et al., 2018). As a result, it is recommended to (i) conduct some of these tests side by side, and (ii) in some cases implement new methods such as ultrasonic (Vuorinen and Hartikainen, 2001) and nuclear magnetic resonance (NMR) spectroscopy along with the conventional test methods.

The service life of HMA pavements in Vermont is shorter compared to the national trend, in part due to rutting and raveling failures. Material (e.g. using aggregate with minerology prone to stripping) or construction practice can be the source of these failures. ASA could be utilized to improve the aggregate coating and the bonding between asphalt and aggregate, leading to reduced moisture damage destruction and reduced risks of rutting and raveling failures. Current VTrans practice is to require HWT testing during mix design approval. In addition, when the source aggregate is known to be prone to stripping, striping testing has be infrequently submitted with designs and MRD-10 is required daily to ensure the ASA is working effectively.

This process deviates from common practice among other State DOTs, which use ASTM D3625. The MRD-1 and MRD-10 tests may not be representative of the pavements susceptibility to stripping, as it is only conducted on aggregate retained above the No. 4 sieve, excluding fine aggregates from testing. This discrepancy makes it difficult to evaluate the effectiveness of the anti-strip tests for additives and its effect on HMA performance. It is essential to determine the difference between MRD-10 and the ASTM D3625, evaluate existing HMA stripping potential, including fine aggregate stripping potential, and determine the required updates to the current testing procedure. In this project, we attempted to assess the effectiveness of the anti-strip tests for additives supplied by HMA producers and evaluate the ASTM D3625 for use in Vermont.

As the first step, a literature review was performed to identify available methods/equipment that improve the ASTM D3625 from being simply a qualitative test to a quantitative test and the findings are summarized in the following section.

1.1 TESTS TO EVALUATE MOISTURE SUSCEPTIBILITY OF HMA MIXTURES

Several studies have attempted to develop indicator tests for stripping. These efforts have produced tests which use semi-subjective and subjective assessments to infer the stripping potential. The tests may be broadly classified into two categories:

(i) Qualitative, and

(ii) Quantitative or engineering-based tests to evaluate stripping.

1.1.1 Qualitative tests to evaluate stripping

Some of the qualitative tests that are performed to evaluate the moisture susceptibility are (Putman and Amirkhanian, 2006):

- ASTM D3625: “Standard Practice for Effect of Water on Bituminous Coated Aggregates using Boiled Water”
- Static Immersion Test
- Texas Freeze-Thaw Pedestal Test

- Gagle Procedure
- The Quick Bottle Test
- The Rolling Bottle Method, and many others.

These qualitative tests procedures involve some sort of visual rating to evaluate the moisture susceptibility of HMA mixtures. Moreover, these qualitative tests are performed on loose mixes (except Texas Freeze-Thaw Pedestal Test) rather than the compacted HMA mixtures. This poses two major limitations of the qualitative tests: (i) the visual ratings are subjective, which often times increases variability in the test results, and (ii) Although these tests could potentially identify the moisture susceptibility of component materials (i.e. lost in adhesion between individual aggregates and asphalt binders), the tests cannot identify the moisture susceptibility of compacted HMA mixtures (e.g. Dave et al. 2018). Due to these limitations, the test results of qualitative tests are qualitative tests are often unreliable. Thus, most of the transportation agencies have abandoned these tests and adopted quantitative engineering-based test methods that evaluates the moisture susceptibility of compacted HMA mixtures

1.1.2 Quantitative tests to evaluate stripping

The objectives of this group of tests are quantitative predictions, developing criteria for assessing failure, and applying/interpreting laboratory test results to predict field performance. These tests usually comprise of moisture conditioning of the compacted HMA mixtures to evaluate the moisture-induced adhesive failures between aggregates and asphalt binders and cohesive failure within the asphalt mastic. These tests include:

- Lottman Test (NCHRP 246; Lottman 1982)
- Modified Lottman Test (AASHTO T283)
- Hamburg wheel tracking (AASHTO T324)
- Tunnicliff and Root Test (NCHRP 274; MHTD 1990)
- Immersion Compression Test (AASHTO T-165)
- Resilient Modulus
- The Double Punch Method
- Dynamic Strip Method (Nevada)
- Cold Water Abrasion Test (Minnesota)

National Center for Asphalt Technology published a report in 1998, presenting review summaries of the state-of-the-art regarding stripping in hot mix asphalt (HMA) mixtures. The review stresses efforts concerned with methods development, evaluation and presents a critical review of select methods including Lottman (NCHRP 246), Tunnicliff-Root (NCHRP 274), Immersion Compression, 10-minute boil test, and the Nevada dynamic strip method. The results of the critical review of methods indicated the following ranking order: Lottman test, Tunnicliff-Root test, 10-Minute Boil test, Immersion Compression, and Nevada Dynamic Strip test. The basis of the analysis was a proposed success/failure pattern which was developed using published data on stripping.

Hydrated lime and the liquid ASAs are the two most commonly used ASAs in HMA mixture to negate the stripping potential of HMAs. In recent years methods have been developed to determine the *quantity of ASAs* present in HMA mixtures. Separate methods have been developed for *lime* and *liquid ASAs*.

1.2 DETERMINATION OF LIME CONTENT AND QUALITY IN HMA MIXTURES

The amount as well as the quality of the hydrated lime used in the HMA as an ASA can be determined by (i) Fourier Transform Infrared (FTIR) spectroscopy, and (ii) chemical analysis (e.g. Arnold et al., 2006; Putman and Amirkhanian, 2006).

The presence of lime in the HMA is identified as a peak at a wave number of 3640 cm-1 in the FTIR spectrum. The area under this peak or the height of the peak could be used to quantify the amount of lime in the HMA. The presence of second and third peak in the FTIR spectrum at 1390 cm-1 and 866 cm-1 indicates the presence of calcium carbonate, which is an indication of poor quality lime (e.g. Arnold et al. 2006; Putman and Amirkhanian, 2006).

In order to determine the lime content in the HMA mixture using chemical analysis, a sample of dust is retrieved by drilling a hole in the compacted HMA mixture. Then, the dust sample is first boiled a 4% acetic acid solution for 30 minutes. Finally, the resulting extract solution is analyzed using Atomic Absorption Spectroscopy (AAS) or Ion Exchange Chromatography (IEC) to determine the amount of lime present in the sample. This method is more accurate than FTIR (e.g. Arnold et al., 2006).

1.3 DETERMINATION OF LIQUID ASA IN HMA MIXTURES

Unlike the hydrated lime that is directly applied to the aggregate of HMA mixture, the liquid ASA are added to the asphalt binder before mixing it with the aggregate. Liquid ASA is chemical amine additive that is added to asphalt binder in a prescribed amount to negate the moisture damage to the AC. Determining the quantity of liquid ASA in a liquid asphalt binder or AC is extremely difficult process (e.g. Maupin, 2004). Often times quick bottle test is performed to check the presence of liquid ASA in the asphalt binder, however, this method cannot determine the amount of ASA present in the binder (e.g. Maupin, 1980a). Gas chromatography can be used to detect ASA, but this process is complicated (Maupin, 1980b). InstroTek Inc. developed a device, StripScan instrument (Figure 3), to measure the amount of liquid ASA persent in either asphalt binder or AC.

In order to determine the amount of liquid ASA using the StripScan device, the sample (binder or AC) is heated. This heating process vaporize the liquid ASA. The vapor passes to a measurement chamber where it reacts with a litmus strip changing its color. Finally, the spectrometer present in the device analuzes the color change of the litmus paper by comparing it against the calibration curve for a specific binder, aggregate, and/or ASA combination (Maupin, 2004).

Figure 3 - Photo of StripScan instrument (Maupin, 2004)

1.4 MOISTURE SUSCEPTIBILITY TESTS

The following subsection discusses some of the commonly used moisture susceptibility tests

1.4.1 Boiling Water Test (ASTM D3625)

Boiling water test is one of the very common and quick test to evaluate the stripping potential of the loose HMA mixture. Loose HMA mixture is boiled in distilled water for 10 minutes, and the loss in the adhesion between asphalt binder and aggregates is visually inspected in the post-boiled mixture. This procedure commonly uses a visual chart such as that developed for Texas Boil Test by Kennedy et al. (1984) to evaluate the stripping potential of the loose HMA mix based on the amount of asphalt binder retained on the post-boiled mixture. Figure 4. shows the rating board for Texas Boiling Test.

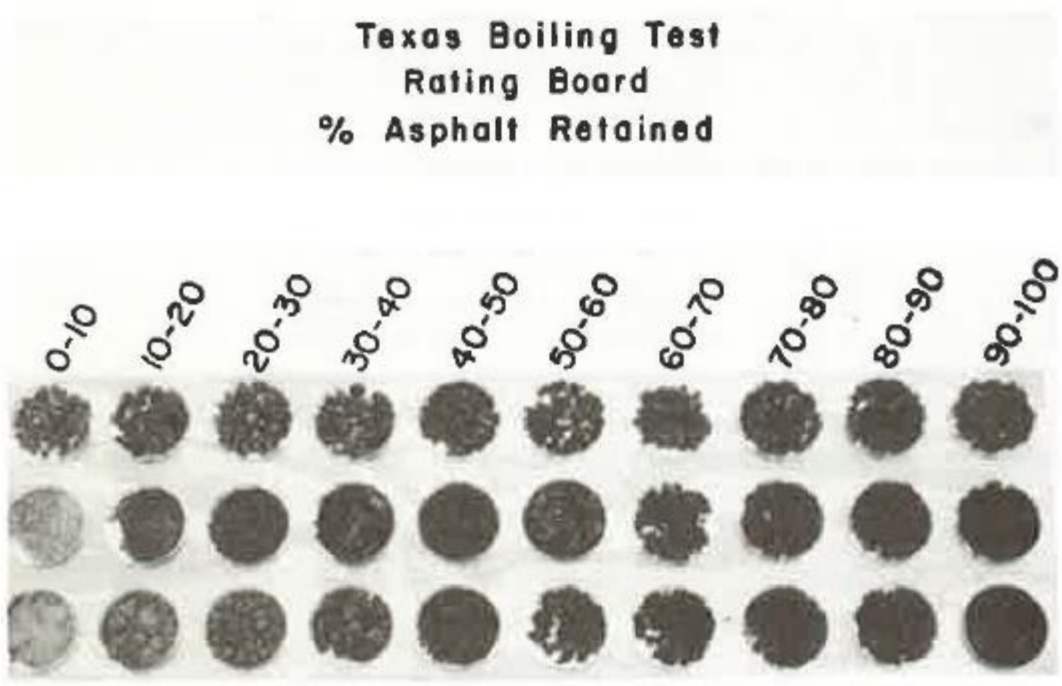


Figure 4 - Texas Boiling Test rating board (Kennedy et al., 1984)

Due to the qualitative nature of the ASTM D3625 test, the results are subjective and unreliable. Instruments that measure the change in color of the asphalt mixture before and after the ASTM D3625 test is used to quantify the result of ASTM D3625. Some of the devices that measures the change in color of the asphalt mixture during the boiling water test are discussed in the following sub-sections.

1.4.1.1 Asphalt Compatibility Tester (ACT)

Asphalt Compatibility Tester (ACT) manufactured by InstroTek Inc. uses LED light and detection system to measure the color change that may occur during boiling water test (ASTM D3625). This device uses light reflection from the surface of the asphalt mixture before and after the boiling water test to measure the color change during the test. The device reports the binder loss index value (L*), which is independent of operator judgement to quantify the result of ASTM D3625 (InstroTek, 2022). Figure 5. shows a picture of ACT.

Figure 5 - InstroTek ACT instrument to measure color change during ASTM D3625 test (source: InstroTek, 2022)

1.4.1.2 Colorimeter Device

Similar to ACT, the colorimeter device can be used to measure the change in color of loose asphalt mixture before and after the boiling water test (ASTM D3625). Tayebali et al. (2019) used a colorimeter device, CR 400, manufactured by Konica Minolta to measure the change in color of the loose asphalt concrete during the boiling water test (Figure 6). The device emits a standard light source onto the target and the reflection from the material is used to measure the change in color of the target (i.e. asphalt concrete) before and after the boiling water test.

Figure 6 - CR 400 colorimeter device (source: Konica Minolta, 2022)

1.4.1.3 Digital Image Processing

Xiao et al. (2022) developed a digital image processing method based on the color images to evaluate the stripping potential of loose HMA mixture. This method automatically measures the asphalt coating ratio in an objective manner to improve the accuracy of boiling water test (ASTM D3625).

1.4.1.4 Weight Method

Liu and Wang (2007) quantified the result of the boil test by measuring the weight of the asphalt mixture to determine the bitumen adhesion to aggregate material. This method can provide a quantitative result for ASTM D3625 to quickly evaluate the moisture susceptibility of the asphalt mixture.

1.4.2 Modified Lottman Test (AASHTO T283)

Modified Lottman Test (AASHTO T283) is the most widely used method by the State Department of Transportation (DOT) to evaluate the moisture susceptibility of asphalt mixtures. 36 out of 50 State DOTs in the U.S. used modified Lottman test procedure with some deviations in the procedure (e.g. Dave and Koktan 2011). Modified Lottman Test measures the indirect tensile strength of conditioned (i.e. subjected to freeze and thaw cycle) and dry asphalt cores and reports the Tensile Strength Ratio (TSR) as the measure of moisture susceptibility. TSR value of 0.8 serves as threshold for moisture susceptibility.

1.4.3 Hamburg Wheel Tracking Test (AASHTO T324)

Hamburg Wheel Tracking Test (HWT) (AASHTO T324) can be used to evaluate the moisture susceptibility of the asphalt concrete. The test imposes a repeated load of 158 lb. on the submerged compacted asphalt concrete by the help of steel wheel of diameter 1.5" and width of 1.9" to simulate the traffic on the road. The rut depths and the number of passes are recorded during the test. AASHTO T324 requires 20,000 passes. Using the data measured during the test, asphalt concrete properties such as creep slope, stripping inflection point, stripping slope, number of passes to failure etc. can be inferred (e.g. Dave et al., 2018). Figure 7 shows the HWT device.

Figure 7 - Hamburg Wheel Tracking test device (source: Pavement Interactive, 2022b)

1.4.4 Moisture Induced Stress Tester (MiST): AASHTO TP 140/ASTM D7870

The Moisture Induced Stress Tester (MiST) is developed by InstroTek to simulate the stress caused by the traffic load over moisture saturated asphalt concrete. MiST device consists of a chamber filled with water and hydraulic system capable of applying pressure and vacuum cycles to the compacted asphalt concrete. The hydraulic system pushes and pulls water into the pores of the compacted asphalt cement to simulate the effect of pore water pressure on debonding of asphalt concrete mixture as a result of traffic load on the road. Figure 8. shows the picture of MiST device.

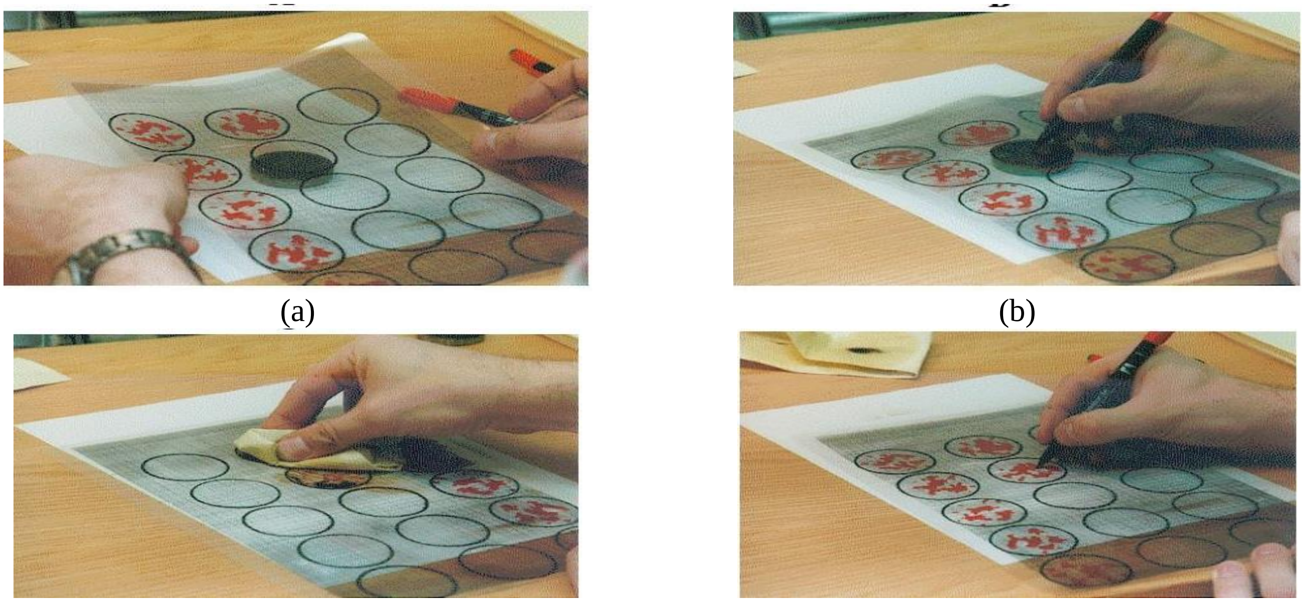
Figure 8 - MiST device (source: InstroTek, 2022b)

1.4.5 Ultrasonic Method

Ultrasonic waves can be used to measure the stripping potential of the asphalt concrete (e.g. McCann and Sebaaly, 2001; Vuorinen and Hartikainen, 2001). When the ultrasonic waves are passed through the water, a repeated cycle of compression and cavitation is formed, which accelerates the detachment of asphalt binder from aggregate's surface (e.g. McCann and Sebaaly, 2001). Vuorinen and Hartikainen (2001) conducted an experiment on compacted asphalt cores using SONOREX ultrasonic cleaner SONOREX ultrasonic cleaner (Figure 9(a)). The asphalt cores were held submerged by the clamps such that the bitumen covered surface faced directly to the ultrasonic source (Figure 9(b)). The percent fraction of the stripped bitumen was reported as the result of the test, as shown in Figure 10(a)-(d).

(a) (b)

Figure 9 - Photo of (a) SORONEX ultrasonic cleaner, and (b) clamps holding the asphalt core during the test (source: Vuorinen and Hartikainen, 2001



(a) (b)

(c) (d)

Figure 10 - Visual evaluation of moisture susceptibility using ultrasonic cleaner (a) transparency adjustment, (b) marking the stripped area, (c) cleaning the transparency, and (d) final stripped area (source: Vuorinen and Hartikainen, 2001

In this study, we investigated the effectiveness of ASTM D3625 to identify the moisture susceptibility of plant produced and lab produced HMA mixtures. We also explored quick and simple measures to quantify the outcome of ASTM D3625. In addition, we performed Modified Lottman Test (AASHTO T283) on the asphalt cores retrieved from four different projects in Vermont to evaluate the moisture susceptibility of these asphalt mixtures. More specifically, we investigated the effect of one extra cycle of Lottman conditioning on the regular and joint cores from these projects.

CHAPTER 2. MATERIALS AND METHODS

2.1 MATERIALS

The materials required to perform all the proposed anti-stripping tests were provided by VTrans. These materials include (i) plant produced asphalt concrete (AC), (ii) raw aggregates and Reclaimed Asphalt Pavement (RAP), (iii) asphalt binders and ASA, and (iv) asphalt cores from four different roadway projects in Vermont.

2.1.1 Plant Produced Asphalt Concrete

Plant produced AC samples from Londonderry-Chester STP PS19(10) project and the Burlington STP project were received in boxes (see Figure 11). The composition of the plant produced HMA mixture, which was adopted to prepare laboratory HMA is shown in Table 2.

Figure 11 - Plant Produced HMA mixture from Londonderry-Chester Project

Table 2 - Composition of the plant produced HMA mixture

S.N.	AC Components	Percentage by weight (%)
1	Washed Stone Screening	37.5
2	Natural Sand	12.2
3	3/8 “Minus Course Aggregate (Prone/ Non- Prone)	25.4
4	RAP	20
5	Asphalt Binder	4.9

2.1.2 Raw Aggregates, RAP, Asphalt Binders, and ASA

Figure 12(a) and (b) show the raw aggregates, which includes RAP, stripping prone and non-prone aggregates, natural sand, asphalt binder, and ASA provided by VTrans to produce the HMA in the laboratory to evaluate the use of different aggregates (i.e. stripping prone and non-prone) and ASA agent in HMA mixture. The gradation of the stripping prone and non-prone aggregates were within the 'Job Aim' range for each sieve (percent passing) as summarized in Tables 3 and 4.

(a) (b)

Figure 12 - Photo of (a) raw aggregates and RAP, and (b) asphalt binder and ASA

Table 3 - Particle size distribution of non-prone aggregates

Sieve Size (mm)	Low (%)	High (%)	Percent Finer (%)
9.5	91	100	100
4.75	64	76	67
2.36	40	48	44
1.18	25	33	28
0.6	15	23	19
0.3	8	16	12
0.15	3	11	3
0.075	3.2	5.2	1

Table 4 - Particle size distribution of non-prone aggregates

Sieve Size(mm)	Low (%)	High (%)	Percent Finer (%)
9.5	91	100	100
4.75	64	76	66
2.36	40	48	40
1.18	25	33	25
0.6	15	23	16
0.3	8	16	10
0.15	3	11	3
0.075	3.2	5.2	1

2.1.3 Asphalt Cores

The asphalt cores were received in three batches from four different roadway projects in Vermont. All the cores were received in a box in a group of six (except for Joint cores) (Figure 13). In total, 95 asphalt cores from four different projects were tested. The project details and the information of the cores are presented in Table 5. The details of the cores such as coring location, dimension of the cores, maximum specific gravity of the asphalt concrete used in these projects are listed in Tables 6-9. The box consists of the cores from the section of the road that was paved using the same HMA mixture on the same day. The cores from the same box (i.e same HMA mixture) are shaded in Tables 6-9.

Figure 13 - Photo of the received asphalt cores in a box

Table 5 - Details of the asphalt cores.

Bat. #	Project Name	Project Number	Lift	Design Depth, in	# cores			Mix Type	Paving Contractor	Plant
					Reg.	Joint	Total			
1	Groton-Newbury	STP PS19(2)	Binder	3	18	6	24	II	J. Hutchins, Inc	J. Hutchins, Inc. - Irasburg, VT
2	Richford-Jay	STP 2914(1)	Binder	2.5	48	8	56	II	Pike	Pike - Swanton, VT
3	Johnson-Morristown	STP 2919(1)	Top	1.5	-	5	5	IV	Kubricky	J. Hutchins, Inc. - Irasburg, VT
	Cavendish-Weathersfield	ER STP 0146(14)	Top	1.5	-	10	10	IV	Pike	Pike - W. Lebanon, NH

Table 6 - Coring location and dimension of cores from Groton-Newbury STP PS19(2) project

Core #	Coring Location		Thickness (in)				Dia (in)	Max. Sp. Gr.
	Station	Offset	#1	#2	#3	#4		
7	N234+28RT	6.72	2.996	2.988	3.027	3.002	6	2.497
8	N221+55RT	2.34	2.726	2.759	2.746	2.744	6	2.497
9	N218+34RT	9.31	2.95	2.945	2.945	2.943	6	2.497
10	N196+09RT	2.60	2.549	2.527	2.623	2.622	6	2.497
11	N190+91RT	2.55	2.242	2.373	2.277	2.201	6	2.497
12	N176+10RT	6.79	3.184	3.212	3.205	3.159	6	2.497
19	N164+53RT	-	2.739	2.694	2.718	2.727	6	2.494
20	N158+37RT	-	2.699	2.825	2.778	2.684	6	2.494
21	N149+60RT	-	2.503	2.484	2.555	2.589	6	2.494
22	N136+31RT	-	2.650	2.668	2.692	2.727	6	2.494
23	N126+58RT	-	2.777	2.748	2.772	2.782	6	2.494
24	N111+08RT	-	2.929	2.94	2.936	2.926	6	2.494
25	N87+61LT	5.18	2.488	2.582	2.557	2.487	6	2.502

Table 6. Contd.

Core #	Coring Location		Thickness (in)				Dia (in)	Max. Sp. Gr.
	Station	Offset	#1	#2	#3	#4		
26	N75+89LT	3.36	2.442	2.452	2.395	2.428	6	2.502
27	N62+76LT	9.14	2.434	2.453	2.421	2.43	6	2.502
28	N49+02LT	1.00	2.543	2.445	2.485	2.548	6	2.502
29	N38+19LT	8.10	2.379	2.283	2.312	2.379	6	2.502
30	N22+20LT	8.67	2.688	2.578	2.535	2.674	6	2.502
J3	N62+62	LT-RT	2.602	2.626	2.667	2.654	6	2.498*
J4	N116+93	LT-RT	2.887	2.971	2.867	2.854	6	2.494*
J5	N138+74	LT-RT	2.904	2.796	2.827	2.952	6	2.494*
J6	N176+48	RT-LT	2.976	2.978	2.89	2.987	6	2.495*
J7	N209+91	RT-LT	3.127	3.082	3.116	3.100	6	2.495*
J8	N220+25	RT-LT	3.195	3.100	3.133	3.243	6	2.495*

Cored by: Kyle Young and Witnessed by: Kevin King
Shaded rows are the core samples collected from the road section paved on same day
Cores labelled as 'J' are joint cores
*Average of first and second pass.

Table 7 - Coring location and dimension of cores from Richford-Jay STP 2914(1) project

Core #	Coring Location		Thickness (in)				Dia (in)	Max. Sp. Gr.
	Station	Offset	#1	#2	#3	#4		
1	270+64	9.70 LT	2.633	2.702	2.772	2.626	6	2.536
2	268+60	9.68 LT	3.032	2.937	2.993	3.034	6	2.536
3	259+49	5.99 LT	2.683	2.775	2.667	2.633	6	2.536
4	254+72	6.61 LT	2.548	2.501	2.499	2.544	6	2.536
5	248+42	5.83 LT	2.511	2.431	2.546	2.507	6	2.536
6	246+87	9.70 LT	2.35	2.261	2.19	2.336	6	2.536
7	-	-	2.524	2.575	2.591	2.525	6	2.527
8	-	-	2.137	2.17	2.088	2.097	6	2.527
9	-	-	2.426	2.403	2.446	2.475	6	2.527
10	-	-	2.531	2.561	2.464	2.479	6	2.527
11	-	-	2.599	2.51	2.616	2.656	6	2.527
12	-	-	2.277	2.205	2.189	2.258	6	2.527

Table 7. Contd.

Core #	Coring Location		Thickness (in)				Dia (in)	Max. Sp. Gr.
	Station	Offset	#1	#2	#3	#4		
13	230+23	2.1	2.135	2.129	2.164	2.137	6	2.523
14	222+61	7.33	2.292	2.293	2.407	2.389	6	2.523
15	213+19	7.01	2.582	2.497	2.391	2.523	6	2.523
16	197+51	3.07	2.468	2.334	2.477	2.553	6	2.523
17	182+68	4.2	2.273	2.359	2.341	2.275	6	2.523
18	172+65	6.32	2.151	2.255	2.275	2.2	6	2.523
19	163+80	1.21 LT	2.312	2.238	2.305	2.332	6	2.527
20	152+86	6.67 LT	2.774	2.673	2.637	2.756	6	2.527
21	152+65	7.39 LT	2.642	2.666	2.601	2.63	6	2.527
22	144+14	6.03 LT	2.366	2.392	2.267	2.268	6	2.527
23	143+26	2.31 LT	2.688	2.618	2.627	2.698	6	2.527
24	133+95	10.46 LT	2.67	2.722	2.81	2.721	6	2.527
25	-	-	2.77	2.798	2.734	2.739	6	2.528
26	-	-	2.564	2.578	2.629	2.581	6	2.528
27	-	-	1.932	1.877	1.914	1.966	6	2.528
28	-	-	2.543	2.553	2.613	2.572	6	2.528
29	-	-	2.374	2.448	2.385	2.346	6	2.528
30	-	-	2.226	2.312	2.243	2.193	6	2.528
31	211+27	3.98 RT	2.46	2.419	2.561	2.495	6	2.531
32	215+18	2.10 RT	2.245	2.335	2.249	2.198	6	2.531
33	293+28	9.48 RT	2.396	2.476	2.393	2.346	6	2.531
34	303+54	3.48 RT	2.352	2.392	2.443	2.357	6	2.531
35	316+74	3.79 RT	2.412	2.466	2.338	2.358	6	2.531
36	326+07	9.78 RT	1.985	2.041	2.031	1.98	6	2.531
37	337+67	2.76 RT	2.237	2.144	2.229	2.226	6	2.529
38	350+14	8.82 RT	2.261	2.371	2.337	2.294	6	2.529
39	359+66	5.53 RT	2.244	2.197	2.248	2.23	6	2.529
40	370+64	3.57 RT	2.082	2.111	2.15	2.1	6	2.529
41	380+16	2.27 RT	2.287	2.362	2.451	2.345	6	2.529

Table 7. Contd.

Core #	Coring Location		Thickness (in)				Dia (in)	Max. Sp. Gr.
	Station	Offset	#1	#2	#3	#4		
42	401+36	1.81 RT	2.438	2.455	2.566	2.467	6	2.529
43	289+15	1.80 LT	2.104	2.2	2.108	2.087	6	2.53
44	299+76	8.56 LT	2.603	2.638	2.563	2.565	6	2.53
45	321+43	10.06 LT	2.368	2.426	2.512	2.413	6	2.53
46	333+80	3.63 LT	2.532	2.547	2.531	2.529	6	2.53
47	347+17	4.15 LT	2.356	2.441	2.386	2.305	6	2.53
48	348+91	7.14 LT	2.414	2.338	2.321	2.41	6	2.53
J1	R148+83	RT	2.515	2.532	2.462	2.466	6	2.528*
J2	R170+00	RT	2.283	2.257	2.366	2.335	6	2.526*
J3	R202+62	RT	2.492	2.386	2.572	2.488	6	2.526*
J4	R216+84	RT	2.089	2.094	2.225	2.083	6	2.527*
J6	R297+06	LT	1.67	1.6	1.704	1.689	6	2.531*
J7	R315+06	LT	1.888	1.821	1.915	1.975	6	2.531*
J8	R336+13	LT	2.398	2.28	2.265	2.39	6	2.530*
J9	R357+09	LT	1.998	2.159	2.074	2.01	6	2.530*

Cored by: Mike Dunican and Witnessed by: Matthew Birchard and Mitchell Mason
Shaded rows are the core samples collected from the road section paved on same day
Cores labelled as ‘J’ are joint cores
*Average of first and second pass.

Table 8**.** Coring location and dimension of cores from Johnson-Morristown STP 2919(1) Project

Core #	Coring Location		Thickness (in)				Dia (in)	Max. Sp. Gr.
	Station	Offset	#1	#2	#3	#4		
J17	M 108+12	CL	1.777	1.869	1.882	1.785	6	2.478*
J18	M 131+62	CL	1.488	1.52	1.524	1.529	6	2.478*
J19	M 159+82	CL	1.144	1.182	1.172	1.141	6	2.475*
J20	M 182+00	CL	1.315	1.33	1.258	1.31	6	2.475*
J21	M 201+73	CL	1.329	1.263	1.274	1.352	6	2.475*

Cored by: S.W. Cole and Witnessed by: Ryan Greene
Cores labelled as ‘J’ are joint cores
*Average of first and second pass.

Table 9. Coring location and dimension of cores from Cavendish-Weathersfield ER STP 0146(14) Project

Core #	Coring Location		Thickness (in)				Dia (in)	Max. Sp. Gr.
	Station	Offset	#1	#2	#3	#4		
J4	83+21	RT	1.23	1.262	1.239	1.23	6	2.559*
J5	130+63	RT	1.667	1.648	1.578	1.657	6	2.559*
J6	134+96	RT	1.418	1.434	1.472	1.441	6	2.559*
J7	166+69	RT	1.476	1.548	1.501	1.475	6	2.559*
J8	206+08	RT	1.84	1.823	1.871	1.888	6	2.602*
J9	223+03	RT	1.628	1.629	1.648	1.669	6	2.602*
J10	244+15	RT	1.397	1.465	1.475	1.42	6	2.598*
J11	274+77	RT	1.464	1.417	1.352	1.446	6	2.598*
J12	315+72	RT	1.867	1.945	1.924	1.877	6	2.600*
J13	320+89	RT	1.464	1.363	1.304	1.35	6	2.600*

Cored by: Mike Dunican and Witnessed by: Leon Oprendek
Shaded rows are the core samples collected from the road section paved on same day
Cores labelled as 'J' are joint cores
*Average of first and second pass.

2.2 MATERIAL STORAGE IN THE LABORATORY

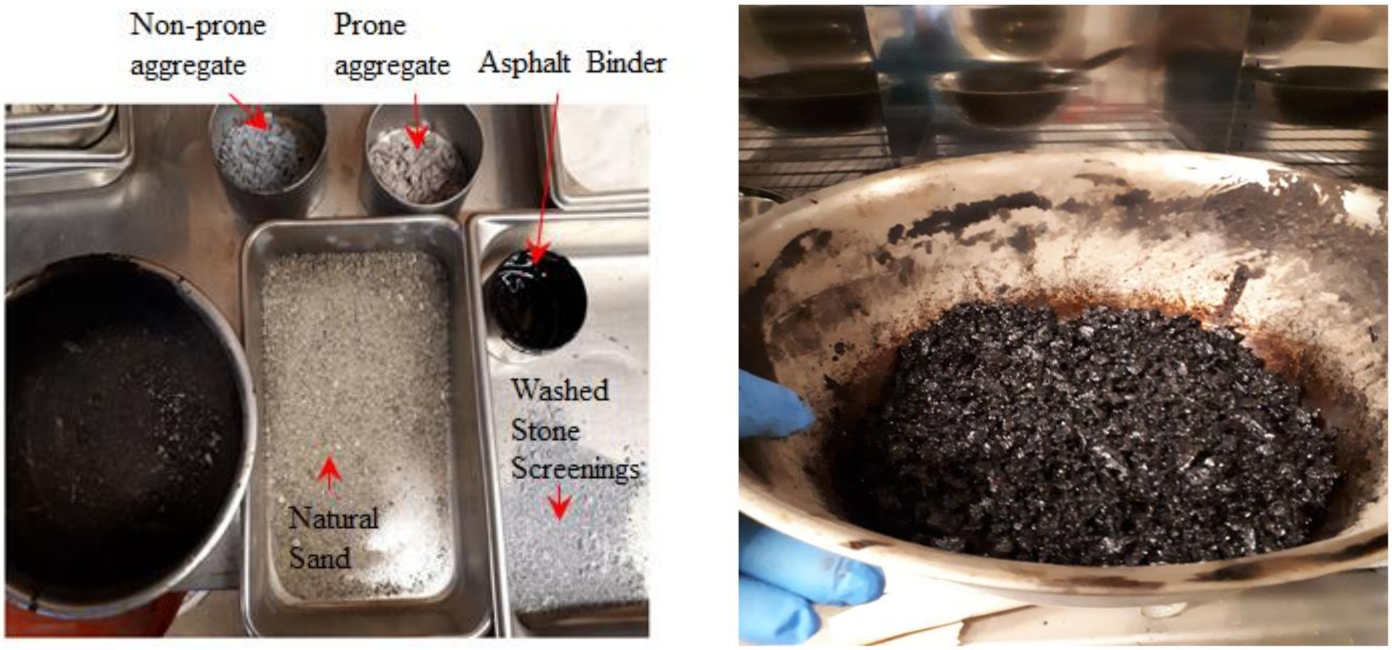
The plant produced AC mixture and asphalt cores were received in boxes, whereas the raw aggregates were received in a buckets (5 gallon buckets). All these materials were stored in a dry area in the laboratory to prevent any moisture intrusion into these materials. In addition, the asphalt cores were stored on a flat surface without any prior loading (i.e from the stacking of the boxes) to prevent any pre-loading and warping of the cores prior to testing (Figure 14). All the materials were stored at the laboratory temperature of ~ 20 ºC.

Figure 14- Storage of the boxes with asphalt cores on a flat surface

2.3 HMA PREPERATION IN THE LABORATORY

To assess the suitability, accuracy, and efficiency of different moisture susceptibility test procedures, it is important to prepare and perform tests on AC samples with different resistance to stripping i.e., with different combinations of aggregate, binder and anti-stripping agent. The procedure to prepare the HMA mixture in the laboratory is as follows:

- Weigh each component (in accordance with the “Job Mix Formula” provided by Dr. Anderson from VTrans) of the asphalt mixture for a 1-kg batch as follows (Figure 15(a)):
  - 375g WSS (washed stone screenings)
  - 122g NASA (Natural sand)
  - 254g Coarse Aggregate (Stripping prone or non-prone)
  - 200g RAP
  - 49g Binder (asphalt cement)
  - 0.29g Anti-Stripping agent (0.5 percent by weight of binder)



(a) (b)

Figure 15 - Photo of (a) Components of the AC, and (b) Final HMA mix. Note that the different components are not as per the proportions mentioned above and RAP and ASA is not shown in the photo.

- Heat the asphalt binder (49 g) and aggregates (951 g) in a separate container by placing them inside a portable oven secured inside a fume hood at UVM laboratory facilities for 85 minutes at 163 ºC (Figure 16).

Figure 16 - Photo of the portable oven used to heat the HMA mixture components.

- After 85 minutes of heating asphalt binders and the aggregates, add 0.29 g anti-stripping agent (0.5 % by weight of binder) to the heated binder.
- Mix the binder containing anti-stripping agent with the heated aggregate in a steel mixing bowl inside the fume hood (Figure 15(b)).
- Let the mixture to cool off to 85 ºC before performing the boiling test.

2.4 MOISTURE SUSCEPTIBILITY TEST METHODS

In this study, we evaluated the effectiveness of two test standards commonly used by the DOTs to examine the moisture susceptibility of HMA mixtures. These two test standards are:

- Qualitative – Boiling Water Test (ASTM D3625)
- Quantitative - Modified Lottman Test (AASHTO T 283)

The test procedure for each of these standards are discussed in detail in the following sub-sections.

2.4.1 Test Procedure for Boiling Water Test – ASTM D3625

The standard procedure in compliance with ASTM D3625 for boiling water test includes the following steps:

- Pour 550 ml of distilled water into a 1000 ml, graduated pyrex beaker placed on the hot plate capable of maintaining water at boiling temperature (100 ºC).
- Heat the plant produced asphalt concrete sample for approximately 2 hours inside the oven at 85 ºC. In the case of lab produced asphalt concrete, let the mixture to cool down from 163 ºC to 85 ºC before the boiling test.
- Weigh ~ 250 g of AC with temperature not less than (85 ºC) in a metal container and record the combined weight of aggregate and metal container.
- Transfer the weighed HMA mixture into the boiling water and keep it boiling for 10 minutes.
- After 10 minutes of boiling, remove the beaker from hot plate and let it cool down to room temperature.
- Decant the water and place the mixture on a paper towel.
- Visually evaluate the mixture in terms of the percentage of the binder loss using related tables after 24 hours when the mixture is fully dried out.
- Weigh the dried mixture to check if any weight loss is appreciable/measurable.

Figure 17 - Boiling water test setting

2.4.2 Test Procedure for Modified Lottman Test (AASHTO T 283)

We performed Modified Lottman Tests on laboratory prepared HMA cores (4” diameter) and the cores retrieved from the field (6” diameter). HMA mixture prepared in the laboratory as discussed in section 2.3 was compacted inside a Marshall mold (4” diameter) by applying 75 blows from each side of the specimen to prepare laboratory mixed HMA cores. The compacted cores were then extracted out of the molds and allowed to cool at room temperature (~ 20 ºC) for 24 hours. The test procedure to perform the Modified Lottman Test (AASHTO T283) is as shown as a flow chart in Figure 24 and discussed in detail below:

- AASHTO T-283 requires one subset of the asphalt samples to be tested dry and the other after moisture conditioning. Each subset should consist of three asphalt cores.
- For the cores in moisture conditioning subset (i.e. 3 cores), the asphalt cores were saturated by immersing them in a water inside the vacuum chamber @ 21 inch of mercury for 5 minutes (Figure 18). The degree of saturation must be between 70 to 80 %.

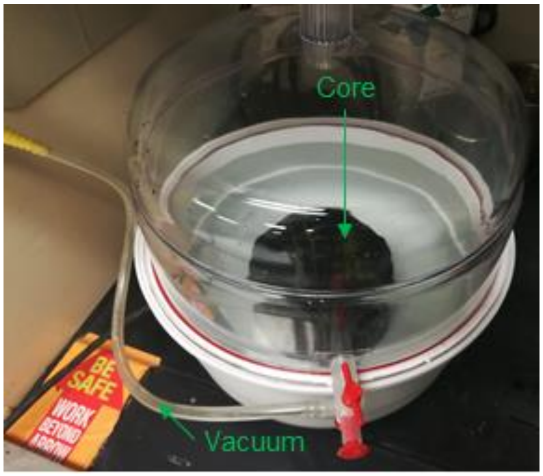


Figure 18 - Vacuum saturation of the asphalt cores

- The saturated samples were immediately transferred to a water bath to measure its immersed weight (Figure 19).

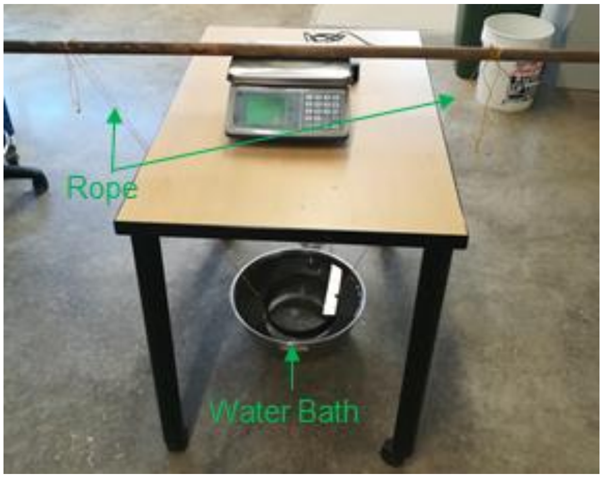


Figure 19 - Set up to measuring the immersed weight of the asphalt cores

- The cores were wiped with the wet towel and the saturated surface dry (SSD) weight was measured.
- The cores were then immersed in the water for 1 second and wrapped with a plastic film (Figure 20(a)) before placing them in a freezer at – 18 ºC (0 ºF) for at least 16 hours (Figure 20(b)).

(a) (b)

Figure 20 - Photo of (a) asphalt cores wrapped with a plastic film, (b) asphalt cores inside the freezer at 0 ºF

- After 16 hours of freezing, the cores were immediately kept in the water bath maintained at 60 ºC (140 ºF) for 24 hours (Figure 21)

Figure 21 - Photo of the asphalt cores submerged in a water bath at 140 ºF

- Finally, the cores were placed in a water bath at 25 ºC (77 ºF) for 2 hours before testing.

- For the cores in dry subset (i.e. 3 cores), the dry cores were placed inside the oven at 25 ºC (77 ºF) for an hour before testing (Figure 22).

Figure 22 - Photo of dry cores inside the oven maintained at 77 ºF (i.e. test temperature)

- The peak load to break the cores (both wet and dry subsets) was determined by loading the cores at the constant rate of 50 mm/min (i.e. 2”/min). We used a Lottman test head with steel guide rods and a LoadTracII (a loading frame) to apply the load along the diameter of the cores (Figure 23(a) and 23(b)). Figure 23(c) is the pictures of the dry and wet conditioned cores after the test.
- The indirect tensile strength of the core is calculated as:

$$S_t = \frac{2000P}{\pi t D}\ (In\ SI\ units) = \frac{2P}{\pi t D}\ (In\ U.S. Customary\ units) \qquad 1$$

where, S_t is the tensile strength (kPa in SI and psi in U.S. Customary units)

P is peak load at breaking (N in SI and lbf in U.S. Customary units)

t is the specimen thickness (mm in SI and inches in U.S. Customary units)

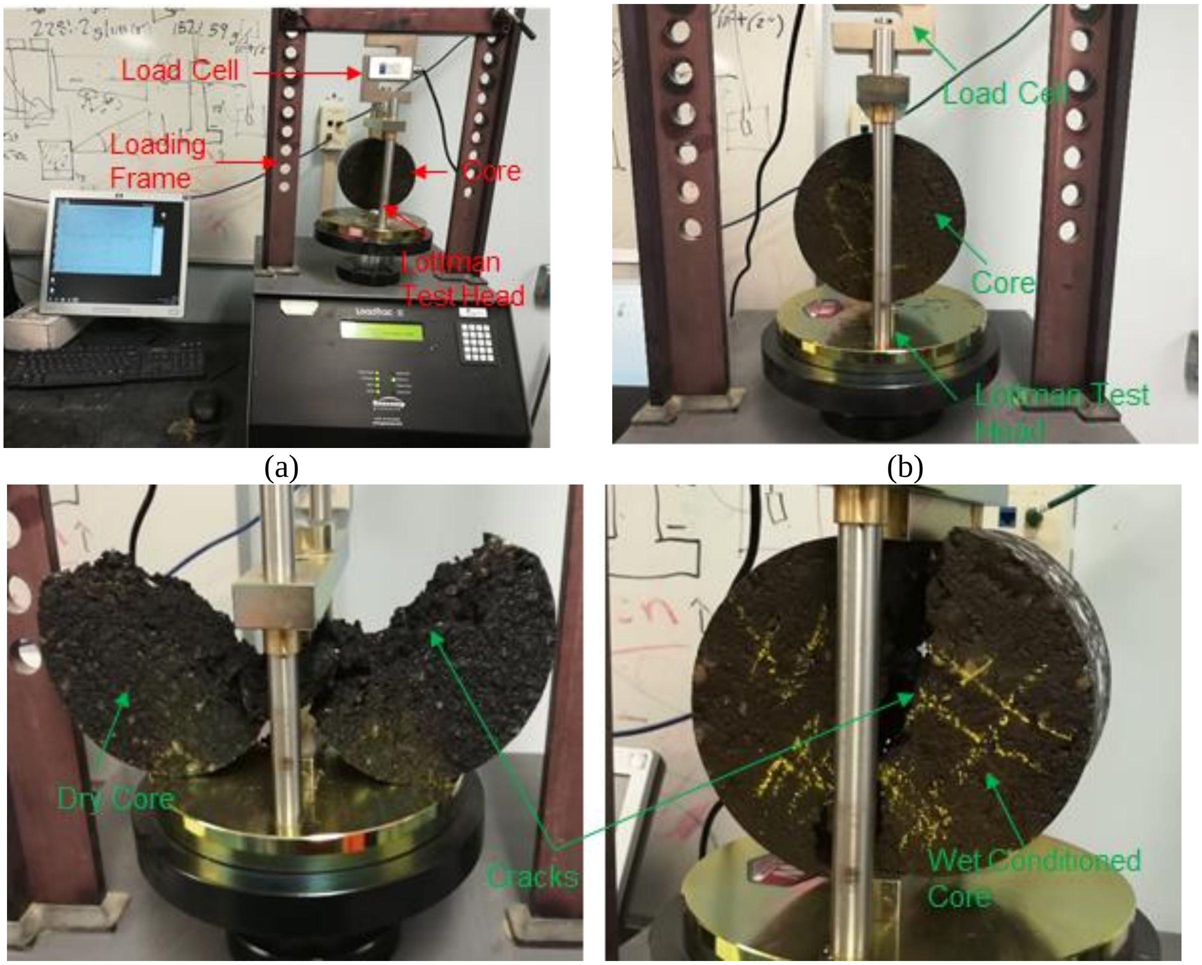
D is the specimen diameter (mm in SI and inches in U.S. Customary units)

- Finally, the tensile strength ratio (TSR), which is the numerical index of resistance of asphalt mixtures to the detrimental effect of water is calculated in accordance with AASHTO T 283 as:

$$Tensile\ strength\ ratio\ (TSR) = \frac{S_{conditioned,avg.}}{S_{dry,avg.}} \qquad 2$$

where, $S_{conditioned,avg.}$ is average tensile strength of the conditioned subset (kPa or psi)

$S_{dry,avg.}$ is average tensile strength of the dry subset (kPa or psi)



(a) (b)

(c)

Figure 23 - Indirect tensile strength test of the cores (a) Loading frame with Lottman test head and test core, (b) Asphalt core before mechanical loading, and (c) photos of post-test asphalt cores.

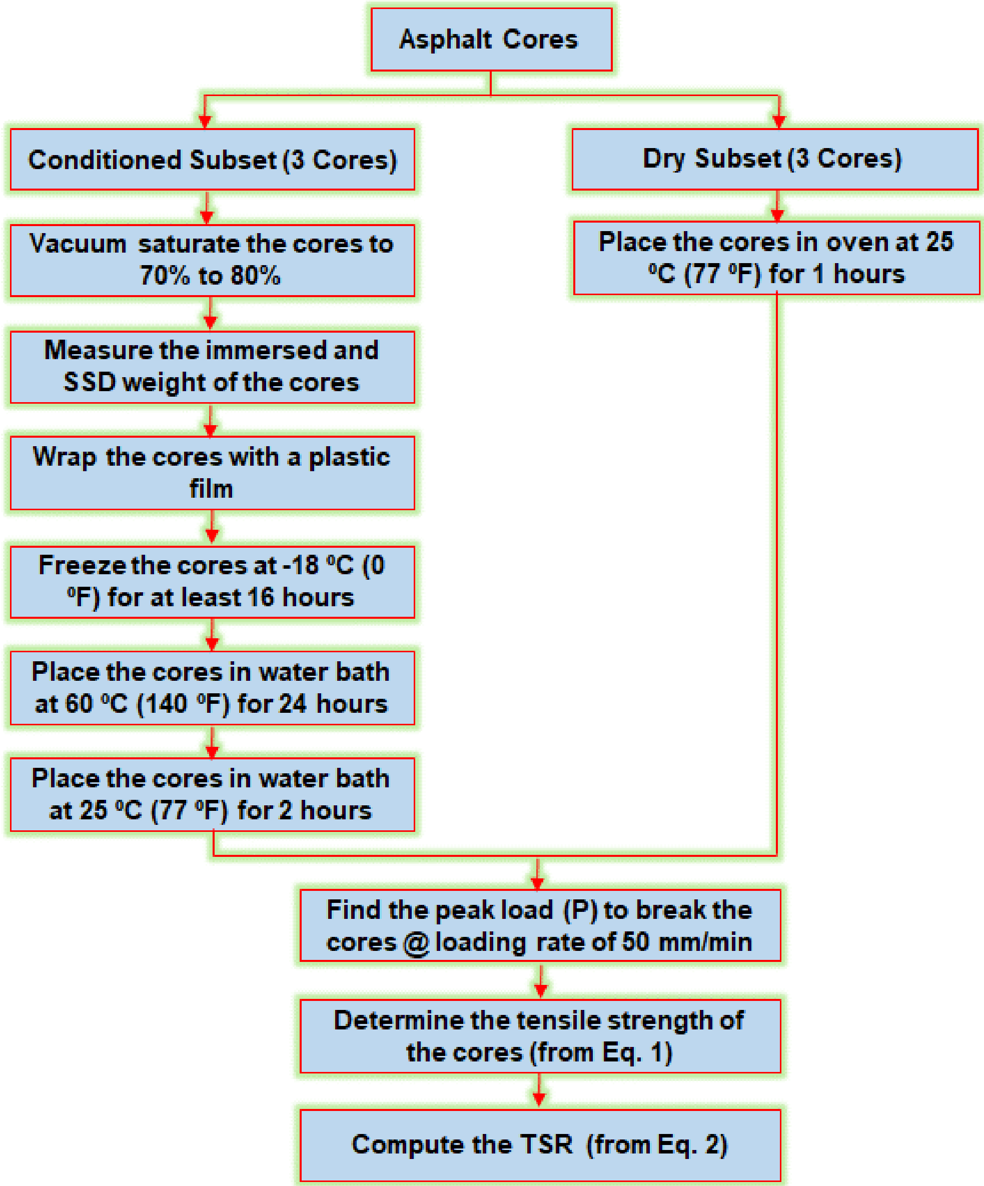


Figure 24 - Flow chart of the modified Lottman test procedure (AASHTO T-283)

- In the case of extended wet conditioned samples (i.e. from the Richford-Jay, Johnson-Morristown, and Cavendish-Weathersfield projects), the cores were subjected to two cycles of freeze-thaw conditioning instead of one cycle as recommended by the AASHTO T 283.

- In the case of wet conditioned and extended wet conditioned cores (i.e. from the Richford-Jay, Johnson-Morristown, and Cavendish-Weathersfield projects), the TSR is calculated as:

$$Tensile\ strength\ ratio\ (TSR) = \frac{S_{exted\ wet\ conditioned,avg.}}{S_{wet\ conditioned,avg.}} \qquad 3$$

CHAPTER 3. RESULTS AND DISCUSSION

A series of laboratory tests were performed, including:

- testing (boiling water test) on plant produced asphalt concrete (AC) specimens and specimens were evaluated visually in terms of percentage of stripping
- testing to establish procedure for producing AC by mixing different combinations of AC component in the laboratory
- trials for producing asphalt concrete specimens by mixing asphalt components containing prone and none-prone to stripping aggregates
- testing (boiling water test) to evaluate the stripping risk posed by addition of RAP in the mix design
- testing to assess the sensitivity of the boiling water test to Anti-Stripping Agent (ASA).
- testing to explore a potential quantification approach for the boiling water test
- Lottman tests (AASHTO T 283) to evaluate the moisture susceptibility of the HMA mixtures used in four projects in Vermont.
- modified Lottman tests (i.e. wet vs extended wet conditioning) on asphalt pavement cores from Richford-Jay, Johnson-Morristown, and Cavendish-Weathersfield projects, and
    - investigated the impact of dry vs wet and wet vs extended wet (i.e. two cycles of wet) conditioning on peak strength and TSR of the regular and joint cores from above mentioned projects.
    - investigated the effect of compaction on the tensile strength of the regular and joint cores subjected to different conditioning.
    - investigated the effect of core thickness on the tensile strength of the cores.
    - compared the compaction level, tensile strength, and TSR values between the joint cores and regular cores.

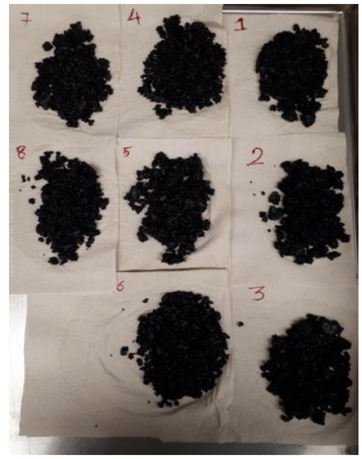
The results from these series of testing are provided in the following sections.

3.1 BOILING WATER TEST - ASTM D3625

3.1.1 Boiling Water Test on Plant Produced Mixtures

The received plant-produced HMA mixtures were mostly the leftovers from the Hamburg Wheel Tracking (HWT) tests, which were performed at VTrans laboratory. The objective of performing the boiling water tests (ASTM D 3625) on these mixtures was to compare and correlate (possibly) the results with the HWT test results. The boiling water test on these plant-produced mixtures is shown in Figures 25(a)-(c). The results of the boiling water tests on these mixtures were evaluated using the Texas rating board and the results are summarized in Table 10.

(a)



(b)

(c)

Figure 25 - Photos of boiling water test (ASTM D3625) on plant-produced HMA mixtures (a) HMA inside the boiling water in a beaker, (b) Asphalt mixtures after boiling water test, (c) close-up of the post-boiled mixtures.

Table 10 - Summary of the boiling water test results on plant-produced HMA mixtures

Sample ID	Mix Design	Box Numbering	Mix Type	Sample Date/Time	Asphalt Retained after boiling (%)
Pserven209H054644	19-752	20-001	IIS	NA	90-100
Pserven209H054644	19-752	20-002	IIS	NA	90-100
Pserven209H054644	19-752	20-003	IIS	NA	90-100
Pserven209H054644	19-752	20-004	IIS	NA	90-100
Pserven209H054644	19-752	20-005	IIS	NA	90-100
Pserven209H054644	19-752	20-006	IIS	NA	90-100
Pserven209H054644	19-752	NA	IIS	09/17/20-12:33	90-100
Pserven209H054644	19-752	NA	IIS	09/17/20-09:54	90-100
Pserven209H054644	19-752	NA	IIS	09/17/20-08:40	90-100
Burlington STP	IVS	NA	IVS	NA	90-100
Burlington STP	IVS	NA	IVS	NA	90-100
Burlington STP	IVS	NA	IVS	NA	90-100
Burlington STP	IVS	NA	IVS	NA	90-100
Burlington STP	IVS	NA	IVS	NA	90-100
NA	SP-18751	NA	IVS	11/03/20-10:30	90-100

3.1.2 Effect of Additional RAP

In order to examine the effect of additional RAP on the moisture susceptibility of the mixture, we added additional 10% RAP to the plant-produced HMA mixture, which already contains 20% RAP. We prepared the HMA in the laboratory using the stripping prone aggregates to get a conservation result for moisture susceptibility when RAP content is increased (plant produced HMA consists of non-prone to stripping aggregates). Table 11 summarizes the information pertinent to this test.

Table 11 - Test information for testing effect of RAP

Mix #	Aggregate type	RAP content	ASA	Production
1	Prone	30	Yes	UVM Lab
2	Non-prone	20	Yes	Plant produced

Figure 26 shows the plant-produced HMA mixture and mixture with additional RAP after boiling water test is performed on them. As it can be seen in Figure 26, addition of extra 10% RAP to the mix design didn't cause more stripping. In fact, the stripping potential for the mix with containing 10% additional RAP appears to be at the same level as that of the plant produced mixture even when the stripping prone aggregate was used in the mixture (Figure 26). This can be attributed to the improved coating of the aggregates due to contribution of the existing binder in the additional RAP and the presence of ASA in the mixture.

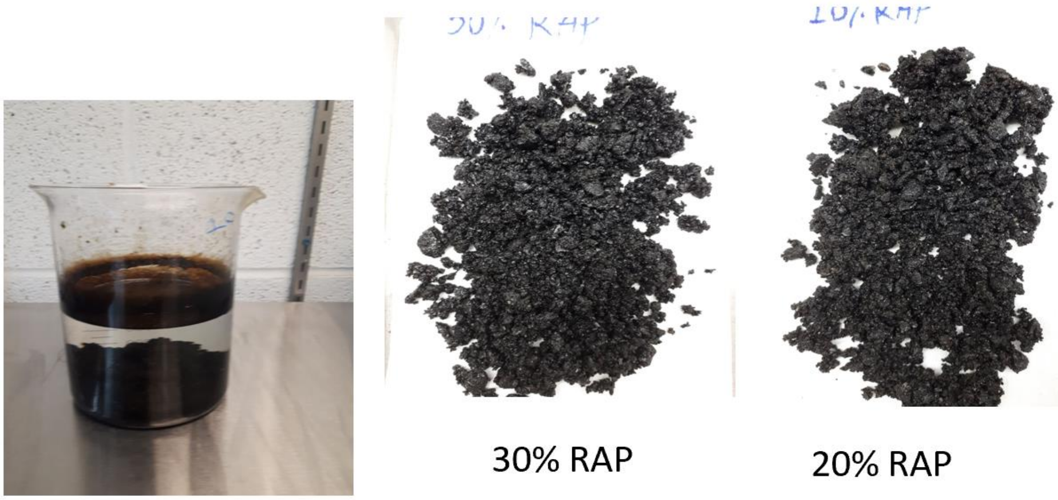


Figure 26 - Boiling water test to evaluate the effect of additional RAP in the mixture

3.1.3 Sensitivity of ASTM D3625 to ASA

To evaluate the sensitivity of the boiling water test to the presence of ASA in the HMA mixture, we prepared two HMA mixtures using stripping prone and non-prone aggregate. The ASA was added to the asphalt binder in both of these mixtures. Figure 27 shows the photos of the post-boiled HMA mixtures containing prone and non-prone aggregate. Based on the visual inspection, we did not observe stripping in any of these mixtures. As expected, the ASA effectively prevented the stripping of the asphalt binder off the aggregate and the effect of ASA is clearly demonstrated using the boiling water test. In other words, the boiling water test can effectively indicate the presence of the ASA in the HMA mixture.

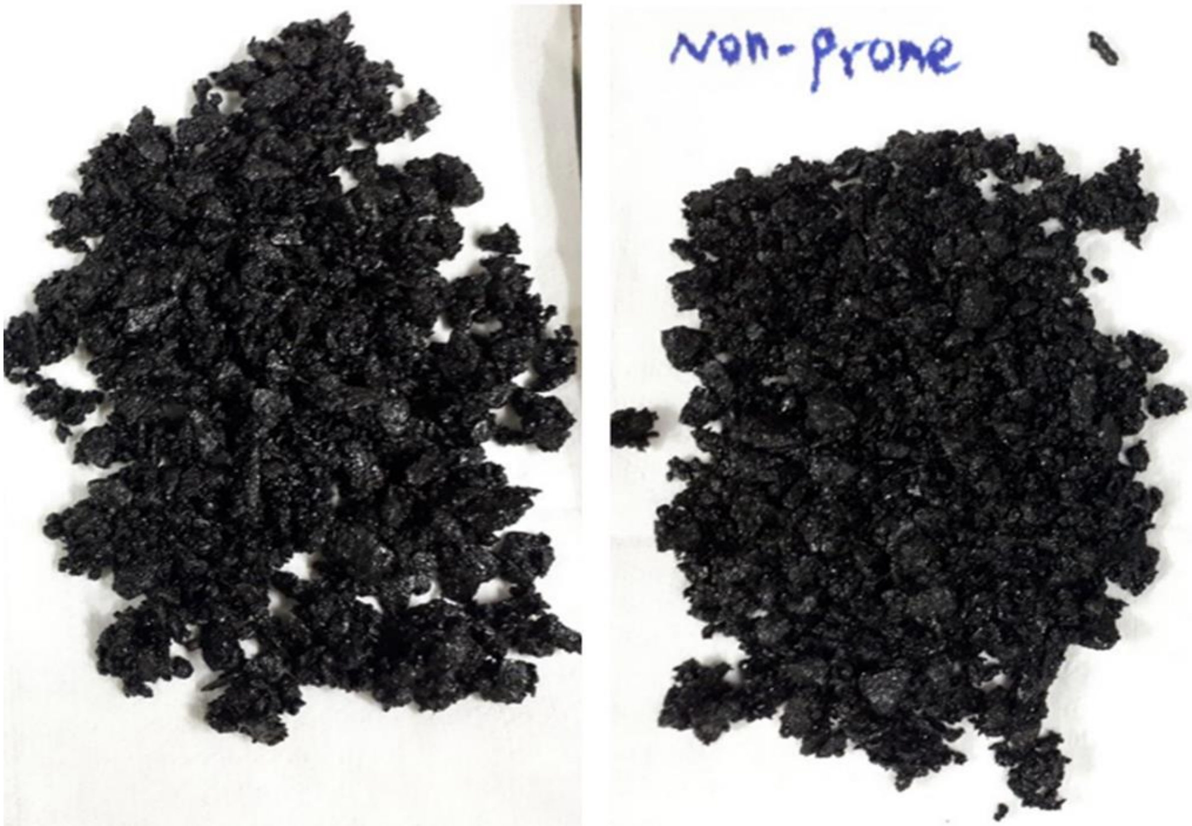


Figure 27 - Photos of HMA mixture after boiling water test (a) mixture with prone aggregate, and (b) mixture with non-prone aggregate

3.1.4 Exploring Quantification Approaches for ASTM D 3625

Since boiling water test interpretation is subjective, a lingering question that remains unanswered: is there some measurable difference between boiled sample or between a stripping and a non-stripping mixture after performing ASTM D3625? If that were the case, and we could come up with some way of quantifying it, then we could look at those quantified results rather than qualitative ones. Two potential approaches were explored. (i) weight loss, which is to measure the weight of the mixture before and after boiling test; and (ii) using maximum specific gravity of the mixture before and after boiling as a quantitative method. These approaches were explored due to the simple, quick, and cost-effective nature of these tests. Both approaches were explored, and the results are provided in the following sections.

3.1.4.1 Weight Loss

The asphalt binder in the moisture susceptible HMA mixture debonds from the aggregate during boiling water test, thereby resulting in loss in weight in the post-boiled mixture. Thus, we explored the possibility of quantifying the stripping magnitude of the mixture by measuring the weight of the mixture pre- and post-boiling test and potentially establishing a methodology. The difference of the two weights is the binder mass loss as a result of boiling the mixture.

Two type of mixtures containing ASA with prone and none-prone aggregate were tested using the standard procedure of ASTM D3625. Mixture 1 was prepared in the lab by mixing asphalt components and mixture 2 is non-stripping plant produced mixture (See Figure 28).

(a) (b) (c)

Figure 28 - Photos of (a) water boiling test on the HMA mixture, (b) weight of the dried mixture after boiling, and (c) asphalt binder stripped out of the aggregate that is floating in water and stuck on beaker wall

The mass of asphalt binder lost as a result of stripping off the aggregate after boiling water test are shown in Table 12. As expected, the percent loss in mass of asphalt binder is 0.1% higher in the mixture with stripping prone aggregate (Table 12). However, the difference in loss in mass between stripping prone and non-prone aggregate was very small. Moreover, the accuracy of the scale that was used for measurements was 0.2 grams and the estimated percent weight loss using this method was 0.4 % for the prone aggregate and 0.3 % for the none-prone aggregate, respectively. Therefore, the insignificant percent loss indicated ineffectiveness of the attempted method for quantification of the level of stripping. Therefore, it is recommended to use a high resolution weighing scale for future attempts.

Table 12 - Mass of asphalt binder lost during boiling water test

Mixture	**Aggregate Type**	**Dry Mass Before Boiling (g)**	**Dry Mass After Boiling (g)**	**Percent Loss in Asphalt Binder (%)**
1	Prone	245.2	244.2	0.4
2	Non-Prone	255.8	255	0.3

3.1.4.2 *Specific Gravity*

Similar to the weight loss approach, the maximum specific gravity of the asphalt mixture changes due to loss of asphalt binder during boiling process. Thus, we investigated maximum specific gravity as another potential approach for quantification of ASTM D3625. To our best knowledge, using maximum specific gravity as the quantification technique of ASTM D3625 has not been attempted. The specific gravity of water at 27 ℃ is approximately 1.0 and the specific gravity of bitumen falls within the range of 0.97 to 1.02 at 27 °C (Civicconcepts, 2022). The minimum specific gravity values standardized by Bureau of Indian Standard for Paving Bitumen at 27 °C for different grades are provided in Table 13.

Table 13 - Specific gravity versus grade of bitumen (Source: Civicconcepts, 2022)

Grade of Bitumen	Specific Gravity
A – 25	0.99
A – 35	0.99
A – 45	0.99
A – 65	0.99
S – 35	0.99
S – 65	0.99
A – 90	0.98
S – 90	0.98
A – 200	0.97
S – 200	0.97

The specific gravity of water is very close to all types of bitumen shown in Table 13, which makes any differentiation after boiling test very difficult. Therefore, this quantification approach turned out to be practically inefficient and unreliable.

3.2 MODIFIED LOTTMAN TEST – AASHTO T283

3.2.1 Laboratory Compacted Cores

The wet and dry subset specimens of both prone and non-prone mixtures were tested using Lottman breaking head for the Tensile Strength Ratio (TSR) and the results are summarized in Tables 14 and 15. The outlier in the value of tensile strength of the non-prone aggregate was due to lower compaction effort (blows) as a result of interruption while compacting the specimen. Table 16 is the result of Lottman test after removing this outlier.

Table 14 - Result of Modified Lottman Test on asphalt mixture with stripping prone aggregate

Conditioned Specimens	Load (N)	$S_{t, cond.}$ (kPa)	Avg. $S_{t, cond.}$	Dry Specimens	Load (N)	$S_{t, dry}$ (kPa)	Avg $S_{t, dry}$	TSR
1	7892.50	0.66	0.65					0.75
2	7359.10	0.62						
3	8047.90	0.67						
				4	11841.00	0.99	0.87	
				5	9294.00	0.78		
				6	9997.10	0.84		

Table 15 - Result of Modified Lottman Test on asphalt mixture with stripping non-prone aggregate

Conditioned Specimens	Load (N)	$S_{t, cond.}$ (kPa)	Avg. $S_{t, cond.}$	Dry Specimens	Load (N)	$S_{t, dry}$ (kPa)	Avg $S_{t, dry}$	TSR
1	7033.90	0.59	0.69					0.88
2	8497.50	0.71						
3	9073.90	0.76						
				4	9989.90	0.84	0.78	
				5	8827.60	0.74		
				6	9140.90	0.77		

Table 16 - Result of Modified Lottman Test on asphalt mixture with stripping non-prone aggregate after removing the outlier

Conditioned Specimens	Load (N)	$S_{t, cond.}$ (kPa)	Avg. $S_{t, cond.}$	Dry Specimens	Load (N)	$S_{t, dry}$ (kPa)	Avg $S_{t, dry}$	TSR
1			0.74					0.94
2	8497.50	0.71						
3	9073.90	0.76						
				4	9989.90	0.84	0.78	
				5	8827.60	0.74		
				6	9140.90	0.77		

As expected, the asphalt mixture with stripping prone aggregate resulted in the TSR value 0.75, which is below the recommended value of 0.8.

3.2.2 Asphalt Cores Retrieved from Field

3.2.2.1 <u>Dry vs One Cycle of Wet Conditioning</u>

The results of the modified Lottman tests on the cores from Groton-Newbury STP PS19(2) project are shown in Table 17. As discussed in the test procedure, the cores cored from the same mixture on the same day were sub-divided into wet conditioned and dry sub-groups. The results were mixed and contrary to the expectation that the wet conditioning would decrease the average tensile stress in some cases. This could be due to the use of anti-stripping additive in the mixture, as a result of which the mixture became resistant to the moisture-induced damaged for one cycle of conditioning.

One interesting thing to note is that the joint cores (J3 –J8) exhibited lower compaction compared to the other cores (Table 17). The lower compaction also resulted in the lower average tensile strength for the joint cores compared to the regular cores.

Table 17 - Result of indirect tensile strength test on cores from Groton-Newbury STP PS19(2) project

Core #	Dia. (in)	Sub-set	Avg. Thickness (in)	Percent Comp. (%)	Peak Strength (N)	Tensile Stress (kPa)	Tensile Stress (psi)	Avg. Tensile Stress (psi)	TSR
7	6	Wet	3.00	95.74	16036.00	892.27	129.38	127.41	1.14
8	6		2.74	94.96	12692.00	772.86	112.06		
9	6		2.95	95.73	17119.00	970.96	140.79		
10	6	Dry	2.58	95.33	11324.00	733.39	106.34	111.31	
11	6		2.27	94.34	9674.20	711.17	103.12		
12	6		3.19	95.34	16388.00	858.40	124.47		
19	6	Wet	2.72	95.32	11305.00	694.48	100.70	103.58	0.82
20	6		2.75	94.70	10636.00	646.96	93.81		
21	6		2.53	96.07	12152.00	801.62	116.23		
22	6	Dry	2.68	92.89	11382.00	708.58	102.74	126.58	
23	6		2.77	95.69	15462.00	932.70	135.24		
24	6		2.93	95.43	17161.00	977.66	141.76		

Table 17. Contd.

Core #	Dia. (in)	Sub-set	Avg. Thickness (in)	Percent Comp. (%)	Peak Strength (N)	Tensile Stress (kPa)	Tensile Stress (psi)	Avg. Tensile Stress (psi)	TSR
25	6	Wet	2.53	94.73	9932.50	656.24	95.16	90.30	1.09
26	6		2.43	95.22	8935.20	614.66	89.13		
27	6		2.44	93.63	8705.60	597.39	86.62		
28	6	Dry	2.51	92.10	8605.10	573.99	83.23	82.89	
29	6		2.34	93.68	8576.50	612.94	88.88		
30	6		2.62	92.08	8277.50	528.10	76.57		
J3	6	Wet	2.64	90.77	7014.70	444.48	64.45	80.77	0.96
J4	6		2.90	92.98	10607.00	612.21	88.77		
J5	6		2.87	92.95	10554.00	614.46	89.10		
J6	6	Dry	2.96	88.20	8629.00	487.44	70.68	83.71	
J7	6		3.11	93.36	12025.00	646.90	93.80		
J8	6		3.17	89.30	11329.00	597.53	86.64		

The average tensile strength values and the TSR values for the asphalt mixtures used in Groton-Newbury project are shown in Figure 29. Dave et al. (2018) reported that the average dry and wet conditioned tensile stress are 107.8 psi and 97.7 psi for good, 90.8 psi and 65.8 psi for poor-moderate, and 75.6 psi and 67.7 psi for poor mixtures. Cores 7-12 and 19-24 fell in the good mix category, whereas cores 25–30 and joints cores fell in poor moderate to poor categories. The low tensile strength of cores 25-30 and joint cores could be the consequence of improper compaction rather than the mixture itself. When we examine the TSR value of the mixtures, all the mixtures pass the AASTHO T-283 criteria of retaining at least 80% of their strength (i.e. TSR >0.8). However, this is known to be inaccurate considering the historic performances of the mixtures with TSR > 0.8 (e.g. Dave et al. 2018).

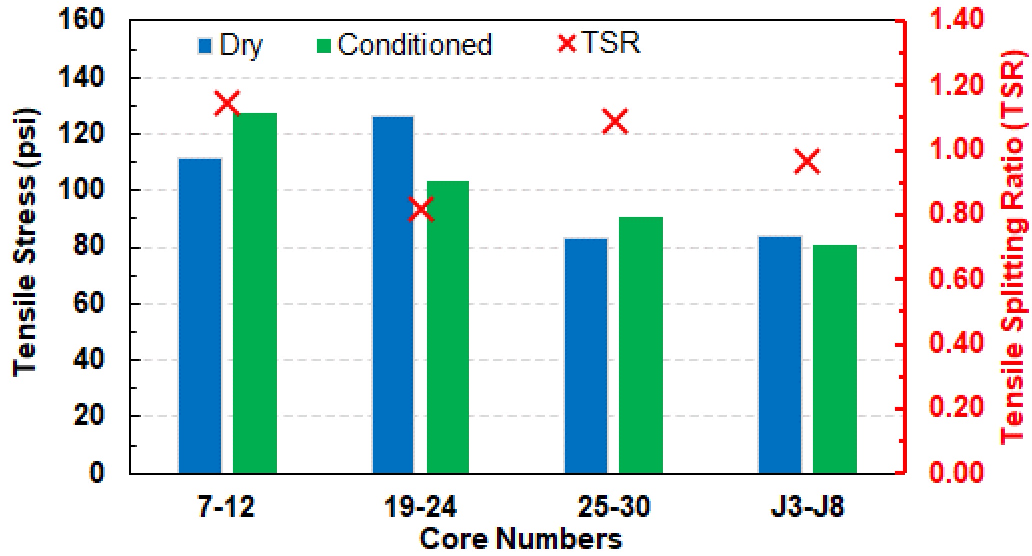


Figure 29 - Average tensile strength for dry and conditioned cores and TSR value of the mixtures.

3.2.2.2 *Wet Vs Extended Wet Conditioning*

Result from the modified Lottman tests on mixtures from Groton-Newbury STP PS19(2) project showed that the mixture were able to retain more than 80% of tensile strength when subjected to single cycle of wet conditioning (Table 17 and Figure 29), which pass the AASTHO T-283 requirement. Thus, for the second batch of the cores (i.e. Richford – Jay STP 2914(1) project), we subjected the cores to single cycle and two cycles of wet conditioning. The temperature, time and procedure of wet conditioning were kept same as mentioned in Section 2.4.2, only the number of cycles was changed. The result of the indirect tensile strength test on the cores and the TSR of the asphalt mixturesused in Richford-Jay STP 2914(1) project are shown in Table 18. The tensile strength of most of the cores with exception of joint core J8, fell in good mix category as identified by Dave et al. (2018).

Table 18 - Result of indirect tensile strength test on cores from Richford-Jay STP 2914(1) project

Core #	Dia. (in)	# of Wet Cycles	Avg. Thickness (in)	Percent Comp. (%)	Peak Strength (N)	Tensile Stress (kPa)	Tensile Stress (psi)	Avg. Tensile Stress (psi)	TSR
1	6	2	2.68	96.31	15115.00	941.33	136.49	129.00	0.86
2	6		3.00	95.92	15725.00	876.13	127.04		
3	6		2.69	95.50	13709.00	851.55	123.47		
4	6	1	2.52	96.79	13604.00	900.96	130.64	149.22	
5	6		2.45	96.25	15531.00	1059.66	153.65		

Table 18. Contd.

Core #	Dia. (in)	# of Wet Cycles	Avg. Thickness (in)	Percent Comp. (%)	Peak Strength (N)	Tensile Stress (kPa)	Tensile Stress (psi)	Avg. Tensile Stress (psi)	TSR
6	6		2.29	96.01	15455.00	1126.70	163.37		
7	6	2	2.55	94.94	12504.00	818.06	118.62	126.69	0.93
8	6		2.12	95.69	11071.00	871.35	126.35		
9	6		2.44	96.59	13594.00	931.68	135.09		
10	6	1	2.51	96.12	13836.00	921.44	133.61	136.09	
11	6		2.60	95.90	14082.00	906.74	131.48		
12	6		2.23	95.29	13192.00	987.58	143.20		
13	6	2	2.14	95.78	10829.00	845.14	122.54	125.13	1.04
14	6		2.35	95.53	12298.00	876.29	127.06		
15	6		2.50	95.71	12968.00	867.43	125.78		
16	6	1	2.46	97.01	12968.00	881.55	127.82	120.37	
17	6		2.31	96.20	8851.50	639.71	92.76		
18	6		2.22	96.27	12877.00	969.21	140.54		
19	6	2	2.30	94.33	8466.50	615.88	89.30	98.29	0.79
20	6		2.71	93.69	10729.00	661.52	95.92		
21	6		2.64	94.16	11925.00	756.19	109.65		
22	6	1	2.32	95.02	11683.00	840.35	121.85	123.93	
23	6		2.66	94.68	13121.00	824.84	119.60		
24	6		2.73	95.40	14690.00	898.78	130.32		
25	6	2	2.76	95.50	14163.00	857.44	124.33	121.62	1.00
26	6		2.59	95.48	13125.00	847.40	122.87		
27	6		1.92	94.41	9334.60	811.52	117.67		
28	6	1	2.57	94.55	12370.00	804.25	116.62	121.57	
29	6		2.39	91.59	10794.00	755.27	109.51		
30	6		2.24	94.87	12834.00	955.64	138.57		
31	6	2	2.48	96.72	14336.00	964.34	139.83	135.54	0.99
32	6		2.26	95.67	12267.00	908.16	131.68		

Table 18. Contd.

Core #	Dia. (in)	# of Wet Cycles	Avg. Thickness (in)	Percent Comp. (%)	Peak Strength (N)	Tensile Stress (kPa)	Tensile Stress (psi)	Avg. Tensile Stress (psi)	TSR
33	6		2.40	96.15	13400.00	931.76	135.11		
34	6	1	2.39	95.59	12420.00	869.77	126.12	137.28	
35	6		2.39	96.27	13367.00	932.96	135.28		
36	6		2.01	96.74	12475.00	1037.57	150.45		
37	6	2	2.21	95.44	12121.00	916.85	132.94	143.54	1.19
38	6		2.32	95.85	13812.00	996.49	144.49		
39	6		2.23	95.68	14099.00	1056.42	153.18		
40	6	1	2.11	94.52	9846.40	779.37	113.01	120.24	
41	6		2.36	95.86	12013.00	850.18	123.28		
42	6		2.48	94.94	12748.00	858.21	124.44		
43	6	2	2.13	95.20	10676.00	839.47	121.72	123.44	1.00
44	6		2.59	94.44	12920.00	832.88	120.77		
45	6		2.43	93.93	12822.00	881.67	127.84		
46	6	1	2.54	95.03	12841.00	846.40	122.73	123.58	
47	6		2.37	95.27	13125.00	924.57	134.06		
48	6		2.37	92.94	11152.00	785.92	113.96		
J1	6	2	2.49	95.54	14039.00	940.58	136.38	135.48	1.21
J2	6		2.31	95.51	12831.00	928.12	134.58		
J3	6	1	2.49	92.89	11269.00	757.73	109.87	112.01	
J4	6		2.12	93.57	10002.00	787.21	114.15		
J6	6	2	1.67	94.98	9035.70	906.24	131.40	117.08	1.30
J7	6		1.90	92.52	8057.50	708.60	102.75		
J8	6	1	2.33	92.26	7524.10	538.88	78.14	90.29	
J9	6		2.06	94.51	8710.40	706.52	102.45		

Figure 30 shows the average indirect tensile strength of cores subjected to single and two cycles of wet conditioning. For majority of the mixtures, introducing the second cycle of wet conditioning showed the reduction in the tensile strength values. Similar to the mixtures on the Groton-Newbury STP PS19(2) project, the TSR value showed that cores subjected to two cycles of the wet conditioning were able to retain ~80 % or more tensile strength compared to the single wet conditioning. This result suggest that the mixtures on the Richford-Jay STP 2914(1) project did not show any potential moisture susceptibility.

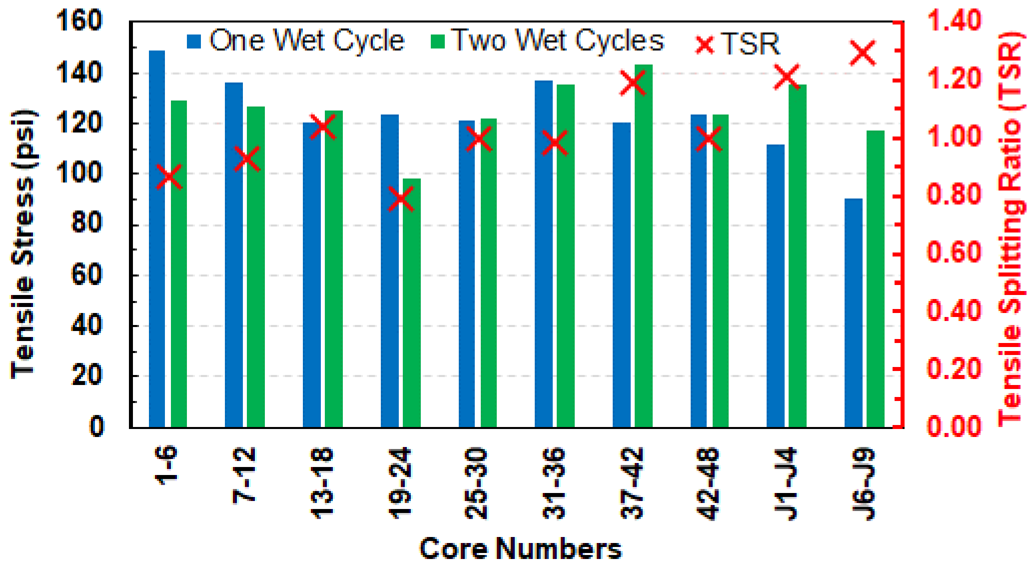


Figure 30 - Average tensile strength of cores subjected to single and two cycles of wet conditioning and TSR value of the mixtures.

In order to compare the percent compaction, TSR, and indirect tensile strength of regular cores and joint cores across various projects in Vermont, more joint cores from the Johnson-Morristown STP 2919(1) and Cavendish-Weathersfield ER STP 0146(14) projects were testes in the Laboratory. The results of these joint cores are listed in Tables 19 and 20, and shown graphically in Figures 31 and 32.

Table 19 - Result of indirect tensile strength test on joint cores from Johnson-Morristown STP 2919(1) project

Core #	Dia. (in)	# of Wet Cycles	Avg. Thickness (in)	Percent Comp. (%)	Peak Strength (N)	Tensile Stress (kPa)	Tensile Stress (psi)	Avg. Tensile Stress (psi)	TSR
J17	6	2	1.83	91.55	5840.40	533.85	77.41	87.04	1.08
J18	6		1.52	92.61	5740.00	633.07	91.80		
J19	6		1.16	93.84	4400.60	633.88	91.91		
J20	6	1	1.30	92.38	3807.50	488.26	70.80	80.22	
J21	6		1.31	94.07	4828.70	618.27	89.65		

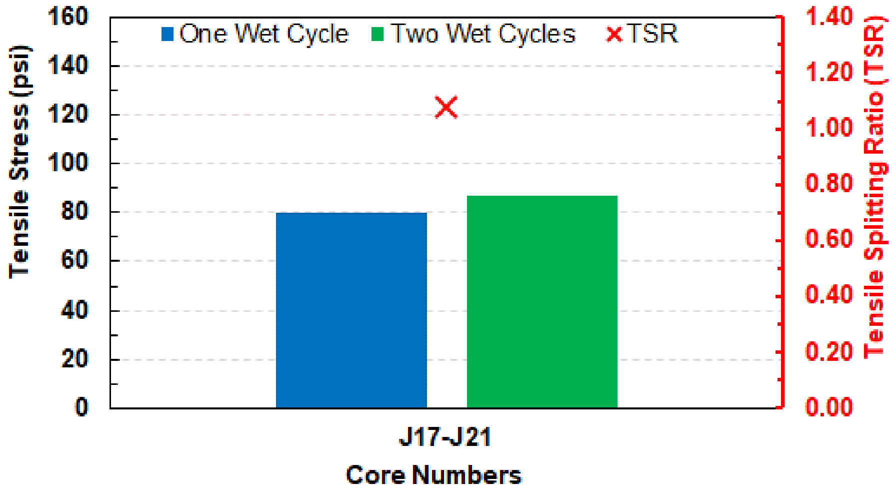


Figure 31 - Average tensile strength of cores subjected to single and two cycles of wet conditioning and TSR value of the mixtures for Johnson-Morristown STP 2919(1) Project.

Table 20 - Result of indirect tensile strength test on joint cores from Cavendish-Weathersfield ER STP 0146(14) Project

Core #	**Dia. (in)**	**# of Wet Cyc-les**	**Avg. Thickness (in)**	**Percent Comp. (%)**	**Peak Strength (N)**	**Tensile Stress (kPa)**	**Tensile Stress (psi)**	**Avg. Tensile Stress (psi)**	**TSR**
J4	6	2	1.24	93.98	5206.60	701.60	101.73	101.10	0.96
J5	6		1.64	93.54	6792.30	692.88	100.47		
J6	6	1	1.44	91.89	5527.10	640.90	92.93	105.01	
J7	6		1.50	95.00	7249.10	807.51	117.09		
J8	6	2	1.856	88.61	5486.50	493.94	71.62	79.17	0.79
J9	6		1.644	92.99	6034.10	613.29	88.93		
J10	6		1.439	91.31	4570.40	530.70	76.95		
J11	6	1	1.42	93.29	6694.20	787.71	114.22	100.04	
J12	6		1.903	92.03	7708.30	676.82	98.14		
J13	6		1.37	90.54	4962.70	605.27	87.76		

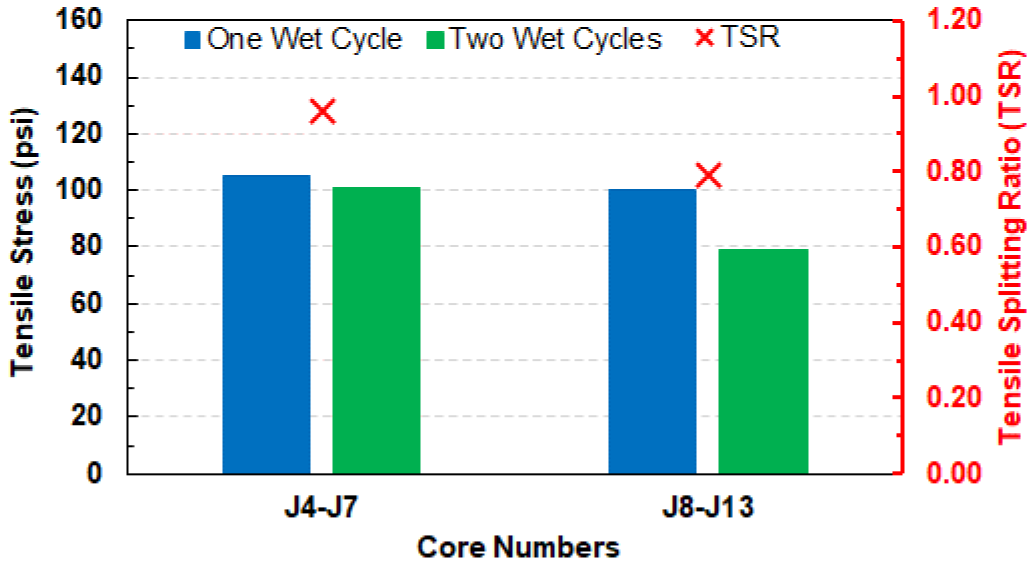


Figure 32 - Average tensile strength of cores subjected to single and two cycles of wet conditioning and TSR value of the mixtures for Cavendish-Weathersfield ER STP 0146(14) Project.

3.2.2.3 Effect of Compaction on Tensile Strength

In this section, we present the trends of the indirect tensile strength with respect to the percent compaction of the cores. Percent compaction is the better metric to examine the trend in tensile strength of the cores, as it remains unaffected by the variations in core materials such as aggregate and binder.

The relationship between the tensile strength and percent compaction of all the cores from Groton-Newbury STP PS19(2) project in shown in Figure 33. The same relationship with respect to core condition (dry or wet) and core type (joint or regular) is presented in Figures 34 and 35, respectively. As observed in Figure 33(c), the wet conditioned cores resulted the lower tensile strength than the dry cores. The difference in tensile strength between dry and wet conditioned cores is lower at higher compaction level (e.g. Figure 33(c)). Similarly, joint cores exhibited lower percent compaction and tensile strength compared to the regular cores in Groton-Newbury STP PS19(2) project. Moreover, the slope of the trend line for regular cores was higher than that of joint cores (Figure 34(c)).

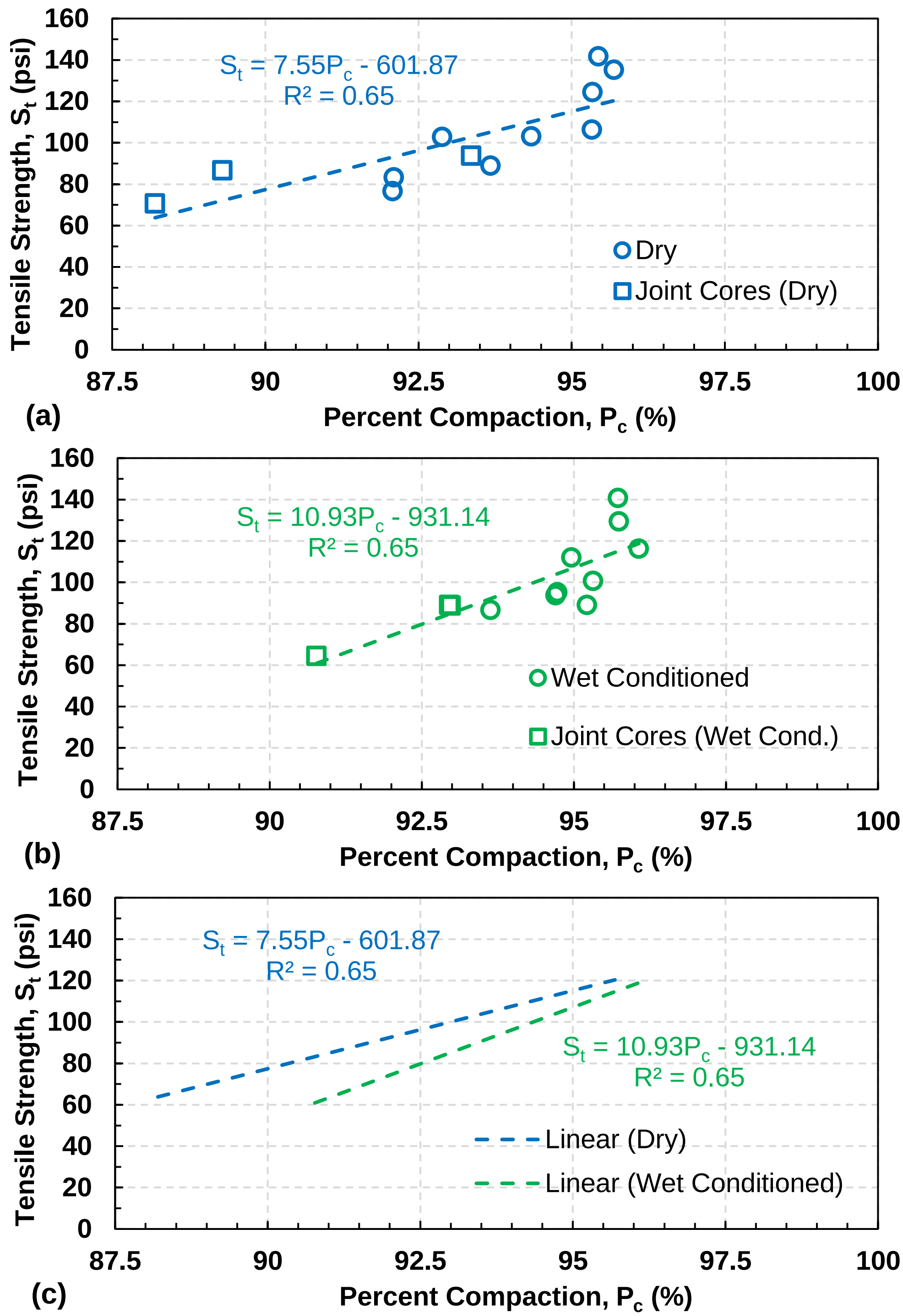


Figure 33 - Indirect tensile strength trend with respect to the percent compaction in the Groton-Newbury STP PS19(2) Project (a) Dry cores, (b) Wet conditioned cores, and (c) trend line of dry and wet conditioned cores.

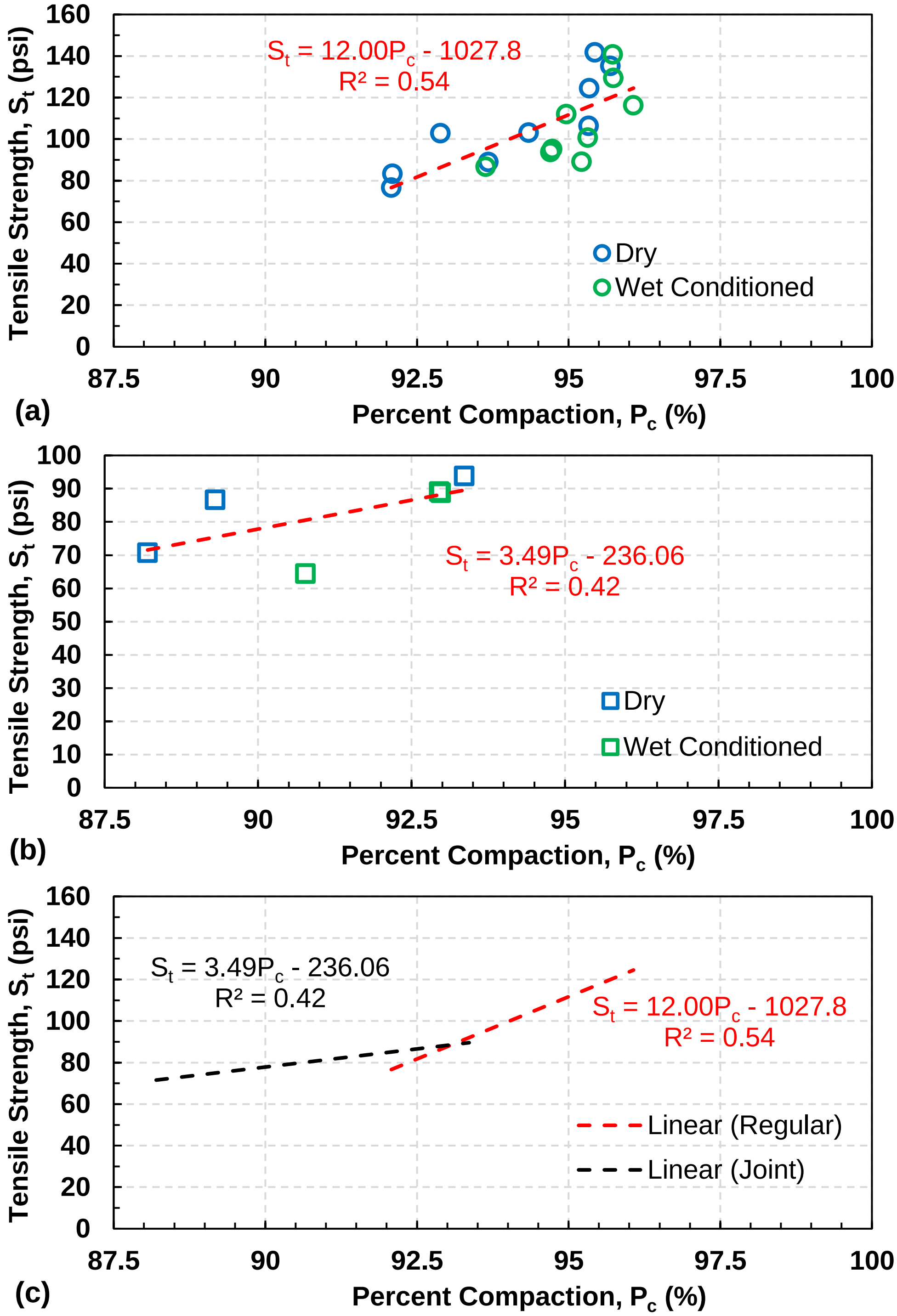


Figure 34 - Indirect tensile strength trend with respect to the percent compaction in the Groton-Newbury STP PS19(2) Project (a) Regular cores, (b) Joint, and (c) trend line of regular and joint cores.

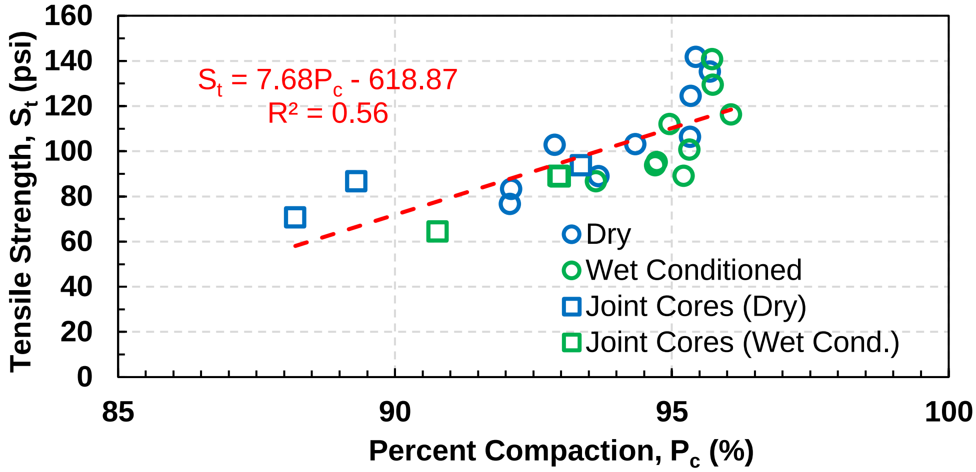


Figure 35 - Indirect tensile strength trend with respect to the percent compaction of all the cores from the Groton-Newbury STP PS19(2) Project

Figure 36 shows the relationship between the tensile strength and percent compaction of all the cores from Richford-Jay STP 2914(1) project. The cores from Richford-Jay STP 2914(1) project were subjected to the extended wet (i.e. 2 cycles of freeze and thaw) and wet condition before the testing. The extended cycle of wet conditioning showed very little to no difference in the tensile strength-percent compaction relationship (Figure 36(c)). Similarly, the joint and regular cores showed no significant difference in the tensile strength – percent compaction relationship (Figure 37). The Joint cores in the Richford-Jay STP 2914(1) project achieved comparable level of compaction as the regular cores (all above 91.5%). This could be the reason four such insignificant difference between joint and regular cores.

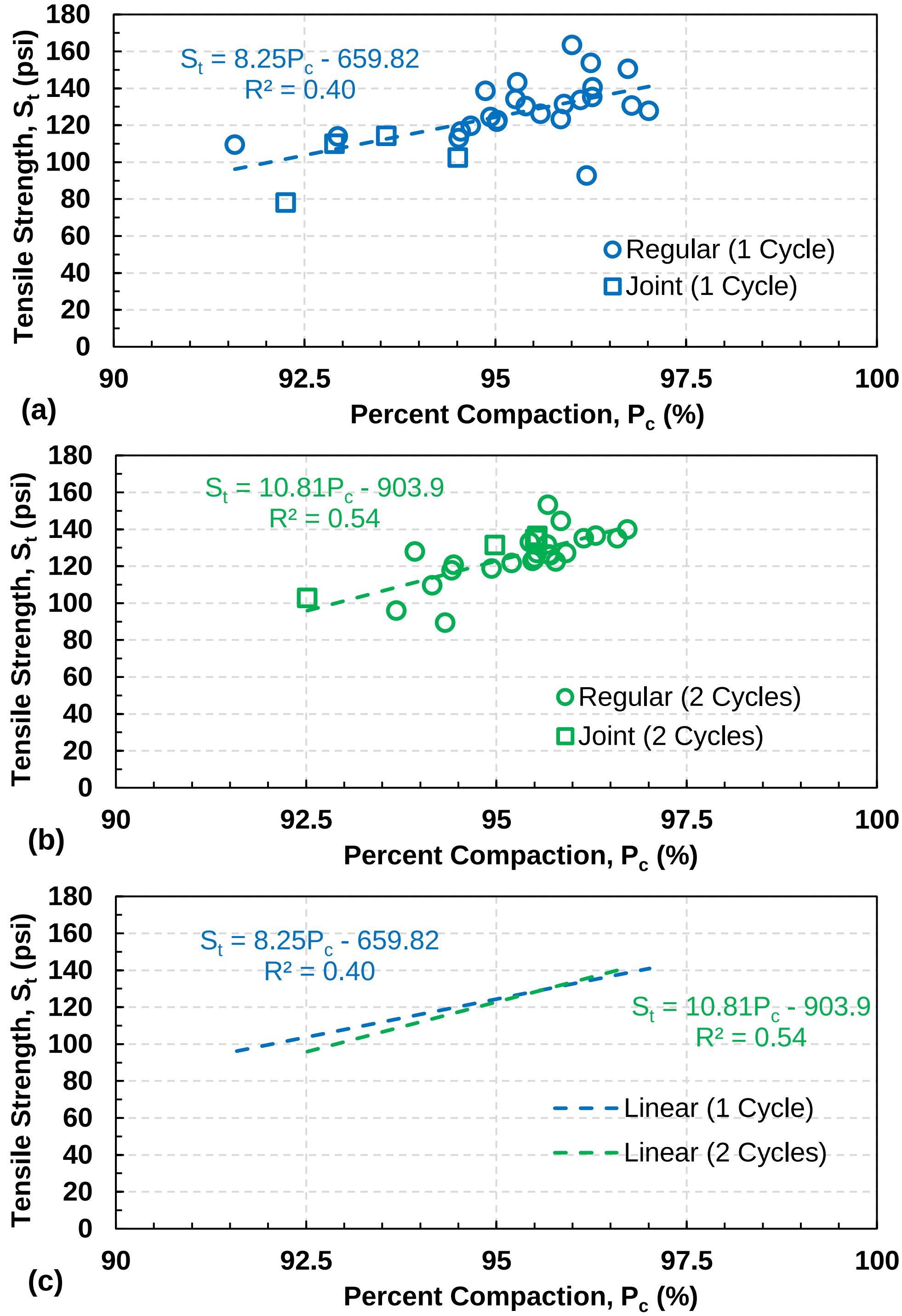


Figure 36 - Indirect tensile strength trend with respect to the percent compaction in Richford-Jay STP 2914(1) Project (a) One cycle of wet conditioning, (b) Two cycle of wet conditioning, and (c) trend line of one cycle and two cycles of wet conditioning.

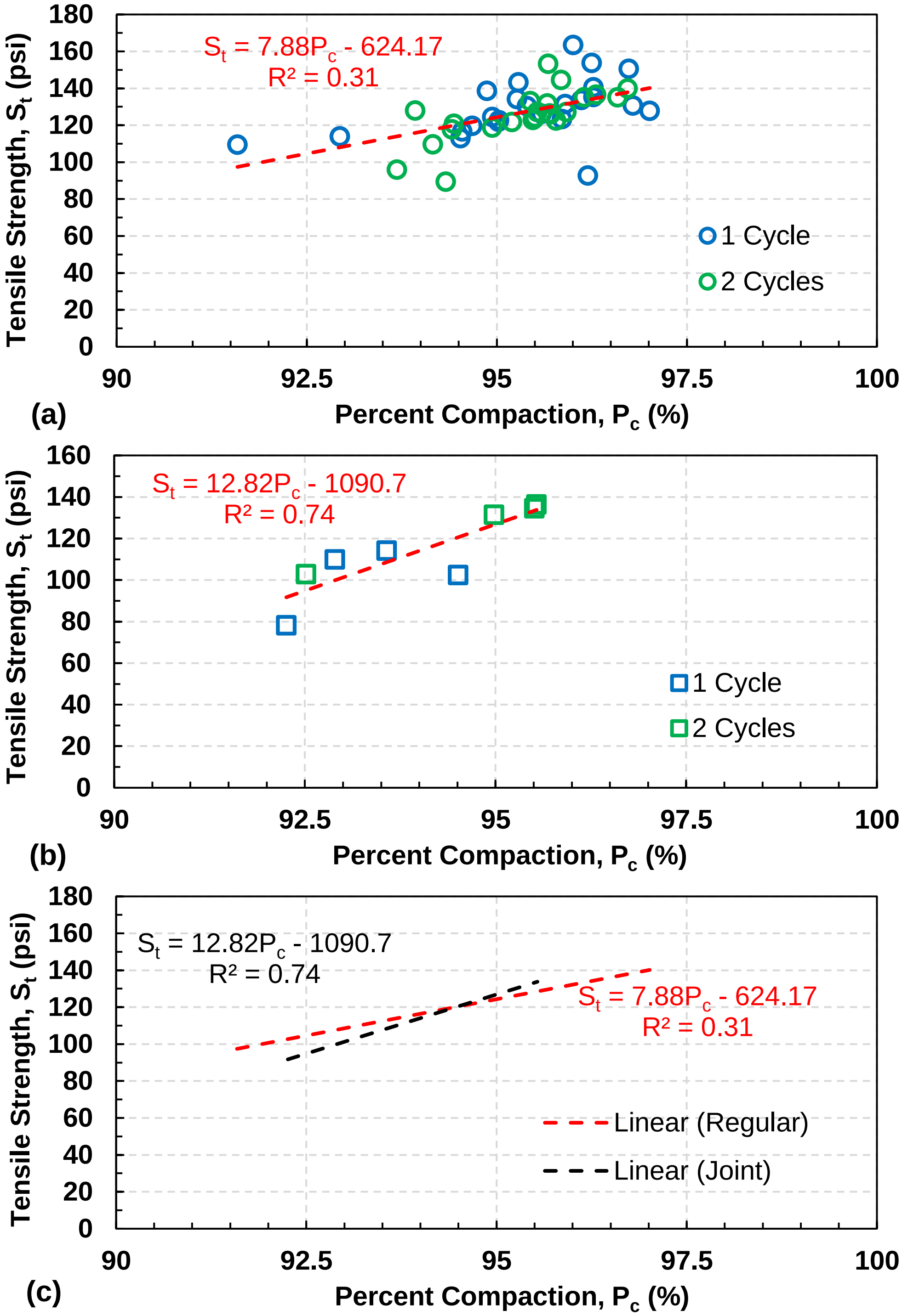


Figure 37 - Indirect tensile strength trend with respect to the percent compaction in Richford-Jay STP 2914(1) Project (a) Regular, (b) Joint, and (c) trend line of combined regular and joint cores

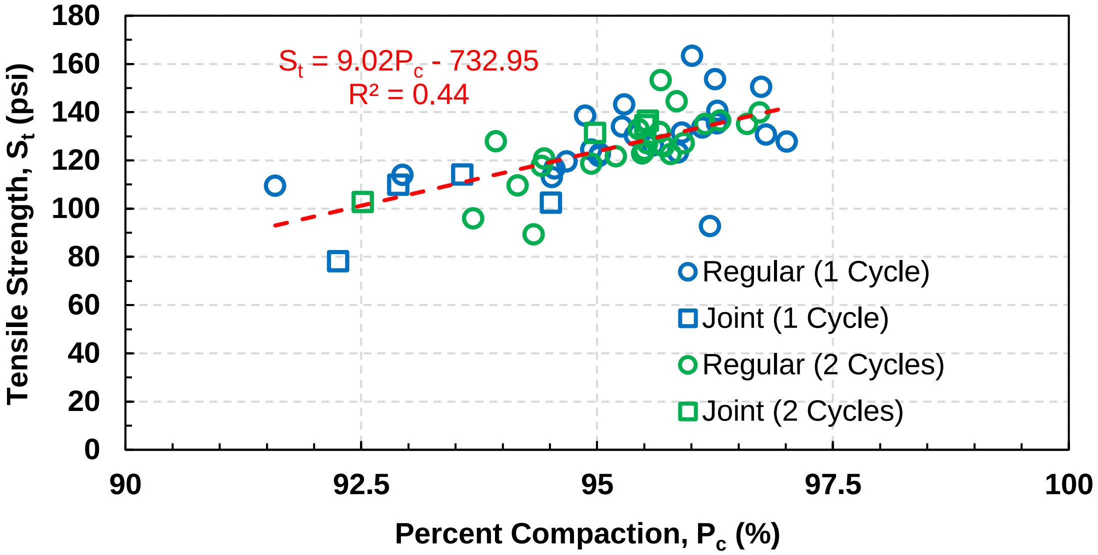


Figure 38 - Indirect tensile strength trend with respect to the percent compaction of all the cores from Richford-Jay STP 2914(1) Project

Figures 39 and 40 shows the tensile strength-percent compaction relationship for the joint cores from Johnson-Morristown STP 2919(1) and Cavendish-Weathersfield ER STP 0146(14) projects, respectively. These cores were also subjected to extended wet (i.e. 2 cycles of freeze and thaw) and wet (i.e. one cycle of freeze and thaw) conditioning before the test. The joint cores subjected to extended wet conditioning from Cavendish-Weathersfield ER STP 0146(14) project exhibited lower percent compaction that that in the Richford-Jay STP 2914(1) project. The lower percent compaction could be the reason for the lower tensile strength observed in extended wet conditioned cores.

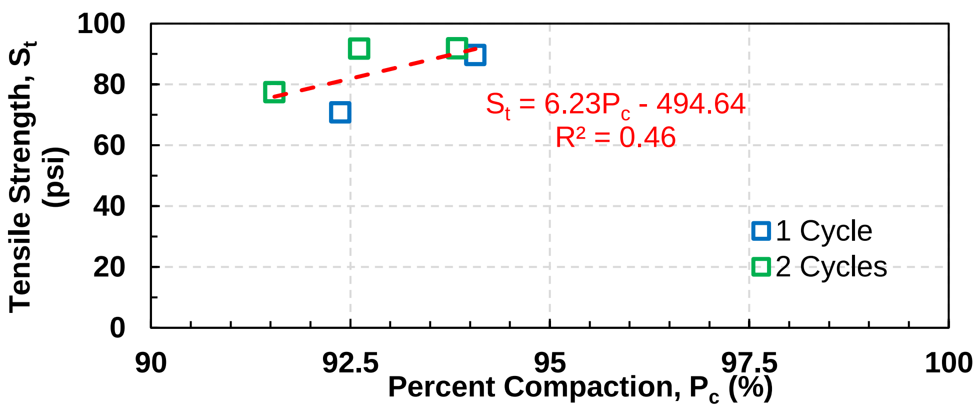


Figure 39 - Indirect tensile strength trend of joint cores with respect to the percent compaction in Johnson-Morristown STP 2919(1) Project.

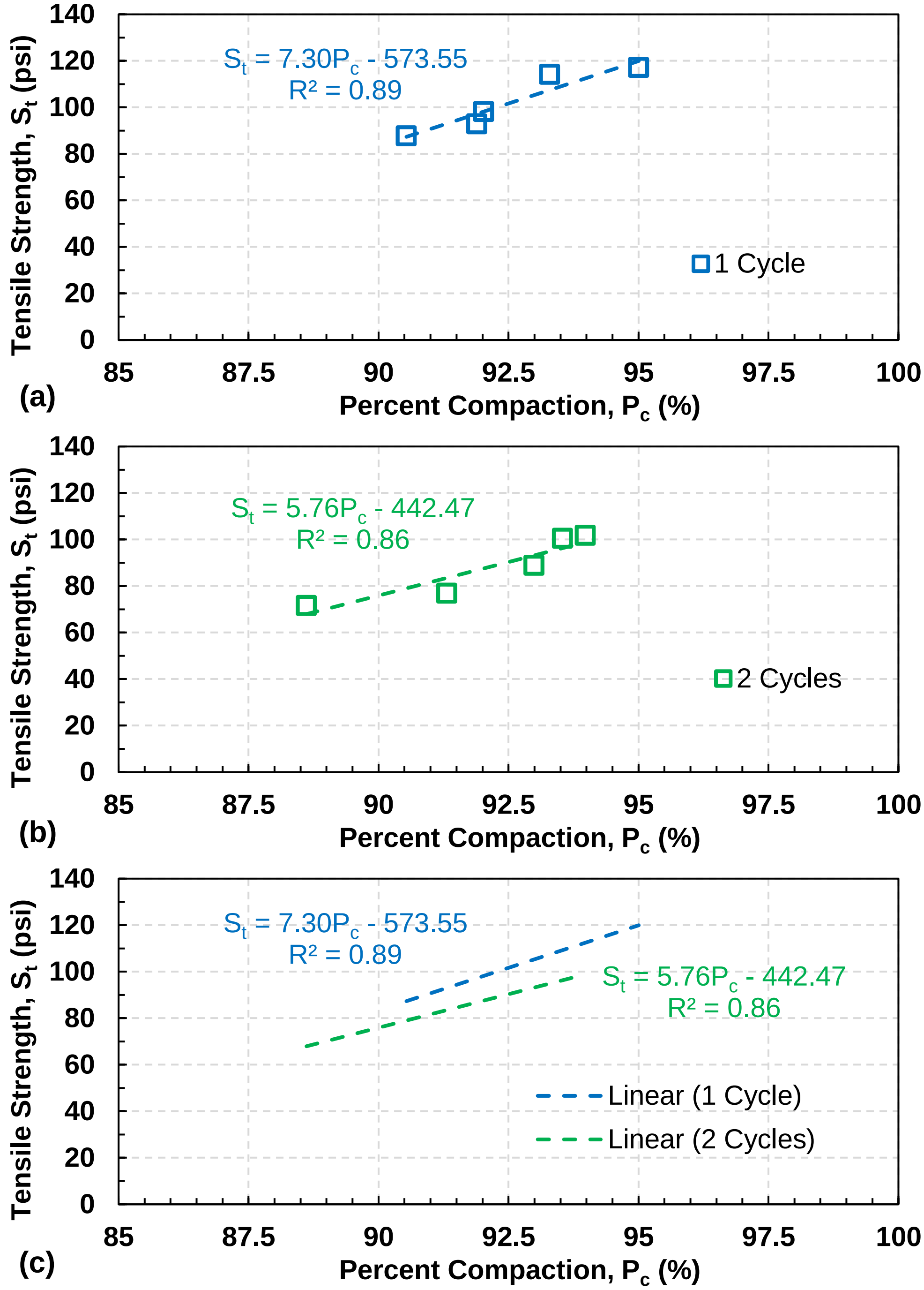


Figure 40 - Indirect tensile strength trend with respect to the percent compaction for the joint cores from Cavendish-Weathersfield ER STP 0146(14) Project (a) One cycle of wet conditioning, (b) Two cycle of wet conditioning, and (c) trend line of one cycle and t

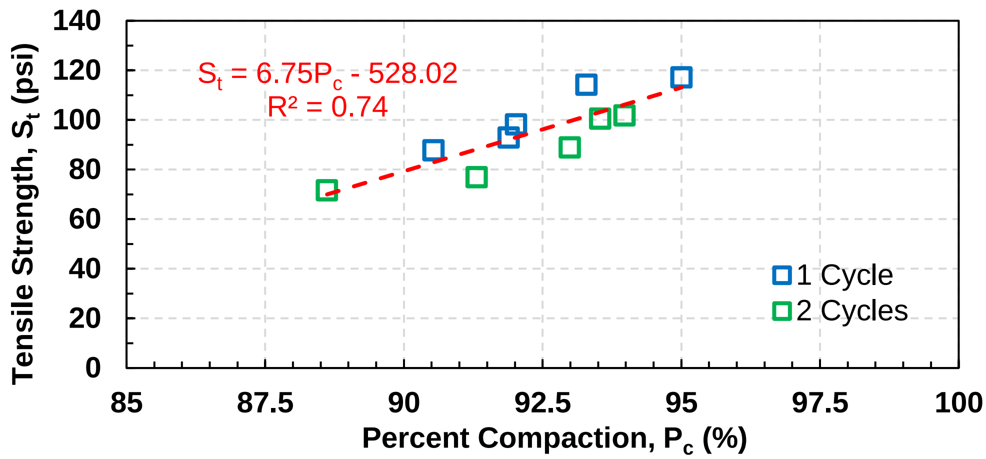


Figure 41 - Indirect tensile strength trend of joint cores with respect to the percent compaction in Cavendish-Weathersfield ER STP 0146(14) Project.

Figure 42(a) shows the tensile strength-percent compaction relationship for all the joint and regular cores tested in this study. As seen in this Figure 42(a) and 42(b), the joint cores exhibited lower compaction and lower tensile strength compared to the regular cores.

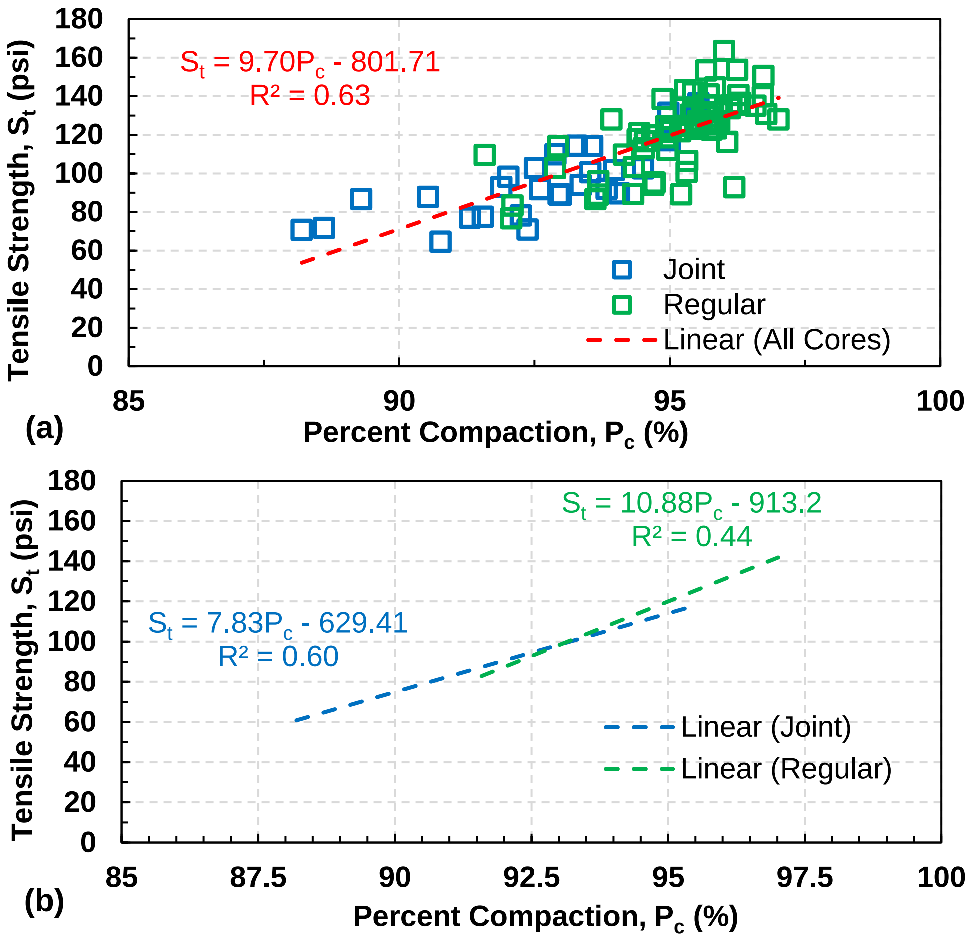


Figure 42- Indirect tensile strength trend with respect to the percent compaction for (a) all the cores tested in this study and (b) joint and regular cores tested in the study.

3.2.2.4 <u>Effect of Core Thickness</u>

The thickness of the cores extracted from the field varied (See Tables 17-20). Thus, it is important to confirm the core thickness had no effect on its indirect tensile strength value. Figure 43 shows the variation of the indirect tensile strength of the core with respect to its thickness. The low R^2 value of the trend line in figure 43 suggests there the core thickness has very little to no effect on its indirect tensile strength. This observation is as expected as the tensile stress is normalized with respect to the core thickness. However, a very thin or thick core may influence the indirect tensile stress due to boundary effects. Based on the result observed in this study, indirect tensile strength of the cored was not influenced when the core thickness was between [1.16, 3.19] inches.

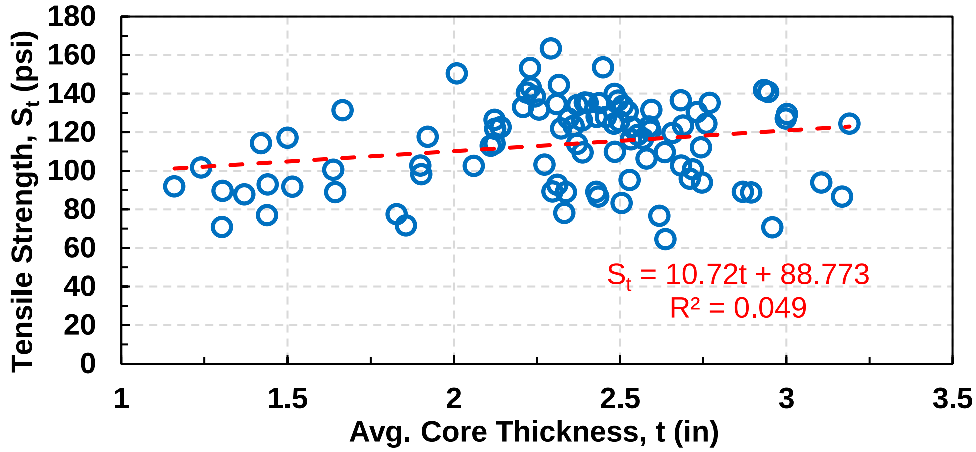


Figure 43 - Effect of core thickness on its tensile strength

3.2.3 Comparison between Joint and Regular Cores

The comparison of percent compaction, indirect tensile strength, and TSR values between the joint cores and regular cores are shown in Figure 44(a), 44(b), and 44(c), respectively. The average percent compaction and the indirect tensile strength of the joint cores were 2.5% and 26 psi lower than that of the regular cores, respectively. On the other hand, the average TSR value of the joint cores was 6.5% higher that of the regular cores. In order to examine whether the observed difference in the average values percent compaction, indirect tensile strength, and TSR were statistically significant, we performed two-tailed t-tests between joint and regular cores. The results of the t-tests are shown in Table 21. The p-values for the average of percent compaction and average indirect tensile strength are smaller than 0.05, suggesting that the observed difference is statistically significant at the significance level of 0.05. However, the difference in the average TSR values between joint cores and regular cores was not statistically significant at the significance level of 0.05. This suggests that the joint cores in the field exhibited lower compaction and as a result lower indirect tensile strength that the regular cores.

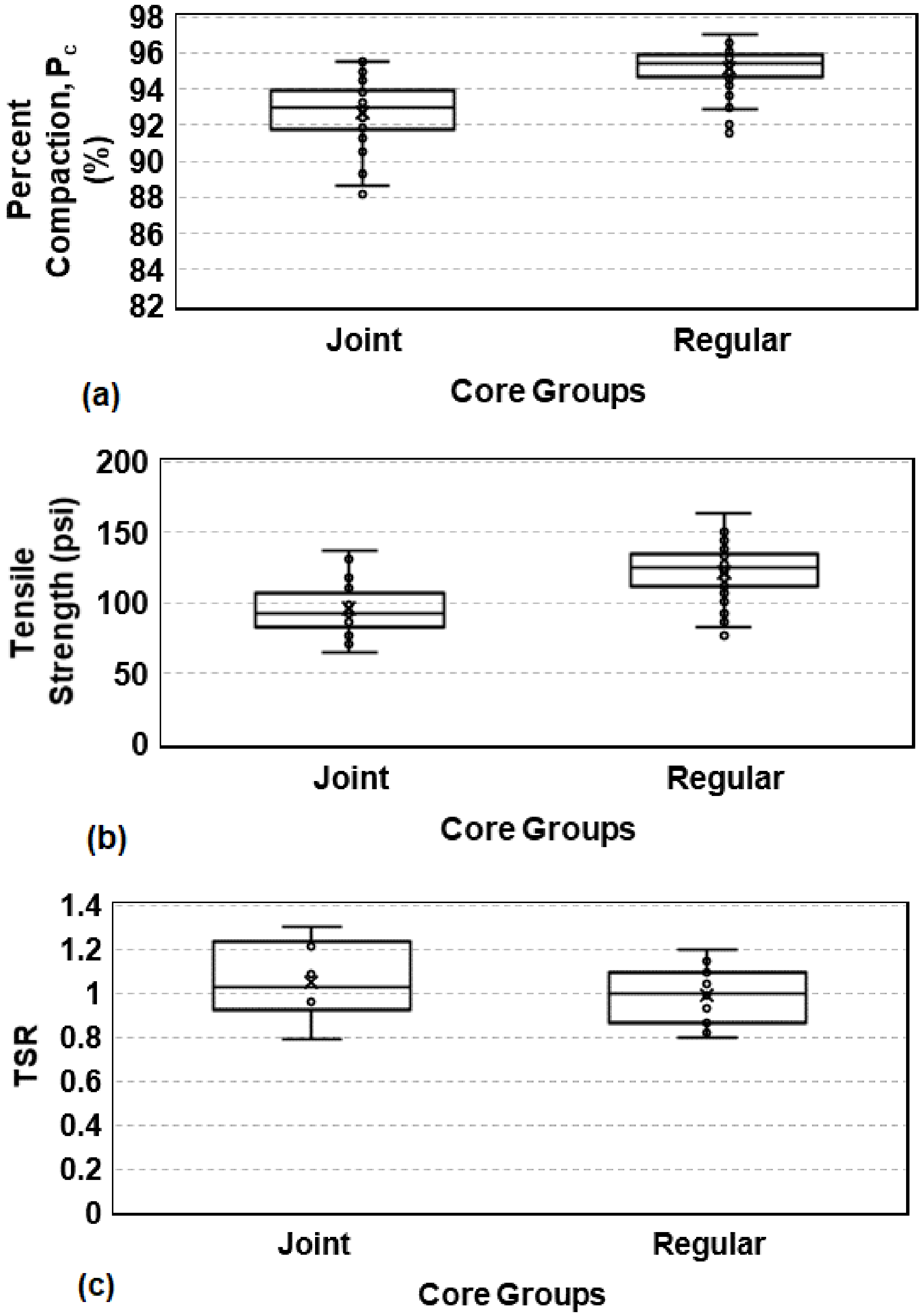


Figure 44 - Comparison of (a) percent compaction, (b) tensile strength, and (c) TSR between joint cores and regular cores.

Table 21 - Results of two-tailed t-test between joint and regular cores

Parameters	Joint Cores	Regular Cores	P-value
Avg. compaction (%)	92.65	95.16	1.1×10^{-5}
Avg. Indirect Tensile Strength (psi)	95.67	121.71	5.2×10^{-5}
TSR	1.05	0.99	0.41

CHAPTER 4. CONCLUSIONS

Based on the results from the laboratory testing, the following conclusions can be made:

- All the plant produced HMA mixtures used in Londonderry-Chester STP PS19(10) project and Burlington STP projects retained 90-100% of asphalt binder coating based on Texas Rating Board after 10 minutes of boiling. This suggests that these HMA mixtures have low moisture susceptibility based on the ASTM D 3625.
- Adding 10% additional RAP (i.e. up to 30%) to the HMA mix showed same level of asphalt binder retainment as the plant produced HMA mix with 20% RAP. This indicates that the RAP content in the HMA could potentially be increased up to 30% while using ASA and without increasing additional moisture susceptibility. However, more quantitative tests are needed to validate the increase of RAP content.
- The boiling test (ASTM D3625) provided similar results for the laboratory prepared HMA mixture containing stripping prone and non-prone aggregates in the presence of ASA. However, the modified Lottman tests on these laboratory HMA mixtures showed a promising result to quantify the moisture susceptibility of HMA mixture. The TSR value for the HMA mixture with stripping prone aggregate was 0.75 (i.e. below the recommended value of 0.8), while that for HMA mixture with stripping non-prone was 0.94. This suggests that modified Lottman test could be used to get a quantitative result of moisture susceptibility of HMA mixture even in the presence of HMA.
- The insignificant difference in the mass loss during boiling test of HMA mixture containing stripping prone and non-prone aggregate and the insignificant difference in the specific gravity of asphalt binders made the quantification of moisture susceptibility using these approaches unreliable.
- Asphalt cores retrieved from the field had large variation in the compaction level (i.e. [87%-97%]), which is directly correlated to its indirect tensile strength. Joint cores usually exhibited lower percent compaction and indirect tensile strength compared to the regular cores
- The TSR values for majorities of the field retrieved asphalt cores were higher than 0.8 for both one cycle of wet vs dry conditioning and extended cycle of wet vs one cycle of wet condition. This indicates that

one extra cycle of wet conditioning was not able to induce additional damage to the cores compared to only one cycle of wet conditioning.

- The tensile strength of the field retrieved cores was independent of the core thickness, within the range of [1.16, 3.19] inches tested in this study.
- The two tailed t-test showed that there is statistical evidence to support the hypothesis that joint cores in the field exhibited lower compaction and lower indirect tensile strength than the regular cores. However, there was no statistical evidence in the observed difference between average TSR values of joint and regular cores.

CHAPTER 5. RECOMMENDATIONS

Based on the observed results from the laboratory testing of the HMA mixtures and asphalt cores, the followings are recommended while evaluating the moisture susceptibility of the pavements in Vermont roadways projects:

- The MRD-1 and MRD-10 tests may not accurately evaluate the pavement's susceptibility to moisture as they exclude the fine aggregates in the AC. Thus, it is recommended to explore other moisture susceptibility tests such as boiling water test (ASTM D 3625), modified Lottman test (AASHTO T283), Hamburg wheel tracking (AASHTO T 324), etc. to accurately evaluate the moisture susceptibility of HMA mixtures.
- ASTM D3625 test is subjective and qualitative, which could lead to inaccurate results. The quantification of ASTM D3625 using (i) weight of asphalt binder lost during boiling, (ii) specific gravity could lead to unreliable results. Thus, it is recommended to explore other quantifying techniques such as image processing, color analyzing methods of pre- and post-boiled samples.
- Addition of 10% extra RAP (i.e. up to 30 %) showed no additional moisture susceptibility in the HMA mixture compared to the HMA mixture used in the field that contained 20% RAP. More testing, especially quantitative tests such as modified Lottman test, Hamburg wheel tracking test, is required to justify the use of 30% RAP in the HMA mixtures.
- Previous experience in the New England region has shown that some of the HMA that passed the AASHTO T283 have failed in the field from moisture induced damage (e.g. Dave et al.). In this study, all the field retrieved asphalt cores passed the AASHTO T283 specification even when subjected to one extra cycle of Lottman conditioning, suggesting one additional freeze-thaw cycle was insufficient to induce damage in the cores. It is recommended to determine the minimum cycles of Lottman conditioning required to reduce the tensile strength by a significant amount as the HMA used in the field will be subjected to multiple freeze-thaw cycles. Cores produced in the laboratory (i.e. Marshall mold) would be more appropriate for such tests due to less variability in compaction and dimension (especially thickness). These tests could potentially help VTrans to develop a robust specification for testing moisture

susceptibility of the HMA mixtures. In addition, it is recommended to consider using the Moisture Induced Stress Tester (MiST) test to evaluate moisture susceptibility.

- The joint cores showed lower compaction level and hence lower tensile strength than the regular cores. It is recommended that VTrans requires the contractors use more compaction efforts to adequately compact the joints in the pavement.

CHAPTER 6. REFERENCES

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