Terminal Blend Asphalt Rubber Hot Mix
Lowell-Westfield, VT Route 100
Final Report

May 2008

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Reporting on Work Plan 94-R-3

State of Vermont
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Materials and Research Section

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16. Abstract

This report summarizes the implementation and evaluation of a terminal blend asphalt rubber hot mix (ARHM) overlay which was constructed on VT Route 100 in the towns of Lowell and Westfield. The investigation compares the performance of this material to that of a standard overlay in terms of thermal, fatigue, and reflective cracking, as well as rutting, and the international roughness index (IRI).

All sites were examined and measured for these factors and ride roughness prior to the commencement of construction and on a yearly basis.

Throughout the duration of the study the two overlay types performed as near equals, with the ARHM doing slightly better in some respects. Of particular note is the fact that the ARHM was comprised of only around 10% crumb rubber by weight rather than the normally required 15%. It may be logical to assume that if the ARHM had the correct amount of crumb rubber it would have performed somewhat better, especially with regards to elastic properties.

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TABLE OF CONTENTS

INTRODUCTION:

In an effort to reduce growing stockpiles of discarded rubber tires, the Intermodal Surface Transportation Efficient Act (ISTEA) of 1991 required an expanding usage of recycled rubber. According to Section 1038 of the referenced Act, 5% of all asphalt produced during 1994 for use on federally funded projects was to contain a nominal amount of recycled rubber from scrap tires. This percentage was to increase each year by 5% until reaching 20% by 1997 and was to be maintained at 20% each year thereafter. However, the U.S. Secretary of Transportation raised concerns regarding substantial cost increases during production and laydown.

Asphalt rubber, as defined by ASTM D 8-02, “Standard Terminology Relating to Materials for Roads and Pavements,” is “a blend of asphalt cement, reclaimed tire rubber, and certain additives in which the rubber component is at least 15% by weight of the total blend and has reacted in the hot asphalt cement sufficiently to cause swelling of the rubber particles.” As of 1994, there were three primary methods for introducing recycled rubber into the hot mix process; dry blend, wet blend and terminal blending. For this project, crumb rubber was incorporated through the “terminal blend” method where blending with the asphalt binder occurred at an asphalt terminal and was then stored until distribution. Documented benefits of asphalt rubber include increased flexibility resulting in improved resistance to abrasion and fatigue, a reduction in the onset and rate of reflective cracking, reduced traffic noise and increased resistance to rutting. From an environmental perspective, this process reduces the amount of waste tires through recycling (University of California, 2).

However, in the early 1990’s, there was some uncertainty regarding overall performance and cost effectiveness. To address national concerns and assess anticipated advantages, the Vermont Agency of Transportation (VTrans) constructed a 6.8 mile section of asphalt rubber hot mix, or ARHM, along VT Route 100 in the towns of Lowell and Westfield. For comparative purposes, one control section consisting of a standard Marshall overlay treatment was applied in conjunction with the project. Pavement studies to characterize the current condition of the various treatments were conducted prior to and following construction on an annual basis. The following report summarizes the findings from annual data collection efforts and subsequent recommendations for the future placement and implementation of ARHM.

PROJECT DESCRIPTION:

The Lowell/Westfield paving project, F 029-2(11), was constructed in 1994 and began on VT Route 100 at mile marker (MM) 2.864 in the town of Lowell and continued northerly to MM 4.700 in the town of Westfield for a distance of 8.867 miles. In accordance with the plans, this project included resurfacing of the existing highway with a leveling course and wearing course, new pavement markings, signs, drainage improvements and safety improvements.

The experimental section, beginning at MM 4.910 in the town of Lowell and extending to MM 4.700 in the town of Westfield for a total of 6.821 miles, consisted of a 1” leveling course followed by 1.5” of ARHM as the wearing course. The mix design for the ARHM was consistent with a standard 50 Blow Type III Marshall wearing course, which contains a maximum aggregate size of size of 0.50”. The liquid binder utilized for this project was a terminal-blend product, known as Ecoflex, produced by Bitumar Inc. of Montreal, Quebec. As specified, the ARHM liquid binder contained a minimum 10% reclaimed vulcanized tire rubber and exceeded the contract specification for a performance graded (PG) binder of 52-34 through PG 58-46 with a PG grade 64-34. This indicates that the binder should perform satisfactorily at an average 7 day high temperature of 64^{o}C, or 147^{o}F, and an average one day low temperature of -34^{o}C, or -29^{o}F. It bears mentioning that the binder type is believed to be an AC 20 binder, but was identified as an equivalent PG binder. It is important to note that the amount of recycled rubber incorporated into the asphalt cement binder was well below the ASTM definition of 15% as referenced within the “Introduction” section potentially resulting in a stiffer pavement which would be more susceptible to reflective cracking.

The control section, beginning at MM 2.864 and extending to MM 4.910 in the town of Lowell for a total of 2.046 miles, consisted of a 1” leveling course followed by 1.5” of a standard 50 Blow Type III Marshall mix. The binder utilized within the mix was an AC 20, provided by Petro Canada, also of Montreal. Both mixes contained the same gradations and job mix formula with the exception of asphalt content. The ARHM design contained 5.8% of asphalt cement while the standard Marshall overlay contained 5.5%. Production occurred at Pike Industry’s Coventry plant, utilizing a combination of crushed gravel and quarried stone aggregate from Calkins Sand and Gravel. Please refer to Table 1 for a summary of project paving limits.

Lowell-Westfield ARHM Project						
Section Type:	Number of Test Sites:	Mile Marker:	Town:	Mile Marker:	Town:	Distance (mi.):
ARHM Overlay	7	4.910	Lowell	4.700	Westfield	6.821
Standard Overlay	4	2.864	Lowell	4.910	Lowell	2.046

Table 1. Project paving limits

Average Annual Daily Traffic					
Mile Marker	Town	Treatment	1994 AADT	2002 AADT	2006 AADT
1.80-4.39	Lowell	Standard	1810	2500	2400
4.39-4.90	Lowell	Standard	1590	2000	3500
4.90-7.03	Lowell	ARHM	1400	1600	1500
0.00-3.77	Westfield	ARHM	1400	1600	1500
3.77-4.94	Westfield	ARHM	2090	2300	2200

Table 2. AADT for Lowell-Westfield portion of VT 100.

The average annual daily traffic, or AADT, on this section of road in 1994 was 1778 as compared to 1920 in 2006. Tables 2 and 3 provide a summary of the AADT over the length of the project.

Average AADT for Each Treatment			
Treatment	1994	2002	2006
Standard	1700	2250	2950
ARHM	1630	1830	1730

Table 3. Average AADT for each treatment type.

Table 2 depicts the AADT for five sections of the Lowell-Westfield portion of VT 100 for three different years, 1994, 2002 and 2006. The first two segments, MM 1.80 through MM 4.90 in Lowell, are within the control treatment while the final three, MM 4.90 in Lowell through MM 4.94 in Westfield, are in the experimental treatment. Table 3 provides average AADT based on treatment type. It is important to note that the standard (control) treatment consistently has a higher AADT as compared to the experimental treatment. Therefore, the control section would have been more susceptible to load induced fatigue. This assumes however, that the percentage of truck traffic traveling over the two treatments is consistent. The Traffic Research Section was contacted to attain information pertaining to equivalent single axle loads (ESALs) and truck traffic over the duration of the investigation. However, this information is not available. While traffic monitoring was conducted, it was only collected at one location in Westfield. Further traffic data can be found in Appendix A.

A summary of preconstruction pavement distresses along with mix production and associated test results are provided with an initial report entitled, “Terminal Blend Asphalt Rubber Binder, Lowell-Westfield, VT Route 100,” 94-9. Of special note are the comparatively advanced preconstruction pavement distresses within the ARHM section which will be discussed in detail within the following sections. Testing performed during mix production indicated a product of reasonably consistent quality with a failure rate of 3% due to deficiencies in the allowable air voids. The concentration of fumes caused some of the workers to complain. It was estimated that rubber from roughly 6000 passenger car scrap tires was recycled during this project.

HISTORICAL INFORMATION:

As with any surface treatment, the overall success of a pavement is often dictated by the underlying structure. Insufficient lateral support may cause fatigue cracking or rutting. An impervious media coupled with surface cracks, allows for further infiltration leading to freeze-thaw cracking which has been shown to compound thermal cracking. Therefore, it is important to examine the history of the pavement structure as well as the underlying soils that support the overall roadway structure. According to historical data, the subbase consists of 12 to 18” of gravel. Unfortunately, there is little additional information concerning original construction.

This area received a standard bituminous overlay in 1948, although little is known of the treatment type or exact thickness.

Historical records indicate that this area was rehabilitated twice before 1994. With respect to the town of Lowell, this length of VT Route 100 received a 0.75" bituminous concrete overlay in 1978 and a 1" plant mix treatment in 1985 as shown in Figure 1. In Westfield, a 0.75" and 1" plant mix was applied in 1978 and 1985, respectively as depicted in Figure 2. The diagrams assume that no cold planning occurred during any rehabilitation efforts.

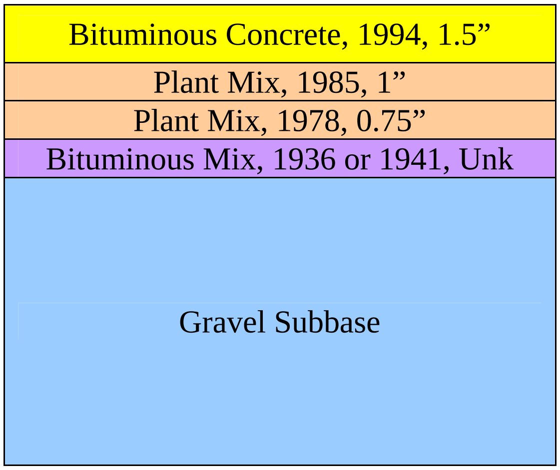

Figure 1. Lowell, MM 2.864 to 7.031

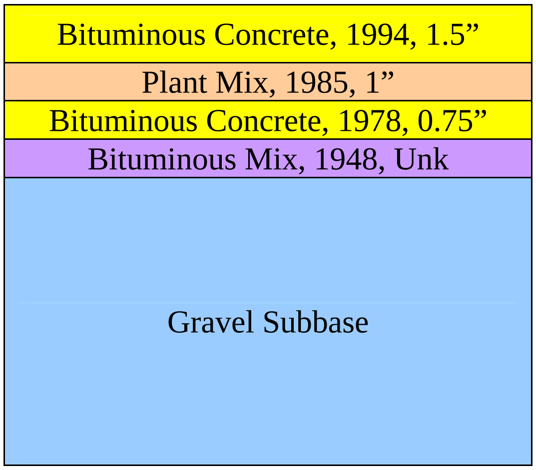

Figure 2. Westfield, MM 0.000 to 4.942

The soils underlying the roadway, as provided by the Natural Resources Conservation Service, primarily consist of a sandy loam and display generally moderate to high drainage capacities. Even though the drainage capacities are sufficient, many of the types of soils are susceptible to frost action, therefore freeze-thaw cycles may be a factor in this area. Of particular note is the difference between frost action classifications between the four test sites with a standard overlay and the seven within the ARHM overlay. The standard overlay section is comprised of soils that have low frost action, in general, whereas the experimental section has moderate to high frost action soils, as can be seen in Appendix B. This is of importance when considering factors that contribute to thermal cracking.

PERFORMANCE:

Cracking, rutting, and IRI values are often utilized to assess the performance and service life of pavement treatments or in this case differing rehabilitation efforts. It has been shown that the surface condition of a pavement is directly correlated to its structural condition. Surface condition is non-linear, characterized by different rates of deterioration. The following is an examination of the surface condition of both the experimental and control pavements.

A total of eleven test sites were established throughout the length of the project. Of these eleven test sites, four sites were located within the control section and seven sites were identified within the experimental section as shown in Table 1. Each test site consisted of a length of 100’ in the direction of travel and were approximately 22’ wide encompassing both the north and southbound lanes. Generally, each test site was examined annually for cracking, rutting, and IRI. Figure 3 and 4 below depict a typical test site within a control and experimental treatment area 13 years following construction.

Figure 3. Test Site 4 (Standard Overlay)

Figure 4. Test Site 11 (ARHM)

CRACKING

Inadequate structural support such as the loss of base, subbase or subgrade support, an increase in loading, inadequate design, poor construction, or poor choice of materials can result in cracking in flexible pavements. For this analysis, longitudinal, transverse and reflective cracking were examined. Longitudinal cracks run parallel to the laydown direction and are usually a type of fatigue or load associated failure. Transverse cracks run perpendicular to the pavement’s centerline and are usually a type of critical-temperature failure or thermal fatigue that may be induced by multiple freeze-thaw cycles. Reflection cracks occur from previous cracking that may exist within the base course, subbase or subgrade material that propagates through the wearing course. In all cases, the cracks allow for moisture infiltration and can result in structural failure over time.

Pavement condition surveys of each test section were conducted annually in accordance with the “Distress Identification Manual for the Long-Term Pavement Performance Program” published in May of 1993 by the SHRP. Crack data was collected by locating the beginning of each test section, often keyed into mile markers or other identifiable land marks. The test section was then marked at intervals of 10’ from the beginning of the test section for a length of 100’. Pavement surveys involved hand drawing the length and locations of cracks on a data collection sheet with a grid representing the 100’ test section. The information was then processed and the total length of transverse, longitudinal, centerline, miscellaneous, and reflective cracks were recorded on the data collection sheet. Failure criterion for this analysis is the point at which post construction cracking surpasses preconstruction cracking. Data presented in Sections I through IV below represent averaged values for all test sites with consideration to specific treatments. Complete cracking data can be found in Appendix C.

I. Fatigue Cracking

The following assessment began with examining longitudinal or fatigue cracking. As indicated by the “Distress Identification Manual”, fatigue cracking occurs in areas subjected to repeated traffic loading, or wheel paths. Fatigue cracking may be a series of interconnected cracks in early stages of development that progresses into a series of chicken wire/alligator cracks in later stages. For this investigation, the wheel paths were determined to be three feet in width with the center of the left and right wheel path 3.5’ and 8.5’ from the centerline, respectively on either side of the roadway. An important parameter considered during the pavement design process is a wheel load characterized as an ESAL, or equivalent single axle load. An ESAL is defined by Clemson University as “the effect on pavement performance of any combination of axle loads of varying magnitude equated to the number of 80-kN (18,000-lb.) single-axle loads that are required to produce an equivalent effect.” Basically, pavements are designed to structurally support traffic loads which are often calculated by AADT or ESALs with regards to roadway use. ESAL information was not available for this investigation. Therefore a comparison between average cumulative fatigue cracking of the experimental and control sections vs. AADT is provided in Figure 5 below. Averages were calculated by adding up all of the recorded linear feet of cracking of each test section within one of the two mix types and dividing by the total number of test sections.

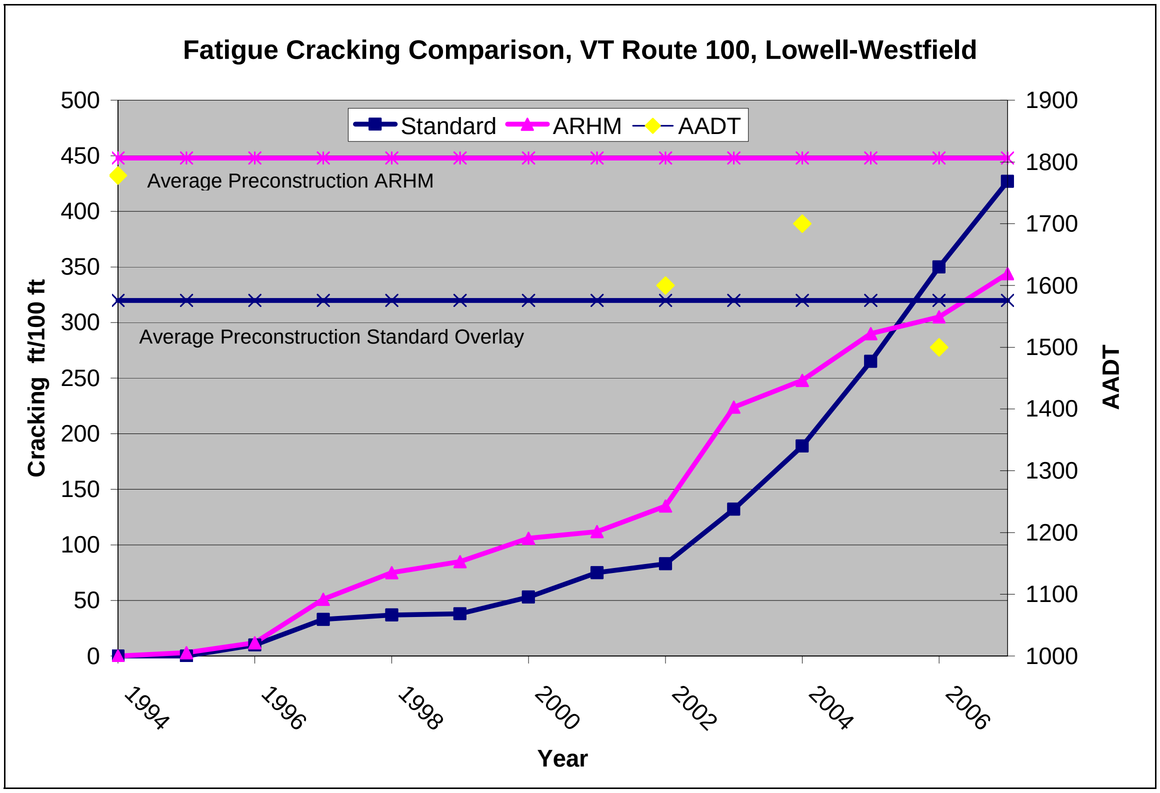

Figure 5. Fatigue Cracking VT 100 Lowell-Westfield

As shown above in Figure 5, there are no significant differences in the condition of the road with respect to total fatigue cracking. However, as stated within the "Project Description" section, the standard section received roughly 33% more traffic on average over the study duration as compared to the experimental section. Therefore, it is easy to presume that the control section should display more fatigue related distresses following construction. Yet, the experimental section originally displayed a much greater amount of fatigue cracking as recorded during the preconstruction survey at a rate of roughly 46% greater than the standard section. This could indicate that the pavement structure below the experimental section is not sufficiently designed to withstand current loading and may not be a reflection performance of the wearing course. In either case the standard overlay reached preconstruction cracking at 11 years of service while the ARHM has yet to meet preconstruction values. This difference is significant, extrapolating to a 40 percent increase in pavement life.

The percentage of truck traffic has a large impact on road deterioration. A heavier truck will cause a greater amount of fatigue related damage as compared to a light weight vehicle such as a passenger car. In order to examine some of the inferences stated above, the percentage of truck traffic recorded on VT Route 100 is summarized in Table 4. The data presented in the table below collected from a traffic monitoring station in the town of Westfield every even year between 1994 and 2004. The number of cars in each FHWA classification was recorded every hour for a period of a week during summer months. Trucks are considered all vehicles that are two axle, six tire single units and larger, including buses. All data was recorded from a single station along the experimental portion of the project.

Percentage Truck Traffic on VT100 in Westfield			
Year	Northbound	Southbound	Total
Precon.	11.8	11.8	11.8
1996	8.2	7.8	8.0
1998	8.7	7.6	8.2
2000	8.6	7.8	8.2
2002	8.0	8.2	8.1
2004	10.1	11.3	10.7

Table 4. Percentage of traffic that are trucks on VT100 in Westfield**.**

As shown in the table, preconstruction values reveal that roughly 12% of all traffic on the roadway, both north and southbound lanes, was classified as truck traffic. The values dropped about 3% for the following 8 years. In 2004 there was a marked upswing in the truck traffic, above 10%. This upswing coincides with a dramatic increase in the amount of fatigue cracking across all test sections along the control and experimental treatments, as shown in Figure 5.

II. Thermal Cracking

The formation of transverse cracking is largely due to climatic conditions and is often induced by freeze-thaw cycles or maximum low temperature shrinkage cracking. Thermal cracks are perpendicular to the centerline and the shoulder. In addition to the comparison of the cumulative transverse cracking between the experimental and control sections, monthly average minimum temperatures were attained from a weather station that resides in Morrisville VT, and are provided in Figure 6.

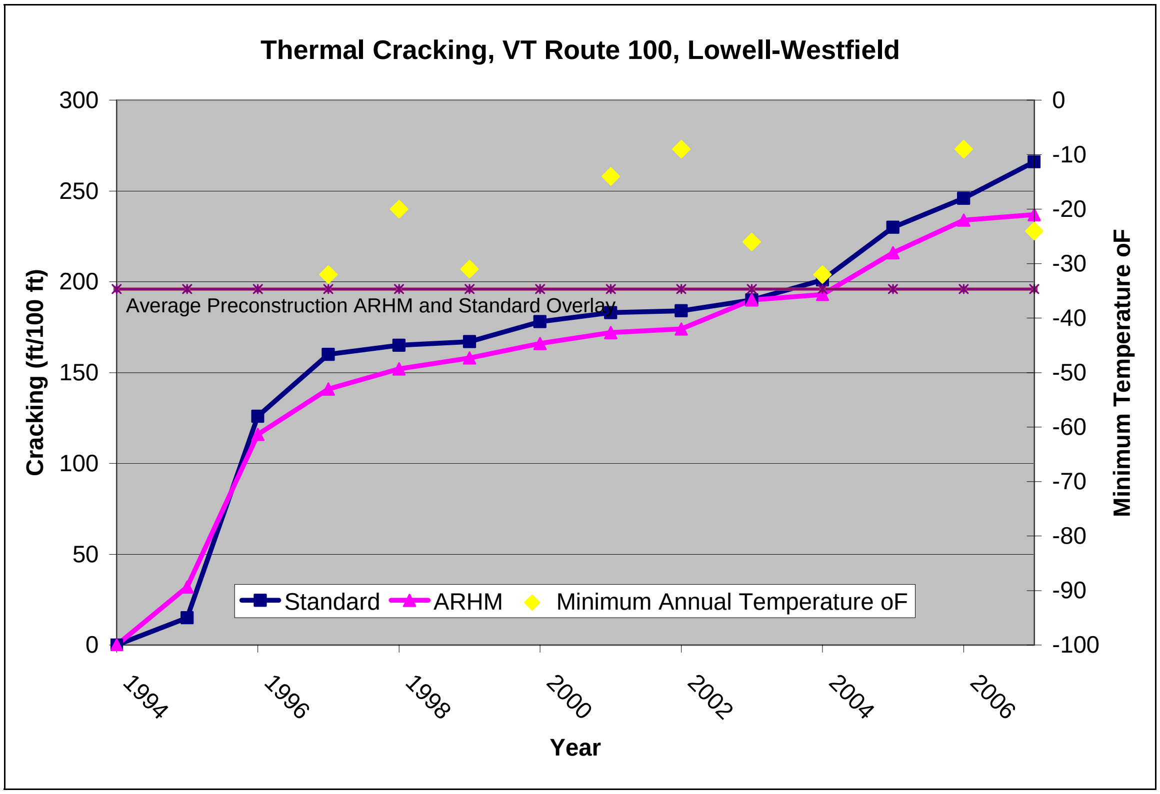

Figure 6. Thermal Cracking VT 100 Lowell-Westfield.

In examining Figure 6 above, it is interesting to note that the amount of preconstruction thermal cracking is the same for both the experimental and control sections. Even more interesting is the fact that the onset and rate of thermal fatigue cracking is approximately the same regardless of the pavement treatment. This indicates that both asphalt binders, the PG 64-34 within the ARHM section and AC 20 within the standard overlay section, performed similarly over the study duration. In addition, there were at least three occurrences when minimum ambient air temperatures fell below specifications, -32^{o}F in 1997, -31^{o}F in 1999 and -32^{o}F in 2004. However, there does not appear to be a large increase in thermal cracking following these events which suggests that the PG binder is performing beyond specified limits. A large increase in thermal cracking is observed between 1995 and 1996, only 1 to 2 years following construction. Unfortunately, ambient temperature data is not available for this timeframe. Both pavement treatments exceeded preconstruction levels in 2004, 10 years following construction.

III. Reflective Cracking

According to Dr. Beatriz Martin-Perez of the National Research Council of Canada, reflective cracking is defined as “the propagation of cracks from the existing pavement into the layer of pavement added (overlay) during rehabilitation.” As stated within the “Project Description” section above, the project used a standard overlay. Since this process doesn’t involve the removal of the preexisting pavement it is much more likely to observe reflective cracking with a standard overlay as compared to a reclaimed stabilized base or other reconstruction treatments. The determination that a crack is reflective is made by examining the cracks in the test section as compared with cracks in the preconstruction pavement within the same test section length.

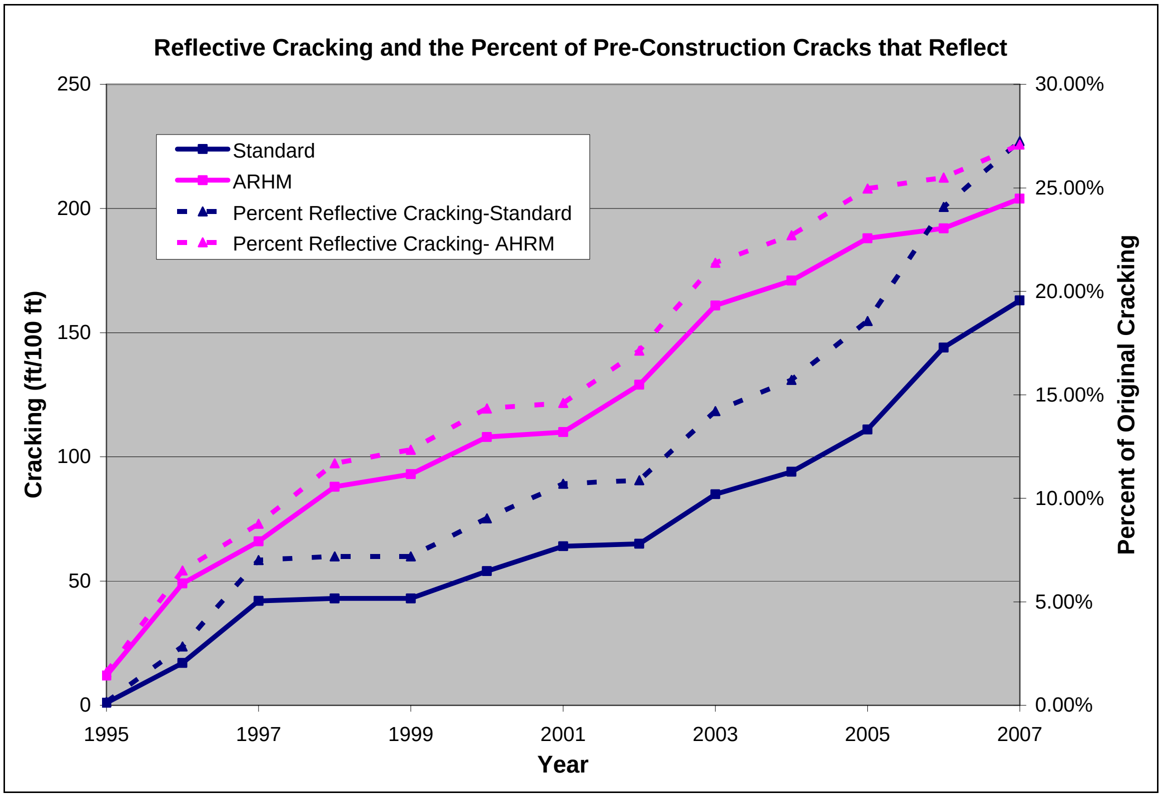

Figure **7**. Reflective Cracking VT 100 Lowell-Westfield **as a percent of pre-construction cracking**.

The amount of reflective cracking depends on the total amount of cracking observed during the preconstruction survey. It is important to note that a much greater amount of cracking was observed within experimental section as compared to the control section. This means that one would expect a greater occurrence of reflective cracking in the ARHM to occur, as is the case. Therefore, the percentage of pre-construction cracks that reflect has been introduced. This includes data that is more relative and provides a more representative comparison. This is calculated simply by dividing the length of reflective cracks observed for a given year by the length of original cracking observed during the pre-construction site visit. As shown in Figure 7, a greater percentage of pre-construction cracks have appeared through the ARHM over time, with the two dotted-line plots finally converging in 2007, where the percentage of reflective cracking showing in both of the current pavement treatments have become equal. This suggests that the ARHM may be more susceptible to reflective cracking than standard overlays. Conversely, the ARHM section may have been more susceptible to cracking due to the underlying soil structure, subgrade or subbase, such as the greater incidence of high frost action soils as noted earlier. Overall, both pavements are performing adequately as only approximately 27 percent of the preexisting cracks have propagated through the wearing course 12 years following construction.

A second methodology in tracking reflective cracking is shown in Figure 8. The percentage axis and data series represent the percent of total cracks for a given year that actually are reflective cracks. This is computed by dividing the length of reflective cracking for a particular year by the total length of cracking for that year.

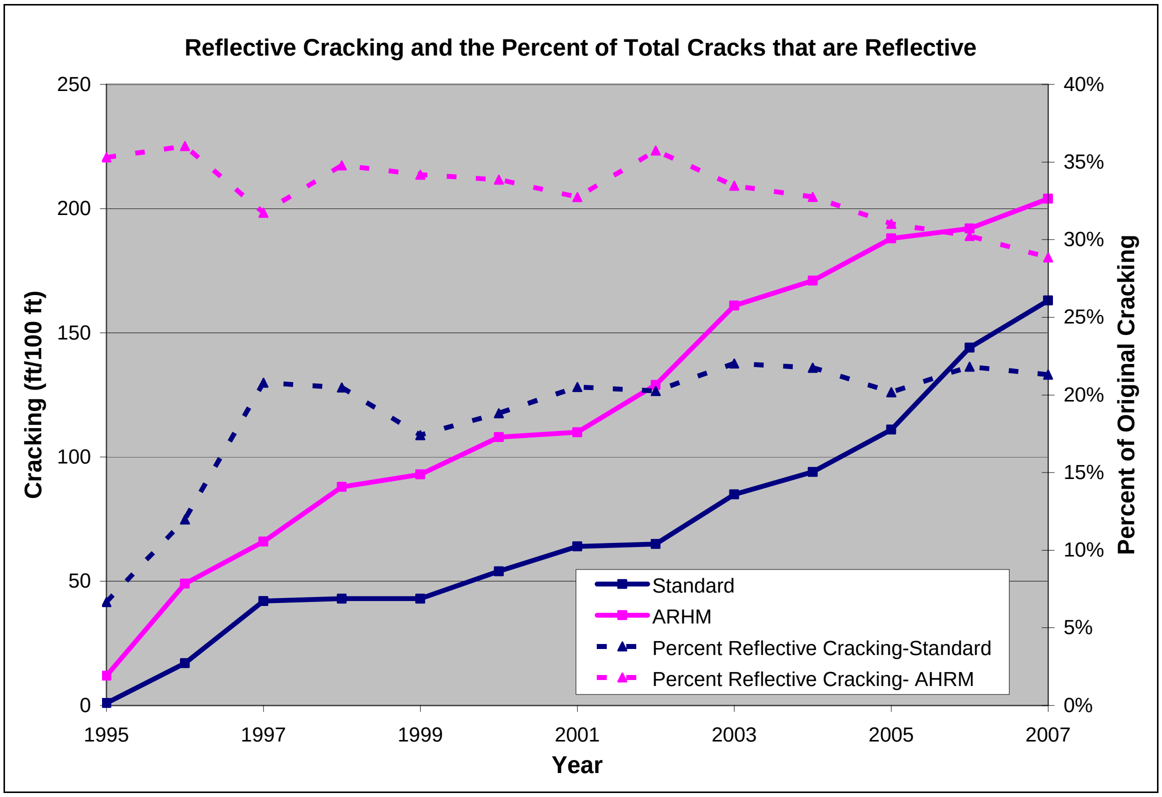

Figure 8. Reflective Cracking VT 100 Lowell-Westfield as a percent of total cracking.

It is generally accepted that the percentage of reflective cracking to increases rapidly during the first few years of a new surface, then level out to a consistent rate throughout the remainder of its life. This is the case with the standard overlay through to the present time. The amount of reflective cracking increased from about 7% to 22% within the first 3 years, and has remained around the 22%. This is not the case for the experimental section; it started at a high level of 35% cracking and remained near this point until the past 4years, at which time it has started a slight decline. This, along with the fact that it has displayed on average roughly a 10% higher ratio of reflective cracking than the standard overlay, is evidence that it did not take on the extra flexibility from the crumb rubber as was expected. This may support the importance of the minimum prescribed dose of 15% crumb rubber in a mix, rather than the only 10% that was actually used on this project.

RUTTING

Rutting is caused by permanent deformation within any of the pavements layers or subgrade and is usually caused by consolidation or lateral movement of the materials due to traffic loading. Throughout the duration of the investigation a rut gauge was utilized to quantify the overall depth of rut within each test section. This was done by collecting rut measurements at 50’ foot intervals from the beginning to the end of each test section. The measurement was collected by extending a string across the width of the road and measuring the vertical length between the string and the deepest depression within all wheel paths identified along the length of the string. All measurements were recorded onto a standard field form in 1/8” intervals. It is important to note that this procedure is highly subjective due to the nature of the data collection procedure. Table 5 below displays the rutting data that was collected throughout the duration of the investigation. Complete rutting data can be found in Appendix D.

Average Rutting Readings, in inches, for VT Route 100, Lowell-Westfield

Year	SB Right WP		SB Left WP		NB Left WP		NB Right WP	
	Standard	ARHM	Standard	ARHM	Standard	ARHM	Standard	ARHM
Preconstruction	0.35	0.41	0.22	0.26	0.39	0.26	0.45	0.52
1994	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1995	0.01	0.03	0.00	0.00	0.00	0.01	0.01	0.01
1996	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.02
1997	0.08	0.05	0.01	0.00	0.07	0.01	0.03	0.05
1998	0.05	0.08	0.03	0.02	0.04	0.05	0.02	0.10
1999	0.00	0.09	0.03	0.04	0.04	0.05	0.00	0.09
2000	0.10	0.14	0.14	0.13	0.17	0.17	0.10	0.15
2001	0.15	0.17	0.15	0.15	0.24	0.18	0.15	0.16
2002	0.17	0.19	0.17	0.13	0.25	0.16	0.15	0.21
2003	0.21	0.26	0.22	0.23	0.36	0.26	0.17	0.27
2004	0.08	0.21	0.36	0.20	0.10	0.15	0.07	0.21
2005	0.21	0.20	0.41	0.23	0.19	0.20	0.25	0.20
2006	0.33	0.37	0.66	0.30	0.25	0.27	0.28	0.35
2007	0.25	0.40	0.55	0.33	0.24	0.26	0.28	0.38
Percent of Preconstruction	72	98	250	127	62	100	62	73

Table 5. Rutting data.

In general the rut values increase each year during the study with few exceptions. As stated above, the testing method is interpretive and includes small fluctuations. However, some of the data from 2004 appears to be erroneous as the depth of rut decreases significantly in some of the test locations, without any known cause. According to the project history extracted from the “Pavement Management

Database", there was no record of a "rut fill" at any point during the investigation period.

As mentioned previously, as of the most recent AADT figures, the control sections have considerably higher number of vehicles traveling on them as compared to the experimental sections, 2400 to 1500 respectability. Since this is the main contributor to rutting, it would be expected that the standard overlay sections would display a greater amount of rutting. However, in examining the data sets, the converse relationship appears to be true as the standard overlay section displayed an average of 112 percent of preconstruction rutting across the full lane width as compared to 100 percent within the referenced experimental section. This is a somewhat significant increase at 12 percent comparatively. However, this finding is biased by the extreme amount of rutting within the southbound left wheel path in the control section.

It is also interesting to note that the inner wheel paths displayed a great amount of rutting at 135 percent of preconstruction as compared to the outer wheel paths at 76 percent of preconstruction. This is counterintuitive as one would expect lateral consolidation to occur along the outer wheel paths due to a reduction in structural support. Additionally, the original rut depth was much greater in the outer wheel paths at 0.43 inches as compared to 0.28 inches in the inner wheel paths. This may be due to laydown and consolidation techniques. For example, there is no specification for compaction of the leveling course. Therefore, inadequate compaction of the leveling course may result in accelerated consolidation following construction. However, there is no physical evidence to support this theory. There was also a greater amount of rutting in the southbound lane at 137 percent of preconstruction as compared to 74 percent of preconstruction in the northbound lane. This is also somewhat counterintuitive as the amount of truck traffic is slightly greater in the northbound lane with the exception of 2006.

IRI

IRI, or International Roughness Index, is utilized to characterize the longitudinal profile within wheel paths and constitutes a standardized measurement of smoothness. According to Better Roads Magazine, "the pavement's IRI in inches per mile measures the cumulative movement of the suspension of the quarter-car system divided by the traveled distance. This simulates ride smoothness at 50 miles per hour." IRI values are directly correlated to pavement distresses. IRI values were collected on an annual basis from 1994 through 2007 with the exceptions of 1999, 2005, and 2006 through the Pavement Management Section of VTrans utilizing road profilers. Please note that the data was collected by different vendors through the investigation which resulted in poor correlation between collection events. Figure 9 provides a summary of the IRI data, while complete IRI data can be found in Appendix E.

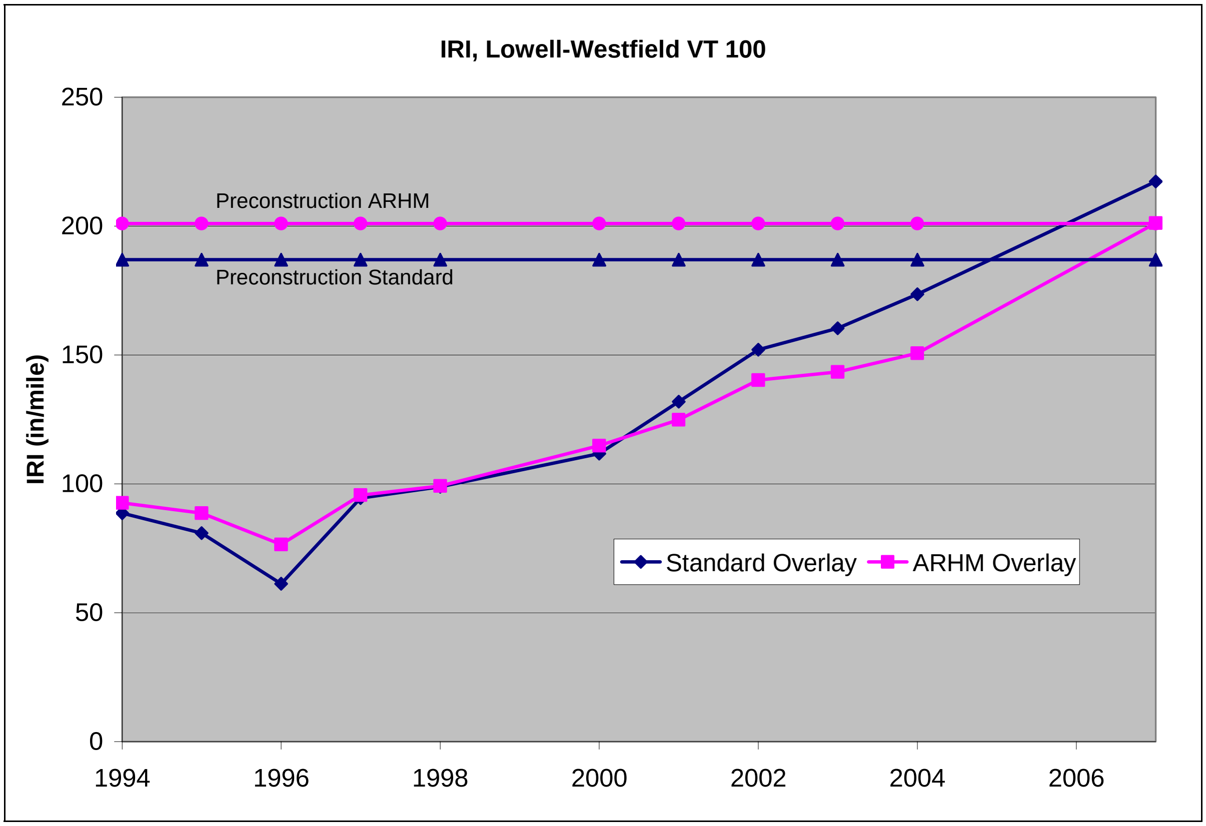

Figure 9. IRI data.

There are some discontinuities within the data set. Usually IRI values are at a minimum immediately following construction as the pavement condition is optimum and will then degrade over time. Therefore, it was anticipated the there would be an upward trend throughout the years of data collection. However, in this project the IRI values fluctuated for the first few years before settling into the pattern of increasing values. The initial IRI values in 1994 (year 0, shortly after project completion) are higher than those from 1995 and 1996. These discrepancies are most likely caused by a variation in testing equipment and calibration methods. It may also be a response from the underlying pavement condition due to frozen conditions increasing the IRI values. However, all IRI values were collected from June through August when the underlying structure would not be subjected to freezing conditions.

There is a general upward trend in the IRI values between 1996 and 2007 for both the experimental and control sections. The values have approximately doubled in the first 10 years of the pavement lifespan. The ARHM overlay seems to exhibit a lower average increase in roughness than the standard overlay, however the standard is on the portion of the road with the higher AADT. From this data, one can conclude that both overlays, as well as both northbound and southbound directions, performed as near equals, as all trends within the graph are consistent to each variable.

The IRI values recorded in 2007 are 217 in/mile for the standard overlay and 201 in/mile for the ARHM overlay. These are considered fairly high values. According to a figure published in "The Little Book of Profiling, Basic Information about Measuring and Interpreting Road Profiles", these values fall in the middle of the 'Older Pavement' range and is quickly approaching the value (around 300) which describes a road as having 'Surface Imperfections'. The standard overlay section exceeded preconstruction values between 2005 and 2006, roughly 11 years following construction. The ARHM section has yet to exceed preconstruction values.

STATISTICAL SIGNIFICANCE:

In order to quantify the statistical significance of the findings above, a non-parametric test was utilized for assessing whether two samples of observations come from the same distribution, known as the Mann-Whitney-Wilcoxon Test. This test does not rely on the assumption of normality and can be applied to small sample sizes. The null hypothesis assumes that the two samples are drawn from a single population and that their probability distributions are the same. The various forms of cracking (total, fatigue, thermal and reflective), as well as rutting were evaluated prior to and thirteen years following construction utilizing an alpha value of 0.05, a common value in statistics. In all cases, the control and experimental populations were found to be equivalent. This means that there is no statistically significant difference in the pavement cracking or rutting prior to or thirteen years following construction and basically implies that both treatments performed similarly. A copy of all non-parametric test data is supplied in Appendix F.

COSTS:

The cost of the experimental pavement at the time of construction was \$4.90 per square yard. This included a cost of \$3.16/yd^2 for the 1.5" overlay of ARHM and \$1.74/yd^2 for the 680 ton/mile leveling course. The cost of the control section was \$4.49 per square yard. This included a cost of \$2.75/yd^2 for the 1.5" standard overlay and \$1.74/yd^2 for the same 680 ton/mile leveling course. The difference between the two materials was \$0.41 per square yard in 1994, or roughly \$5300 more per mile of road for the asphalt rubber hot mix. According to a recent report from the Turner-Fairbank Highway Research Center's website concerning asphalt rubber hot mix, the cost for ARHM is roughly 1.5 to 2.0 times greater as compared to conventional asphalt.

SUMMARY:

To address national concerns and assess anticipated advantages, the Vermont Agency of Transportation constructed a 6.8 mile section of asphalt rubber hot mix, or ARHM, along VT Route 100 in the towns of Lowell and Westfield. Reported benefits of ARHM include improved resistance to abrasion and fatigue, a reduction in the onset and rate of reflective cracking, reduced traffic noise and increased resistance to rutting. Testing performed during mix production indicated a product of reasonably consistent quality with a failure rate of 3% due to deficiencies in the allowable air voids. The concentration of fumes caused some of the workers to complain. It was estimated that roughly 6000 passenger car scrap tires were recycled during this project.

For comparative purposes, one control section consisting of a standard Marshall overlay treatment was applied in conjunction with the project. Pavement studies to characterize the current condition of the various treatments were conducted prior to and following construction on an annual basis. With respect to data collection efforts, the experimental asphalt rubber hot mix overlay and the standard asphalt overlay performed as near equals. Table 6 below summarizes the years in which each of the treatments failed with respect to each of the quantified elements. Failure is considered to have occurred when the post-construction values exceed the preconstruction values. N/A represents the fact that the treatments have not yet met the failure criterion for the given performance characteristic.

Age, in years, When Failure Occurred		
Performance Characteristic	Standard Overlay	ARHM Overlay
Fatigue Cracking	12	(15)
Thermal Cracking	10	11
Environmental Cracking	11	11
Reflective Cracking	n/a	n/a
Total Cracking	12	(14)
Rutting	12	(14)
IRI	11	13

Table 6. Failure ages of the two overlay types for all performance criteria. (#) indicates an expected outcome.

An examination of fatigue cracking reveals that the standard overlay reached preconstruction cracking at 11 years of service while the ARHM has yet to meet preconstruction values. Additionally, the experimental section originally displayed a much greater amount of fatigue cracking which could indicate that the pavement structure below the experimental section is not sufficiently designed to withstand current loading. With consideration to thermal cracking, the onset and rate is approximately the same regardless of the pavement treatment. This indicates that both asphalt binders, the PG 64-34 within the ARHM section and AC 20 within the standard overlay section, performed similarly over the study duration. Reflective cracking was more prominent within the experimental section at an average increase of 5% as compared to the control section over the life of the pavements.

Other forms of assessing pavement performance include rutting and the International Roughness Index, or IRI. The standard overlay section displayed an average of 112 percent of preconstruction rutting across the full lane width as compared to 100 percent within the ARHM section 13 year following construction. However, this finding is biased by the extreme amount of rutting within the southbound left wheel path in the control section. Of significance is the greater amount of rutting within the inner wheel paths as compared to the outer wheel paths, 135 and 76 percent, respectively, especially because there was a greater amount of rutting within the outer wheels paths prior to construction. This may be due to laydown and consolidation techniques and additional examination of this phenomenon is warranted. With respect to IRI, the treatments once again perform similarly. The ARHM performed better throughout the study, with a 2007 average of 179 to 207 in/mile at the 13 year mark of the study.

Also of note is that the portion of VT 100 with the control section (standard overlay) has significantly higher AADT than the experimental section, currently at 2400 and 1500 respectively. Therefore it is expected that given identical treatments on both sections, the current control section would display higher roughness, rutting, and amounts of cracking, as higher volumes of traffic contribute greatly to all of these ailments. Since all of the data is relatively close in all aspects of testing, it is reasonable to conclude that the standard overlays most likely would perform equally to the experimental ARHM sections if all variables were equal, especially given that the ARHM is roughly 11 % or $5300 more per linear mile of roadway.

As noted earlier, different binders were used in each of the two treatment types; the ARHM binder was a PG 64-34 while the control was an AC 20. For consistency in analysis, the same binder should have been used (if possible) in order to eliminate a very important material variable. Additionally, in accordance with ASTM, asphalt rubber is defined by at least 15% by weight of the total blend. However, only 10% by weight was incorporated into the terminal blend operation. It is recommended that rubber content be determined in accordance with industry standards in order to achieve the full benefit of the binder modification.

Given that there would appear to be no disadvantage (based on the aspects of this study) to placing an asphalt rubber hot mix overlay, one needs to give thought to the one major advantage that it does have over standard overlays. Given the fact that scrap tires are recycled and placed into this type of asphalt, thus recycling an energy consumptive product, it is a very practical and possibly necessary technology. In the future designers will have to decide whether the increase in cost outweighs any environmental advantages this type of product accrues.

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The Little Book of Profiling, Basic Information about Measuring and Interpreting Road Profiles, Michael W. Sayers and Steven M. Karamihas, The Regent of the University of Michigan, September 1998.

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Appendix A

Traffic Data, VT 100, Lowell-Westfield

Town	Mile Marker From To	Treatment	Length	AADT		
				2002	2004	2006
Lowell	MM 1.804 - MM 4.388	Stand.	2.584	2500	2400	2400
Lowell	MM 4.388 – MM 4.896	Stand.	0.508	2000	1900	3500
Lowell	MM 4.896 – MM 7.031	ARHM	2.135	1600	1700	1500
Westfield	MM 0.000 – MM 3.774	ARHM	3.774	1600	1700	1500
Westfield	MM 3.774 – MM 4.942	ARHM	1.168	2300	2400	2200
Weighted AADT			10.169	1900	2000	1900

Example Weighting Formula, for 2006:

$$\frac{(2400 \times 2.584) + (3500 \times 0.508) + (1500 \times 2.135) + (1500 \times 3.774) + (2200 \times 1.168)}{2.584 + 0.508 + 2.135 + 3.774 + 1.168} = 1900$$

Appendix B

Primary Soil Types at Each Test Site

Overlay		Soil Name	Soil Number	Frost Action
Standard	TS1	Colton-Duxbury complex	38E	Low
	TS2	Silt loam, frequently flooded	72A	High
	TS3	Gravelly fine sandy loam	31A	Low
	TS4	Gravelly fine sandy loam	31A	Low
ARHM	TS5	Adams loamy fine sand	26B	Low
	TS6	Dixfield sandy loam	15C	High
	TS7	Nicholville very fine sandy loam	5B-C	High
	TS8	Tunbridge-Lyman complex, very rocky	12D	Moderate
	TS9	Irasburg loamy fine sand	14C	Moderate
	TS10	Roundabout silt loam	8A	High
	TS11	Irasburg loamy fine sand	14A	Moderate

Appendix C

Crack Counts in feet, VT 100, Lowell-Westfield

Control Section, Standard Overlay					
Preconstruction	**Thermal**	**Fatigue**	**Reflective**	**Longitudinal**	**Total**
TS1	191	202	N/A	152	415
TS2	115	266	N/A	367	575
TS3	207	347	N/A	417	654
TS4	270	463	N/A	477	747
Post Construction	**Thermal**	**Fatigue**	**Reflective**	**Longitudinal**	**Total**
TS1	0	0	0	0	0
TS2	0	0	0	0	0
TS3	0	0	0	0	0
TS4	0	0	0	0	0
Year 1	**Thermal**	**Fatigue**	**Reflective**	**Longitudinal**	**Total**
TS1	37	0	0	0	37
TS2	0	0	0	0	0
TS3	7	0	5	0	7
TS4	15	0	0	0	15
Year 2	**Thermal**	**Fatigue**	**Reflective**	**Longitudinal**	**Total**
TS1	163	32	45	41	204
TS2	41	0	0	6	47
TS3	172	2	44	7	179
TS4	127	4	20	9	136
Year 3	**Thermal**	**Fatigue**	**Reflective**	**Longitudinal**	**Total**
TS1	201	56	65	70	271
TS2	68	0	3	9	77
TS3	226	31	71	36	262
TS4	146	46	28	53	199
Year 4	**Thermal**	**Fatigue**	**Reflective**	**Longitudinal**	**Total**
TS1	210	59	65	76	286
TS2	68	0	3	21	89
TS3	226	31	71	36	262
TS4	154	57	32	48	202
Year 5	**Thermal**	**Fatigue**	**Reflective**	**Longitudinal**	**Total**
TS1	213	59	65	83	296
TS2	68	0	3	91	159
TS3	231	36	71	96	327
TS4	154	57	32	51	205
Year 6	**Thermal**	**Fatigue**	**Reflective**	**Longitudinal**	**Total**
TS1	237	62	89	86	323
TS2	87	17	14	126	213
TS3	231	56	73	146	377
TS4	158	78	41	78	236
Year 7	**Thermal**	**Fatigue**	**Reflective**	**Longitudinal**	**Total**
TS1	244	108	107	135	379
TS2	87	17	14	126	213
TS3	233	96	92	176	409
TS4	167	78	44	78	245
Year 8	**Thermal**	**Fatigue**	**Reflective**	**Longitudinal**	**Total**
TS1	244	124	109	151	395
TS2	87	21	14	130	217
TS3	236	109	92	189	425
TS4	167	78	44	78	245
Year 9	**Thermal**	**Fatigue**	**Reflective**	**Longitudinal**	**Total**
TS1	244	205	115	240	484
TS2	90	52	32	180	270
TS3	246	133	100	222	468
TS4	180	137	91	140	320
Year 10	**Thermal**	**Fatigue**	**Reflective**	**Longitudinal**	**Total**

TS1	256	252	127	292	548
TS2	98	158	35	194	292
TS3	259	184	120	273	532
TS4	191	161	92	164	355
Year 11	**Thermal**	**Fatigue**	**Reflective**	**Longitudinal**	**Total**
TS1	284	295	127	348	632
TS2	118	218	53	268	386
TS3	301	324	150	433	734
TS4	218	223	112	229	447
Year 12	**Thermal**	**Fatigue**	**Reflective**	**Longitudinal**	**Total**
TS1	299	365	138	418	717
TS2	146	322	95	394	540
TS3	314	451	200	576	890
TS4	223	263	141	269	492
Year 13	**Thermal**	**Fatigue**	**Reflective**	**Longitudinal**	**Total**
TS1	317	423	148	479	796
TS2	156	377	111	452	608
TS3	351	605	241	749	1100
TS4	239	302	150	316	555

Experimental Section, ARHM Overlay					
Preconstruction	**Thermal**	**Fatigue**	**Reflective**	**Longitudinal**	**Total**
TS5	178	388	N/A	407	630
TS6	192	566	N/A	688	1045
TS7	241	520	N/A	503	744
TS8	149	277	N/A	286	483
TS9	141	511	N/A	626	775
TS10	181	306	N/A	513	694
TS11	288	570	N/A	56	903
Post-construction	**Thermal**	**Fatigue**	**Reflective**	**Longitudinal**	**Total**
TS5	0	0	0	0	0
TS6	0	0	0	0	0
TS7	0	0	0	0	0
TS8	0	0	0	0	0
TS9	0	0	0	0	0
TS10	0	0	0	0	0
TS11	0	0	0	0	0
Year 1	**Thermal**	**Fatigue**	**Reflective**	**Longitudinal**	**Total**
TS5	0	0	0	0	0
TS6	43	19	17	19	62
TS7	53	0	4	0	53
TS8	6	0	3	0	6
TS9	48	0	48	0	48
TS10	71	0	15	0	71
TS11	1	0	0	0	1
Year 2	**Thermal**	**Fatigue**	**Reflective**	**Longitudinal**	**Total**
TS5	102	0	63	0	102
TS6	101	65	46	65	166
TS7	122	0	11	8	130
TS8	61	7	52	33	94
TS9	119	1	102	1	120
TS10	142	6	31	23	165
TS11	168	2	36	7	175
Year 3	**Thermal**	**Fatigue**	**Reflective**	**Longitudinal**	**Total**
TS5	148	16	28	30	178
TS6	121	127	73	127	248
TS7	144	14	9	25	169
TS8	76	9	57	43	119

TS9	133	67	176	134	267
TS10	153	45	80	94	247
TS11	211	6	41	14	225
Year 4	**Thermal**	**Fatigue**	**Reflective**	**Longitudinal**	**Total**
TS5	163	39	45	59	222
TS6	139	147	84	153	292
TS7	159	28	11	50	209
TS8	85	17	72	65	150
TS9	140	175	233	181	321
TS10	155	82	124	146	301
TS11	226	36	48	48	274
Year 5	**Thermal**	**Fatigue**	**Reflective**	**Longitudinal**	**Total**
TS5	163	39	45	59	222
TS6	145	159	93	167	312
TS7	159	28	11	50	209
TS8	85	38	84	86	171
TS9	148	183	237	189	337
TS10	158	92	129	162	320
TS11	250	56	54	80	330
Year 6	**Thermal**	**Fatigue**	**Reflective**	**Longitudinal**	**Total**
TS5	203	97	95	119	322
TS6	152	196	104	204	356
TS7	162	51	20	106	268
TS8	85	59	111	131	216
TS9	148	193	242	252	400
TS10	162	92	133	180	342
TS11	250	56	54	80	330
Year 7	**Thermal**	**Fatigue**	**Reflective**	**Longitudinal**	**Total**
TS5	203	97	95	119	322
TS6	155	196	104	204	359
TS7	175	78	24	145	320
TS8	85	59	111	131	216
TS9	155	199	244	263	418
TS10	168	95	136	192	360
TS11	266	60	55	89	355
Year 8	**Thermal**	**Fatigue**	**Reflective**	**Longitudinal**	**Total**
TS5	225	97	108	119	344
TS6	155	196	104	204	359
TS7	175	78	24	145	320
TS8	85	59	111	131	216
TS9	155	199	244	263	418
TS10	157	255	258	357	514
TS11	266	60	55	89	355
Year 9	**Thermal**	**Fatigue**	**Reflective**	**Longitudinal**	**Total**
TS5	232	186	140	211	443
TS6	185	328	141	338	523
TS7	178	194	52	307	485
TS8	118	116	145	215	333
TS9	164	292	313	388	552
TS10	155	199	244	263	418
TS11	298	253	90	312	610
Year 10	**Thermal**	**Fatigue**	**Reflective**	**Longitudinal**	**Total**
TS5	240	198	140	223	463
TS6	190	336	144	346	536
TS7	178	194	52	307	485
TS8	118	116	145	215	333
TS9	172	384	366	543	715
TS10	157	255	258	357	514
TS11	298	253	90	312	610

Year 11	Thermal	Fatigue	Reflective	Longitudinal	Total
TS5	280	249	164	304	584
TS6	237	508	232	529	766
TS7	204	222	62	390	594
TS8	160	149	147	265	425
TS9	172	384	366	543	715
TS10	162	267	258	383	545
TS11	298	253	90	312	610
Year 12	**Thermal**	**Fatigue**	**Reflective**	**Longitudinal**	**Total**
TS5	297	301	179	362	659
TS6	243	528	235	553	796
TS7	204	222	62	390	594
TS8	172	157	147	273	445
TS9	172	384	366	543	715
TS10	162	267	258	383	545
TS11	317	277	94	374	691
Year 13	**Thermal**	**Fatigue**	**Reflective**	**Longitudinal**	**Total**
TS5	312	322	188	386	698
TS6	267	600	263	639	906
TS7	208	235	68	448	656
TS8	188	178	149	311	499
TS9	184	425	378	599	783
TS10	176	310	276	470	646
TS11	326	336	108	437	763

Appendix D

Rut Readings in inches, VT 100, Lowell-Westfield

Test Site 1 (overlay)					
		Rut depths (in.)			
Year	Location	SB outer WP	SB inner WP	NB inner WP	NB outer WP
1994	0+00	0.000	0.000	0.000	0.000
	0+50	0.000	0.000	0.000	0.000
	1+00	0.000	0.000	0.000	0.000
1995	0+00	0.000	0.000	0.000	0.000
	0+50	0.000	0.000	0.000	0.000
	1+00	0.000	0.000	0.000	0.125
1996	0+00	0.000	0.000	0.000	0.000
	0+50	0.000	0.000	0.000	0.000
	1+00	0.000	0.000	0.000	0.000
1997	0+00	0.000	0.000	0.125	0.000
	0+50	0.000	0.000	0.000	0.000
	1+00	0.000	0.000	0.000	0.125
1998	0+00	0.125	0.125	0.000	0.000
	0+50	0.000	0.000	0.000	0.000
	1+00	0.000	0.000	0.000	0.125
1999	0+00	0.000	0.000	0.125	0.000
	0+50	0.000	0.000	0.000	0.000
	1+00	0.000	0.125	0.000	0.000
2000	0+00	0.125	0.125	0.125	0.125
	0+50	0.125	0.125	0.125	0.125
	1+00	0.000	0.250	0.125	0.125
2001	0+00	0.125	0.125	0.125	0.125
	0+50	0.250	0.125	0.250	0.125
	1+00	0.125	0.250	0.125	0.125
2002	0+00	0.125	0.125	0.125	0.125
	0+50	0.250	0.125	0.250	0.125
	1+00	0.125	0.250	0.125	0.250
2003	0+00	0.250	0.250	0.250	0.125
	0+50	0.250	0.250	0.375	0.125
	1+00	0.250	0.375	0.250	0.250
2004	0+00	0.000	0.125	0.125	0.125
	0+50	0.000	0.250	0.125	0.125
	1+00	0.250	0.250	0.000	0.125
2005	0+00	0.125	0.250	0.250	0.250
	0+50	0.125	0.375	0.250	0.375
	1+00	0.250	0.250	0.375	0.250
2006	0+00	0.250	0.375	0.250	0.250
	0+50	0.125	0.250	0.375	0.375
	1+00	0.375	0.500	0.500	0.250
2007	0+00	0.125	0.250	0.250	0.375
	0+50	0.250	0.375	0.250	0.250
	1+00	0.375	0.375	0.625	0.250
Pre-construction	0+00	0.250	0.250	0.500	0.375
	0+50	0.125	0.125	0.125	0.250
	1+00	0.250	0.375	0.125	0.375

Test Site 2 (overlay)					
		Rut depths (in.)			
Year	Location	SB outer WP	SB inner WP	NB inner WP	NB outer WP
1994	0+00	0.000	0.000	0.000	0.000
	0+50	0.000	0.000	0.000	0.000
	1+00	0.000	0.000	0.000	0.000
1995	0+00	0.125	0.000	0.000	0.000
	0+50	0.000	0.000	0.000	0.000
	1+00	0.000	0.000	0.000	0.000
1996	0+00	0.000	0.000	0.000	0.000
	0+50	0.000	0.000	0.000	0.000
	1+00	0.000	0.000	0.000	0.000
1997	0+00	0.250	0.000	0.250	0.000
	0+50	0.250	0.000	0.250	0.125
	1+00	0.125	0.125	0.250	0.125
1998	0+00	0.125	0.000	0.125	0.000
	0+50	0.125	0.000	0.000	0.000
	1+00	0.000	0.125	0.125	0.125
1999	0+00	0.000	0.000	0.000	0.000
	0+50	0.000	0.000	0.000	0.000
	1+00	0.000	0.000	0.250	0.000
2000	0+00	0.125	0.125	0.125	0.125
	0+50	0.125	0.125	0.250	0.250
	1+00	0.125	0.250	0.375	0.125
2001	0+00	0.125	0.250	0.375	0.125
	0+50	0.125	0.125	0.250	0.375
	1+00	0.125	0.375	0.375	0.250
2002	0+00	0.250	0.250	0.250	0.125
	0+50	0.125	0.125	0.375	0.375
	1+00	0.125	0.375	0.375	0.250
2003	0+00	0.250	0.250	0.375	0.125
	0+50	0.125	0.125	0.500	0.375
	1+00	0.250	0.500	0.375	0.125
2004	0+00	0.000	0.250	0.125	0.250
	0+50	0.375	0.500	0.000	0.000
	1+00	0.000	0.375	0.375	0.000
2005	0+00	0.250	0.500	0.250	0.500
	0+50	0.500	0.500	0.125	0.125
	1+00	0.250	0.375	0.375	0.375
2006	0+00	0.500	0.625	0.250	0.500
	0+50	0.625	0.875	0.250	0.250
	1+00	0.375	0.500	0.625	0.500
2007	0+00	0.125	0.375	0.125	0.375
	0+50	0.625	0.875	0.125	0.250
	1+00	0.125	0.375	0.500	0.250
Pre-construction	0+00	0.625	0.375	1.125	0.375
	0+50	0.500	0.250	0.500	0.750
	1+00	0.625	0.250	0.500	0.375

Test Site 3 (overlay)					
		Rut depths (in.)			
Year	Location	SB outer WP	SB inner WP	NB inner WP	NB outer WP
1994	0+00	0.000	0.000	0.000	0.000
	0+50	0.000	0.000	0.000	0.000
	1+00	0.000	0.000	0.000	0.000
1995	0+00	0.000	0.000	0.000	0.000
	0+50	0.000	0.000	0.000	0.000
	1+00	0.000	0.000	0.000	0.000
1996	0+00	0.000	0.000	0.000	0.000
	0+50	0.000	0.000	0.000	0.000
	1+00	0.000	0.000	0.000	0.000
1997	0+00	0.000	0.000	0.000	0.000
	0+50	0.125	0.000	0.000	0.000
	1+00	0.125	0.000	0.000	0.000
1998	0+00	0.125	0.000	0.000	0.000
	0+50	0.000	0.000	0.125	0.000
	1+00	0.125	0.000	0.125	0.000
1999	0+00	0.000	0.125	0.000	0.000
	0+50	0.000	0.000	0.125	0.000
	1+00	0.000	0.125	0.000	0.000
2000	0+00	0.125	0.125	0.250	0.000
	0+50	0.125	0.125	0.250	0.125
	1+00	0.125	0.125	0.125	0.000
2001	0+00	0.125	0.125	0.375	0.000
	0+50	0.125	0.000	0.250	0.250
	1+00	0.125	0.000	0.375	0.125
2002	0+00	0.250	0.125	0.500	0.000
	0+50	0.125	0.125	0.250	0.125
	1+00	0.125	0.125	0.375	0.125
2003	0+00	0.250	0.125	0.625	0.125
	0+50	0.125	0.125	0.375	0.250
	1+00	0.125	0.125	0.500	0.125
2004	0+00	0.000	0.750	0.000	0.125
	0+50	0.250	0.500	0.000	0.000
	1+00	0.125	0.625	0.125	0.000
2005	0+00	0.000	0.750	0.125	0.250
	0+50	0.375	0.375	0.000	0.375
	1+00	0.250	0.750	0.125	0.250
2006	0+00	0.250	1.000	0.250	0.250
	0+50	0.250	0.500	0.000	0.250
	1+00	0.375	0.875	0.125	0.125
2007	0+00	0.125	1.000	0.000	0.375
	0+50	0.375	0.750	0.125	0.375
	1+00	0.250	1.000	0.125	0.250
Pre-construction	0+00	0.250	0.250	0.250	0.375
	0+50	0.375	0.125	0.500	0.375
	1+00	0.125	0.125	0.625	0.750

Test Site 4 (overlay)					
		Rut depths (in.)			
Year	Location	SB outer WP	SB inner WP	NB inner WP	NB outer WP
1994	0+00	0.000	0.000	0.000	0.000
	0+50	0.000	0.000	0.000	0.000
	1+00	0.000	0.000	0.000	0.000
1995	0+00	0.000	0.000	0.000	0.000
	0+50	0.000	0.000	0.000	0.000
	1+00	0.000	0.000	0.000	0.000
1996	0+00	0.000	0.000	0.000	0.000
	0+50	0.000	0.000	0.000	0.000
	1+00	0.000	0.000	0.000	0.000
1997	0+00	0.000	0.000	0.000	0.000
	0+50	0.000	0.000	0.000	0.000
	1+00	0.000	0.000	0.000	0.000
1998	0+00	0.000	0.000	0.000	0.000
	0+50	0.000	0.000	0.000	0.000
	1+00	0.000	0.125	0.000	0.000
1999	0+00	0.000	0.000	0.000	0.000
	0+50	0.000	0.000	0.000	0.000
	1+00	0.000	0.000	0.000	0.000
2000	0+00	0.000	0.125	0.000	0.125
	0+50	0.125	0.125	0.125	0.125
	1+00	0.125	0.000	0.125	0.000
2001	0+00	0.125	0.125	0.125	0.125
	0+50	0.125	0.125	0.125	0.000
	1+00	0.250	0.125	0.125	0.125
2002	0+00	0.125	0.125	0.125	0.125
	0+50	0.125	0.125	0.125	0.000
	1+00	0.250	0.125	0.125	0.125
2003	0+00	0.125	0.125	0.250	0.250
	0+50	0.250	0.250	0.250	0.000
	1+00	0.250	0.125	0.250	0.125
2004	0+00	0.000	0.250	0.125	0.000
	0+50	0.000	0.250	0.125	0.000
	1+00	0.000	0.250	0.125	0.125
2005	0+00	0.125	0.250	0.125	0.000
	0+50	0.125	0.250	0.125	0.125
	1+00	0.125	0.250	0.125	0.125
2006	0+00	0.250	1.000	0.250	0.250
	0+50	0.250	0.500	0.000	0.250
	1+00	0.375	0.875	0.125	0.125
2007	0+00	0.250	0.375	0.250	0.125
	0+50	0.125	0.500	0.250	0.250
	1+00	0.250	0.375	0.250	0.250
Pre-construction	0+00	0.375	0.125	0.000	0.375
	0+50	0.375	0.125	0.375	0.500
	1+00	0.375	0.250	0.000	0.750

Test Site 5 (ARHM)

Year	Location	Rut depths (in.)			
		SB outer WP	SB inner WP	NB inner WP	NB outer WP
1994	0+00	0.000	0.000	0.000	0.000
	0+50	0.000	0.000	0.000	0.000
	1+00	0.000	0.000	0.000	0.000
1995	0+00	0.125	0.000	0.000	0.000
	0+50	0.125	0.000	0.000	0.000
	1+00	0.000	0.000	0.000	0.000
1996	0+00	0.000	0.000	0.000	0.000
	0+50	0.000	0.000	0.000	0.000
	1+00	0.000	0.000	0.000	0.000
1997	0+00	0.125	0.000	0.000	0.000
	0+50	0.125	0.000	0.000	0.000
	1+00	0.000	0.000	0.000	0.000
1998	0+00	0.125	0.000	0.000	0.125
	0+50	0.125	0.000	0.000	0.000
	1+00	0.000	0.000	0.000	0.000
1999	0+00	0.125	0.000	0.000	0.125
	0+50	0.000	0.000	0.000	0.000
	1+00	0.000	0.000	0.000	0.000
2000	0+00	0.125	0.125	0.125	0.125
	0+50	0.125	0.125	0.125	0.125
	1+00	0.125	0.125	0.125	0.125
2001	0+00	0.250	0.125	0.125	0.125
	0+50	0.125	0.125	0.125	0.125
	1+00	0.125	0.125	0.125	0.125
2002	0+00	0.250	0.125	0.125	0.250
	0+50	0.125	0.125	0.125	0.125
	1+00	0.000	0.125	0.000	0.000
2003	0+00	0.250	0.250	0.250	0.250
	0+50	0.125	0.125	0.250	0.250
	1+00	0.125	0.125	0.250	0.250
2004	0+00	0.000	0.125	0.125	0.250
	0+50	0.125	0.125	0.125	0.000
	1+00	0.000	0.125	0.125	0.000
2005	0+00	0.125	0.250	0.250	0.250
	0+50	0.125	0.125	0.250	0.125
	1+00	0.125	0.250	0.250	0.000
2006	0+00	0.375	0.250	0.250	0.250
	0+50	0.125	0.125	0.125	0.125
	1+00	0.250	0.250	0.250	0.125
2007	0+00	0.375	0.125	0.125	0.375
	0+50	0.125	0.250	0.125	0.125
	1+00	0.250	0.250	0.250	0.125
Pre-construction	0+00	0.875	0.125	0.250	0.375
	0+50	0.250	0.250	0.375	0.250
	1+00	0.625	0.250	0.250	0.375

Test Site 6 (ARHM)					
Year	Location	Rut depths (in.)			
		SB outer WP	SB inner WP	NB inner WP	NB outer WP
1994	0+00	0.000	0.000	0.000	0.000
	0+50	0.000	0.000	0.000	0.000
	1+00	0.000	0.000	0.000	0.000
1995	0+00	0.000	0.000	0.000	0.000
	0+50	0.000	0.000	0.000	0.000
	1+00	0.000	0.000	0.000	0.000
1996	0+00	0.000	0.000	0.125	0.000
	0+50	0.000	0.000	0.125	0.000
	1+00	0.000	0.000	0.000	0.000
1997	0+00	0.000	0.125	0.000	0.125
	0+50	0.000	0.000	0.000	0.125
	1+00	0.000	0.000	0.000	0.000
1998	0+00	0.125	0.125	0.125	0.125
	0+50	0.125	0.000	0.000	0.125
	1+00	0.000	0.000	0.000	0.000
1999	0+00	0.125	0.125	0.125	0.125
	0+50	0.125	0.000	0.000	0.125
	1+00	0.000	0.125	0.000	0.125
2000	0+00	0.125	0.125	0.125	0.125
	0+50	0.125	0.125	0.250	0.250
	1+00	0.125	0.125	0.125	0.125
2001	0+00	0.125	0.125	0.250	0.125
	0+50	0.250	0.125	0.250	0.375
	1+00	0.125	0.125	0.125	0.125
2002	0+00	0.125	0.000	0.250	0.125
	0+50	0.125	0.250	0.250	0.250
	1+00	0.125	0.250	0.125	0.125
2003	0+00	0.125	0.250	0.250	0.375
	0+50	0.375	0.250	0.250	0.250
	1+00	0.125	0.250	0.250	0.250
2004	0+00	0.250	0.250	0.250	0.125
	0+50	0.125	0.250	0.250	0.375
	1+00	0.125	0.125	0.125	0.000
2005	0+00	0.250	0.375	0.250	0.250
	0+50	0.125	0.250	0.250	0.625
	1+00	0.125	0.125	0.125	0.125
2006	0+00	0.250	0.375	0.375	0.250
	0+50	0.375	0.375	0.375	0.500
	1+00	0.250	0.250	0.250	0.125
2007	0+00	0.375	0.375	0.375	0.125
	0+50	0.250	0.500	0.375	0.625
	1+00	0.250	0.250	0.250	0.000
Pre-construction	0+00	0.750	0.250	0.375	0.750
	0+50	0.375	0.000	0.125	0.625
	1+00	0.500	0.375	0.125	0.375

Test Site 7 (ARHM)					
		Rut depths (in.)			
Year	Location	SB outer WP	SB inner WP	NB inner WP	NB outer WP
1994	0+00	0.000	0.000	0.000	0.000
	0+50	0.000	0.000	0.000	0.000
	1+00	0.000	0.000	0.000	0.000
1995	0+00	0.125	0.000	0.125	0.125
	0+50	0.125	0.000	0.000	0.000
	1+00	0.125	0.000	0.000	0.000
1996	0+00	0.125	0.000	0.000	0.125
	0+50	0.125	0.000	0.000	0.000
	1+00	0.000	0.000	0.000	0.125
1997	0+00	0.125	0.000	0.000	0.250
	0+50	0.250	0.000	0.000	0.125
	1+00	0.125	0.000	0.125	0.250
1998	0+00	0.125	0.000	0.125	0.250
	0+50	0.250	0.000	0.250	0.250
	1+00	0.125	0.000	0.125	0.250
1999	0+00	0.125	0.000	0.125	0.125
	0+50	0.000	0.000	0.000	0.125
	1+00	0.125	0.000	0.125	0.250
2000	0+00	0.250	0.000	0.250	0.250
	0+50	0.250	0.000	0.125	0.250
	1+00	0.250	0.125	0.250	0.250
2001	0+00	0.375	0.125	0.250	0.250
	0+50	0.250	0.125	0.125	0.250
	1+00	0.250	0.250	0.250	0.250
2002	0+00	0.250	0.125	0.250	0.375
	0+50	0.250	0.125	0.125	0.250
	1+00	0.250	0.125	0.125	0.250
2003	0+00	0.250	0.250	0.375	0.500
	0+50	0.375	0.250	0.250	0.375
	1+00	0.250	0.125	0.250	0.250
2004	0+00	0.375	0.250	0.125	0.250
	0+50	0.375	0.250	0.125	0.125
	1+00	0.250	0.250	0.125	0.125
2005	0+00	0.375	0.250	0.250	0.250
	0+50	0.375	0.375	0.125	0.125
	1+00	0.375	0.250	0.125	0.125
2006	0+00	0.375	0.375	0.250	0.375
	0+50	0.500	0.375	0.250	0.375
	1+00	0.375	0.250	0.250	0.375
2007	0+00	0.625	0.375	0.125	0.375
	0+50	0.500	0.250	0.250	0.375
	1+00	0.375	0.250	0.125	0.375
Pre-construction	0+00	0.375	0.000	0.250	1.000
	0+50	0.250	0.000	0.125	0.875
	1+00	0.375	0.250	0.500	0.750

Test Site 8 (ARHM)					
Year	Location	Rut depths (in.)			
		SB outer WP	SB inner WP	NB inner WP	NB outer WP
1994	0+00	0.000	0.000	0.000	0.000
	0+50	0.000	0.000	0.000	0.000
	1+00	0.000	0.000	0.000	0.000
1995	0+00	0.000	0.000	0.000	0.000
	0+50	0.000	0.000	0.000	0.000
	1+00	0.000	0.000	0.000	0.000
1996	0+00	0.000	0.000	0.000	0.000
	0+50	0.000	0.000	0.000	0.000
	1+00	0.000	0.000	0.000	0.000
1997	0+00	0.125	0.000	0.000	0.000
	0+50	0.125	0.000	0.000	0.000
	1+00	0.000	0.000	0.000	0.000
1998	0+00	0.125	0.000	0.000	0.000
	0+50	0.125	0.000	0.000	0.000
	1+00	0.000	0.000	0.000	0.000
1999	0+00	0.125	0.125	0.000	0.000
	0+50	0.000	0.000	0.000	0.125
	1+00	0.000	0.125	0.125	0.000
2000	0+00	0.125	0.250	0.250	0.000
	0+50	0.125	0.125	0.125	0.125
	1+00	0.000	0.125	0.125	0.000
2001	0+00	0.125	0.125	0.250	0.000
	0+50	0.125	0.125	0.125	0.125
	1+00	0.000	0.125	0.125	0.125
2002	0+00	0.125	0.125	0.125	0.250
	0+50	0.125	0.125	0.000	0.125
	1+00	0.125	0.125	0.125	0.125
2003	0+00	0.250	0.250	0.125	0.125
	0+50	0.250	0.125	0.125	0.125
	1+00	0.125	0.125	0.250	0.125
2004	0+00	0.000	0.250	0.125	0.125
	0+50	0.125	0.000	0.125	0.125
	1+00	0.000	0.125	0.125	0.000
2005	0+00	0.125	0.250	0.125	0.250
	0+50	0.250	0.125	0.125	0.125
	1+00	0.000	0.125	0.250	0.125
2006	0+00	0.250	0.375	0.250	0.375
	0+50	0.125	0.125	0.250	0.250
	1+00	0.125	0.250	0.125	0.000
2007	0+00	0.000	0.250	0.250	0.250
	0+50	0.125	0.125	0.250	0.250
	1+00	0.125	0.250	0.125	0.000
Pre-construction	0+00	0.250	0.250	0.250	0.375
	0+50	0.250	0.250	0.375	0.250
	1+00	0.250	0.375	0.375	0.250

Test Site 9 (ARHM)					
		Rut depths (in.)			
Year	Location	SB outer WP	SB inner WP	NB inner WP	NB outer WP
1994	0+00	0.000	0.000	0.000	0.000
	0+50	0.000	0.000	0.000	0.000
	1+00	0.000	0.000	0.000	0.000
1995	0+00	0.000	0.000	0.000	0.000
	0+50	0.000	0.000	0.000	0.000
	1+00	0.000	0.000	0.000	0.000
1996	0+00	0.000	0.000	0.000	0.000
	0+50	0.000	0.000	0.000	0.000
	1+00	0.000	0.000	0.000	0.000
1997	0+00	0.000	0.000	0.000	0.125
	0+50	0.000	0.000	0.000	0.000
	1+00	0.125	0.000	0.000	0.000
1998	0+00	0.375	0.000	0.000	0.125
	0+50	0.125	0.000	0.125	0.000
	1+00	0.000	0.000	0.125	0.000
1999	0+00	0.250	0.125	0.000	0.000
	0+50	0.125	0.000	0.000	0.000
	1+00	0.125	0.000	0.000	0.000
2000	0+00	0.375	0.125	0.125	0.125
	0+50	0.125	0.125	0.125	0.125
	1+00	0.125	0.125	0.125	0.125
2001	0+00	0.250	0.250	0.125	0.125
	0+50	0.125	0.125	0.125	0.000
	1+00	0.125	0.125	0.125	0.125
2002	0+00	0.625	0.125	0.250	0.250
	0+50	0.125	0.125	0.250	0.125
	1+00	0.375	0.125	0.250	0.125
2003	0+00	0.625	0.375	0.250	0.125
	0+50	0.125	0.250	0.375	0.250
	1+00	0.250	0.250	0.250	0.125
2004	0+00	0.250	0.125	0.375	0.750
	0+50	0.125	0.375	0.250	0.125
	1+00	0.000	0.125	0.250	0.375
2006	0+00	0.375	0.250	0.500	0.875
	0+50	0.250	0.500	0.375	0.250
	1+00	0.125	0.250	0.250	0.375
2007	0+00	0.500	0.250	0.875	1.125
	0+50	0.250	0.375	0.250	0.250
	1+00	0.250	0.375	0.250	0.750
Pre-construction	0+00	0.875	0.625	0.250	0.500
	0+50	0.250	0.375	0.375	0.375
	1+00	1.000	0.625	0.375	0.750

Test Site 10 (ARHM)					
Year	Location	Rut depths (in.)			
		SB outer WP	SB inner WP	NB inner WP	NB outer WP
1994	0+00	0.000	0.000	0.000	0.000
	0+50	0.000	0.000	0.000	0.000
	1+00	0.000	0.000	0.000	0.000
1995	0+00	0.000	0.000	0.000	0.000
	0+50	0.000	0.000	0.000	0.000
	1+00	0.000	0.000	0.000	0.000
1996	0+00	0.000	0.000	0.000	0.000
	0+50	0.000	0.000	0.000	0.000
	1+00	0.000	0.000	0.000	0.000
1997	0+00	0.000	0.000	0.000	0.000
	0+50	0.000	0.000	0.000	0.125
	1+00	0.000	0.000	0.000	0.125
1998	0+00	0.000	0.000	0.000	0.000
	0+50	0.000	0.125	0.000	0.125
	1+00	0.000	0.000	0.125	0.125
1999	0+00	0.000	0.000	0.125	0.125
	0+50	0.125	0.125	0.125	0.125
	1+00	0.250	0.000	0.000	0.250
2000	0+00	0.125	0.125	0.125	0.250
	0+50	0.125	0.125	0.250	0.000
	1+00	0.125	0.125	0.250	0.125
2001	0+00	0.125	0.125	0.250	0.250
	0+50	0.125	0.375	0.250	0.000
	1+00	0.125	0.250	0.125	0.125
2002	0+00	0.250	0.000	0.000	0.125
	0+50	0.125	0.125	0.250	0.250
	1+00	0.125	0.125	0.125	0.250
2003	0+00	0.375	0.250	0.250	0.375
	0+50	0.250	0.250	0.250	0.375
	1+00	0.125	0.250	0.375	0.250
2004	0+00	0.375	0.125	0.125	0.375
	0+50	0.375	0.250	0.000	0.250
	1+00	0.375	0.250	0.125	0.125
2006	0+00	0.500	0.250	0.125	0.625
	0+50	0.750	0.375	0.250	0.250
	1+00	0.500	0.375	0.250	0.250
2007	0+00	0.750	0.250	0.250	0.500
	0+50	0.750	0.750	0.250	0.250
	1+00	0.500	0.625	0.250	0.250
Pre-construction	0+00	0.000	0.000	0.125	0.125
	0+50	0.125	0.125	0.125	0.125
	1+00	0.250	0.000	0.000	0.250

Test Site 11 (ARHM)					
		Rut depths (in.)			
Year	Location	SB outer WP	SB inner WP	NB inner WP	NB outer WP
1994	0+00	0.000	0.000	0.000	0.000
	0+50	0.000	0.000	0.000	0.000
	1+00	0.000	0.000	0.000	0.000
1995	0+00	0.000	0.000	0.000	0.000
	0+50	0.000	0.000	0.000	0.000
	1+00	0.000	0.000	0.000	0.000
1996	0+00	0.000	0.000	0.000	0.000
	0+50	0.000	0.000	0.000	0.000
	1+00	0.000	0.000	0.000	0.000
1997	0+00	0.000	0.000	0.000	0.000
	0+50	0.000	0.000	0.000	0.000
	1+00	0.000	0.000	0.000	0.000
1998	0+00	0.000	0.000	0.000	0.125
	0+50	0.000	0.000	0.000	0.250
	1+00	0.000	0.125	0.000	0.125
1999	0+00	0.000	0.000	0.125	0.000
	0+50	0.125	0.125	0.125	0.250
	1+00	0.125	0.000	0.000	0.125
2000	0+00	0.000	0.125	0.125	0.250
	0+50	0.125	0.125	0.125	0.250
	1+00	0.125	0.125	0.250	0.125
2001	0+00	0.125	0.125	0.125	0.250
	0+50	0.125	0.125	0.250	0.250
	1+00	0.125	0.125	0.375	0.250
2002	0+00	0.000	0.125	0.125	0.375
	0+50	0.250	0.125	0.250	0.375
	1+00	0.250	0.125	0.250	0.250
2003	0+00	0.250	0.250	0.250	0.375
	0+50	0.500	0.250	0.375	0.500
	1+00	0.375	0.250	0.250	0.250
2004	0+00	0.375	0.125	0.125	0.000
	0+50	0.375	0.375	0.125	0.625
	1+00	0.250	0.250	0.125	0.250
2006	0+00	0.500	0.375	0.375	0.500
	0+50	0.750	0.375	0.250	0.625
	1+00	0.625	0.250	0.250	0.375
2007	0+00	0.875	0.250	0.250	0.250
	0+50	0.875	0.500	0.250	1.000
	1+00	0.375	0.375	0.250	0.625
Pre-construction	0+00	0.500	0.250	0.375	0.500
	0+50	0.375	0.250	0.125	0.875
	1+00	0.125	0.125	0.250	1.250

Appendix E

Ride Roughness Values for VT 100, Lowell-Westfield

Year	**Standard Overlay**		**ARHM Overlay**	
	Northbound	**Southbound**	**Northbound**	**Southbound**
Preconstruction	187	187	201	201
1994	91	86	96	90
1995	85	77	94	83
1996	61	62	81	72
1997	99	90	95	96
1998	106	92	100	98
2000	135	88	127	103
2001	150	114	135	115
2002	171	133	149	132
2003	183	138	152	135
2004	204	143	161	140
2007	259	176	201	201

- All values were collected using the ‘Mays’ trailer.

All values represented are averages of all IRI values within the given sections.

Appendix F

Statistical Analysis of Pre- and Post-construction Populations

Preconstruction – Population Assessment

Mann-Whitney Test and CI: Control, Experimental (Total Cracking)

```
             N  Median
Control      4   614.5
Experimental  7   744.0

Point estimate for ETA1-ETA2 is -138.5
95.3 Percent CI for ETA1-ETA2 is (-391.0,91.9)
W = 17.0
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.2193
```

Mann-Whitney Test and CI: Control, Experimental (Thermal Cracking)

```
             N  Median
Control       4   199.0
Experimental  7   181.0

Point estimate for ETA1-ETA2 is 4.5
95.3 Percent CI for ETA1-ETA2 is (-81.0,58.0)
W = 24.0
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 1.0000
The test is significant at 1.0000 (adjusted for ties)
```

Mann-Whitney Test and CI: Control, Experimental (Fatigue Cracking)

```
             N  Median
Control       4   306.5
Experimental  7   511.0

Point estimate for ETA1-ETA2 is -114.5
95.3 Percent CI for ETA1-ETA2 is (-308.9,69.9)
W = 15.0
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.1082
```

Post construction – Population Assessment

Mann-Whitney Test and CI: Control, Experimental (Total Cracking)

```
              N  Median
Control       4   688.0
Experimental  7   763.0

Point estimate for ETA1-ETA2 is -26.5
95.3 Percent CI for ETA1-ETA2 is (-248.0,346.9)
W = 23.0
Test of ETA1 = ETA2 vs. ETA1 not = ETA2 is significant at 0.9247
```

Mann-Whitney Test and CI: Control, Experimental (Thermal Cracking)

```
              N  Median
Control       4   278.0
Experimental  7   208.0

Point estimate for ETA1-ETA2 is 35.0
95.3 Percent CI for ETA1-ETA2 is (-87.0,143.0)
W = 27.0
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.6366
```

Mann-Whitney Test and CI: Control, Experimental (Fatigue Cracking)

```
              N  Median
Control       4   400.0
Experimental  7   322.0

Point estimate for ETA1-ETA2 is 77.0
95.3 Percent CI for ETA1-ETA2 is (-123.1,283.1)
W = 29.0
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.3951
```

Mann-Whitney Test and CI: Control, Experimental (Reflective Cracking)

```
              N  Median
Control       4   149.0
Experimental  7   188.0

Point estimate for ETA1-ETA2 is -36.5
95.3 Percent CI for ETA1-ETA2 is (-165.0,82.0)
W = 21.0
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.6366
```

Mann-Whitney Test and CI: Control, Experimental (Rutting)

```
              N  Median
Control       4    67.0
Experimental  4    99.0

Point estimate for ETA1-ETA2 is -27.0
97.0 Percent CI for ETA1-ETA2 is (-65.0,176.9)
W = 14.0
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.3123
The test is significant at 0.3094 (adjusted for ties)
```