Cost Benefit Analysis of Anti-Strip Additives in Hot Mix Asphalt with Various Aggregates

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16. Abstract

This report documents research on moisture sensitivity testing of hot-mix asphalt (HMA) mixes in Pennsylvania and the associated use of antistrip. The primary objective of the research was to evaluate and compare benefit/cost ratios of mandatory use of antistrip, and of antistrip usage conditional on the results of moisture resistance testing, based upon life cycle cost analyses. A secondary objective was to evaluate a unique version of the modified Lottman procedure used in Pennsylvania between 2003 and October 2014, which involved a relatively low level of saturation in specimen conditioning. This procedure (low-saturation method) typically results in saturation between about 30 % and 67 %, as compared to the 70 to 80 % required in the test version used by Pennsylvania prior to 2003 and after October 2014 (high-saturation method). It was found that the low-saturation method passed all HMA mixes, even those with a documented history of high susceptibility to moisture damage. This procedure therefore had a benefit/cost ratio of zero. For the high-saturation method, it was found that both antistrip usage dependent on the results of testing and mandatory usage for all mixes had benefit/cost ratios that were greater than one and in general much greater than one. The benefit/cost ratios for mandatory antistrip usage were greater than those for conditional usage, because of the high cost associated with the failure of moisture resistance testing to identify all moisture susceptible mixes.

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ABSTRACT

This report documents research on moisture sensitivity testing of hot-mix asphalt (HMA) mixes in Pennsylvania and the associated use of antistrip. The primary objective of the research was to evaluate and compare benefit/cost ratios of mandatory use of antistrip, and of antistrip usage conditional on the results of moisture resistance testing, based upon life cycle cost analyses. A secondary objective was to evaluate a unique version of the modified Lottman procedure used in Pennsylvania between 2003 and October 2014, which involved a relatively low level of saturation in specimen conditioning. This procedure (low-saturation method) typically results in saturation between about 30 % and 67 %, as compared to the 70 to 80 % required in the test version used by Pennsylvania prior to 2003 and after October 2014 (high-saturation method). It was found that the low-saturation method passed all HMA mixes, even those with a documented history of high susceptibility to moisture damage. This procedure therefore had a benefit/cost ratio of zero. For the high-saturation method, it was found that both antistrip usage dependent on the results of testing and mandatory usage for all mixes had benefit/cost ratios that were greater than one and in general much greater than one. The benefit/cost ratios for mandatory antistrip usage were greater than those for conditional usage, because of the high cost associated with the failure of moisture resistance testing to identify all moisture susceptible mixes.

EXECUTIVE SUMMARY

The work documented in this report had three primary parts: (1) a literature review; (2) laboratory testing of mixes for moisture resistance; and (3) a life cycle cost analysis and calculation of cost-benefit ratios. Surveys of paving materials producers and PennDOT personnel were also conducted, but low participation rates meant that the results had little significance.

A review of the literature concerning moisture damage and antistrip usage in asphalt concrete lead to several important findings. Pennsylvania has an unusually harsh environment for asphalt concrete and related materials; it is subject to a very large number of freeze thaw cycles, and also has a moderately high amount of precipitation. Pennsylvania is also more heavily populated than many other states and many of its roads see very heavy traffic. All of these factors tend to increase moisture damage to asphalt concrete pavements. A variety of test methods have been used to evaluate the susceptibility of asphalt concrete mixes to moisture damage; by far the most commonly used at this time is the modified Lottman test, AASHTO T 283. Various versions of this test are in use, the most common—and the one now in use by PennDOT—use relatively high levels of saturation (typically 55 to 80 %) and include a freeze-thaw cycle.

In discussing error rates for moisture resistance tests it is useful to categorize errors as either type I or type II; a type I error occurs when a mixture resistant to moisture damage is incorrectly identified as being susceptible. A type II error occurs when a mix that is susceptible to moisture damage is incorrectly identified as being resistant to damage. Based upon results reported in the literature, modified Lottman tests conducted at a high level of saturation tend to have a very low type I error rate, but a type II error rate of approximately 20 to 30 %. Although the modified Lottman test is far from perfect, it has been more thoroughly studied than any other method, and at this time is the accepted standard.

A variety of antistrip additives are available for improving the performance of asphalt concrete mixes containing aggregates susceptible to moisture damage. Hydrated lime—added to the aggregate as a slurry—is the most common type of antistrip. Liquid antistrips—surfactants that are often added to the asphalt binder at the refinery or terminal—are significantly cheaper and more convenient compared to hydrated lime, but there is evidence that the field performance of mixes treated with hydrated lime is in general significantly better compared to mixes treated with liquid antistrip.

Moisture damage in asphalt concrete is in part dependent on the type of aggregate used. Limestone and dolomite aggregates tend to produce mixes that are resistant to moisture damage, whereas granite, quartzite and some sandstone and crushed gravel aggregates tend to produce mixes that are susceptible to moisture damage. Approximately 65 % of the aggregates produced in Pennsylvania for use in asphalt concrete are limestone and/or dolomite and for the most part produce mixes that are resistant to moisture damage. About 10 % of the aggregate used in asphalt concrete in Pennsylvania are crushed gravels; gravels tend to vary in moisture sensitivity, but in Pennsylvania most of the asphalt concrete produced with crushed gravel are highly susceptible to moisture damage. The balance of the aggregates produced in Pennsylvania for use in asphalt concrete vary in their susceptibility to moisture damage.

A total of 45 asphalt concretes, all produced in Pennsylvania under PennDOT standards, were tested as part of this research. Sixteen of these mixes had known histories of moisture resistance: six had low potential for moisture damage, two had moderate potential and eight had a high potential for moisture damage. Two different procedures were used, a low-saturation version of the modified Lottman test, and a high-saturation version of the modified Lottman test. The low-saturation version has no control over the level of saturation during specimen conditioning, and typically produces saturation levels between 30 and 67 %. This procedure was discontinued in Pennsylvania in October of 2014, and the high-saturation method is now being used. This version of the modified Lottman procedure requires specimen saturation levels between 70 and 80 %, and is more typical of testing performed by other agencies. The low-saturation method of testing failed to identify any mixes as being susceptible to moisture damage—that is, every mix passed this version of the test, even those with a known history of significant moisture damage.

The high saturation method produced error rates consistent with those reported in the literature for Lottman tests of similar (level 2) severity: a type I error rate (good mixes that failed) of 0 % and a type II error rate (poor mixes that passed) of 50 % for mixes moderately susceptible to moisture damage and 25 % for mixes highly susceptible to moisture damage. Final, average error rates for the modified Lottman test as currently used in Pennsylvania (after October 2014, high-saturation or level 2 severity) were calculated by averaging values found in this study with those reported in the literature: type I error rate of 6 %; type II error rate of 62 % for mixes moderately susceptible to moisture damage; and a type II error rate of 23 % for mixes highly susceptible to moisture damage. These values were then used in the calculation of benefit/cost ratios. An important, consistent finding in the laboratory testing conducted in this project and reported in numerous other research projects is that modified Lottman testing tends to be reasonably accurate in differentiating between mixes with low and high susceptibility to moisture damage, but is poor at accurately identifying mixes with moderate susceptibility to moisture damage.

Standard PennDOT methodology was used in performing the life cycle cost analysis. However, a range of assumptions were used for critical variables in order to evaluate the sensitivity of the analysis to changes in these values. For example, two different discount rates were used, along with two different traffic growth rates. The analyses were also performed including and excluding user delay costs. It was assumed that highly susceptible mixes on average had half the life of mixes resistant to moisture damage along with increased maintenance costs. Use of antistrip was assumed to only partially restore the performance of mixes susceptible to moisture damage. The results of the analysis, as would be expected, showed increasing costs at higher levels of moisture susceptibility, and decreasing costs with use of antistrip.

The cost/benefit analysis incorporated the results of the LCCA and the error rates estimated from the laboratory testing and literature review to calculate benefit/cost ratios for antistrip usage. The cost in this case is that of adding antistrip to the mix. The benefit is the partial increase in life and the reduced maintenance costs that result when antistrip is added to mixes susceptible to moisture damage. An important input into this analysis is the error rate of testing. Type I errors—where mixes resistant to moisture damage are incorrectly identified as susceptible—are associated with the minor cost of having to include antistrip when it is not needed. Type II errors—where mixes susceptible to moisture damage are incorrectly identified as resistant—are associated with a much higher cost: that of having a significantly shortened life and higher maintenance costs because antistrip was not included in the mix. Even considering the effect of these errors, the use of high-saturation moisture resistance testing in conjunction with liquid antistrip usage showed benefit/cost ratios that were always greater than one, usually much greater. The benefit/cost ratio of low-saturation testing was zero, since this test has essentially no ability to identify moisture susceptible asphalt concrete mixtures.

The low cost of type I errors in testing and the high cost of type II errors suggests an alternative approach to moisture resistance testing and treatment—the mandatory use of antistrip in all mixes. This is potentially cost effective because it greatly reduces or even eliminates the incidence of type II errors, since all mixes will contain antistrip. This approach was considered in the cost/benefit analysis, and the results—even when user delay costs are not considered and when the most optimistic performance assumptions are made—show savings compared to the approach where antistrip use is conditional upon the results of testing. Estimated potential savings from mandatory use of antistrip compared to conditional use range from several hundred thousand dollars per year to as much as six million dollars per year.

There are several potential practical applications to the results of this research. One application, already implemented (October 2014), is the abandonment of the low-saturation modified Lottman procedure and its replacement with the high-saturation version.

A second possible application is the adoption of mandatory antistrip usage in all asphalt concrete. This would still include moisture resistance testing, since not all antistrip additives are effective with all asphalt/aggregate combinations. Implementation might be difficult, as producers of asphalt concrete mixes traditionally resistant to moisture damage will likely object to the added cost and effort involved. Implementation of mandatory antistrip usage only in Districts where there is a significant amount of aggregate susceptible to moisture damage might meet less resistance.

A third possible application of the results of this research would be the use of hydrated lime as an antistrip additive in Pennsylvania. There is significant evidence in the literature that the use of hydrated lime, as opposed to liquid antistrip, results in significantly better field performance overall in mixes prone to moisture damage. Widespread implementation of the use of hydrated lime would be difficult because its use is significantly more costly and complicated for producers. Furthermore, since hydrated lime has not been used in Pennsylvania as an antistrip additive, there is no definite evidence that it would result in better performance for asphalt concrete mixtures made with local materials that are susceptible to moisture damage. It is therefore recommended that if PennDOT determines that the use of hydrated lime might be feasible, that a limited number of carefully controlled pilot projects be constructed, which would include sections constructed with liquid antistrip so that the performance of pavements made with these alternate approaches to controlling moisture damage can be compared over the course of several years.

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1. INTRODUCTION

The purpose of this report is to document the results of the research project Cost Benefit Analysis of Antistrip-Additives in Hot Mix Asphalt with Various Aggregates, Contract 355I01. The objective of this project was to perform a cost/benefit analysis on the usage of antistrip additive in hot-mix asphalt (HMA). This information is to be used by the Pennsylvania Department of Transportation (PennDOT) in helping to determine if it would be cost effective to require airstrip additives in all HMA mixes in Pennsylvania, rather than requiring antistrip only in mixes in which it is needed to pass moisture resistance testing.

When this project was initiated (2013) HMA mixes in Pennsylvania were evaluated for moisture resistance by using a variation of modified Lottman procedure. The Lottman procedure involves vacuum saturating a specimen of asphalt concrete, and in some cases—including the test as performed in Pennsylvania—the specimens are subjected to a freeze-thaw cycle. After saturation and freezing and thawing, the specimens are tested for indirect tensile strength. The strength after this condition is compared to the strength without saturation and freeze/thaw; the results are reported as a tensile strength ratio (TSR), typically as a percentage. A TSR of 80 % is required to pass this test in Pennsylvania and in many other states that use this procedure. The version of the modified Lottman test in use in Pennsylvania at the start of this research project (August 2012) was unusual in that the specimen saturation was specified as occurring under 254 mm vacuum for 30 minutes; as will be discussed later in this report, this results in a very low level of saturation, which in turn means that few if any mixes ever fail to pass this procedure. Even when performed using procedures that produce significantly higher levels of saturation the modified Lottman procedure is far from perfect, and a significant number of mixes susceptible to moisture damage fail to be identified and so are produced without an effective antistrip additive.

One of the secondary objectives of this research was to review the literature to determine if there are other, more effective procedures than the modified Lottman test for evaluating the moisture resistance of asphalt mixtures. It is clear from reviewing the literature that the Lottman procedure is at this time still by far the most widely used method for testing the moisture resistance of asphalt concrete, largely because it still appears to be the best test for this purpose. For this reason, this was the method used in the research project to evaluate the moisture resistance of HMA mixes produced in Pennsylvania. Such an evaluation was necessary to establish as accurately as possible the likely error rate for moisture resistance testing. These error rates can be classified as type I errors and type II errors. Type I errors occur when mixes resistant to moisture damage fail a test and are incorrectly identified as susceptible to moisture damage. Type II errors occur when mixtures susceptible to damage pass a test, and are incorrectly identified as resistant to moisture damage. The rates of these errors are important, because they directly impact the life cycle cost of HMA pavements and the resulting benefit/cost ratio.

Another secondary objective of this project was to compare the low-saturation and high-saturation versions of this test, as used in Pennsylvania in the recent past. At the start of this research it was suspected that the low-saturation test method was not very effective at identifying mixes susceptible to moisture damage, but documentation was needed to clearly establish its accuracy and the accuracy of the high-saturation version of the test. Almost all of the laboratory testing in fact related to this issue. A total of 45 HMA mixes from Pennsylvania representing a wide range of aggregate types and geographic areas were tested for this project. Sixteen of these mixes had known levels of moisture resistance, and so could be used to evaluate the accuracy of the two procedures. As mentioned above, the low-saturation method failed to identify any mixes as having poor moisture resistance. This extensive testing also helped to develop estimates of the type I and type II error rates for the high-saturation test method, which were used in calculating the benefit/cost ratios.

This report has nine chapters and an appendix. After this introduction the literature review is presented, followed by a short chapter giving the results of several surveys of producers and PennDOT personnel. Unfortunately the response to these surveys was not extensive and they were of limited value. Chapter 4 describes the experimental methods, materials and experiment design used in the laboratory testing. This is followed by a chapter in which the results of the laboratory testing are presented. Chapter 6 describes the methods used in the LCCA and in calculating the benefit/cost ratios for different scenarios. Chapter 7 is a summary of the information developed during the project, and Chapter 8 presents conclusions and recommendations. The final chapter is a list of references for the report. The Appendix to the report is a detailed listing of the maintenance and repair assumptions made in the LCCA for the various scenarios considered.

2. LITERATURE REVIEW

Moisture damage in hot-mix asphalt (HMA) is a widespread problem over most areas in the U.S., including the Commonwealth of Pennsylvania. In fact, a variety of conditions in Pennsylvania combine to create an especially severe environment for HMA pavements: relatively heavy precipitation, often acidic; a large number of freeze-thaw cycles; and heavy traffic in many regions of the commonwealth. Although there are a wide variety of additives (antistrip additives) that can be used to improve the moisture resistance of HMA mixes, current laboratory methods for identifying HMA mixes susceptible to moisture damage are not 100 % effective. As a result, some HMA mixes that should contain antistrip additives do not, and consequently exhibit poorer field performance than they would if a proper antistrip additive were used in their production. Conversely, some HMA mixes contain unnecessary antistrip additive—that is, they contain such an additive but would exhibit adequate performance without their use. This situation results in unnecessary costs to the commonwealth—on one hand in the form of premature failure of HMA pavements, and on the other in the unnecessary use of antistrip additives.

The purpose of this literature review is to examine the current state of the art concerning HMA moisture damage, concentrating on the issue of the cost effectiveness of different approaches to addressing this problem. What would the benefit/cost ratio be of modifications of the standard moisture resistance test method? Potentially such modifications might involve making the requirements more severe (or less severe), or even requiring that all HMA mixes contain an effective antistrip additive, regardless of the result of moisture resistance testing.

This literature review has been composed specifically to provide information for use in executing the research Project “Cost Benefit Analysis of Antistrip-Additives in Hot Mix Asphalt with Various Aggregates.” The literature review therefore focuses on issues relevant to the research project: widely used moisture resistance tests for HMA, the effectiveness of such tests, use of antistrip additives to reduce moisture damage in HMA mixes, moisture damage in Pennsylvania, and standards/specifications concerning HMA moisture damage. Scientific details of the mechanisms of moisture damage are not considered central to the objectives of the research and so are not emphasized in this literature review.

2.1. Moisture Related Damage in Asphalt Concrete

Moisture damage in HMA is the result of water removing, or “stripping” the asphalt binder from aggregate surfaces. It is a complex process with both physical and chemical components. The mechanical action of traffic loading can contribute to the stripping problem, as can chemical processes such as the spontaneous formation of water/asphalt emulsions. A wide range of factors can affect moisture damage in HMA mixes:

- Aggregate type
- Binder chemistry (crude oil source(s), refining method)
- Binder performance grade
- Use of asphalt binder modifiers
- Aggregate gradation
- HMA in-place air void content

- Traffic level
- Amount of rainfall
- Number of freeze-thaw cycles
- Use of additives designed to reduce moisture damage in HMA
- Presence (or absence) of water within the pavement structure, that is effectiveness of drainage

Many engineers consider the last factor listed to be the most critical. After all, moisture damage cannot occur if there is no water in a pavement. Kandhal and Richards (2001) stated in a research paper on moisture damage that the three most important factors affecting moisture damage in HMA pavements were "drainage, drainage and drainage."

Although aggregates are often identified as being prone to moisture damage, it is important to understand that moisture damage tends to be highly dependent on the specific combination of aggregate and binder. An aggregate combined with one binder might exhibit significant stripping, while with a different binder the performance might be acceptable. This makes identifying and preventing moisture damage in HMA mixes complicated.

Moisture damage can occur early and be severe, significantly reducing the life of a flexible pavement. Furthermore, if an existing pavement is exhibiting significant moisture damage, correcting the problem is not simply one of milling the pavement surface and placing an overlay. Moisture damage often occurs from the bottom of the pavement upward, so that the entire pavement structure is often compromised. Moisture damage is a serious and expensive problem in HMA pavements.

As mentioned above, one of the most effective ways of preventing moisture damage is by ensuring that flexible pavements are properly designed and constructed so that good drainage is maintained through the life of the pavement. However, it is not always possible to totally prevent HMA pavements from being exposed to water. Therefore, in mixes prone to moisture damage antistrip additives are often used to help improve performance.

2.2. Antistrip Additives for Asphalt Concrete

Antistrip additives are often placed into two broad categories: (1) hydrated lime $Ca(OH)_2$; and (2) liquid antistrip additives. Hydrated lime is quicklime that has been hydrated with water and pulverized. It should not be confused with agricultural lime, which is powdered calcium carbonate and is not effective as an antistrip agent. There are various ways of adding hydrated lime to HMA at the plant. In some cases, a lime solution is sprayed on the aggregate. Some plants "marinate" aggregate stockpiles in a lime slurry. The hydrated lime can be added to the aggregate on the cold feed belt. In general it is considered more effective if the aggregate is somehow coated with the hydrated lime prior to mixing with the asphalt binder.

There are many different types of liquid antistrip additives; most are surfactants. Sometimes liquid antistrip additives are added to the asphalt binder at the terminal prior to delivery to the hot mix plant. Some plants are equipped to add liquid antistrip to the HMA during mixing.

Hydrated lime is the most widely used antistrip additive in the U.S. (Epps et al., 2003). Some agencies require its use on all or most of the HMA produced in their state (Aschenbrenner, 2003). However, use of hydrated lime can be expensive, particularly if the marination process is used. Liquid antistrip additives are more convenient and less expensive to use. However, the effectiveness of liquid antistrips tends to vary significantly from one aggregate/binder system to another. In fact, it is possible that while generally effective with many mixes, a certain antistrip additive might actually make moisture damage worse with some aggregate/binder combinations. Therefore, any liquid antistrip used in an HMA mix has to be evaluated with that mix to ensure its effectiveness. This is probably the reason that some states that require antistrip in all their HMA mixes still require testing to evaluate moisture resistance—to make certain that the specific additive used is effective with the specific aggregates and binder used in the mix. Figure 1 is a map of the U.S. showing which type of antistrip additive (if any) is used in each state, as reported by Hicks et al. (2003) based on a survey performed by the Colorado DOT (Aschenbrenner, 2003). Pennsylvania's approach to treatment is listed as "liquid seldom," as is New York's. Four neighboring states—New Jersey, Delaware, West Virginia and Ohio—are listed as using antistrip treatment "rarely or never."

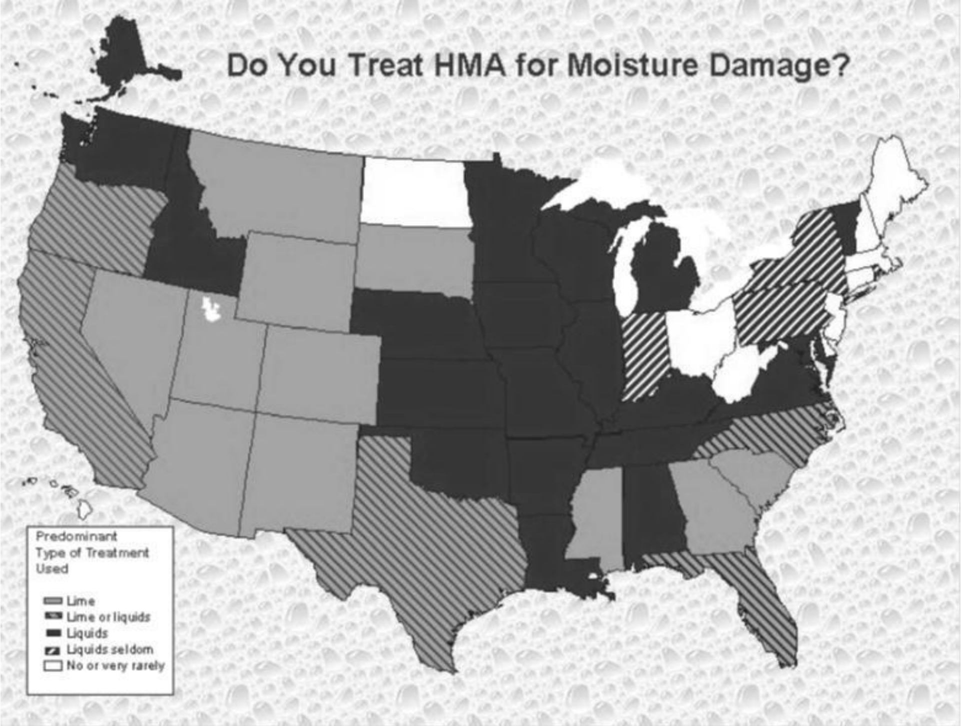


Figure 1. Use of Antistrip Additives in the United States (Hicks et al., 2003).

Effectiveness of Antistrip Additives in Preventing Moisture Damage and Extending Pavement Life

Only a limited number of reports and papers could be found that discussed the effect of moisture resistance and antistrip usage on the performance of HMA pavements. Aschenbrenner et al. (1994) categorized the performance of HMA pavements with respect to moisture damage in general terms. "Good" performers exhibited a good history of resistance to moisture damage. Unfortunately, no details were given concerning typical pavement life and/or maintenance history. However, it can be reasonably assumed that "good" performers showed a more or less normal pavement life with typical maintenance procedures. "High maintenance" HMA pavements required significant maintenance—including significant patching and in some cases overlays—within two to five years due to moisture damage. Again, specific information on total pavement life was not given, perhaps because of time limitations for the study. "Disintegrators" are pavements that totally disintegrate soon after construction due to moisture damage. Such incidents were rare at the time of the study because the materials that contributed to disintegration due to moisture damage were identified and no longer in use in Colorado. It can be concluded on the basis of this categorization that in the early 1990s in Colorado good moisture resistance was associated with a normal pavement life, without significant maintenance during the first two to five years after construction. Poor resistance to moisture damage was associated with significant maintenance during the first two to five years after construction, and probably also resulted in a decreased pavement life.

Researchers in Nevada have examined the effect of hydrated lime on the life of HMA pavements prone to moisture damage (Sebaaly et al., 2001; Martin el al., 2004). Based on a study of 12 actual pavements, they found an average pavement life of 8 years for HMA prone to moisture damage, which could be increased by an average of 3 years with the use of hydrated lime as an antistrip agent. This indicates an increase in life of about 40 % with the use of hydrated lime. The authors did not discuss the average life of HMA pavements not susceptible to moisture damage, perhaps because of the widespread nature of the problem in Nevada. However, they did estimate based on laboratory tests that hydrated lime would extend the pavement life of HMA mixes susceptible to moisture damage by an average of six years. Therefore, it can be assumed that the average HMA pavement life in Nevada, where moisture damage either is not a problem or has been completely controlled, is at least 14 years, and probably somewhat longer.

An important question related to the findings of the Nevada studies is whether liquid antistrip agents are in general as effective as hydrated lime. In 1995, Maupin published the results of a study in Virginia in which the field performance of 12 pavements were evaluated (Maupin, 1995). Nine of these had been treated with liquid antistrip, and three with hydrated lime. Maupin found that after 3 to 4 years, 8 of the 9 sections with liquid antistrip exhibited significant moisture related damage, while all three of the sections treated with hydrated lime exhibited significantly better performance. There were unfortunately no control sections using no antistrips. Also, it should be noted that this study is 20 years old, and that significant advances in the use of liquid antistrip agents in HMA have probably been made. It should be noted that all of the mixes treated with liquid antistrip passed the laboratory test meant to identify HMA mixes prone to moisture damage (a version of the Lottman procedure). This suggests that although the test might be accurate at identifying mixes prone to moisture damage when no antistrip agents are used, its accuracy in evaluating the effectiveness of antistrip agents may not be as good.

A question not answered by any of this research is the typical life of an HMA pavement not prone to moisture damage. Von Quintus and his associates evaluated HMA pavements in the Long Term Pavement Performance (LTPP) Program and determined that the average life of HMA pavements in this study was 22 years, based on reaching a level of moderate to severe distress (Von Quintus et al., 2005). However, it must be remembered that this represents an overall average; the situation in specific climates and states might differ from this national average. Specifically, because of the relatively high traffic volume and severe climate in

Pennsylvania, it should not be surprising if the average HMA life in the Commonwealth was significantly less than 22 years. Washington State lists a range in HMA pavement life of from 8 to 18 years, with an average of 14.7 years. However, in the eastern part of the state, where the weather is most severe, the average life of an HMA pavement is only 11.3 years, while it is 16.5 years in the western part of the state, where the climate is much milder (Washington State Department of Transportation). Based upon these numbers, a rough estimate of HMA pavement life in severe climates such as Pennsylvania would be about 12 years.

Based upon the admittedly limited information on the effects of moisture damage and antistrip additives on the life of HMA pavements, the following rough guidelines are provided:

- Average HMA pavement life in Pennsylvania (no moisture damage): 12 years
- Average HMA pavement life in Pennsylvania (with moisture damage): 6 years
- Average HMA pavement life in Pennsylvania (in mixes with susceptible aggregates but with an appropriate antistrip additive): 9 years

It should be noted that these are meant only to be rough guidelines, to be considered in the assumptions of the life cycle cost analysis, along with the results of the surveys conducted during the study, and considering engineering experience. Furthermore, the final cost/benefit analyses will include a range of assumptions in order to cover a wide range of scenarios and to provide information on the sensitivity of the analyses to the various assumptions.

2.3. Predicting Moisture Resistance in the Laboratory

In order to evaluate the effectiveness of an antistrip additive—in order to even determine if such an additive is needed in a given HMA mix—a laboratory procedure is needed to determine if a mix is prone to moisture damage. A variety of tests are currently used by state agencies and commercial laboratories to evaluate HMA moisture resistance. By far the most common is the modified Lottman procedure—AASHTO T 283 and its variations However, this procedure has long been recognized as not being highly accurate in predicting moisture resistance in HMA mixtures. Because of its shortcomings, an alternative was developed during SHRP—the Environmental Conditioning System (ECS). This procedure has continued to be refined, but has yet to be adopted for routine use by any state highway agency. Some highway agencies require the use of the Hamburg wheel tracking test to evaluate moisture resistance of HMA mixes. Table 1 is a list of various tests being used by state highway agencies as of 2003 (Aschenbrenner, 2003). Note that the Tunnicliff & Root procedure is a modification of the Lottman test. Therefore, of 46 states reporting the use of a moisture resistance testing, 39 use some form of the Lottman procedure.

The main objective of this research project is to determine the benefit/cost ratio of various alternative approaches to addressing moisture damage in HMA mixes. An important component of this research is the use of a laboratory test for evaluating moisture resistance. Such a test is important for two reasons. The reliability of the procedure used to identify mixes that need antistrip will affect the results of the cost/benefit analysis. For example, a test that produces a large number of false positive results (identifying good mixes as susceptible to moisture damage) would have a less than ideal benefit/cost ratio because it would result in unnecessary use of antistrip additives. But probably even worse would be a test that produces a large number of false negatives (identifying poor mixes as resistant to moisture damage), since the result would be a significant number of pavements susceptible to moisture damage that would be prevented—or at least meliorated—with the use of an appropriate antistrip additive. Therefore, it is essential to have at least an estimate of the reliability of the test procedure used to determine the need for antistrip additive.

Table 1. HMA Moisture Resistance Tests in Use by State Agencies as of 2003 (Aschenbrenner, 2003).

Test Procedure	No. of States
Lottman (NCHRP 246)	3
Tunnicliff & Root (ASTM D 4867)	6
Modified Lottman (AASHTO T 283)	30
Immersion-Compression (ASHTO T 165)	5
Hamburg Wheel Tracking	2

Another important potential use for moisture resistance tests in this research project is to categorize a wide range of HMA mixes according to their susceptibility to moisture damage. However, use of a test for this purpose would require that the test have a proven record of reasonable accuracy in predicting susceptibility to moisture damage. So here again, a review of potential moisture damage test procedures is needed, with special emphasis on research linking test data to actual field records of moisture damage.

An additional point must be made concerning moisture resistance tests and the goals of this project. Because having a thorough understanding of the accuracy of a test method is essential to the results of this project, only test procedures that have seen wide use and have been studied extensively will be useful. Although it might be possible to evaluate one or two “new” tests in the laboratory phase of this project by evaluating a number of mixes in the laboratory and comparing the results to the observed resistance to moisture damage for the mixes, it would probably be impossible to include a large enough number and a wide enough range of materials to provide a statistically reliable estimate of their accuracy. Therefore, the review below focuses on test methods with a reasonably long record of use, and with significant data on their reliability.

The Lottman Procedure and Related Tests

The modified Lottman procedure, as described in AASHTO T 283, is currently the most widely used procedure for evaluating the moisture resistance of HMA in the U.S (Aschenbrenner, 2003). It should, however, be noted that there are numerous variations of this procedure, and that in none of its forms is the procedure considered highly accurate in predicting susceptibility to moisture damage. A survey by Hicks (1991) categorized the Lottman and modified Lottman tests as “highly” effective, and the fact that it is still widely used suggests that there is still a reasonably high level of confidence in the ability of these tests to identify HMA mixes susceptible to moisture damage.

The procedure involves preparing six HMA gyratory specimens, leaving three specimens unconditioned, and conditioning the other three with saturation and freezing (optional), followed by a 24-hour soaking at 60°C. Both sets of specimens are equilibrated to a temperature of 25°C and then tested using the indirect tension (IDT) strength test. The ratio of conditioned to unconditioned strength, called the tensile strength ratio (TSR) is then calculated. Current Superpave design methods require a minimum TSR of 0.80. AASHTO T 283 and Pennsylvania's modified version are discussed in more detail below.

Original Development—the Lottman procedure was originally developed by R. P. Lottman in the 1970s and early 1980s, and was documented in two closely related reports, NCHRP Report 192 (Lottman, 1978) and NCHRP Report 246 (Lottman, 1982). As with all versions of this procedure, two sets of three specimens each are prepared—in this case, with Marshall compaction. One set is left unconditioned, while the other is conditioned with saturation, freezing, soaking in hot water, and testing. The original procedure as developed by Lottman involved compacting specimens to an air void content of 3 to 5 %, followed by severe vacuum saturation. Although the saturation level was not specified, it was reported by Aschenbrenner and McGennis (1993) to be near 100 %. Saturation is followed by a freezing cycle at -18°C for 15 hours, followed by soaking in water at 60°C for 24 hours. In the original Lottman procedure, the mechanical testing was performed at 13°C, and could be either diametral resilient modulus, IDT strength, or both. In both cases, the results were reported as ratios of conditioned/unconditioned modulus or strength (Lottman, 1978; Lottman, 1982).

Modifications by Tunnicliff, Root and Others—Tunnicliff and Root, primarily during research investigating the effect of antistrip additives on HMA in NCHRP Project 10-17, recommended several modifications to the Lottman procedure. These included increasing the air void content of the specimens to 6 to 8 %, and eliminating the freezing cycle (Tunnicliff and Root, 1982, 1983, 1984). Tunnicliff and Root also suggested that the saturation procedure used by Lottman was too severe, and that over-saturation of specimens should be avoided. Tunnicliff and Root's version of the Lottman procedure was the basis for ASTM D 4867. Maupin (1979) suggested performing the IDT strength test at 51 mm/min at 25°C, instead of at the 1.6 mm/min and 13°C recommended by Lottman. Dukatz (1987) recognized the extreme effect that variation in air void content could have on the calculation of tensile strength ratio (TSR), and recommended grouping specimens so that the average air void content for the unconditioned and conditioned sets are as much as possible equal. These modifications, along with several others, applied to Lottman's original procedure became the basis for AASHTO T 283, generally referred to as the modified Lottman procedure.

Implementation within the Superpave System—When the Superpave system of mix design and evaluation was implemented in the mid-1990s, further modifications of Lottman-based moisture sensitivity tests were needed. These were addressed by Epps et al. (2000) in NCHRP Project 9-13, the results of which were reported in NCHRP Report 444. Of primary concern was change in specimen type brought about by Superpave. The procedures developed by Lottman, and by Tunnicliff and Root involved 4-inch-diameter specimens compacted using a Marshall hammer (or in some cases a Hveem compacter). Superpave, on the other hand, uses 150-mm-diameter specimens prepared using a gyratory compactor. Superpave also specified short term oven aging for volumetric analysis, and long-term oven aging of compacted specimens for performance testing. As part of NCHRP Project 9-13 Epps and his associates examined the effects of not only specimen size and compaction method, but short- and long-term oven conditioning and saturation level. Their recommendations included several changes to AASHTO T 283 (Epps et al., 2000):

- Loose mix should be aged 16 hours at 60°C prior to compaction
- Specimens should be saturated to between 50 and 80 % saturation
- A freeze-thaw cycle should be included in the procedure

The NCHRP 9-17 researchers also recommended that state highway agencies perform research to ensure effective implementation of the Superpave system within the context of moisture resistance testing. Although NCHRP Report 444 did not include specific recommendations for a minimum TSR, it was suggested that minimum values of between 70 and 80 % would be effective in most cases, and that individual states should determine specific minimum TSR values suitable for their materials and conditions (Epps et al., 2000).

Current Procedure for AASHTO T 283—the modified Lottman procedure is described in AASHTO Standard Test Method T 283. Six specimens are prepared, three of which are tested after conditioning, and three of which are tested without conditioning. The steps for the conditioned specimens are as follows:

1. Specimen dimensions normally are 150 mm diameter by 95 ± 5 mm thick.
2. After preparing loose mix, it is conditioned in an oven for 16 ± 1 hours at 60 ± 3°.
3. The loose mix is then conditioned at the compaction temperature for 2 ± 0.5 hours.
4. Specimens are grouped according to air voids, so that the average air void content for the two groups are as much as possible equal.
5. The specimens selected for conditioning are vacuum saturated using a vacuum of from 13 to 67 kPa absolute, for from 5 to 10 minutes.
6. The vacuum is removed and the specimens are allowed to soak in water for an additional 5 to 10 minutes.
7. The degree of saturation is determined; it should be between 70 and 80 %. If it is below 70 %, additional vacuum saturation is applied until the saturation level is between 70 and 80 %.
8. The specimens are placed in a freezer at –18 ± 3°C for a minimum of 16 hours.
9. The specimens are then placed in a water bath at 60 ± 1°C for 24 ± 1 hours.
10. Both conditioned and unconditioned specimens are then placed in a water bath at 25 ± 0.5°C for 2 hours ± 10 minutes.
11. The specimens are then tested for IDT strength using a loading rate of 50 mm/min.

12. The tensile strength ratio (TSR) is calculated as the ratio of conditioned to unconditioned strength. The failure surfaces of the conditioned specimens are examined for evidence of stripping and rated on a scale of 1 to 5, with 5 being severe stripping (loss of asphalt coating on aggregate particles).

The Modified Lottman Procedure in the Superpave System—in the Superpave system, AASHTO T 283 is performed as described above, except for conditioning of the loose mix. Instead of conditioning at 60°C for 16 hours, the loose mix is conditioned for 2 hr ± 5 min at the compaction temperature for the mixture, which will normally depend on the binder used.

The Modified Lottman Procedure in Pennsylvania—at the start of this project (August 2012) an unusual procedure was used for moisture resistance testing in Pennsylvania that had a number of differences compared to standard version of AASHTO T 283. Conditioning of the loose mix was done for 4 hr ± 5 min, at a temperature that depends on the binder PG grade. For example, loose mix made with a PG 64-22 binder is conditioned at 145 ± 3°C.

Specimens were to be tested for moisture resistance within 24 hours of the completion of short-term oven conditioning. The vacuum applied to conditioned specimens was specified at 254 mm of mercury, for a time of 30 minutes regardless of the degree of saturation. This was an important deviation from the standard procedure, in that it could result in a wider range of saturation levels than specified in AASHTO T 283, including significantly lower saturation levels that could result in some cases in passing mixes with inadequate moisture resistance.

At the conclusion of T 283 testing, if the conditioned specimens exhibit 5 % or more stripping (loss of asphalt binder coating on the aggregate), then the mix was to be tested using ASTM 3625 (Boiling Water Test). If the particle coating is 95 % using this procedure, then the mix is retested using the modified T 283 procedure. All available test data was then to be considered in evaluating the moisture resistance of the mix. If there was any doubt, the mix was considered to be moisture sensitive. This version of T 283 testing was ended in Pennsylvania in October 2014, when it was replaced with a procedure much closer to the AASHTO standard, requiring much higher saturation levels. An important question addressed in this research project is the type I and type II error rates for the different versions of modified Lottman testing and how this affects the benefit/cost ratio for addressing moisture resistance issues in HMA produced in the commonwealth.

The Environmental Conditioning System

Initial Development of the ECS During SHRP— The Environmental Conditioning System was developed during SHRP as an improved procedure for evaluating the moisture resistance of HMA (Al-Swailmi and Terrel, 1994). In the original ECS procedure, a 102 mm-diameter by 102 mm-high specimen is conditioned and tested using the following steps:

1. The resilient modulus is measured
2. The specimen is saturated
3. The temperature is elevated to 60°C and maintained there for 6 hours while the specimen is subjected to cyclic haversine loading

4. The temperature is lowered to 25°C and held there for 2 hours
5. The resilient modulus is again determined
6. Steps 3 through 5 are repeated two additional times

Air and water permeability measurements are also made at several points during the procedure. A mix is considered moisture susceptible if the conditioned to unconditioned resilient modulus ratio falls below 0.7. After the procedure is completed, the specimen is split in half and visually inspected for signs of stripping. The procedure is somewhat complicated, as is the equipment required to perform it. Figure 2 is a schematic of the ECS (Solaimanian et al., 2003). Although the ECS was promising, the effectiveness of the test in predicting HMA susceptibility to moisture damage did not appear to be any better than that of AASHTO T 283.

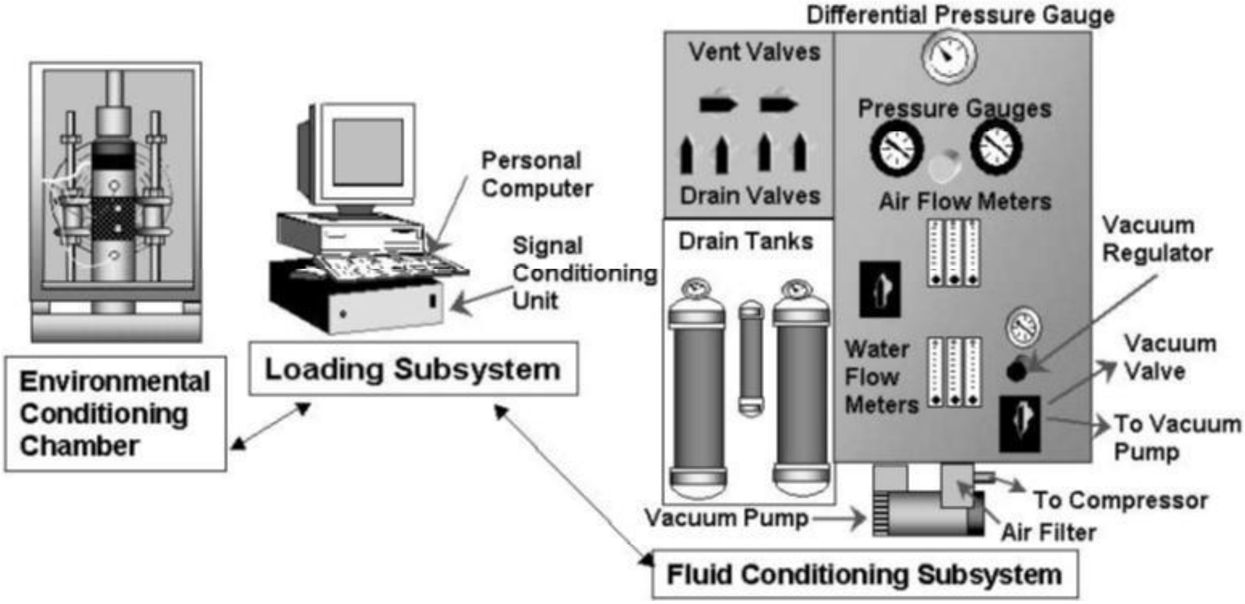


Figure 2. Schematic of Environmental Conditioning System (Solaimanian et al., 2003).

Modifications to the ECS—after the conclusion of SHRP, a number of researchers proposed improvements to the ECS, including Alam et al. (1998) and Solaimanian et al. (2007). The latter research was done as part of NCHRP 9-34 and is more significant to this project. The objective of NCHRP 9-34 was to develop an improved moisture resistance test for HMA which could be incorporated by the ECS and the asphalt mixture performance tester (AMPT). It was determined that of the various tests that can be performed using the AMPT, the frequency sweep test was best suited for use in moisture resistance testing in conjunction with the ECS. The ECS conditioning used on the specimens consisted of bringing the temperature of the specimens to 60°C, saturating them with water and then pumping water slowly through the specimen while applying a pulse load of 0.1 s duration followed by 0.9 s of recovery. This conditioning was continued for 18 hours. The specimens were tested using an E* frequency sweep before conditioning, after saturation with water and after full conditioning. The authors reported that the proposed test method better predicted the field performance of eight HMA mixes tested, compared with the modified Lottman procedure and the Hamburg wheel tracking device. The procedure appears to have some promise, as it correctly identified all five poor performing mixtures, and correctly categorized two of the three good performing mixes. As a comparison, both the modified Lottman test and the HWTD also correctly categorized two of the three good performing mixes, but only correctly identified three of the five poor performing mixes (Solaimanian et al., 2007). However, this is a relatively small data set, so the real effectiveness of the test is still uncertain. Furthermore, at this time no state agency is using the ECS on a routine basis so its effectiveness in everyday use is unknown.

The Immersion-Compression Test

The immersion-compression test (AASHTO T 165) is used by several agencies for evaluating the moisture resistance of HMA. In some ways it is similar to T 283; six specimens are prepared; three are conditioned, and three are unconditioned. The conditioned specimens are submerged in hot water, either 48.9°C for 4 days or 60°C for 1 day. The specimens are then tested for compressive strength using a loading rate of 0.05 mm/mm height. The minimum ratio of conditioned to unconditioned strength is typically 0.7 (Stuart, 1990). In a detailed review of this method, Stuart (1990) reports that correlations with moisture resistance in the field have ranged from poor to good. He also notes that a common criticism for this method has been that the retained strength sometimes will approach 100 % even when there is significant stripping visible in the failed specimens. States that use this procedure to evaluate moisture resistance include New Mexico, Idaho and Arizona (Aschenbrenner, 2003).

The Hamburg Wheel Tracking Test

The Hamburg wheel tracking test was developed in Germany, and involves simultaneous loading of two HMA specimens using a small steel wheel. The test can be run dry or wet—the latter procedure is the one used to evaluate moisture resistance. The test is most often run at 50°C, but other temperatures can be used. Specimens are loaded for 20,000 wheel passes or until a total deformation of 20 mm is reached (Aschenbrenner et al., 1995). Figure 3 illustrates a typical plot of rut depth versus loading cycles for a Hamburg test in water. There are several parameters calculated from this test. The creep slope is the inverse of the slope of the initial linear portion of the deformation curve. The stripping slope is the inverse of the slope of the second linear portion of the deformation curve. The stripping inflection point is the number of cycles at which these two linear parts of the deformation curve intersect. These three parameters are shown graphically in Figure 3. As discussed below, Aschenbrenner et al. (1995) found good correlations between moisture resistance of HMA pavements in the field and the results of the Hamburg wheel tracking test.

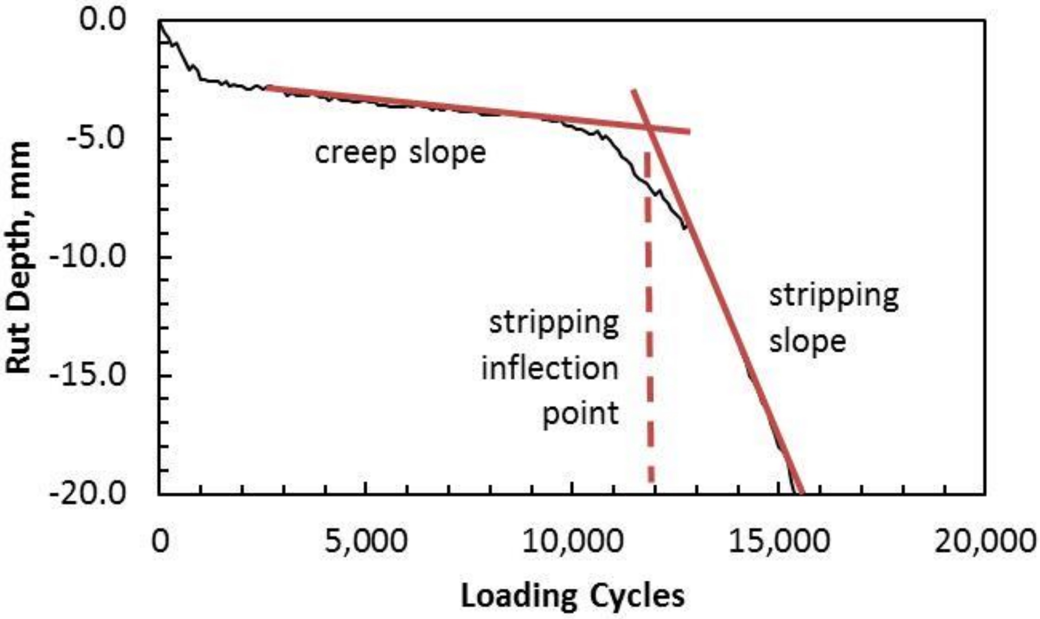


Figure 3. Typical Data from a Hamburg Wheel Loading Test (Wet).

Boiling Water Test

This test procedure involves boiling HMA mixture in water for 10 minutes. After draining and cooling the mixture is examined to evaluate the extent of stripping on the aggregate (or the percent retained coating). It has been standardized in ASTM D 3625. Stuart reported in 1990 that the reports on the effectiveness of this test were mixed, and that it often fails to accurately predict field performance. He suggests that it might be useful in conjunction with another more reliable moisture resistance test, which is in fact the way the test is used in Pennsylvania.

Accuracy of Currently Used Procedures for Predicting HMA Moisture Resistance

Several studies have been done in which the accuracy of various moisture resistance tests have been evaluated. Perhaps the most extensive recent study was done by Aschenbrenner and various associates in the early to mid-1990s (Aschenbrenner and McGennis, 1993; Aschenbrenner, Terrel and Zamora, 1994; Aschenbrenner, McGennis and Terrel, 1995). In this research, 20 HMA mixes from Colorado with known moisture resistance performance were evaluated using a number of tests: (1) AASHTO T 283; (2) AASHTO T 283 with 30 minute saturation; (3) the boiling test (ASTM D 3625); (4) the Hamburg wheel tracking test; and (4) the ECS. Table 2 summarizes the results of this research, showing the error rates and overall accuracy for the various tests. The table breaks down error rates in terms of the type of error; a type I error occurs when a mix with a good performance record fails to pass a given test, while a type II error occurs when a mix with a poor performance record passes a given test. Overall accuracy takes both types of error into consideration. AASHTO T 283 (original) showed a 65 % accuracy, but this improved to 80 % with a 30 minute saturation—somewhat more severe than the standard procedure. The Hamburg wheel tracking test also did reasonably well, with an accuracy of 75 % using the standard failure criteria, which increased to 85 % using a modified, less severe failure criteria. The other tests—the boiling test and the ECS—did not show acceptable levels of accuracy in predicting moisture sensitivity.

Table 2. Error Rate and Overall Accuracy of Various Moisture Resistance Tests as Reported by Aschenbrenner et al. (1995).

Test	**% Good Mixes that Failed Test** *Type I Error*	**% Poor Mixes that Passed Test** *Type II Error*	**Overall Accuracy, %**
AASHTO T 283	0	54	65
AASHTO T 283 30 Minute Saturation	14	23	80
Boiling Test	86	23	55
Hamburg	57	8	75
Hamburg, Modified Criteria	13	15	85
ECS 3 Cycles	0	85	45
ECS 4 Cycles	0	77	50

The significance of rates for type I and type II errors for a moisture resistance test bear further discussion because they become extremely important in the cost benefit analysis. A type I error—concluding a mix has poor moisture resistance when it in fact exhibits good moisture resistance—will result in unnecessary costs because of the addition of antistrip additive to the mix. A type II error—concluding a mix has adequate moisture resistance when in fact it has poor moisture resistance—is potentially a much costlier mistake, since it could result in the premature failure of an entire pavement section, or even multiple pavement sections. It is therefore likely that rather than seeking a balance between the two types of error, a moisture resistance test should be constructed so that type I errors are much more common than type II errors. This ratio should be selected to maximize the life cycle cost of the pavement (including costs of moisture resistance testing and antistrip additive, if used). The ratio of type I and type II error rates can probably be controlled by adjusting the acceptance criteria for a given test. For example, increasing the minimum TSR for AASHTO T 283 would be expected to increase the type I error rate and decrease the type II error rate. Another factor that affects the costs of type I and type II errors is the frequency of moisture resistance problems in a given state. If moisture damage is a common problem, then the cost of type II errors increases and the cost of type I errors decrease. On the other hand, if moisture resistance problems are relatively rare, the cost of type I errors increases while the cost of type II errors decrease. The latter is probably the case in the commonwealth, so the relative rarity of moisture resistance problems should offset to a certain extent the high cost of premature pavement failures associated with classifying a poor performing mix as having good moisture resistance. The relative rates of type I and type II errors in Pennsylvania’s T 283 testing and how these vary with minimum TSR will have a critical effect on the benefit/cost ratio of addressing moisture resistance problems in HMA produced in

Pennsylvania, as will the overall frequency of moisture susceptible mixes. For these reasons, these issues will be an important focus in the execution of Tasks 3 and 4 of the project.

Accuracy of the Modified Lottman Procedure

Several studies have been done in which the accuracy of the various forms of the modified Lottman test have been evaluated. Perhaps the most extensive recent study was done by Aschenbrenner and various associates in the early to mid-1990s (Aschenbrenner and McGennis, 1993; Aschenbrenner, Terrel and Zamora, 1994; Aschenbrenner, McGennis and Terrel, 1995). Because of the wide variation in test conditions used in the modified Lottman procedure, Aschenbrenner and McGennis developed a classification system based on the severity of the test conditions, as shown in Table 2. Level 1 is the most severe, and involves saturating specimens using a vacuum of 24 inches of mercury for 30 minutes. This provides a typical level of saturation of about 90 %, and the authors refer to this as “total saturation.” Levels 2B and 2C are similar, with the final level of saturation being specified at 55 to 80 %, with a typical level of 70 %. These two levels differ only in that 2B includes a freeze cycle, whereas 2A does not (level 1 includes a freeze cycle). Aschenbrenner and McGennis considered levels 2A and 2B similar in severity (Aschenbrenner and McGennis, 1993).

The results of testing reported by Aschenbrenner and McGennis are summarized in Tables 3 through 6. This table breaks down the results into passing and failing mixes according to the moisture resistance category: good, moderate and poor. As would be expected, the more severe procedure (level I) results in an increase in the type I error rate and a decrease in the type II error rate compared to the less severe level 2B testing. The level I severity shows a nearly equal balance between type I and type II error rates, whereas the levels 2B and 2C have a significantly higher type II error rate—that is, a greater proportion of poor mixes pass these tests than good mixes fail. It is significant that for all severity levels, the type II error rate is quite high for mixes of moderate moisture resistance. This suggests that modified Lottman procedures have difficulty correctly identifying mixes with marginal moisture resistance.

Table 3. Classification of Modified Lottman-Type Moisture Resistance Tests by Aschenbrenner and McGennis (1993).

Tested at 7 % Air Voids.

Severity Level	**Air Void Content**	**Vacuum**	**Freeze Cycle?**	**Typical Degree of Saturation**
1	7 %	24 in. Hg for 30 minutes	Yes	90 %
2B	7 %	To between 55 and 80 % saturation	Yes	70 %
2C	7%	To between 55 and 80 % saturation	No	70 %

Table 4. Results of Modified Lottman Testing, Level 1 Severity, as Reported by Aschenbrenner and McGennis (1993).

	Moisture Resistance of Aggregates in Mix		
Test Result	**Good**	**Moderate**	**Poor**
Passed	6	***2***	***1***
Failed	***1***	3	7
Error Rates	*Type I*	*Type II*	
	17 %	40 %	14 %

Table 5. Results of Modified Lottman Testing, Level 2B Severity, as Reported by Aschenbrenner and McGennis (1993).

	Moisture Resistance of Aggregates in Mix		
Test Result	**Good**	**Moderate**	**Poor**
Passed	7	***5***	***2***
Failed	0	0	6
Error Rates	*Type I*	*Type II*	
	0 %	100 %	33 %

Table 6. Results of Modified Lottman Testing, Level 2C Severity, as Reported by Aschenbrenner and McGennis (1993).

Test Result	*Moisture Resistance of Aggregates in Mix*		
	Good	**Moderate**	**Poor**
Passed	7	***5***	***1***
Failed	0	0	7
Error Rates	*Type I*	*Type II*	
	0 %	100 %	14 %

Tables 7 and 8 summarize the accuracy of modified Lottman tests as reported by Kennedy et al. (1983) and Stuart (1986). Kennedy and his associates used a severe, level I type version of the test procedure, so the results (Table 7) can be compared with those shown in Table 4. Kennedy et al. did not test nearly as many mixes as Aschenbrenner and McGennis, so the error rates should not be expected to be very accurate; Kennedy et al. founda type I error rate of 33 %, higher than that observed by Aschenbrenner and McGennis, but probably within a reasonable range of variability. Similarly, Kennedy's observed the 'type II error rate for poor mixes was 0 %, lower than that reported by Aschenbrenner and McGennis, but again, probably in reasonable agreement. Stuart (1986) used a version of the modified Lottman procedure with a level 2C severity, that is, identical to level 2B but without a freeze cycle. The results summarized in Table 8 can be compared with those in Table 6, for level 2C severity as reported by Aschenbrenner and McGennis (1993). There does seem to be some discrepancy in the results of these two studies; the type II error rate reported by Aschenbrenner and McGennis, at 46 % overall, is much higher than the 12 % rate reported by Stuart. However, it should be kept in mind that the variability in these test procedures is high, and the variability in error rates estimated from such studies should also be expected to be high.

Table 7. Results of Modified Lottman Testing, Level I Severity, as Reported by Kennedy et al. (1983).

Test Result	*Moisture Resistance of Aggregates in Mix*		
	Good	**Moderate**	**Poor**
Passed	2	N/A	0
Failed	***1***	N/A	5
Error Rates	*Type I*	*Type II*	
	33 %	N/A	0 %

Table 8. Results of Modified Lottman Testing, Level 2C Severity, as Reported by Stuart (1986).

Test Result	*Moisture Resistance of Aggregates in Mix*		
	Good	**Moderate**	**Poor**
Passed	5	***1***	0
Failed	1	3	4
Error Rates	*Type I*	*Type II*	
	17 %	25 %	0 %

Kiggundu and Newman (1987) tested two mixes using the modified Lottman procedure without a freeze cycle (severity 2C). Both of these mixes failed the test. Gharaybeh (1987) tested a total of five mixtures using this same procedure, and all five mixtures passed. Two of these mixtures had good moisture resistance, one had moderate and two had exhibited poor moisture resistance in the field. The results of these two studies have been lumped together in Table 9 below.

Table 9. Results of Modified Lottman Testing, Level 2C Severity, as Reported by Kiggundu and Newman (1987) and Garaybeh (1987).

Test Result	*Moisture Resistance of Aggregates in Mix*		
	Good	**Moderate**	**Poor**
Passed	2	***1***	***2***
Failed	0	1	1
Error Rates	*Type I*	*Type II*	
	0%	50%	67 %

The results of all projects discussed above are summarized in Tables 10 and 11 below. Table 10 includes all results from testing of Level 1 severity, while table 11 includes all results from Level 2 severity (levels 2B and 2C). Because Aschenbrenner and McGennis used the exact same materials when evaluating levels 2B and 2C, and because the results were nearly identical, they were averaged and entered as a single data set in order to avoid giving undo weight to these results. From this summary, it would appear that the level 1 severity for the modified Lottman procedure provides better accuracy and balance compared to tests of level 2 severity. Also, importantly, neither level of severity appears to do a good job of correctly categorizing mixes with moderate moisture resistance.

Table 10. Results of Modified Lottman Testing, Level I Severity, as Reported by Various Researchers (Aschenbrenner and McGennis, 1993; Kennedy et al., 1983).

Test Result	*Moisture Resistance of Aggregates in Mix*		
	Good	**Moderate**	**Poor**
Passed	8	***2***	***1***
Failed	***2***	3	12
Error Rates	*Type I*	*Type II*	
	20%	40 %	8 %

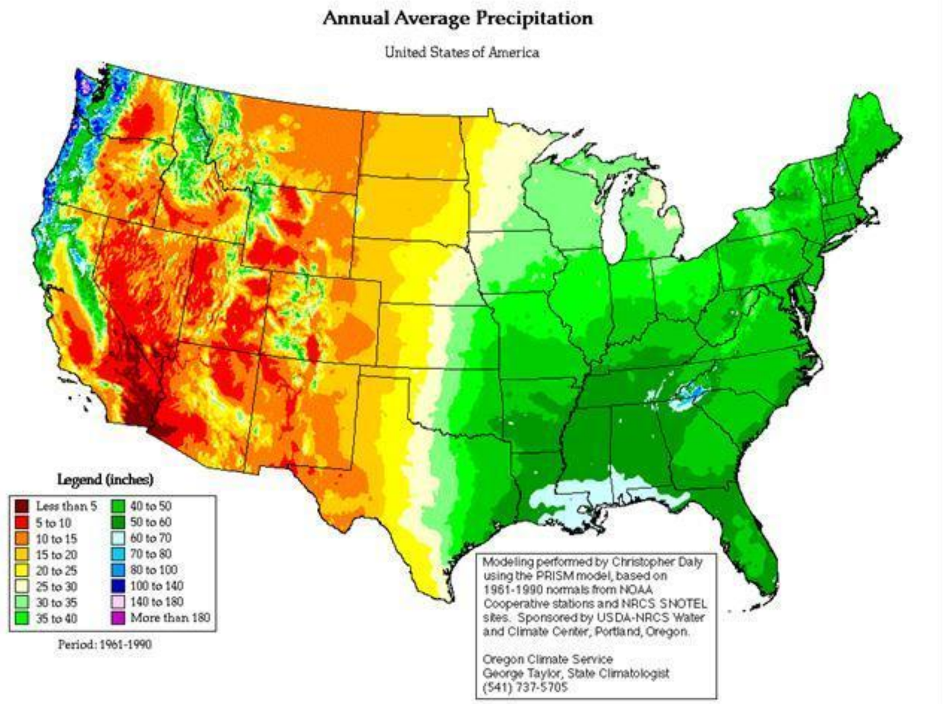
Table 11. Results of Modified Lottman Testing, Level 2B and 2C Severity, as Reported by Various Researchers (Aschenbrenner and McGennis, 1993; Stuart, 1986; Kiggundu and Newman, 1987; Garaybeh, 1987).

Test Result	*Moisture Resistance of Aggregates in Mix*		
	Good	**Moderate**	**Poor**
Passed	14	***7***	***3.5***
Failed	***1***	4	11.5
Error Rates	*Type I*	*Type II*	
	7 %	64 %	23 %

2.4. Moisture Related Damage to Flexible Pavements in Pennsylvania

Severe Conditions for Pavements in Pennsylvania

Pennsylvania probably offers some of the most severe conditions for HMA pavements in the U.S. It has a relatively wet climate, has a very large number of freeze-thaw cycles, and also a large population leading to heavy traffic levels in many parts of the state. Figures 4 through 7 graphically depict the severity of the Commonwealth's climate relative to other regions of the continental U.S. Figure 4 shows annual average precipitation; Figure 5, annual average freeze-thaw cycles; Figure 6, population density; and Figure 7, hydrogen ion (pH) concentration of rainfall.



Modeling performed by Christopher Daly using the PRISM model, based on 1961-1990 normals from NOAA Cooperative stations and NRCS SNOTEL sites. Sponsored by USDA-NRCS Water and Climate Center, Portland, Oregon.

Oregon Climate Service
George Taylor, State Climatologist
(541) 737-5705

Figure 4. Annual Average Precipitation for the Continental United States (Oregon Climate Service).

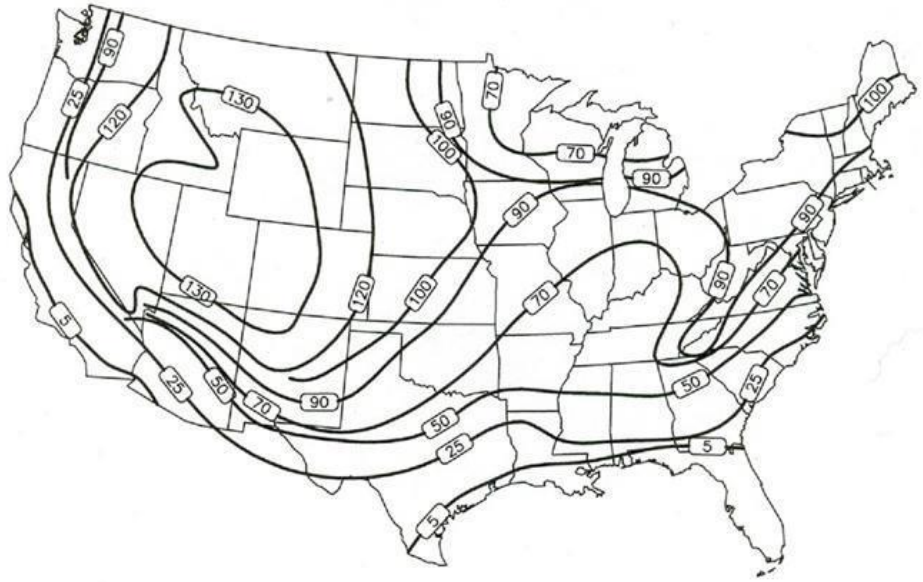


Figure 5. Average Annual Number of Freeze-Thaw Cycles in the Continental United States (from the Marble Institute).

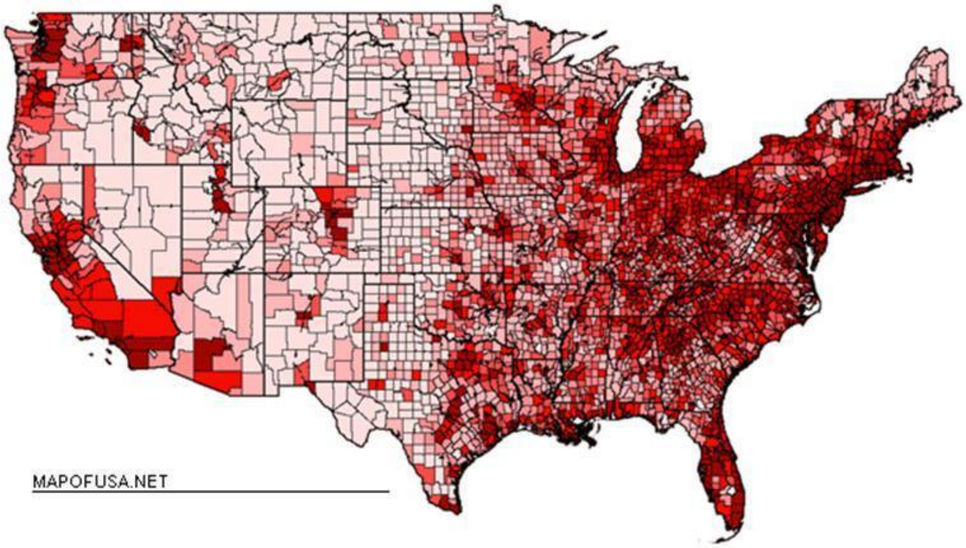


Figure 6. Population Density of Continental U.S. (darker shades of red indicate higher population density, from MAPOFUSA.NET).

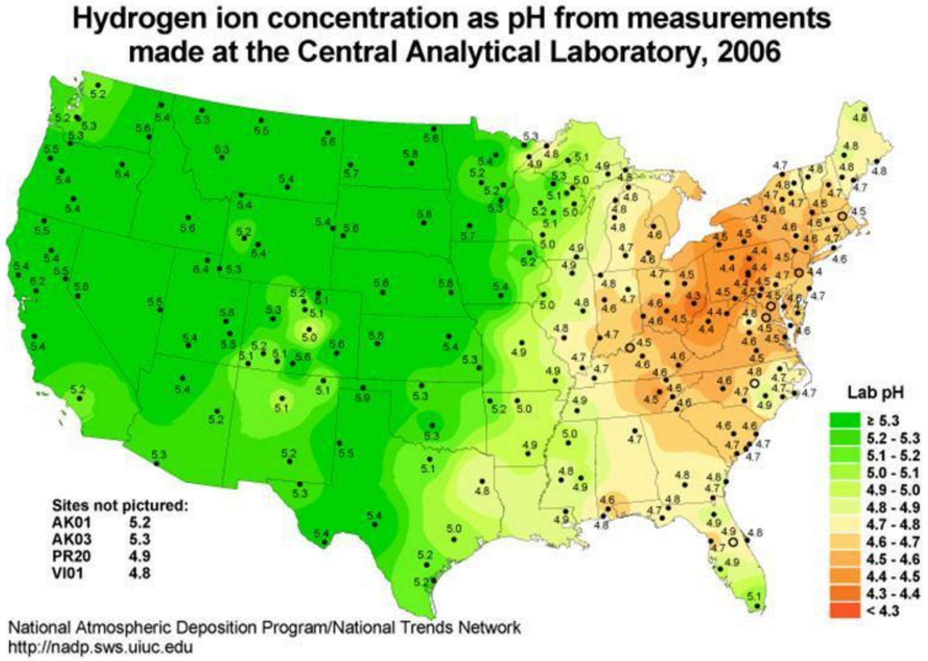


Figure 7. Hydrogen Ion Concentration of Rainwater in the Continental U.S. (lower values indicate more acidic values, from the University of Illinois).

The last figure is indicative of the acidity of rainfall in the U.S.; values for Pennsylvania are the lowest in the continental U.S., ranging from about 4.4 to 4.7. Although it has not been studied, the highly acidic nature of rainfall in Pennsylvania (and virtually all other states) could affect moisture damage to HMA pavements. It is possible that acidic water is more damaging to asphalt coatings compared to the tap water normally used in AASHTO T 283 and other similar procedures (tap water is normally buffered to a pH of about 8.0). It is also possible that the effect of acidic water on the moisture damage to HMA, both in the field and in laboratory tests, vary depending on the aggregate type and/or asphalt source.

The research team originally proposed evaluating the hypothesis that acid rain was a significant factor in explaining variation in the moisture resistance of HMA mixes, and still believes that this is an interesting and promising idea. However, successful completion of this project, as discussed previously, is highly dependent on having an accurate estimate of the error rates (both for type I and type II errors) for the moisture resistance testing method used in Pennsylvania. Currently, a variation of AASHTO T 283 is used in Pennsylvania; the research team believes that the error rates for this procedure and for the standard AASHTO procedure should both be characterized, since it is possible that the standard AASHTO procedure might be more cost effective, and could be easily re-adopted in Pennsylvania. However, even if the use of simulated acid rain solution in T 283 appeared promising, its implementation would take substantial additional research and its final adoption—if ever occurring—would require many years. This suggests that project efforts should emphasize AAHTO T 283 and PennDOT's modified version of this procedure rather than possible improvements in moisture resistance testing my using simulated acid rain solutions.

Studies of HMA Moisture Damage in Pennsylvania

A recent study evaluated the moisture resistance and other performance related properties of aggregates from District 1 in Pennsylvania (Solaimanian et al., 2009). This research was carried out because of the depletion of quality aggregates in this part of the state. This is the region of the state where crushed gravel aggregates—those that would be expected to in general exhibit lower levels of moisture resistance—are common. Four of the materials tested were crushed gravels meeting the requirements of a PennDOT class C aggregate; this is the lowest quality class of aggregate. These potentially marginal materials fell into the class C category because of high sodium sulfate loss and high absorption. One class A crushed gravel was included in the study, as was one class A crushed limestone, included as a control. The moisture resistance of these materials was evaluated using AASHTO T 283, with four different treatments: (1) a control (no treatment); use of a liquid antistrip additive; (3) use of hydrated lime (applied to wet aggregate and cured for 24 hours); and (4) replacing half of the aggregate passing the number 8 sieve with crushed limestone. Two of the untreated mixes passed T 283 requirements, while three failed. The use of the liquid antistrip additive was the most effective treatment, causing significant improvement in TSR values for most of the mixes; four of the five mixes exceeded a TSR of 0.80 after treatment with the liquid antistrip. The limestone blends and treatment with hydrated lime were not particularly effective in improving moisture resistance. It should be noted that the percentage of crushed gravel mixes failing T 283 requirements was 60 %, suggestive of an overall poor level of moisture resistance for HMA made with crushed gravel in Pennsylvania. As will be discussed below, this is consistent with data from other states, where use of crushed gravel is often associated with a frequent need of antistrip additives in order to obtain adequate moisture resistance.

Kandhal and Richards published a report consisting of several case studies of moisture damage in HMA overlays (2001). Figure 8 below is a photograph of the section of the Pennsylvania Turnpike considered in this study. In this particular case, an old overlay made with crushed gravel was replaced with a similar, crushed gravel mix. The underlying layer was HMA made with crushed limestone. The overlay was constructed in 1994, and portions of it began showing distress in 1996. The investigation showed substantial stripping in both the underlying limestone mix and the crushed gravel overlay. The authors believed that there was already significant moisture damage in the underlying limestone HMA when the overlay was placed, which in part lead to the early failure.

Figure 8. Pennsylvania Turnpike Westbound Lane Near Milepost 217.65, Showing Potholes Due to Moisture Damage (Kandhal and Richards, 2001).

The authors proposed that saturation of HMA overlays will lead to rapid failure regardless of the inherent moisture resistance of the HMA mixture. It is therefore essential to prevent such overlays from becoming saturated, and also important to understand that such failures will occur even when using mixtures with known good moisture resistance. Four case histories were discussed, including one in Pennsylvania—a stretch of the Pennsylvania Turnpike in Cumberland County (see figure below). The authors present a large number of conclusions, but perhaps the most important are as follows (Kandhal and Richards, 2001):

1. The three most important factors in preventing moisture damage in HMA pavements are “drainage, drainage and drainage.”
2. In dense graded HMA overlays, it is essential that the underlying base course be highly permeable, so that provides good drainage from the lower part of the

pavement structure to the edge drains. The surface course should be relatively impermeable.

3. For open graded friction courses (OGFC), it is important that the underlying pavement have low permeability and good moisture resistance. Kandhal recommends the use of hydrated lime as an antistrip additive to ensure that the pavement layer underlying an OGFC has good moisture resistance.
4. The authors suggest that a new moisture resistance test is needed, better than AASHTO T 283. They point out that the degree of saturation in the case studies presented in this report was near 100 %, whereas T 283 only requires 55 to 80 % saturation. They suggest that the newly developed (at that time) Environmental Conditioning System (ECS) has promise as a moisture resistance test.

It should be noted that this last conclusion/recommendation is somewhat at odds with information presented early in the report, suggesting that the mechanism of stripping in these (and many other cases) had little to do with traditional moisture damage, but was related to a severe mechanical scouring of the binder while the mix was in a saturated state. The authors' apparent recommendation for blanket use of hydrated lime in the HMA layer under an OGFC also seems to contradict one of Kandhal's main conclusions in a report on moisture resistance made nine years earlier, where he emphasized that the performance of antistrip additives can vary substantially from mix to mix, sometimes even making the performance worse rather than improving it (Kandhal, 1992). This observation was in fact confirmed in the study discussed above by Solaimanian et al. The main significance of this study in characterizing the overall problem of moisture resistance of HMA pavements in Pennsylvania is that (1) moisture damage to HMA pavements is often not the result of poor moisture resistance of the HMA materials, but instead is due to poor drainage in the pavement; and (2) a mixture with crushed gravel, as might be expected, was implicated in a failure related to moisture resistance, emphasizing the potential problem with these materials.

2.5. Aggregates and Asphalt Concrete Moisture Resistance

An issue critical to the outcome of this research is what percentage of Pennsylvania aggregates are prone to stripping, and what percentage are resistant. This, in combination with the accuracy of the laboratory test used to identify moisture sensitive mixes, will determine how many poor performing pavements are typically misidentified and constructed without antistrip, and how many good-performing pavements are misidentified and constructed with antistrip. Along with reasonable assumptions about pavement maintenance and associated costs, this will determine the outcome of the cost/benefit analysis. Unfortunately at this time very little information is available on the percentage of flexible pavements in the Commonwealth prone to moisture damage, or even the percentage of HMA requiring antistrip additive. Some useful information in other states is available that can be used to make estimates concerning the prevalence of moisture damage in HMA placed in Pennsylvania.

In general, HMA made using siliceous rocks or minerals tend to be more prone to moisture damage than calcareous rocks. It should be expected that the aggregates tending to produce more moisture resistance problems in the commonwealth would be sandstones and crushed gravels. HMA produced using dolomite and/or limestone should be expected to in general exhibit adequate resistance to moisture damage. The fine aggregate used in a mix is particularly important in establishing the moisture resistance, because of its surface area. Therefore the use of significant amounts of siliceous fine aggregate—natural sand or sand manufactured from sandstone, quartzite or other mineral with substantial amounts of silica—could be prone to moisture damage.

In Aschenbrenner's survey of state highway agencies (2003) several states indicate the percentage of HMA produced in their state which requires antistrip, and is therefore probably prone to moisture damage:

- Indiana, 10 %
- Kansas, 30 to 50 %
- Minnesota, 30 %
- Tennessee, "a majority"

Furthermore, a number of states require antistrip in all mixes but don't mention the percentage of mixes that are actually prone to moisture damage. These states include, but are not limited to Georgia, South Carolina, and Mississippi. At least 10 states were identified as requiring the use of antistrip additives in HMA according to the 2002 AASHTO Survey. Because this survey is 10 years old, specifications for these states were reviewed to determine if the mandated use of antistrip is still in place. It was found that eight of these states still require antistrip in all HMA mixes. One does not currently have such a requirement (South Dakota), and in another case (Wyoming) it is not clear if there is a mandate, but it appears required use of hydrated lime is common. Some states, including New Jersey and Delaware, indicate that they rarely encounter stripping problems. Although the National Seminar does not mention the specific aggregate types used in HMA mixes in these various states, this information is available—though not in great detail—from the U.S. Geological Service (USGS) in the USGS 2008 Minerals Yearbook, which is available online and includes a chapter for each state (USGS 2008). This publication lists the aggregate usage in each state, typically listing the types of aggregate used in bituminous concrete production. This information can be combined with that from the National Seminar to provide general information concerning the relationship between HMA aggregate types and susceptibility to moisture damage. Tables 12 through 14 summarize information prevalence of moisture damage, as estimated from information in the National Survey, and predominant aggregate type(s) used in HMA as taken from the USGS Minerals Yearbook. Table 12 summarizes information for states requiring antistrip in 2002 in which HMA moisture damage is widespread. Table 13 summarizes information for states with intermediate levels of moisture damage, while Table 14 is a summary of information for states reporting little or no moisture damage in their HMA pavements.

Table 12. States Requiring the Use of Antistrip Additive in HMA as of 2002 and the Predominant Aggregate Type Used in Each State for Producing HMA (Aschenbrenner, 2003; USGS, 2008).

State	Predominant Aggregate Type(s) Used in HMA	Verified Mandate Continues in 2012
Colorado	Crushed gravel	Yes
Georgia	Crushed granite	Yes
Idaho	Crushed gravel	Yes
Mississippi	Crushed gravel	Yes
Montana	Crushed gravel	Yes
North Carolina	Crushed gravel and crushed granite	Yes
South Carolina	Crushed granite	Yes
South Dakota	Crushed gravel	South Dakota does not currently require antistrip additive in all HMA mixes
Virginia	Crushed limestone/dolomite (not in surface courses), granite, trap rock and/or sandstone	Yes
Wyoming	Crushed gravel	Requirements for addition of hydrated lime are apparently done on a project-by-project basis; overall extent of mandated use is not clear

Table 13. States Reporting Intermediate Levels of Moisture Sensitivity Problems in HMA Mixes as of 2002 and the Predominant Aggregate Type(s) Used in Producing HMA (Aschenbrenner, 2003: USGS, 2008).

State	Predominant Aggregate Type(s) used in HMA	% of Mixes Requiring Antistrip Additive
Kansas	Gravel in western 2/3 of state, limestone in eastern 1/3	30 to 50 %
Minnesota	Mostly crushed gravel with limited amounts of limestone	About 30 %

Table 14. States Reporting Little or No Problems with Moisture Sensitivity Problems in HMA Mixes as of 2002 and the Predominant Aggregate Type(s) Used in Producing HMA (Aschenbrenner, 2003: USGS, 2008).

State	Predominant Aggregate Type(s) used in HMA	% of Mixes Requiring Antistrip Additive
Delaware	Crushed gravel	Near 0
Indiana	Crushed limestone	About 10 %
New Hampshire	Crushed gravel, granite and/or trap rock	Near 0
New Jersey	Crushed gravel, trap rock and/or granite	Near 0
New York	Crushed limestone, limited amounts of crushed gravel	Minimal
Ohio	Crushed limestone	Near 0
West Virginia	Crushed limestone	Near 0

Examining these tables, it appears clear that the use of crushed gravel and/or crushed granite tends to promote high levels of moisture damage in HMA concrete. On the other hand, the use of crushed limestone often is associated with little or no moisture damage in HMA pavements. However there are some exceptions to these rules. Tennessee reports high levels of moisture damage even though the predominant aggregate is crushed limestone. Delaware and New Hampshire report little or no moisture damage even though these states are using crushed gravel and or crushed granite in the HMA mixes. We must however keep in mind that numerous other factors contribute to moisture damage in HMA—including pavement drainage and overall traffic levels. It is possible, for instance, that the lack of moisture damage in HMA pavements in Delaware is the result of generally good drainage in their pavements because the state consists almost entirely of well-drained sandy soil. New Hampshire may not experience high levels of stripping because of relatively low traffic levels throughout most of the state. It is also likely that state highway agencies differ in their propensity to characterize HMA failures as moisture damage.

In another section of the National Seminar a discussion is presented concerning aggregate type and moisture damage; Figure 9 is reproduced from this document (D’Angelo and Anderson, 2003). Aggregates that appear resistant to moisture damage, such as limestone, are more basic in nature. On the other hand, aggregates that are prone to moisture damage, such as granite, are more acidic in nature. Based on the discussion above and Figure 9, the following approximate ranking of stripping potential for HMA aggregates can be made (from most resistant to least resistant to moisture damage):

- limestone
- dolomite
- basalt (trap rock)
- sandstone

- granite
- quartzite

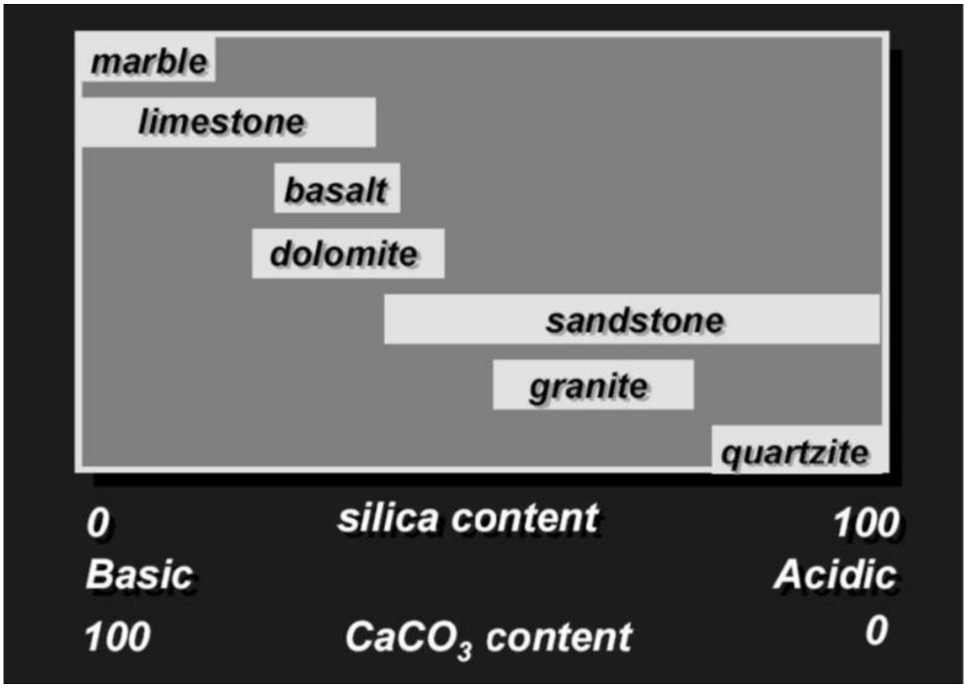


Figure 9. Calcium Carbonate Content ($CaCO_3$) and Acid/Base Characteristics of Aggregates Commonly Used in HMA (D'Angelo and Anderson, 2003).

Gravel is composed of a variety of minerals, its exact composition varying depending on where and how the gravel was produced. Most gravel contains significant amounts of siliceous minerals such as sandstone, quartzite and granite, which is why crushed gravel is commonly associated with moisture resistance problems in HMA.

HMA Aggregate Production in Pennsylvania and its Impact on Moisture Damage

Pennsylvania produces a very large quantity of construction aggregates, much of which is used in the production of hot-mix asphalt. The geology of the commonwealth is complex, and as a result there are a wide range of aggregate types used in the production of HMA in the commonwealth. The Pennsylvania Department of Conservation and Natural Resources (DCNR) publishes a document listing aggregate producers: *Listing of Non-Coal Mineral Producers in Pennsylvania*. Although this publication does not provide summary information, reviewing its contents does allow an approximate listing of the most common construction aggregate types in the commonwealth:

- Dolomite, including the Nittany, Ontelaunee, Ledger, Vintage and Bellefonte formations
- Limestone, including the Coburn-Loysburg, Anville, Jacksonburg, Keyser-Tonoloway and Chambersburg formations

- Crushed gravel
- Sandstone, including the Pottsville and Catskill formations
- Lockatong Argillite

Unfortunately, the listing does not in general indicate which of these are used in HMA production, although these aggregates in general appear suitable for this purpose. PennDOT Bulletin 14 lists producers of construction aggregates in Pennsylvania, and includes the gradation type and the rock type, but the rock type is generic and does not refer to specific formations. Also, production data for specific mixes are not given, and so this information cannot be used to estimate HMA production for different aggregate types. It is clear from this document that dolomites, limestones, crushed gravel, sandstone and argillite are in fact all used in bituminous construction in the Commonwealth.

The U.S. Geological Survey (USGS) provides summary reports on aggregate production in Pennsylvania in its Annual Yearbook (U.S. Geological Service, 2013). The USGS Yearbook indicates that 90 % of the aggregate produced in Pennsylvania for HMA is crushed stone, while only 10 % is crushed gravel and/or sand. This is significant because in Pennsylvania, crushed gravel and sand are much more likely to be susceptible to moisture damage than crushed stone. Of the crushed stone produced in Pennsylvania, approximately 70 % is limestone and/or dolomite, which tend to be very resistant to moisture damage, while the balance includes but is not limited to a variety of other rocks and minerals, including diabase, gabbro, granite, sandstone, quartzite, gneiss and schist. These latter rocks and minerals exhibit a range of moisture sensitivities when used in HMA. Unfortunately, the USGS does not break down crushed stone production for HMA by rock and mineral type. Furthermore, the available PennDOT bulletins do not provide the information needed to make such estimates. Based upon these numbers, a reasonable assumption would be that HMA production in Pennsylvania uses the following breakdown of aggregates;

- 65 % limestone and/or dolomite, resistant to moisture damage
- 10 % crushed gravel and natural sand, susceptible to moisture damage
- 15 % other aggregates (granite, gneiss, sandstone, etc.) resistant to moisture damage
- 10 % other aggregate (granite, gneiss, sandstone, etc.) susceptible to moisture damage

The breakdown of other aggregate into 15 % resistant and 10 % susceptible is based upon the results of laboratory testing during this project, as reported in Chapter 5 of this Report. Of twelve mixes that contain at least some of these aggregate types, approximate one-third appear to be susceptible to moisture damage. Thus, the overall breakdown of aggregates is 80 % resistant to moisture damage, 20 % susceptible to moisture damage. However, when applying these percentages to HMA mixes, the results will be affected by aggregate blending to meet skid resistance requirements. Such blending—required for mixes designed for higher traffic levels using limestone and dolomite aggregates—will tend to decrease the number of resistant mixes and increase the number of susceptible mixes, since mixes that would otherwise only contain limestone and/or dolomite will contain other aggregates such as sandstone and quartzite that are often at least moderately susceptible to moisture damage. It was not possible to find specific information on the amount of asphalt concrete produced in Pennsylvania in which aggregates have been blended for purposes of meeting skid resistance requirements, so estimating the effect of such blending on the percentage of mix production susceptible to moisture damage must be approximate at best. However, the amount of sandstone and other miscellaneous aggregates that are susceptible to moisture damage was estimated at only 10 % of total aggregate production for HMA. This would seem to limit the effect of aggregate blending for skid resistance on the percentage of susceptible mixes. As a rough estimate, it is assumed that aggregate blending increases the percentage of moisture susceptible mix produced in Pennsylvania from 20 % to 30 %, reducing the percentage of resistant mixes from 80 to 70.

An important issue related to the percentage of moisture susceptible aggregates is the total HMA production in Pennsylvania, and the total number of mix designs that are subject to moisture resistance testing every year. This information—or at least a reasonable estimate thereof—is needed in order to properly account for the cost of moisture resistance testing in the cost/benefit analysis. At the 54th Annual Asphalt Paving Conference of the Pennsylvania Asphalt Pavement Association (PAPA), Deputy Secretary of Transportation R. Scott Christie gave the total asphalt concrete production in Pennsylvania as 6.1, 5.3 and 4.1 million tons in 2011, 2012 and 2013, respectively. Although there was a significant ongoing decline in production over this time period, the recently passed highway bill in Pennsylvania should reverse that trend. Therefore, a reasonable estimate for yearly HMA (and WMA) production would be 5 million tons per year. This is consistent with the total aggregate production for bituminous products given in the USGS yearbook of 5.2 million tons in 2009, which at 5 % asphalt binder would suggest a total asphalt concrete production of 5.5 million tons. Estimating the total number of mixes subject to moisture testing each year in Pennsylvania is more difficult. This information might be available from PennDOT records, but based upon information available at the writing of this report only an estimate can be made. In the current version of PennDOT Bulletin 41 a total of 208 bituminous plants are listed. If each of these plants tests five mixes a year, this would suggest a total of 1,040 asphalt concrete mixes a year subject to moisture resistance testing. However, it is likely that some of these would be tested more than once—because of double checking results and/or the initial selection of an ineffective antistrip agent. Therefore a reasonable estimate for total moisture resistance tests performed per year in Pennsylvania is 1,500.

2.6. Standards and Specifications Concerning Asphalt Concrete Moisture Damage

AASHTO HMA Mix Design Procedure

The current AASHTO standards for HMA (Superpave) mix design are described in R 35 and M 323. The requirements for evaluating moisture susceptibility are described in Section 11 of R 35, which specifies short-term oven conditioning according to R 30, compaction to 7.0 ± 0.5 % air voids, and testing according to AASHTO T 283. For purposes other than mechanical testing, R 30 specifies conditioning for 2 hours at the specified compaction temperature.

Standards and Specifications in Important States

In the initial part of the TRB National Seminar (2003) the results of an AASHTO survey conducted in 2002 and compiled by Tim Aschenbrenner on how state highway agencies address moisture sensitivity of HMA mixes is presented—some of the results have been referred to in earlier parts of this review. Although some of the states have no doubt revised their standards, it is still a useful summary of how this problem is being addressed in the U.S. Table 15 is a summary table from the 2002 AASHTO Survey (Aschenbrenner, 2003). Most states test and treat their HMA for moisture damage. Liquid antistrip additives are the most common treatment method, but many states use hydrated lime and some states allow both approaches. As mentioned above, by far the most common method of testing for moisture susceptibility are tension tests—here meaning the Lottman procedure and related procedures, including AASHTO T 283. The prevalence of modified Lottman testing among state highway agencies emphasizes the finding stated above, that this approach, though far from perfect, is as accurate if not more accurate than the various alternatives. Furthermore, there is much more experience with this type of test, meaning it is more likely to provide reasonable results for a wide range of materials. Although this survey is now 10 years old, a review of state highway specifications indicates that AASHTO T 283 (or closely related methods) is still by far the most common method of testing the moisture resistance of HMA. This supports its use in the proposed work for this project.

Table 15. Summary of 2002 AASHTO Survey as Compiled by Aschenbrenner (2003).

Treat for Moisture Damage in HMA?	44 Yes 3 Yes but not often 10 No
Treatment Method?	25 Liquid antistrip additive 13 Hydrated lime 7 Liquid antistrip additive or hydrated lime
Test for Moisture Susceptibility?	44 Yes 4 Yes/conditional 7 No
Test Method Used?	39 Tensile (AASHTO T 283, ASTM D 4867, etc.) 5 Compressive test (AASHTO T 165) 2 Retained Marshall stability 2 Wheel tracking and tensile test
When is Testing Done?	30 Mix design only 18 Mix design and field acceptance

The way in which antistrip is used in the HMA mix design process was discussed above in the section on aggregates, and was summarized in Tables 5 through 7. The most important piece of information presented in this discussion was that as of 2002, at least 11 state highway agencies required the use of antistrip additives in all or virtually all HMA mixes. However, it must be emphasized that even when the type of antistrip was specified—typically hydrated lime—moisture resistance testing was still required by these states. This is no doubt because of the effectiveness of antistrip additives varies from mix to mix, and sometimes will even tend to make the moisture resistance of a given mix worse.

States that Mandate Antistrip Usage in Hot Mix Asphalt

As discussed above, there are a number of states that require antistrip additive in virtually all HMA mixes (See Table 5). In many cases, no information exists in how and/or why the decision was made to require antistrip in all HMA. However, in some cases information is available in the literature. Additionally, a number of personnel from agencies in several other states with such mandates were contacted to gather information concerning how this decision was made.

Nevada—Nevada first noticed moisture damage in HMA pavements in a single road in 1983 (Martin et al., 2003). To address this problem, moisture resistance testing was implemented, using the modified Lottman procedure. Initially, use of antistrip was not required, but depended on the results of testing. Also, hydrated lime or liquid antistrip was permitted when an antistrip additive was needed to pass moisture resistance testing. However, within a few years Nevada determined that hydrated lime was much more effective in preventing stripping than liquid antistrips. In 1986 Nevada began requiring hydrated lime in all HMA mixes placed in the central and northern regions of the state. Because of continued problems with moisture damage, in 1998 Nevada began to require the use of hydrated lime in all HMA placed in the state. Nevada requires that the hydrated lime be applied to the aggregate using the lime-slurry marination (LSM) procedure, where a lime-water slurry is applied to aggregate stockpiles at least 48 hours prior to mixing (Martin et al., 2003). Nevada did a study on the effect of using hydrated lime on actual pavement performance, and found that its use added on average 3 years to the life of an HMA pavement (Sebaaly et al., 2001). The additional cost from the hydrated lime treatment was only 6 %, suggesting a very good benefit/cost ratio in Nevada for the mandated use of hydrated lime.

Virginia—Virginia first noticed stripping in HMA pavements in the late 1960's, and began requiring the use of antistrip additive in the 1970's (Martin et al., 2003). Although Virginia does have substantial limestone/dolomite aggregates, these are not allowed in surface course mixes because of their tendency to polish. The most commonly used aggregate in HMA is apparently granite, but trap rock and sandstone are also used. At one time quartzite was used in HMA, but is now disallowed because of several catastrophic failures caused by rapid and severe moisture damage (Martin et al., 2003). The majority of moisture damage problems in Virginia are associated with mixes containing granite aggregate, partly because this is the most widely used aggregate in the state, and partly because of the high degree of moisture susceptibility for these materials.

Mississippi—Mississippi began using 1.0 to 1.5 % hydrated lime as an antistrip additive in the early 1990s, but still observed significant moisture damage (D'Angelo et al., 2003). Starting in 1992, Mississippi required the use of hydrated lime in all HMA placed in the state. The lime is added to damp aggregate on the cold feed belt, and is often used in combination with liquid antistrip additives.

Georgia—In a short survey done as part of this research, Peter Wu of the Georgia DOT indicated that most of their aggregates have "moisture issues," and that research performed in the

1970’s and 1980’s indicated that hydrated lime was the best way to address this problem. Georgia currently requires all HMA mixes placed in permanent state route pavements to contain hydrated lime. In Georgia, hydrated lime is added to the drum rather than applied to the aggregate as a slurry. This apparently provides adequate protection against moisture damage.

North Carolina—in the same survey, Todd Whittington of the North Carolina DOT indicated that he wasn’t sure of the exact decision process, but believed that it was based on engineering judgment and experience with their local aggregates suggesting that most require antistrip additives to achieve the minimum TSR in modified Lottman testing.

Florida—although Florida does not require antistrip additive in all HMA, it does require antistrip additive in all open graded friction courses (OGFC), according to Gregory Sholar of the Florida DOT. For mixes using limestone aggregate, a liquid antistrip is used, but OGFC mixes made using granite aggregate must contain 1.0 % hydrated lime as an antistrip additive. This is a somewhat unusual example of a specification designed to address moisture resistance problems in a particular aggregate type.

FHWA Position on HMA Moisture Damage

No specific standards or position papers could be found describing a particular FHWA policy or guidelines concerning the handling of moisture related damage in HMA mixes. Because the FHWA has in the past and continues to support the Superpave system of mix design, and has published several documents promoting this method, it can be assumed that the FHWA supports the handling of HMA moisture sensitivity as handled in this mix design procedure. This would mean specifically testing according to AASHTO T 283, with a minimum TSR of 0.80. Any type of antistrip additive can be used to improve the TSR value of a mix so that it meets this minimum requirement. It is not clear if the FHWA objects to the blanket use of antistrip additives in those states that take this approach, although in most cases these are states in which the use of moisture susceptibility aggregates (typically crushed gravel and/or granite) is widespread.

2.7. Literature Review Summary and Findings

Moisture damage of HMA, although a serious problem in the commonwealth, is not widespread. Based upon information presented above, it is expected that moisture susceptible HMA in the Commonwealth is mostly associated with crushed gravel aggregates, and to a lesser extent with some mixes containing quartzite, sandstone and several other aggregate types. The test procedure used by the commonwealth—a variation of AASHTO T 283, combined with a boiling test—appears to represent a reasonably accurate means of identifying moisture susceptible HMA mixes when high saturation levels (above 55 %) are used. There is virtually no information in the literature concerning versions of the Lottman test using very low saturation levels, such as the version used in Pennsylvania between 2003 and October 2014. Variations of this test procedure are by far the most widely used test for this purpose and are generally acknowledged to be the best available and practical technology. Significant research has been done over the years to estimate the accuracy of this procedure, which appears to be between 65 and 80 % for high saturation levels. That is, 20 to 35 % of mixes are incorrectly classified in terms of their moisture resistance by this procedure. Furthermore, it would appear that the test as generally performed favors type II errors (passing a mix with poor moisture resistance) as opposed to type I errors (failing a mix with good moisture resistance). The relative rate of these two types of errors can be controlled by the minimum TSR and other test parameters, such as the degree of specimen saturation.

In a cost/benefit analysis of addressing moisture resistance in HMA, the costs stem from two sources: (1) moisture resistance testing of mixes; and (2) the use of antistrip additives. The benefits arise from preventing premature failures of pavements due to moisture damage, by identifying susceptible mixes and improving their performance by use of antistrip additives. The final results of this cost/benefit analysis will depend not only upon these costs and benefits, but on the rates of type I and type II errors associated with AASHTO T 283 and the method as implemented in Pennsylvania. Type II errors potentially involve premature failure of pavements and so are more costly than type I errors, which involve the unnecessary use of antistrip additives. The benefit/cost ratio will also depend on the frequency of moisture susceptible mixes in the commonwealth; because moisture sensitive mixes are not common, the overall relative cost of type II errors relative to type I errors will be reduced. There are several important questions related to these issues. What is the effect of different minimum TSR values on the benefit/cost ratio of addressing HMA moisture problems? Can the benefit/cost ratio be improved by changing the current acceptance criteria? What is the benefit/cost ratio of the standard AASHTO procedure as compared to PennDOT’s current version of T 283? Is the benefit/cost ratio substantially different in different regions of the Commonwealth (that is, in regions where crushed gravel is the dominant HMA aggregate versus regions where limestone/dolomite is common).

Based upon the reports, research papers and other documents reviewed as part of this project, the following findings are made:

- A variety of antistrip additives are available for improving the performance of asphalt concrete mixes containing aggregates susceptible to moisture damage. Hydrated lime—added to the aggregate as a slurry—is the most common type of antistrip. Liquid antistrips, surfactants that are often added to the asphalt binder at the refinery or terminal, are significantly cheaper and more convenient compared to hydrated lime, but there is evidence that the field performance of mixes treated with hydrated lime is in general significantly better compared to mixes treated with liquid antistrip.

- The average life of an asphalt concrete pavement in Pennsylvania with good moisture resistance is estimated to be about 12 years. For pavements susceptible to moisture damage, this figure is estimated to be only 6 years if no antistrip additive is used. If an appropriate antistrip additive is added to a mix susceptible to moisture damage, the average life is estimated to increase to 9 years. These are only very approximate estimates, based upon limited amount of such data reported in the literature.

- The modified Lottman test (AASHTO T 283) and a variety of variations of this method are by far the most common means of evaluating the moisture resistance of asphalt concrete mixtures in the U.S. This method has been extensively studied and a reasonably good estimate of its accuracy can be made based upon published reports. Based upon the literature reviewed in this report, the type I error rate (moisture resistant mixes that fail the test) is 7 %; the type II error rate (susceptible mixes that pass the test) is 64 % for moderately susceptible mixes and 23 % for highly moisture susceptible mixes, when saturation levels above 55 % are used in the procedure.

- State highway departments address moisture damage in a variety of ways. Some states, because of climate and/or the types of aggregates available, have little or no problems with moisture damage. Some states have severe problems, typically because all or most of their aggregates are highly susceptible to moisture damage. Many states use liquid antistrip in some of their mixes; some require the use of lime slurry to treat susceptible aggregates. A small number of states require antistrip in all asphalt concrete; these are most often states in which the majority of aggregates are susceptible to moisture damage; typically these materials would be crushed gravel and/or granite.
- Pennsylvania has an environment that promotes moisture damage in asphalt concrete pavements—there is ample precipitation, a large number of freeze-thaw cycles, and relatively heavy traffic in many parts of the state.
- The majority of aggregate used for asphalt concrete in Pennsylvania (65 %) are crushed limestone and dolomite, which are generally resistant to moisture damage. However, Approximately 10 % of the aggregate produced in Pennsylvania for use in asphalt concrete is crushed gravel, which tends to be highly susceptible to moisture damage. The balance of aggregate production in Pennsylvania (25 %) is made up of a variety of aggregates, such as crushed granite and sandstone, of which 10 % is estimated to be susceptible to moisture damage and 15 % resistance. Thus, the total percentage of aggregate for asphalt concrete produced in Pennsylvania that is susceptible to moisture damage is estimated to be 20 %. However, because of aggregate blending to meet skid resistance requirements, it is estimated that approximately 30 % of asphalt concrete produced in the Commonwealth is susceptible to moisture damage.
- It is estimated that total asphalt concrete production in Pennsylvania is about 5 million tons per year. It is also estimated that in order to meet moisture resistance requirements approximately 1,500 mix designs per year are tested for moisture resistance.

3. SURVEY RESULTS

During the first few months of the project, QES collected and tabulated results from a survey of PennDOT engineers on the use of antistrip additives and related issues, including the cost of antistrip additives and the typical performance enhancement provided by typical antistrip additives. The results of this survey are summarized in Tables 16 through 18, which present information on antistrip usage, antistrip cost and effect of antistrip on HMA performance, respectively.

Table 16. District Survey on the Use of Antistrip Additives in HMA.

District	Respondent	Using Antistrip Additives in HMA？	Remarks
1	Stephen Snyder	Yes	Used since 2007
2	Neal Fannin	Yes	Used since 1992
3	Frederick T Squires	Yes	Used since 2003
4	Joseph Kollar	No	Used once in 1997
5	Keith Fink	No	/
6	Joseph Bianchi	No	/
7	/	/	/
8	/	/	/
9	Kevin Gnegy	Yes	Used since 2011
10	Richard Polenik	No	Used in WMA since 2013
11	Richard R. Jucha	No	/
12	Robert P. Russell	No	/

Table 17. Survey Results on Typical Costs.

	Antistrip Treated HMA ($/ton)			Conventional HMA ($/ton)		
District	10%	Average	90%	10%	Average	90%
1	62	82	102	60	80	100
2	73	79	85	57	63	70
3	66	71	76	65	70	75
4	NA	NA	NA	NA	NA	NA
5	NA	NA	NA	NA	NA	NA
6	NA	NA	NA	NA	NA	NA
7	NA	NA	NA	NA	NA	NA
8	NA	NA	NA	NA	NA	NA
9	55	69	95	54	68	94
10	NA	NA	NA	NA	NA	NA
11	NA	NA	NA	NA	NA	NA
12	NA	NA	NA	NA	NA	NA

Table 18. Survey Results on Life Expectancy of HMA Applications.

	Antistrip Treated HMA			Conventional HMA		
District	10%	Average	90%	10%	Average	90%
Interstate						
1	7	10--12	15	7	10--12	15
2	NA	NA	NA	5	12	20
3	8	10	12	8	10	12
4	NA	NA	NA	NA	NA	NA
5	NA	NA	NA	NA	NA	NA
6	NA	NA	NA	NA	NA	NA
7	NA	NA	NA	NA	NA	NA
8	NA	NA	NA	NA	NA	NA
9	7	12	17	5	10	15
10	NA	NA	NA	NA	NA	NA
11	NA	NA	NA	NA	NA	NA
12	NA	NA	NA	NA	NA	NA
State and USA Highways						
1	7	10--12	20	7	10--12	20
2	NA	NA	NA	5	10	15
3	8	10	12	8	10	12
4	NA	NA	NA	NA	NA	NA
5	NA	NA	NA	NA	NA	NA
6	NA	NA	NA	NA	NA	NA
7	NA	NA	NA	NA	NA	NA
8	NA	NA	NA	NA	NA	NA
9	7	15	17	5	12	15
10	NA	NA	NA	NA	NA	NA
11	NA	NA	NA	NA	NA	NA
12	NA	NA	NA	NA	NA	NA
Local Roads						
1	7	10--12	15	7	10--12	15
2	NA	NA	NA	5	12	20
3	8	10	12	8	10	12
4	NA	NA	NA	NA	NA	NA
5	NA	NA	NA	NA	NA	NA
6	NA	NA	NA	NA	NA	NA
7	NA	NA	NA	NA	NA	NA
8	NA	NA	NA	NA	NA	NA
9	12	16	20	8	12	17
10	NA	NA	NA	NA	NA	NA
11	NA	NA	NA	NA	NA	NA
12	NA	NA	NA	NA	NA	NA

4. EXPERIMENTAL METHODS, MATERIALS AND DESIGN

4.1. Test Procedures

During the initial phases of this project, an alternative procedure for moisture resistance testing was considered which involved modifying AASHTO T 283 by using acidic water—water in which the composition was altered to mimic typical acid rain water in Pennsylvania. This was done because it was believed that acidic rainfall might have a significant effect on moisture susceptibility compared to the somewhat basic water typically used in T 283 testing. This experimental method was soon abandoned, for two reasons: (1) it was decided that it was extremely important for the success of this project to use a moisture resistance test for which the error rates have been well documented by a variety of researchers; and (2) preliminary tests using acid water in T 283 testing showed no significant difference in test results compared to T 283 tests conducted with slightly basic water. Ultimately, the testing performed in Tasks 2 and 3 of this project involved evaluating the moisture resistance of a variety of HMA mixes recently used in Pennsylvania, using two different versions of the modified Lottman procedure (AASHTO T 283), as explained in the paragraphs below.

Prior to 2003, PennDOT used a moisture resistance test method very similar to the standard version delineated in AASHTO T 283. Specimens are subjected to short-term oven aging at 135 °C for 4 hours, rather than the 60°C for 16 hours specified in AASHTO T 283. A wide range of vacuum levels is permitted during the saturation procedure, but the final degree of saturation is limited to a narrow range of 70 to 80 %; in the tests conducted as part of this research, the average saturation using this procedure was 74 %. In this report, this procedure is called the *high-saturation method*.

From 2003 until October 2014, a modified version of this procedure was used in Pennsylvania which included several important changes. Most mixtures are subjected to short-term oven conditioning for four hours at a temperature that is dependent on the binder used. High absorption mixtures are subjected to a longer conditioning time of eight hours. A more important deviation from the standard AASHTO T 283 procedure (and the approach described in the previous paragraph) is that the specified vacuum saturation involved applying a 254-mm vacuum for 30 minutes, and did not require a specific level of saturation. In the testing performed during this research project, saturation levels using this method ranged from 30 to 67 %, with an average of 43 %. In this report this method of T 283 is referred to as *the low-saturation method.*

In October of 2014, PennDOT again changed their moisture resistance test method, returning to the high-saturation method employed prior to 2003. As described previously, this method of T 283 testing requires specimen saturation ranging from 70 to 80 %, and is very similar to the standard AASHTO procedure. This change back to the high-saturation method was in part the result of the interim results of this research, which—as discussed in detail later in this report—that virtually no mixes fail moisture resistance testing conducted using the low-saturation method.

4.2. Materials

A total of 45 mixes were tested during the project. These are summarized in Table 19, which describes various characteristics for the mixes: nominal maximum aggregate size (NMAS);

aggregate type; PennDOT district in which the mix is produced; and moisture susceptibility/antistrip usage. One mix used a PG 76-22 binder, the balance all used PG 64-22 binder. Table 20 is a sampling matrix, which shows the region from which the mixes were sampled and the geologic type of the predominant aggregate in the mix. The districts (and states) in Table 20 have been grouped to approximately correspond to geologic regions in Pennsylvania and neighboring states.

An important question in this research is how aggregate type relates to moisture susceptibility. As discussed in the literature review, limestone/dolomite aggregates tend to be among the most resistant to moisture damage, while granite and quartzite tend to be among the most susceptible. Sandstone tends to be moderately susceptible to moisture damage. Gravel is made up of a mixture of rocks and minerals, and so varies in its susceptibility, although the crushed gravel aggregates used in asphalt concrete in Pennsylvania tend to be highly susceptible to moisture damage. There were a total of 16 mixes sampled in this project with known moisture susceptibility. Five of the six resistant mixes contained limestone and/or dolomite aggregates, one of these resistant mixes was a blend of limestone and sandstone. Of the eight mixes highly susceptible to moisture damage, six used crushed gravel aggregate and two used blends of limestone and sandstone. Of the two moderately susceptible mixes, one contained a gravel aggregate and one contained a sandstone aggregate. In general, the observed relationship between aggregate type and moisture susceptibility confirms the findings of the literature review: limestone/dolomite aggregates are almost always resistant to moisture damage, while at least in Pennsylvania, mixes made with crushed gravel aggregates are generally highly susceptible to moisture damage. Mixes made of blends of limestone/dolomite and sandstone (often done to meet skid resistance requirements) range from being resistant to moisture damage to being highly susceptible to moisture damage.

Table 19. Characteristics of Tested Mixes.

Characteristic	Value (Number of Mixes)
Aggregate NMAS	9.5 mm (28), 12.5 mm (8), 25 mm (9)
Aggregate Type	Limestone (17), crushed gravel (16), sandstone (1), limestone/sandstone blend (9)
PennDOT District	**1** (4), **2** (9), **3** (10), **4** (3), **5** (2), **6** (2), **8** (4), **9** (9), **12** (2)
Moisture Susceptibility	Low (6), moderate/without AS (2), high/without AS (8), moderate/with AS (1), high/with AS (10), undocumented/without AS (17), undocumented/with AS (1)

Table 20. Sampling Matrix with Number of Plants Sampled

District(s)	Other State(s)	Limestone, Dolomite, Etc.	Crushed Gravel	Diabase, Granite, Gneiss	Sandstone, Quartzite
1	OH		1		
2, 9		7	3		2
3, 4	NY	1	3		3
5, 6, 8	MD, NJ, VA	3	XX	1	
10, 11			XX		
12	WV				1

Note: Multiple mixes have been sampled from many plants. “XX” denotes targeted mix types that were not sampled because they are not currently produced in Pennsylvania or neighboring states.

4.3. Experimental Design

There were several objectives of the laboratory testing performed during this project:

1. To estimate the type I and type II error rates for the two moisture resistance test methods of interest—the low-saturation technique, and the high-saturation technique.
2. To develop a combined estimate for type I and type II error rates for high-saturation testing, based upon both the results of laboratory testing performed during this project and upon error rates reported in the literature.

The objectives were relatively straightforward and did not require use of statistical methods such as analysis of variance and/or multiple regression. The main factor of importance was to sample a wide variety of mixes with a range of aggregates typical of those used in Pennsylvania, from a representative selection of geologic formations. This was the primary purpose for developing the sampling matrix in Table 20. The data developed during the laboratory testing will then be used in the life cycle cost analyses and cost/benefit analyses discussed later in this report. The results of these analyses, especially the cost/benefit analyses, are the most important results produced during this research.

5. RESULTS OF LABORATORY TESTING

The purpose of this chapter is to summarize the results of laboratory tests performed as part of Tasks 2 and 3 for the project *Cost Benefit Analysis of Antistrip-Additives in Hot Mix Asphalt with Various Aggregates*. The results of this testing are summarized in Table 21, which includes a variety of information about each mix tested, including the results of moisture resistance testing in terms of TSR values for the two procedures evaluated (low and high-saturation). In Table 21 the stripping potential of the mixes is coded as follows:

L—low stripping potential
M—moderate stripping potential
H—high stripping potential
HA—high stripping potential, tested with antistrip as designed/approved
MA—moderate stripping potential, tested with antistrip as designed/approved
U—unknown stripping potential, tested without antistrip as designed/approved
UA—unknown stripping potential, tested with antistrip as designed/approved

5.1. Summary of Test Results

The results of the testing are further summarized in Table 22, which shows the results of all tests, broken down by stripping potential. Using the low-saturation method, all mixes passed moisture resistance testing, indicating that this method is essentially unable to identify moisture susceptible mixes. The results of the high-saturation method were reasonable; for the mixes of documented performance, all mixes with low stripping potential passed the test. For mixes with moderate stripping potential, one mix passed and one mix failed. For mixes with documented histories of high stripping potential, six failed and two passed. This indicates error rates reasonably close to those reported in the literature. Ten mixes with documented high potential for stripping were tested with antistrip additives (the same additives used when these mix designs were approved); nine of these passed the high-saturation Lottman testing and one failed, which is a reasonable outcome, since these mixes should be expected to pass moisture resistance testing. The remaining mixtures tested had undocumented histories of moisture resistance; some included antistrip, and some did not. All of these passed high-saturation testing, which is as expected.

Table 23 is a summary of the results of all tests on mixes of known moisture resistance level, for low-saturation testing. As mentioned above, all mixes passed this test. This indicates a type I error rate (“good” mixes that fail testing) of 0 % and a type II error rate (“bad” mixes that pass testing) of 100 %. As noted previously, the saturation levels achieved with this method were quite low, ranging from 30 to 67 %, with an average of 43 %. Table 24 is a similar summary, but for high-saturation testing. In this case, the type I error rate was 0 %, while the type II error rate was 50 % for mixes with moderate moisture resistance, and 25 % for mixes with low moisture resistance. The saturation levels achieved with this method ranged from 70 to 80 % (as specified in the test method), with an average of 74 %.

Table 21. Summary of HMA Mixes and Moisture Resistance Test Results.

District	Asphalt Plant Code	Company Name, Asphalt Plant Location	Material Type	Antistrip	County	Stripping Potential (H, M, L)	TSR (Low Sat. / High Sat.)
2	HRI14B41	HRI, Curtain Gap - Plant 103, Exit 161 SR 0080	Dolomite, 9.5 mm	None	Centre	L	98/95
2	INA42A41	IA Construction Co., Lafayette PA	Gravel, 9.5 mm	None	Mckean	H	80/69
3	DAC08A41	Dalrymple Gravel, Athens Township, PA	Gravel, 9.5 mm	None	Bradford	H	86/79
3	HGO08A41	Glenn O. Hawbaker Inc., Greens Landing (Milan) PA	Gravel, 9.5 mm	None	Bradford	H	84/66
3	EAF59C41	Eastern Industries Inc., Lewisburg, PA	Limestone, Sand Stone, Shale, 9.5 mm	None	Union	L	88/82
4	HAP63A41	Hanson Aggregates LLC, Lake Ariel PA	Sand Stone, Shale, 9.5 mm	None	Wayne	M	84/80
4	BAR40B41	Barletta Materials & Construction, Inc., Nescopeck, PA	Gravel, 9.5 mm	None	Luzerne	H	85/79
9	KEI55A41	Keystone Lime Co., Springs, PA	Calcareous Sandstone, Limestone, 9.5 mm	None	Somerset	H	94/92
9	NEW31A41	New Enterprise Stone & Lime Inc., Stover Station, PA	Dolomite, 9.5 mm	None	Hunting ton	L	92/84
1	INA61A41	IA Construction Co., Starbrick, PA	Gravel, 9.5 mm	None	Warren	H	87/74
9	NEW55BB41	New Enterprise Stone & Lime Inc., Bakersville, PA	Calcareous Sandstone, Limestone, 9.5 mm	None	Somerset	H	93/90

District	Asphalt Plant Code	Company Name, Asphalt Plant Location	Material Type	Antistrip	County	Stripping Potential (H, M, L)	TSR (Low Sat. / High Sat.)
2	BLDNYD41	AL Blades, Cuba, NY	Gravel, 9.5 mm	None	Allegany, NY	M	87/78
2	INA42A41	IA Construction Co., Lafayette PA	Gravel, 9.5 mm	Morelife 5000	Mckean	HA	87/82
3	DAC08A41	Dalrymple Gravel, Athens Township, PA	Gravel, 9.5 mm	ARR-MAZE	Bradford	HA	93/90
3	HGO08A41	Glenn O. Hawbaker Inc., Greens Landing (Milan) PA	Gravel, 9.5 mm	No ID	Bradford	HA	83/68
2	BLDNYD41	AL Blades, Cuba, NY	Gravel, 9.5 mm	No ID	Allegany, NY	MA	93/89
9	KEI55A41	Keystone Lime Co., Springs PA	Calcareous Sandstone, Limestone, 9.5 mm	Adhere 6601-LS	Somerset	HA	96/93
1	INA61A41	IA Construction Co., Starbrick, PA	Gravel , 9.5 mm	Morelife 5000	Warren	HA	95/84
9	NEW55BB41	New Enterprise Stone & Lime Inc., Bakersville, PA	Calcareous Sandstone, Limestone, 9.5 mm	ARR-MAZE	Somerset	HA	95/92
3	DAC08A41	Dalrymple Gravel, Athens Township, PA	Gravel, 25 mm	Suit-Kote	Bradford	HA	92/91
4	BAR40B41	Barletta Materials & Construction, Inc., Nescopeck, PA	Gravel, 19 mm	None	Luzerne	H	89/77
9	KEI55A41	Keystone Lime Co., Springs, PA	Calcareous Sandstone, Limestone, 19 mm	Adhere 6601-LS	Somerset	HA	92/94
3	EAF59C41	Eastern	Limestone, 25 mm	None	Union	L	100/86
9	NEW31A41	New Enterprise Stone & Lime Inc., Stover Station, PA	Dolomite, 25 mm	None	Hunting ton	L	91/83

District	Asphalt Plant Code	Company Name, Asphalt Plant Location	Material Type	Antistrip	County	Stripping Potential (H, M, L)	TSR (Low Sat. / High Sat.)
2	HRI14B41	HRI, Curtain Gap - Plant 103, Exit 161 SR 0080	Dolomite, 25 mm	None	Centre	L	95/99
3	HGO08A41	Glenn O. Hawbaker Inc., Greens Landing (Milan) PA	Gravel, 19 mm	No ID	Bradford	HA	89/85
2	INA42A41	IA Construction Co., Lafayette PA	Gravel, 19 mm	Morlife5000	McKean	HA	87/84
5	EAI39A41	Eastern Industries, Wescosville, PA	Dolomite, 9.5 mm	None	Lehigh	U	91/84
5	EAI39A41	Eastern Industries, Wescosville, PA	Dolomite, 19 mm	None	Lehigh	U	94/81
8	PES38B41	Pennsy Supply, Inc., Prescott, PA	Dolomite/limestone, 9.5 mm	None	Lebanon	U	93/92
8	PES38B41	Pennsy Supply, Inc., Prescott, PA	Dolomite/limestone, 19 mm	None	Lebanon	U	94/95
8	VAL28A41	Valley Quarries, Inc., Chambersburg, PA	Limestone, 9.5 mm	None	Franklin	U	102/96
8	VAL28A41	Valley Quarries, Inc., Chambersburg, PA	Limestone, 25 mm	None	Franklin	U	89/92
12	HBM26A41	Hanson-Better Materials, Connelsville, PA	Calcareous sandstone, limestone/sandstone, 9.5 mm	None	Fayette	U	92/85
12	HBM26A41	Hanson-Better Materials, Connelsville, PA	Calcareous sandstone, limestone/sandstone, 25 mm	None	Fayette	U	89/82
9	NEW07C41	New Enterprise Stone & Lime, Roaring Springs, PA	Dolomite, 9.5 mm	None	Blair	U	89/87

District	Asphalt Plant Code	Company Name, Asphalt Plant Location	Material Type	Antistrip	County	Stripping Potential (H, M, L)	TSR (Low Sat. / High Sat.)
9	NEW07C41	New Enterprise Stone & Lime, Roaring Springs, PA	Dolomite, 25 mm	none	Blair	U	96/89
6	HAP23C41	Hanson Aggregates PA, LLC, Glen Mills, PA	Gneiss, 9.5 mm	none	Delaware	U	81/84
6	HAP23C41	Hanson Aggregates PA, LLC, Glen Mills, PA	Gneiss, 25 mm	none	Delaware	U	81/80
1	HGO60A41	Glenn O. Hawbaker, Barkeyville, PA	Gravel, 9.5 mm	not identified	Venango	UA	95/89
1	HGO60A41	Glenn O. Hawbaker, Barkeyville, PA	Limestone, 25 mm	none	Venango	U	95/96
2	HGO14A41	Glenn O. Hawbaker, Pleasant Gap, PA	Sandstone coarse, limestone fine, 9.5 mm	none	Centre	U	94/92
2	HGO14A41	Glenn O. Hawbaker, Pleasant Gap, PA	Limestone, 19 mm	none	Centre	U	91/100
3	HGO41B41	Glann O. Hawbaker, Montoursville, PA	Limestone, 9.5 mm	none	Lycoming	U	92/90
3	HGO41B41	Glenn O. Hawbaker, Montoursville, PA	Limestone, 19 mm	none	Lycoming	U	98/87

Table 22. Summary of Test Results by Moisture Resistance Category.

Stripping Potential Category	*Low-saturation Method*		*High-saturation Method*	
	Pass	**Fail**	**Pass**	**Fail**
L—Low	6	0	6	0
M—Moderate	2	0	1	1
H—High	8	0	2	6
HA—High, tested with antistrip as designed/approved	10	0	9	1
MA—Moderate, tested with antistrip as designed/approved	1	0	1	0
U—Unknown, tested without antistrip as designed/approved	17	0	17	0
UA—Unknown, tested with antistrip as designed/approved	1	0	1	0

Table 23. Results of Modified Lottman Testing, Low-saturation Method (level 3 severity).

Test Result	*Stripping Potential of Aggregates in Mix*		
	Low	**Moderate**	**High**
Passed	6	***2***	***8***
Failed	***0***	0	0
Error Rates	*Type I*	*Type II*	
	0 %	100 %	100 %

Table 24. Results of Modified Lottman Testing, High-saturation Method (level 2D severity).

Test Result	*Stripping Potential of Aggregates in Mix*		
	Low	**Moderate**	**High**
Passed	6	***1***	***2***
Failed	***0***	1	6
Error Rates	*Type I*	*Type II*	
	0 %	50 %	25 %

Table 25 is a summary of results for modified Lottman tests of level 2 severity that combines test results from the literature with those from this project; this has been done to try to provide the most accurate estimates of error rates possible. The final type I error rate is 6 %, and the final type II error rates were 62 % for mixes with moderate moisture resistance and 23 % for mixes with low moisture resistance. An important conclusion of this testing and analysis is that modified Lottman testing, using level 2 severity (which includes the high-saturation method as performed in Pennsylvania) does a reasonably good job of differentiating mixes with high moisture resistance from those with low moisture resistance. However, this type of test appears to be poor at identifying mixes with moderate moisture resistance.

Table 25. Overall Accuracy of Modified Lottman Procedure, Level 2 Severity as Reported in Literature and from Laboratory Testing.

Test Result	*Stripping Potential of Aggregates in Mix*		
	Low	**Moderate**	**High**
Passed	18	***8***	***5.5***
Failed	***1***	5	18.5
Error Rates	*Type I*	*Type II*	
	6 %	62 %	23 %

5.2. Laboratory Test Results: Findings

The laboratory testing and other activities performed as part of this research, as described in this report, lead to the following findings:

- 45 HMA mixes were subjected to moisture resistance testing using the modified Lottman procedure, both the low-saturation and high-saturation versions recently employed by PennDOT.
- All 45 mixes passed the low-saturation version of the test. This represents a type II error rate of 100 %; the low-saturation procedure appears totally ineffective in identifying HMA mixes with poor moisture resistance.
- Using the high-saturation procedure—more typical of the modified Lottman procedure—all six mixes with good moisture resistance passed the test. Of eight mixes with poor moisture resistance, two passed the test, representing an error rate (type II) of 25 %. Of two mixes with moderate moisture resistance, one passed and one failed the procedure, resulting in an error rate of 50 %.
- Based upon the results of testing for this project and test data reported in the literature, the average type I error rate for the modified Lottman procedure (high-saturation) is expected to be 6 %, while the average type II error rate is expected to be 23 % for HMA mixes with poor moisture resistance, and 62 % for mixes with moderate moisture resistance.
- Based upon the results of testing performed during this project and upon similar testing reported in the literature, modified Lottman testing of level 2 severity—similar to high-saturation testing as done in Pennsylvania—does a good job differentiating mixes with high moisture resistance from those with low moisture

resistance. This type of test however is poor at identifying mixes with moderate moisture resistance.

6. LIFE CYCLE COST ANALYSIS AND COST/BENEFIT ANALYSIS

The purpose of this chapter is to present a summary of the impact of moisture damage, moisture resistance testing, and antistrip usage on the costs of asphalt concrete construction in Pennsylvania using a life cycle cost analyses (LCCA) and cost/benefit analysis (CBA). The introductory portion of this chapter is followed by a section describing the LCCA in detail. This section, in turn, is divided into two subsections: *Scenarios, Approach and Assumptions*, followed by *Results*. The section on LCCA is then followed with a discussion of the CBA, which uses the same information presented in the LCCA but presents the results in terms of benefit/cost ratios. The chapter concludes with several significant findings based upon the LCCA and CBA.

6.1. Life Cycle Cost Analysis

In the LCCA, whether or not moisture resistance testing is used and what type of testing is used is not an issue. These calculations are for a given type of mix (moisture resistance level) and for antistrip usage (with or without). The test procedures used and the effects of different test methods (a result of errors in the test procedures) are discussed in the last two sections of this chapter.

Scenarios, Approach and Assumptions

In this study, LCCA scenario analysis was conducted on the following seven scenarios:

- Scenario C-Control Scenario without Stripping Damage Issues
- Scenario RHN-Realistic Highly Susceptible Mixes without Antistrip Additives
- Scenario RHS-Realistic Highly Susceptible Mixes with antistrip
- Scenario RMN-Realistic Moderately Susceptible Mixes without antistrip
- Scenario RMS-Realistic Moderately Susceptible Mixes with antistrip
- Scenario OHN-Optimistic Highly Susceptible Mixes without antistrip
- Scenario OHS-Optimistic Highly Susceptible Mixes with antistrip
- Scenario OMN-Optimistic Moderately Susceptible Mixes without antistrip
- Scenario OMS-Optimistic Moderately Susceptible Mixes with antistrip

The terms “realistic” and “optimistic” as used in the list above and elsewhere in this chapter refer to the overall level of performance of asphalt mixes made using aggregates susceptible to moisture damage. The realistic performance assumption represents the current best estimate of how moisture susceptible mixes perform in the field; the optimistic performance assumption assumes a somewhat better level of performance for such mixes. Including both scenarios in the CBA provides an indication of how sensitive the analysis is to the performance level of mixes susceptible to moisture damage. The specific assumptions for maintenance cycles of each scenario are given in Table 26. The details of maintenance activities are presented in the Appendix to this report. These are based on the LCCA guidelines presented in PennDOT

Pavement Policy Manual (Publication No. 242), hereafter referred as Pub. 242. The analyses were based on the PennDOT LCCA Spreadsheet (Version 5.1.1), which was modified to match the proposed maintenance cycles for each scenario included in this analysis.

The analysis was limited to the HMA overlay of existing asphalt pavements, since this is the predominant type of work required of PennDOT**.** Several features were common to each analysis:

1) Maintenance activities and cycles followed LCCA guidelines of Pub.242.
2) Each maintenance activity triggered a user cost, which is affected by ADT.
3) An analysis period of 24 years was selected based on comments from the project panel.
4) A 2% discount rate was selected based on PennDOT Memo dated on February 10, 2014.
5) All costs were converted to equivalent annual uniform cost (EAUC) values to facilitate the comparison of alternatives

Key inputs common to all scenarios are summarized in the Table 27; these values were used for all analyses presented in this chapter.

In order to quantify the impact of traffic levels on the cost effectiveness of HMA with anti-stripping additives four traffic levels consistent with PennDOT's SRL levels were assumed, as shown in Table 28. The intention of these assumptions is to bracket the range of highway traffic conditions typically found on PennDOT highways.

As a critical part of conducting a LCCA, costs for all maintenance activities throughout the analysis period must be reasonably represented. These costs typically include agency costs and user delay costs as provided for the guidance in Pub. 242. Agency costs typically include expenditures for engineering, contract administration, construction, all future maintenance (routine and preventive), resurfacing and rehabilitation. User delay costs are incurred when a work zone is required to allow for the repair of pavements. User delay costs are divided into three categories: idling cost, time value costs, and stopping cost.

Agency costs can be calculated using the PennDOT LCCA Spreadsheet based on price information provided in Table 29, while user delay costs can be calculated based on typical traffic information representing initial ADT, design year ADT, design year, composition of traffic mix by vehicle class, and directional factor. The production rate of each maintenance activity was also provided in Table 29, which was used to determine working days required for each maintenance activity. The assumed antistrip price of $0.50 per ton of mix, at an average HMA price of $67 per ton, is equivalent to 0.75 % of the HMA price. Throughout this chapter antistrip price will be given as a percentage of HMA cost since it is the price of antistrip relative to that of the mix that is most important in the final CBA.

Table 26. Maintenance Cycles Assumptions.

General Performance Assumption for Susceptible Mixes	Antistrip Usage	Resistant Mixes			Highly Susceptible Mixes			Moderately Susceptible Mixes		
		Maintenance Cycles:			Maintenance Cycles:			Maintenance Cycles:		
		No.	**Duration (years)**	**Total (years)**	**No.**	**Duration (years)**	**Total (years)**	**No.**	**Duration (years)**	**Total (years)**
Realistic	**Without**	2	12	24	4	6	24	3	8	24
	With	N/A	N/A	N/A	3	8	24	2	12	24
Optimistic	**Without**	2	12	24	3	8	24	2	12	24
	With	N/A	N/A	N/A	2	12	24	2	12	24

Table 27. Key Inputs Common to All Scenarios.

Variable	Value
Discount Rate*	2%
Analysis Period (Years)	24
Assumed Project Length (Mile)	1
Lane Width (Feet)	12
HMA Density (lb/sy/in)	110
Asphalt Adjustment Multiplier (AAM)*	1.12

*Current values posted on the ECMS system were used

Table 28. Key Traffic Inputs Based on SRL Levels.

SRL Level	Two-way ADT	% Truck	Lanes in One Direction	Divided Roadway	PennDOT Functional Classification
E	50,000	15 (20% S.U. and 80% Comb.)	2	Yes	2
H	15,000	12 (20% S.U. and 80% Comb.)	2	Yes	4
G	5,000	10 (20% S.U. and 80% Comb.)	1	No	6
M	2,000	8 (20% S.U. and 80% Comb.)	1	No	8

Table 29. Maintenance Activity Unit Prices and Production Rates.

Maintenance Activity		Unit Price (based on price history, not adjusted for AAM)	Units	Production Rate		
				Short Term Closure	Long Term Closure	Units
Bituminous Inlay or Overlay	SRL-E	**73.00**	tons	1,800	2,400	ton/Day
	SRL-H	**69.00**	tons	1,800	2,400	ton/Day
	SRL-G	**65.00**	tons	1,800	2,400	ton/Day
	SRL-M	**60.00**	tons	1,800	2,400	ton/Day
Clean & Seal Joints – bituminous surface		**0.85**	LF	6,000	8,000	LF/Day
Concrete Patching		**150.00**	SY	300	400	SY/Day
Crack Seal		**0.85**	LF	6,000	8,000	LF/Day
Full Depth (Bituminous) Patching		**97.27**	SY	300	600	SY/Day
Scratch Course, 60 PSY		**112.76**	tons	1,800	2,400	ton/Day
Mill Wearing Course		**1.25**	SY	16,400	21,900	SY/Day
Saw & Seal Transverse Joints		**1.20**	LF	6,400	8,500	LF/Day
Seal Coat or Micro Surface Shoulders		**1.74**	SY	16,000	18,000	SY/Day
Type 7 Paved Shoulders		**99.40**	tons	1,800	2,400	ton/Day
Antistrip Additive		**0.50**	ton-mix	1,800	2,400	ton-Mix/Day

LCCA analyses were conducted at two experimental levels: performance evaluation and sensitivity analysis. The performance evaluation was performed on realistic scenarios and optimistic scenarios for different traffic levels, with both traffic growth rate and discount rate at 2%. Sensitivity analyses were performed on realistic scenarios for one traffic level, namely SRL-H, to evaluate the impact of traffic growth rate and discount rate on the EAUC. Three levels, 2%, 4%, and 6% were used for both traffic growth and discount rates. The experimental designs for scenario performance evaluation and sensitivity analysis are provided in Table 30 and Table 31, respectively.

Table 30. Experimental Design for Performance Evaluation.

Performance Evaluation- under All Traffic Levels					
Realistic Scenario	T1	D1	Optimistic Scenario	T1	D1
	2%	2%		2%	2%
	TD Combination #			TD Combination #	
C	D1T1		OHN	D1T1	
RHN	D1T1		OHS	D1T1	
RHS	D1T1		OMN	D1T1	
RMN	D1T1		OMS	D1T1	
RMS	D1T1				

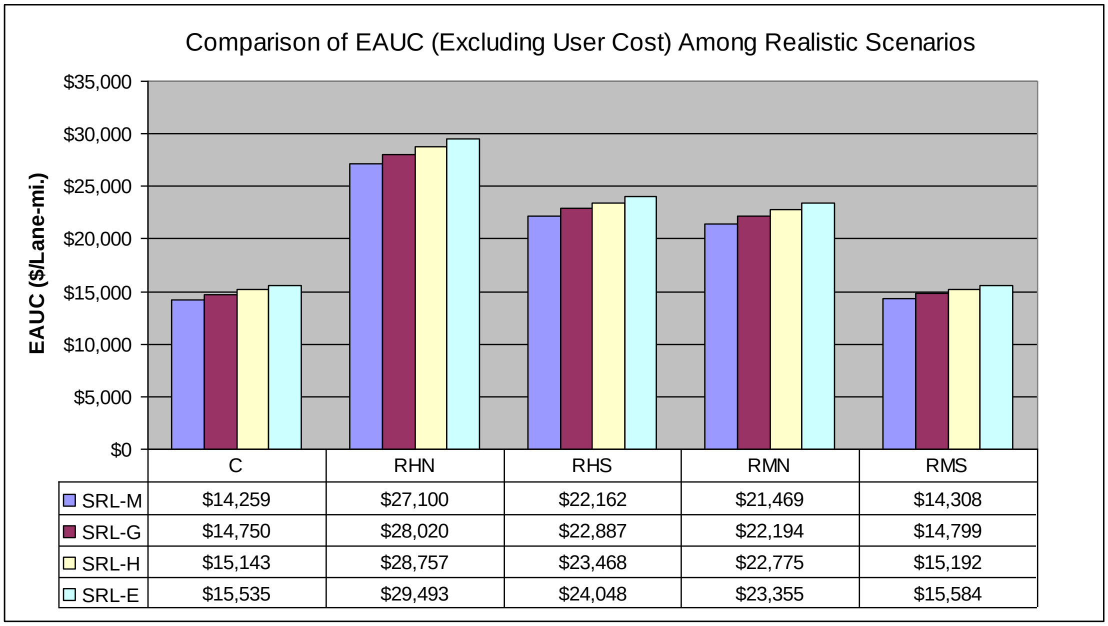
Table 31. Experimental Design for Sensitivity Analysis.

Scenario	Sensitivity Analysis-under One Traffic Level (SRL-H)					
	Traffic Growth Rate			Discount Rate		
	T1	T2	T3	D1	D2	D3
	2%	4%	6%	2%	4%	6%
	TD Combination #			TD Combination #		
C	D1T1	D1T2	D1T3	D1T1	D2T1	D3T1
RHN	D1T1	D1T2	D1T3	D1T1	D2T1	D3T1
RHS	D1T1	D1T2	D1T3	D1T1	D2T1	D3T1
RMN	D1T1	D1T2	D1T3	D1T1	D2T1	D3T1
RMS	D1T1	D1T2	D1T3	D1T1	D2T1	D3T1

LCCA: Results

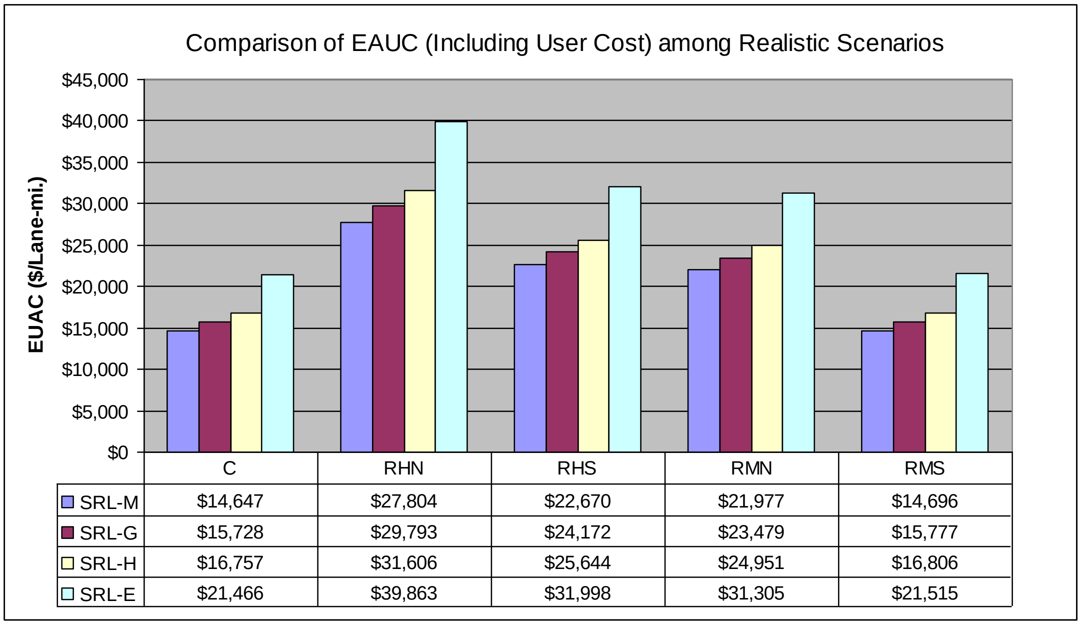
Performance Evaluation—the performance evaluations of the realistic scenarios for different traffic levels are presented in Figures 10 and 11. As shown, when the total life cycle cost (LCC) expressed as EAUC increased when the mix has stripping damage, as compared with the control scenario (scenario C). In general the more severe the stripping damage, the greater the EAUC. EAUC also increases with an increase in traffic. However, as compared to a stripping mix without including antistrip, adding antistrip to the stripping mixture significantly reduces LCC, as shown in Figures 12 and 13. To better illustrate the cost reduction due to the inclusion of antistrip, scenarios RMN and RMS at the SRL-H traffic level are discussed in detail. When including AS in the mix, the total cost (including user delay) in terms of EUAC for RMS was only increased by $49 per lane mile as compared to control scenario. For RMN without antistrip, the total cost was increased by $8,194. Therefore, the total cost reduction for the mix with antistrip in this case will be $8,145 per lane mile.

The performance evaluation of the optimistic scenarios for different traffic levels are presented in Figures 14 and 15. Again, the EAUC of each optimistic scenario increases with an increase in traffic. The inclusion of antistrip results in significant cost reduction for the optimistic case highly susceptible mixtures. For the case of optimistic moderately susceptible mixtures, however, antistrip seems to have little impact on the change in EAUC, as shown in Figures 16 and 17. This indicates that the inclusion of antistrip in the optimistic moderately susceptible mixtures may not be cost effective.



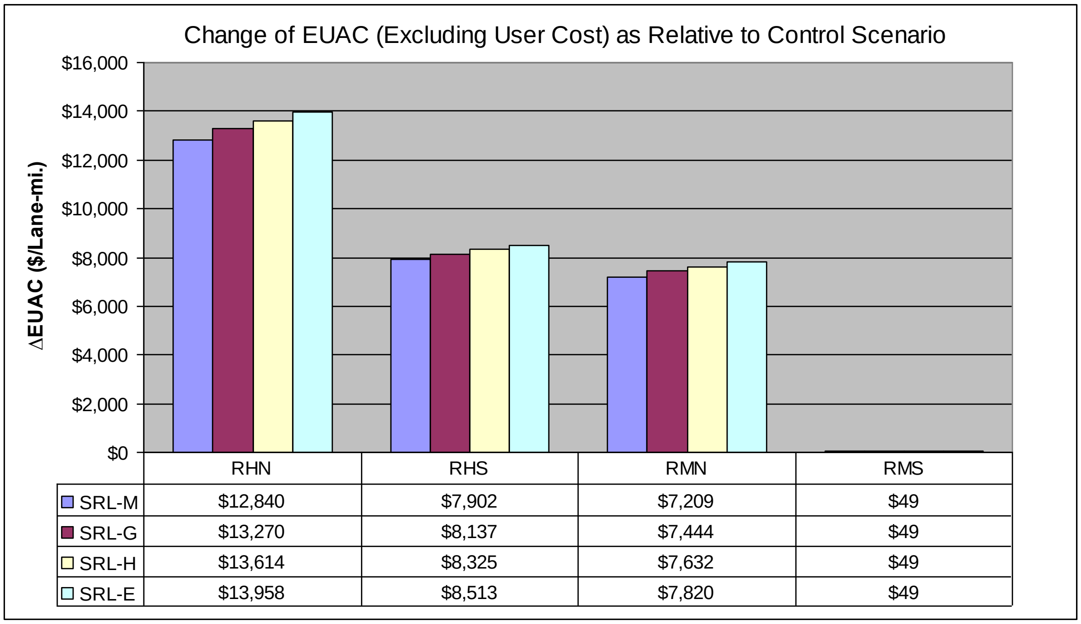
	C	RHN	RHS	RMN	RMS
SRL-M	$14,259	$27,100	$22,162	$21,469	$14,308
SRL-G	$14,750	$28,020	$22,887	$22,194	$14,799
SRL-H	$15,143	$28,757	$23,468	$22,775	$15,192
SRL-E	$15,535	$29,493	$24,048	$23,355	$15,584

Figure 10. Comparison of EAUC (excluding user cost) among realistic scenarios. *C= no moisture damage; RHN= highly susceptible mix, no antistrip; RHS = highly susceptible mix with antistrip; RMN = moderately susceptible mix, no antistrip; RMS = moderately susceptible mix with antistrip.*



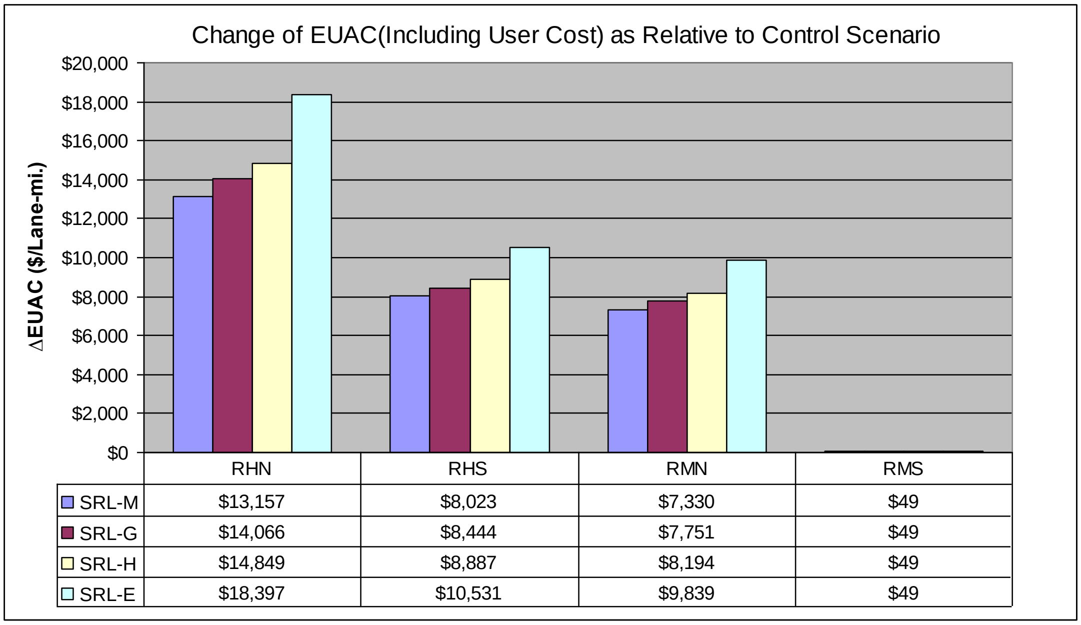
	C	RHN	RHS	RMN	RMS
SRL-M	$14,647	$27,804	$22,670	$21,977	$14,696
SRL-G	$15,728	$29,793	$24,172	$23,479	$15,777
SRL-H	$16,757	$31,606	$25,644	$24,951	$16,806
SRL-E	$21,466	$39,863	$31,998	$31,305	$21,515

Figure 11. Comparison of EAUC (including user cost) among realistic scenarios. *C= no moisture damage; RHN= highly susceptible mix, no antistrip; RHS = highly susceptible mix with antistrip; RMN = moderately susceptible mix, no antistrip; RMS = moderately susceptible mix with antistrip.*



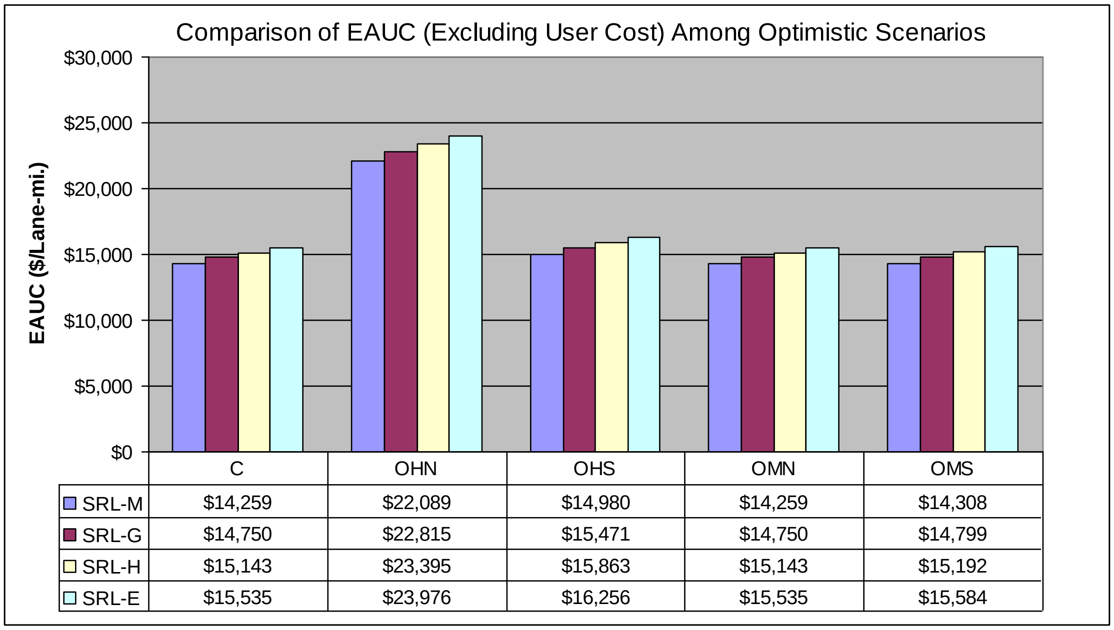
	RHN	RHS	RMN	RMS
SRL-M	$12,840	$7,902	$7,209	$49
SRL-G	$13,270	$8,137	$7,444	$49
SRL-H	$13,614	$8,325	$7,632	$49
SRL-E	$13,958	$8,513	$7,820	$49

Figure 12. Change of EAUC (excluding user cost) as relative to control scenario. *C= no moisture damage; RHN= highly susceptible mix, no antistrip; RHS = highly susceptible mix with antistrip; RMN = moderately susceptible mix, no antistrip; RMS = moderately susceptible mix with antistrip.*



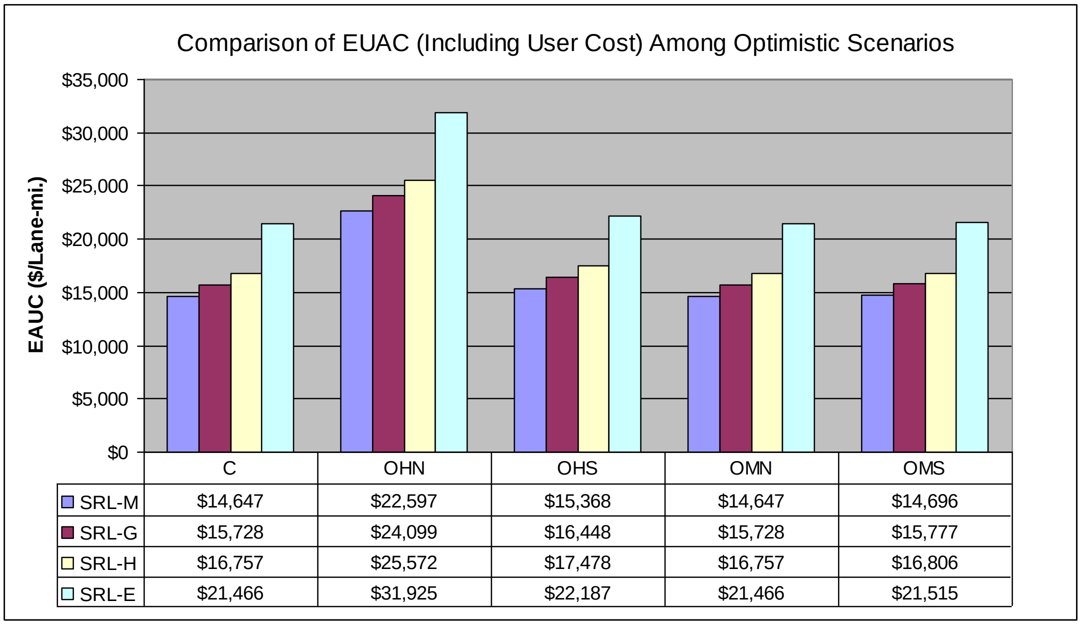
	RHN	RHS	RMN	RMS
SRL-M	$13,157	$8,023	$7,330	$49
SRL-G	$14,066	$8,444	$7,751	$49
SRL-H	$14,849	$8,887	$8,194	$49
SRL-E	$18,397	$10,531	$9,839	$49

Figure 13. Change of EAUC (including user cost) as relative to control scenario. *C= no moisture damage; RHN= highly susceptible mix, no antistrip; RHS = highly susceptible mix with antistrip; RMN = moderately susceptible mix, no antistrip; RMS = moderately susceptible mix with antistrip.*



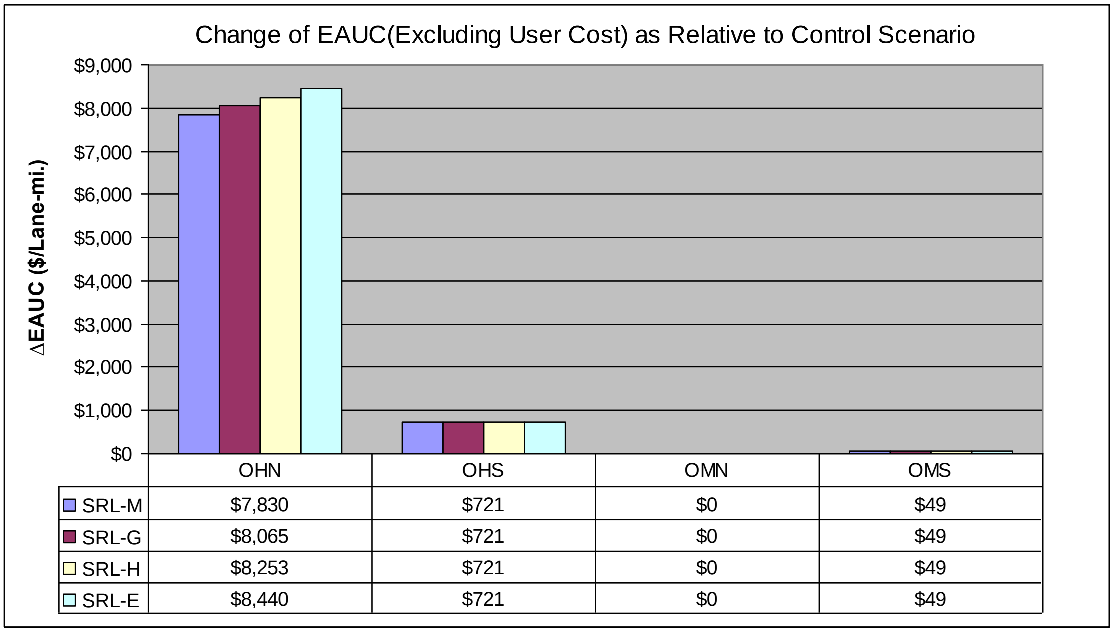
	C	OHN	OHS	OMN	OMS
SRL-M	$14,259	$22,089	$14,980	$14,259	$14,308
SRL-G	$14,750	$22,815	$15,471	$14,750	$14,799
SRL-H	$15,143	$23,395	$15,863	$15,143	$15,192
SRL-E	$15,535	$23,976	$16,256	$15,535	$15,584

Figure 14. Comparison of EAUC (excluding user cost) among optimistic scenarios. *C= no moisture damage; OHN= highly susceptible mix, no antistrip; OHS = highly susceptible mix with antistrip; OMN = moderately susceptible mix, no antistrip; OMS = moderately susceptible mix with antistrip.*



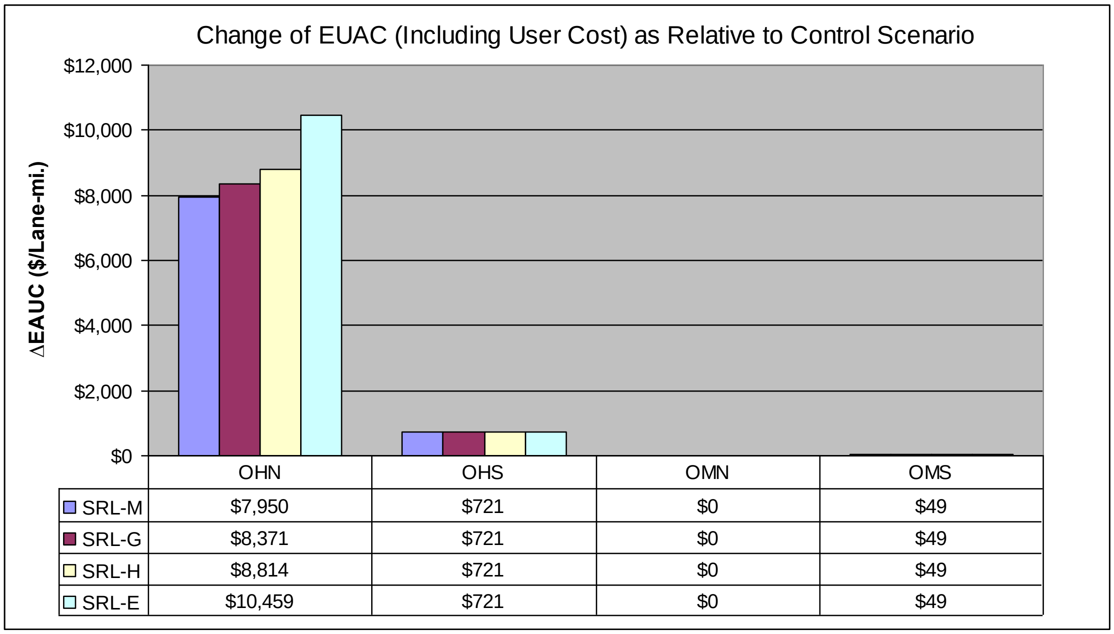
	C	OHN	OHS	OMN	OMS
SRL-M	$14,647	$22,597	$15,368	$14,647	$14,696
SRL-G	$15,728	$24,099	$16,448	$15,728	$15,777
SRL-H	$16,757	$25,572	$17,478	$16,757	$16,806
SRL-E	$21,466	$31,925	$22,187	$21,466	$21,515

Figure 15. Comparison of EAUC (including user cost) among optimistic scenarios. *C= no moisture damage; OHN= highly susceptible mix, no antistrip; OHS = highly susceptible mix with antistrip; OMN = moderately susceptible mix, no antistrip; OMS = moderately susceptible mix with antistrip.*



	OHN	OHS	OMN	OMS
SRL-M	$7,830	$721	$0	$49
SRL-G	$8,065	$721	$0	$49
SRL-H	$8,253	$721	$0	$49
SRL-E	$8,440	$721	$0	$49

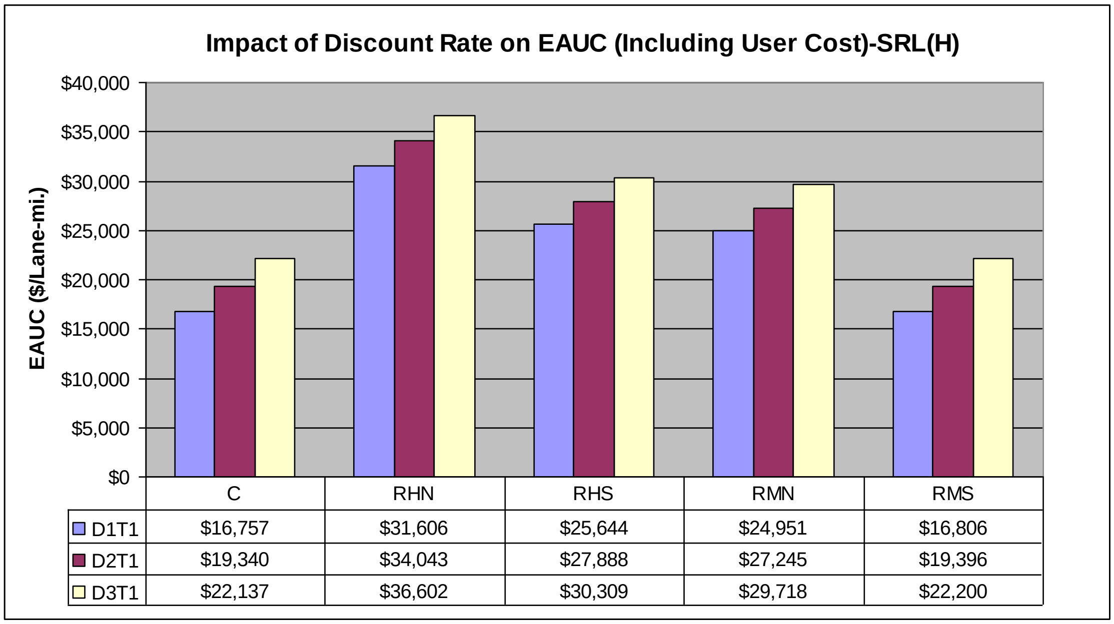
Figure 16. Change of EAUC (excluding user cost) as relative to control scenario. *C= no moisture damage; OHN= highly susceptible mix, no antistrip; OHS = highly susceptible mix with antistrip; OMN = moderately susceptible mix, no antistrip; OMS = moderately susceptible mix with antistrip.*



	OHN	OHS	OMN	OMS
■ SRL-M	$7,950	$721	$0	$49
■ SRL-G	$8,371	$721	$0	$49
□ SRL-H	$8,814	$721	$0	$49
□ SRL-E	$10,459	$721	$0	$49

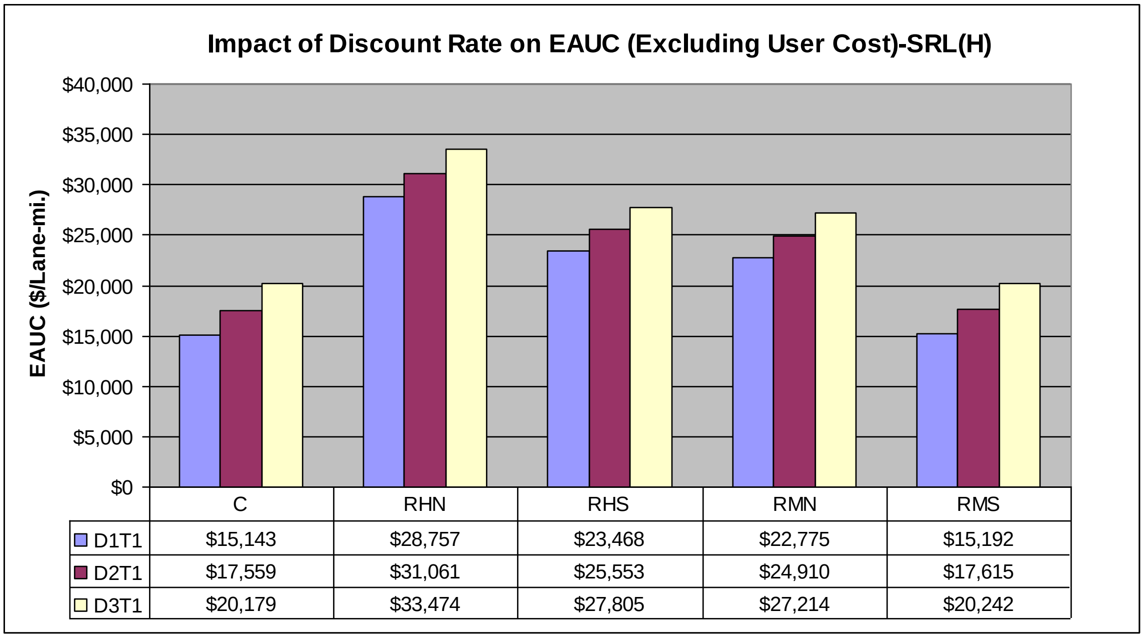
Figure 17. Change in EAUC (including user cost) relative to the control scenario. *C= no moisture damage; OHN= highly susceptible mix, no antistrip; OHS = highly susceptible mix with antistrip; OMN = moderately susceptible mix, no antistrip; OMS = moderately susceptible mix with antistrip.*

Sensitivity Analysis—the impact of discount rate on EAUC with and without the inclusion of user costs is presented in Figures 18 and 19, respectively. As shown, the EAUC increases with an increase in the discount rate. The impact of traffic growth rate on EAUC without and with user delay costs is presented in Figures 20 and 21, respectively. As shown in Figure 20, the traffic growth rate has no impact on EAUC when user costs are not included. In other words, traffic growth rate has no impact on agency costs. Conversely, the traffic growth rate has significant impact on EAUC when user cost is included. This illustrates that traffic growth rate has an impact on user costs. The higher the traffic growth rate the greater the EAUC.



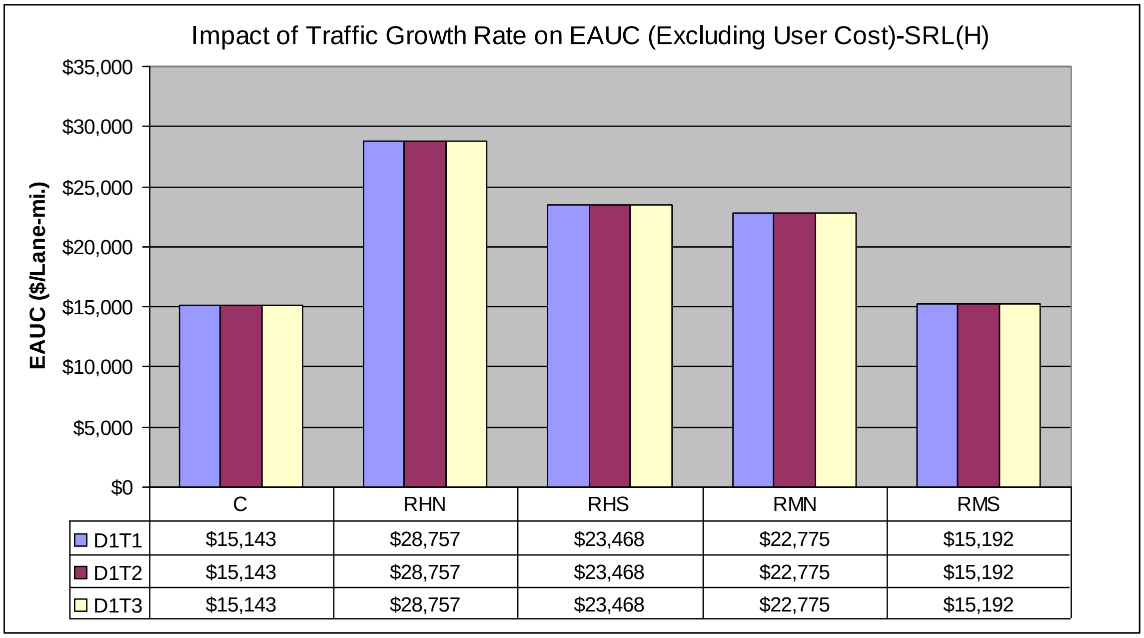
	C	RHN	RHS	RMN	RMS
🟦 D1T1	$16,757	$31,606	$25,644	$24,951	$16,806
🟥 D2T1	$19,340	$34,043	$27,888	$27,245	$19,396
🟨 D3T1	$22,137	$36,602	$30,309	$29,718	$22,200

Figure 18. Impact of discount rate on EAUC (including user cost). *C= no moisture damage; RHN= highly susceptible mix, no antistrip; RHS = highly susceptible mix with antistrip; RMN = moderately susceptible mix, no antistrip; RMS = moderately susceptible mix with antistrip.*



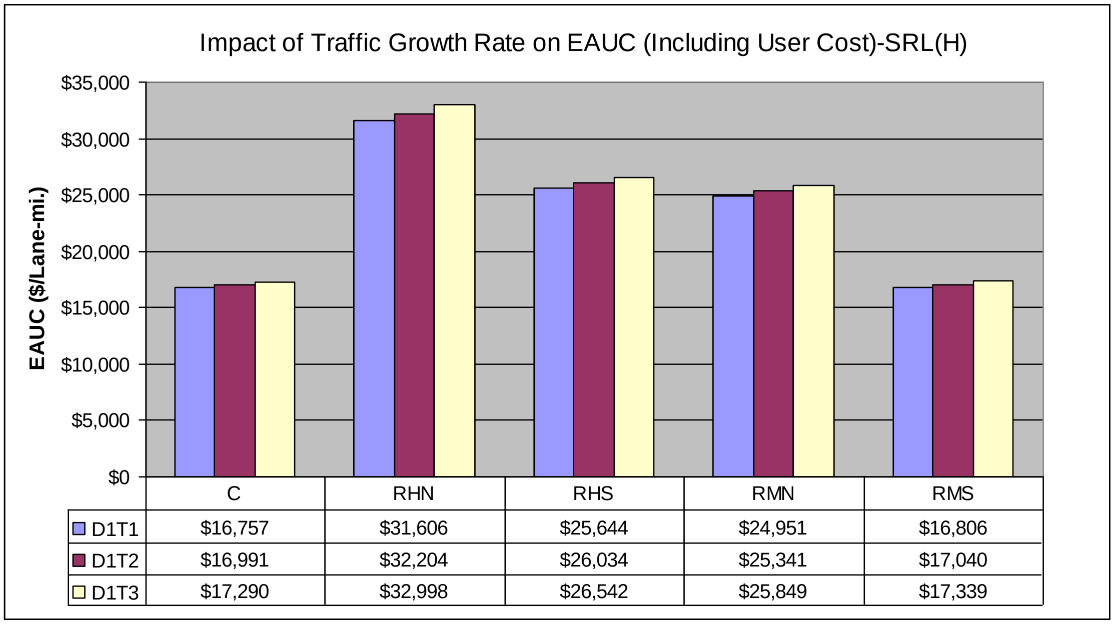
	C	RHN	RHS	RMN	RMS
🟦 D1T1	$15,143	$28,757	$23,468	$22,775	$15,192
🟥 D2T1	$17,559	$31,061	$25,553	$24,910	$17,615
🟨 D3T1	$20,179	$33,474	$27,805	$27,214	$20,242

Figure 19. Impact of discount rate on EAUC (excluding user cost). *C= no moisture damage; RHN= highly susceptible mix, no antistrip; RHS = highly susceptible mix with antistrip; RMN = moderately susceptible mix, no antistrip; RMS = moderately susceptible mix with antistrip.*



	C	RHN	RHS	RMN	RMS
▨ D1T1	$15,143	$28,757	$23,468	$22,775	$15,192
■ D1T2	$15,143	$28,757	$23,468	$22,775	$15,192
□ D1T3	$15,143	$28,757	$23,468	$22,775	$15,192

Figure 20. Impact of traffic growth rate on EAUC (Excluding user cost). *C= no moisture damage; RHN= highly susceptible mix, no antistrip; RHS = highly susceptible mix with antistrip; RMN = moderately susceptible mix, no antistrip; RMS = moderately susceptible mix with antistrip.*



	C	RHN	RHS	RMN	RMS
▨ D1T1	$16,757	$31,606	$25,644	$24,951	$16,806
■ D1T2	$16,991	$32,204	$26,034	$25,341	$17,040
□ D1T3	$17,290	$32,998	$26,542	$25,849	$17,339

Figure 21. Impact of traffic growth rate on EAUC (Including user cost). *C= no moisture damage; RHN= highly susceptible mix, no antistrip; RHS = highly susceptible mix with antistrip; RMN = moderately susceptible mix, no antistrip; RMS = moderately susceptible mix with antistrip.*

6.2. Benefit/Cost Ratios

Perhaps the most important objective of this project was to compare two different methods of moisture resistance testing (both variations of the Lottman procedure, AASHTO T 283) that have been used in Pennsylvania in recent years. In the first procedure, most mixtures are subjected to short-term oven conditioning for four hours at a temperature that is dependent on the binder used. High absorption mixtures are subjected to a longer conditioning time of eight hours. A more important deviation from the standard AASHTO T 283 procedure is that the specified vacuum saturation involves applying a 254-mm vacuum for 30 minutes, and does not require a specific level of saturation. This results in saturation levels that typically range from about 30 to 50 %, much lower than the 70 to 80 % specified in the standard AASHTO procedure. In this report, this procedure is referred to as “low-saturation.” It was used in Pennsylvania until October 20, 2014 when the procedure described below was adopted. Laboratory testing indicated that this low-saturation procedure passed every mix tested, and was essentially equivalent to doing no moisture resistance testing. For this reason, the benefit associated with this procedure is by definition zero, and the benefit/cost (B/C) ratio is also zero.

The second procedure used is closer to the standard version delineated in AASHTO T 283. Specimens are subjected to short-term oven aging at 135 °C for 4 hours, rather than the 60°C for 16 hours specified in AASHTO T 283. A wide range of vacuum levels is permitted during the saturation procedure, but the final degree of saturation is limited to a narrow range of 70 to 80 %. This procedure is called “high-saturation” in this report.

Figures 13 through 20 show the results of the cost/benefit analysis in terms of benefit/cost (B/C) ratios which is probably the most common way of showing results for a cost/benefit analysis (CBA). These figures are all based upon high-saturation testing, since as discussed above the low-saturation procedure has a B/C ratio of zero for all situations. A B/C ratio greater than one indicates a favorable outcome, where the estimated benefits are greater than the estimated costs. In calculating the B/C ratios, the accuracy of the moisture resistance testing was applied to the LCCA results described above, so that these numbers considered both the costs associated with different scenarios and the results of errors in testing. Included in the analysis were two options for antistrip usage: (1) conditional usage, in which antistrip is only used when needed to pass moisture resistance testing; and (2) mandatory usage, in which antistrip must be used in all mixes, regardless of the outcome of testing. In addition to the assumptions given above for the LCCA, the following assumptions were used in calculating the B/C ratios:

- Level 2 AASHTO T 283 testing, such as the high-saturation method used in Pennsylvania, correctly identifies mixes as moisture susceptible 77 % of the time for highly susceptible mixes, and 38 % of the time for moderately susceptible mixes. This testing correctly identifies mixes that are resistant to moisture damage 94 % of the time; that is, such mixes are incorrectly identified as being susceptible to moisture damage 6 % of the time.
- Level 3 AASHTO T 283 testing, such as the low-saturation method once used in Pennsylvania, correctly identifies mixes as moisture susceptible 0 % of the time, for both highly susceptible and moderately susceptible mixes. This is in effect equivalent to no moisture resistance testing.

- The estimated percentage of aggregates in Pennsylvania susceptible to moisture damage is 20 %; in the calculation of B/C ratios, in order to judge the sensitivity of the analysis to this value, three levels were assumed—10, 20 and 40 %. In all three cases, it was assumed that half of the susceptible aggregates are highly susceptible to moisture damage, and half are moderately susceptible.
- It was assumed that the total lane-miles for each traffic category are equal (note that because the savings as a percentage is similar for all traffic categories the results of the summary analysis are relatively insensitive to this assumption)
- Average asphalt concrete thickness of 1.75 inches, average lane width 12 feet
- Total asphalt concrete contracted by PennDOT is 5.0 million tons per year, of which 4.0 million tons per year is subject to moisture resistance testing and potential antistrip usage
- Average cost to the producer of moisture resistance testing $320 per mix
- Total number of mixes subject to moisture resistance testing 1,500 per year

Several observations can be made concerning the information summarized in Figures 22 through 29. In all cases, the B/C ratio is well above 1.0, indicating that moisture resistance testing (high-saturation) and antistrip usage significantly reduces the life cycle cost of HMA pavements in Pennsylvania compared to no testing or antistrip usage. As would be expected, the B/C ratio increases significantly as the assumed percentage of susceptible aggregates increases. However, B/C ratio cannot in general be used to compare scenarios, only to determine if any given scenario is cost effective because the B/C does not necessarily reflect overall net savings which do not necessarily correlate to B/C ratio. This is illustrated in the last paragraph of this section, in which the economics of conditional vs. mandatory antistrip usage are discussed.

Figures 26 through 29, which show the results of the sensitivity of the CBA to discount rate and traffic growth rate, indicate that different assumptions for these inputs have very little effect on the resulting B/C ratios. The analysis does appear to be somewhat sensitive to the assumed performance level (realistic vs. optimistic), although in both cases the B/C ratios for moisture resistance testing and antistrip usage are all greater than one.

One of the major objectives of this research was to determine if mandatory use of antistrip would be cost effective compared to antistrip usage conditional upon the results of moisture resistance testing. This was considered possible because T 283 testing is not 100 % accurate; some mixes susceptible to moisture damage pass the test, while some mixes resistant to moisture damage fail the test. By requiring antistrip usage in all mixes, all susceptible mixes are then treated, increasing life cycle benefits but increasing costs. Note that in Figures 22 through 25 the B/C ratio of mandatory antistrip usage is always lower than that for conditional usage. However, the costs associated with mandatory antistrip usage are significantly higher, and the net savings are much higher. This is shown in Tables 32 and 33, which show the estimated total savings per year for mandatory and conditional antistrip usage, for the realistic and optimistic performance assumptions and without user delay costs (Table 32) and with user delay costs (Table 33). These

Tables also show the savings for different assumed percentages of aggregates susceptible to moisture damage. In all cases there is a net savings for mandatory antistrip usage as compared to usage conditional upon moisture resistance test results. As should be expected the savings realized from mandatory antistrip usage depend strongly on the assumptions made in the calculation, with lower savings associated with lower percentages of susceptible aggregates and optimistic estimates of the performance of mixes made with such materials. The best estimates of the annual savings for mandatory antistrip usage are about \$3.5 million per year or about 3 % of the total expenditures on bituminous paving. As mentioned at the beginning of this paragraph, mandatory antistrip usage results in savings compared to conditional usage because of the failure of moisture resistance testing to identify 100 % of susceptible mixes. Mandatory usage ensures that all mixes susceptible to moisture damage contain antistrip.

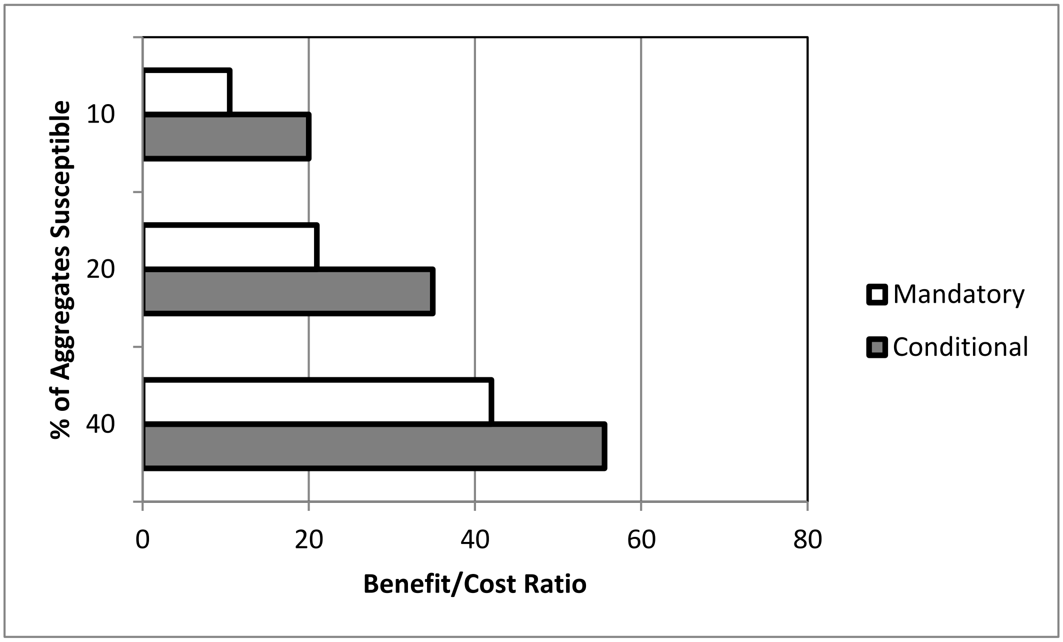


Figure 22. B/C Ratio for Realistic Performance, without User Delay Costs, for Different Percentages of Aggregates Susceptible to Moisture Damage, Averaged for All Traffic Levels. *Legend refers to whether antistrip usage is mandatory or conditional upon test results.*

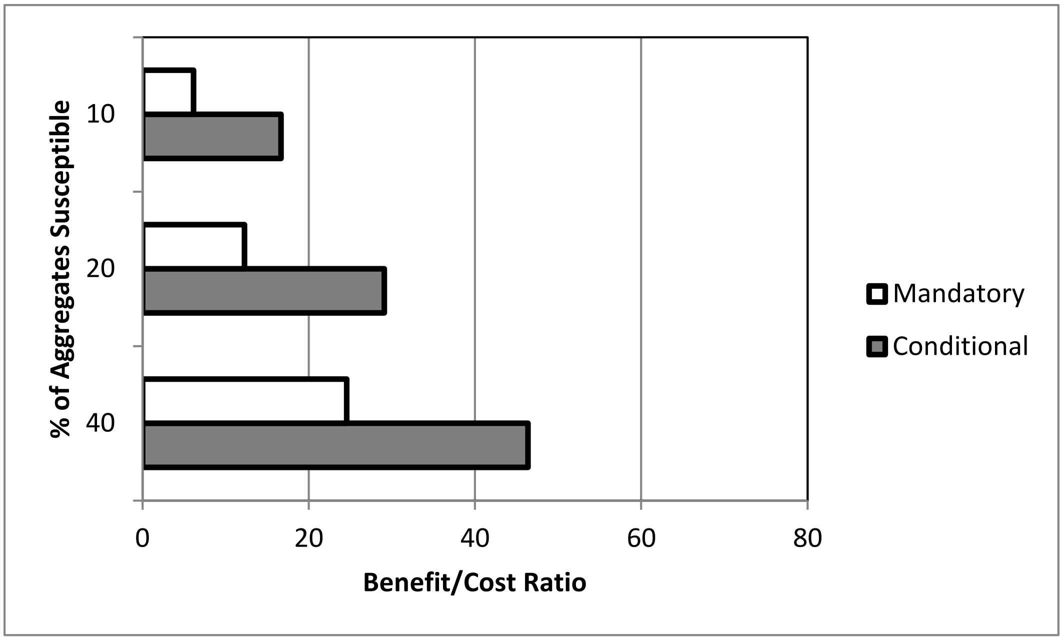


Figure 23. B/C Ratio for Optimistic Performance, without User Delay Costs, for Different Percentages of Aggregates Susceptible to Moisture Damage, Averaged for All Traffic Levels. *Legend refers to whether antistrip usage is mandatory or conditional upon test results.*

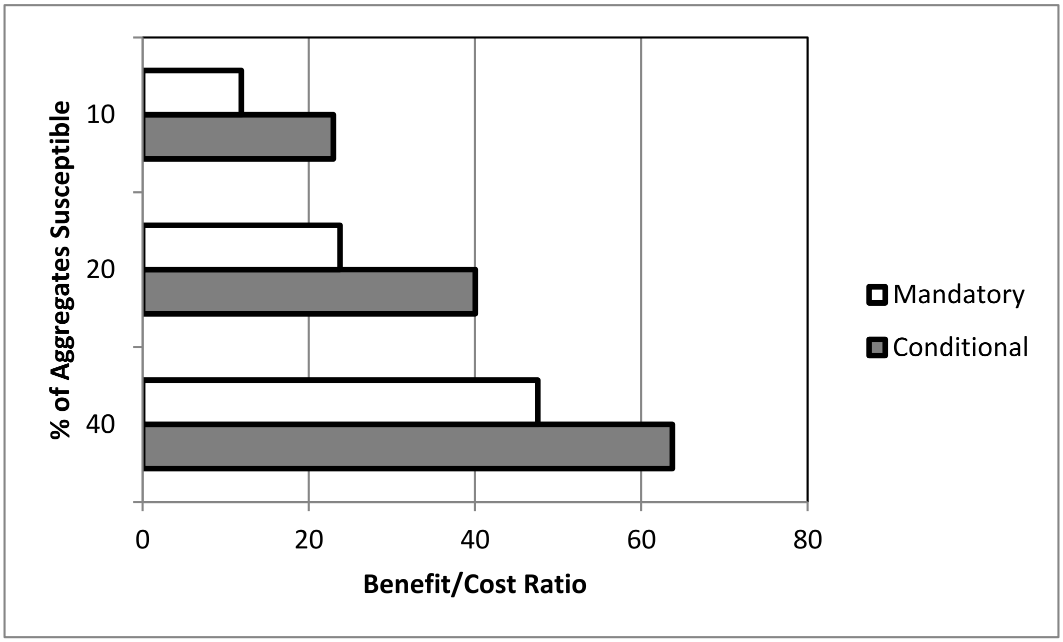


Figure 24. B/C Ratio for Realistic Performance, with User Delay Costs, for Different Percentages of Aggregates Susceptible to Moisture Damage, Averaged for All Traffic Levels. *Legend refers to whether antistrip usage is mandatory or conditional upon test results.*

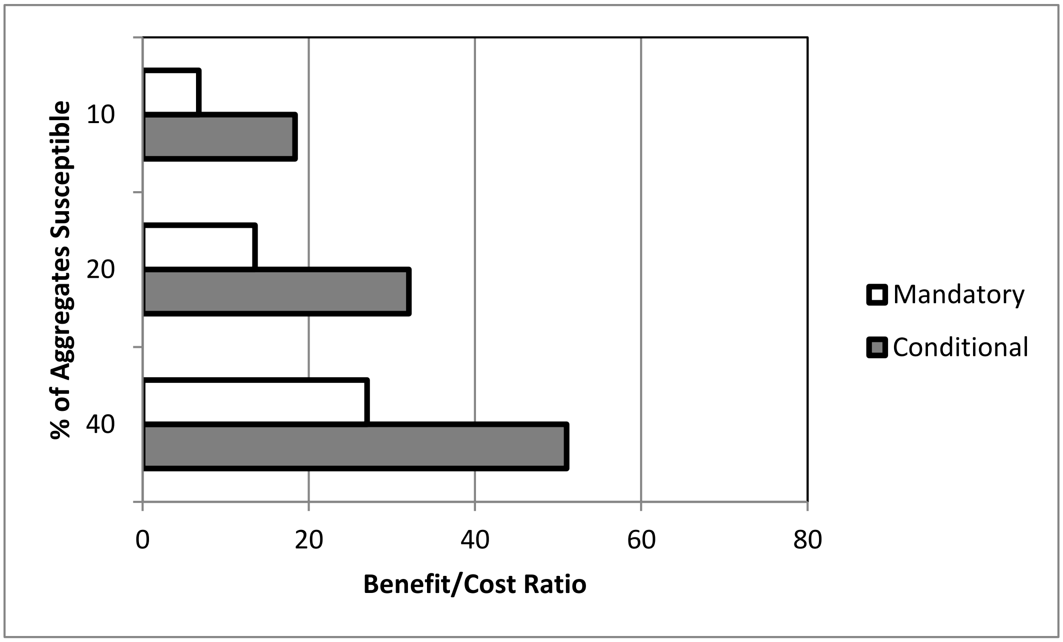


Figure 25. B/C Ratio for Optimistic Performance, with User Delay Costs, for Different Percentages of Aggregates Susceptible to Moisture Damage, Averaged for All Traffic Levels. *Legend refers to whether antistrip usage is mandatory or conditional upon test results.*

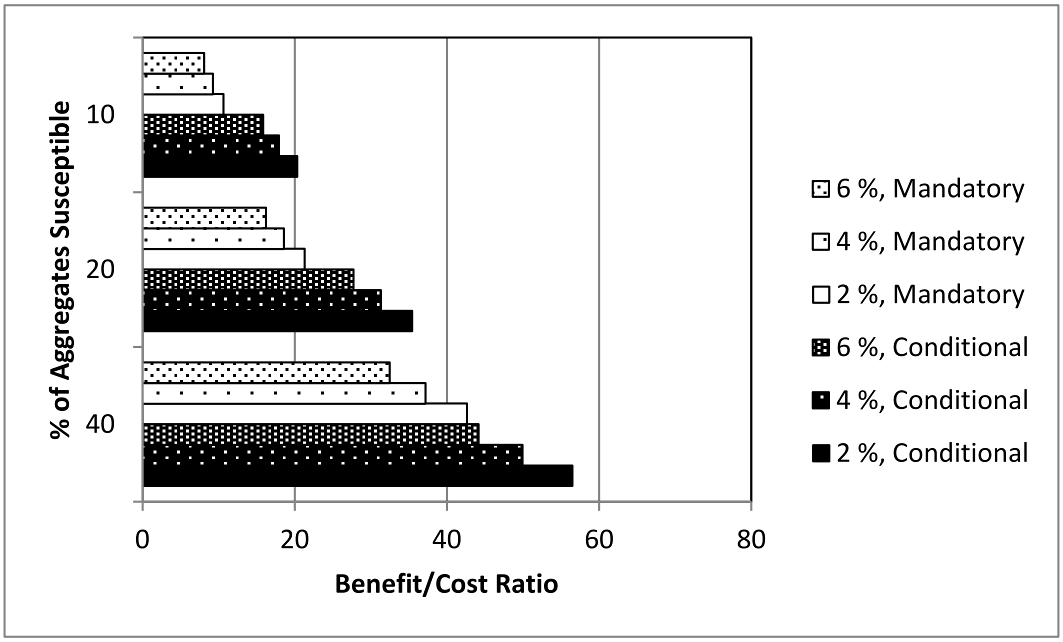


Figure 26. B/C Ratio for Realistic Performance, without User Delay Costs, for Different Percentages of Aggregates Susceptible to Moisture Damage, for "H" Traffic/Skid Resistance Level. *Legend refers discount rate and to whether antistrip usage is mandatory or conditional upon test results.*

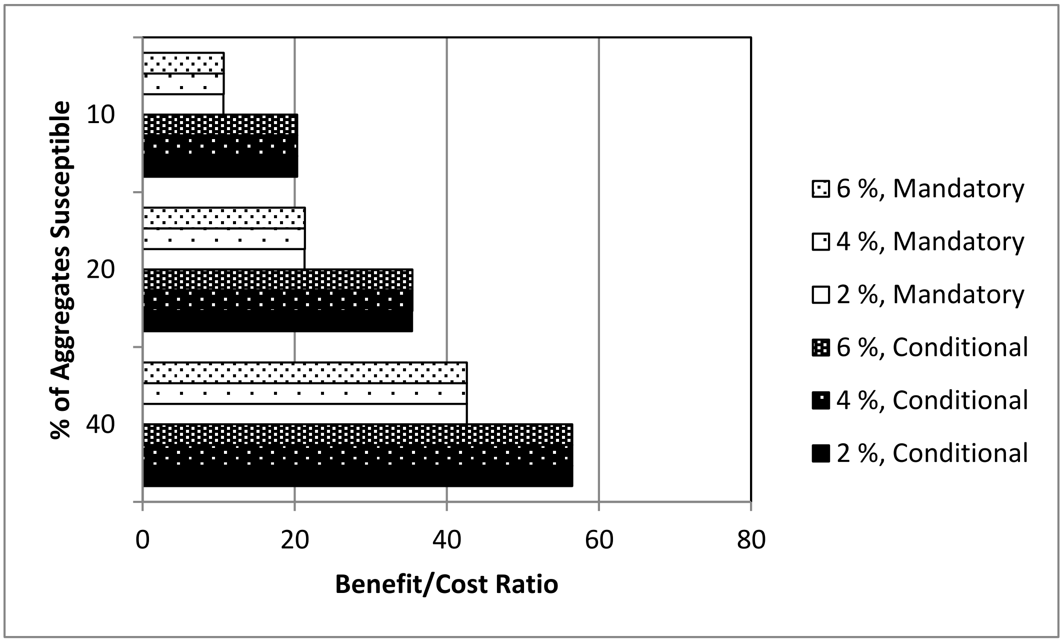


Figure 27. B/C Ratio for Realistic Performance, without User Delay Costs, for Different Percentages of Aggregates Susceptible to Moisture Damage, for "H" Traffic/Skid Resistance Level. *Legend refers traffic growth rate and to whether antistrip usage is mandatory or conditional upon test results.*

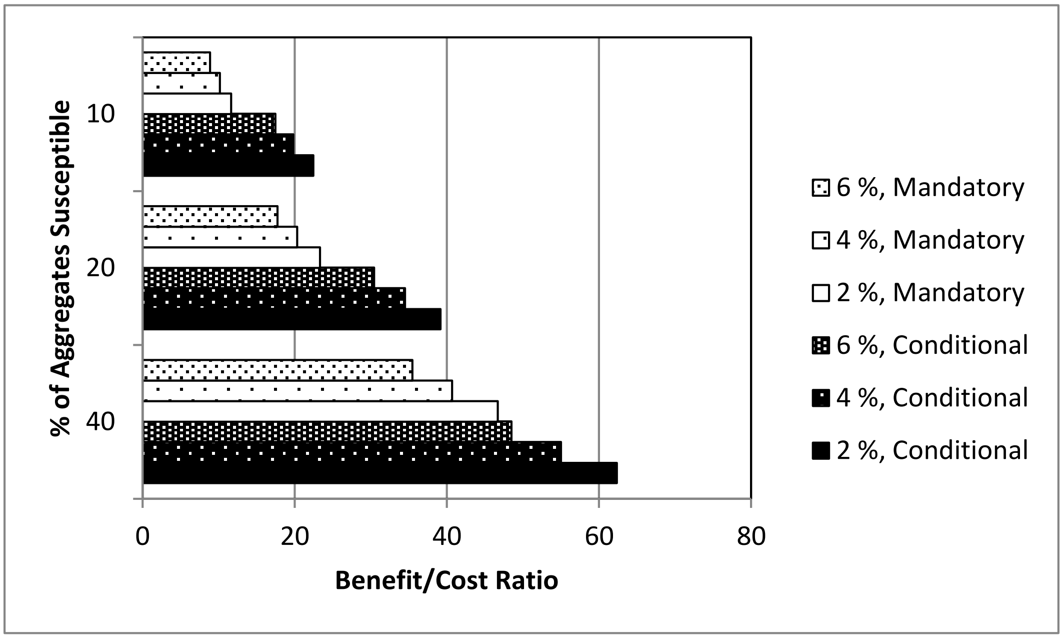


Figure 28. B/C Ratio for Realistic Performance, with User Delay Costs, for Different Percentages of Aggregates Susceptible to Moisture Damage, for "H" Traffic/Skid Resistance Level. *Legend refers discount rate and to whether antistrip usage is mandatory or conditional upon test results.*

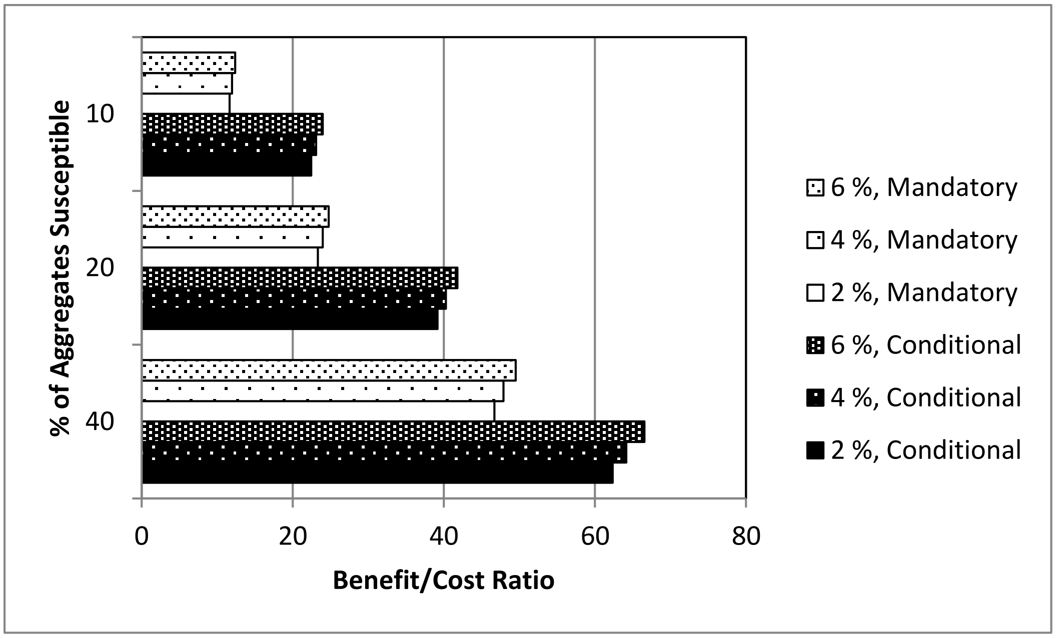


Figure 29. B/C Ratio for Realistic Performance, with User Delay Costs, for Different Percentages of Aggregates Susceptible to Moisture Damage, for "H" Traffic/Skid Resistance Level. *Legend refers traffic growth rate and to whether antistrip usage is mandatory or conditional upon test results.*

Table 32. Summary Results of LCCA Comparing High-saturation Moisture Resistance Testing to No Testing, without User Delay Costs.

Performance of Susceptible Mixes/ Antistrip Usage	*Cost Savings for Percentage of Susceptible Aggregates:*		
	40	**20**	**10**
Realistic Performance/Conditional on Test Result	$8,003,222	$3,958,155	$1,935,622
Realistic Performance/Mandatory for All Mixes	$14,725,686	$7,183,226	$3,411,995
Savings, Mandatory over Conditional	$6,722,464	$3,225,071	$1,476,374
Savings, % of Total Cost	6.0	3.2	1.6
Optimistic Performance/Conditional on Test Result	$6,649,216	$3,281,152	$1,597,120
Optimistic Performance/Mandatory for All Mixes	$8,466,489	$4,053,627	$1,847,196
Savings, Mandatory over Conditional	$1,817,273	$772,475	$250,076
Savings, % of Total Cost	1.9	0.8	0.3

Table 33. Summary Results of LCCA Comparing to High-saturation Moisture Resistance Testing to No Testing, with User Delay Costs.

Performance of Susceptible Mixes/ Antistrip Usage	*Cost Savings for Percentage of Susceptible Aggregates:*		
	40	**20**	**10**
Realistic Performance/Conditional on Test Result	$9,199,060	$4,556,074	$2,234,581
Realistic Performance/Mandatory for All Mixes	$16,728,406	$8,184,586	$3,912,675
Savings, Mandatory over Conditional	$7,529,346	$3,628,511	$1,678,094
Savings, % of Total Cost	5.9	3.2	1.6
Optimistic Performance/Conditional on Test Result	$7,332,850	$3,622,969	$1,768,029
Optimistic Performance/Mandatory for All Mixes	$9,354,325	$4,497,545	$2,069,155
Savings, Mandatory over Conditional	$2,021,475	$874,576	$301,126
Savings, % of Total Cost	1.8	0.8	0.3

6.3. LCCA and BCA Findings

Based upon the LCCA and CBA presented in this chapter, the following conclusions are made:

- The B/C ratio of the low-saturation moisture resistance testing procedure is zero, and is therefore uneconomical under any set of assumptions.
- The B/C ratio of antistrip usage in conjunction with high-saturation moisture resistance testing was found to be, under all scenarios much greater than one, indicating that antistrip usage and appropriate moisture resistance testing significantly lower the net life cycle cost of HMA pavements in Pennsylvania.
- The B/C ratio of antistrip usage in conjunction with high-saturation moisture resistance testing was greater than one (again, much greater in most cases) for both conditional use of antistrip and mandatory use of antistrip, indicating that both approaches are very economical. “Conditional” in this case means antistrip is only used when needed to pass moisture resistance testing, while “mandatory” means that antistrip is used in all mixes, regardless of the results of moisture resistance testing.
- Mandatory antistrip usage, in conjunction with high-saturation testing appears to always result in greater net savings compared to antistrip usage dependent on the results of moisture resistance testing. This is because of the failure of such testing to identify all susceptible mixes and the high costs associated with the poor performance and increased maintenance that occurs in these cases.

7. DISUCSSION

7.1. Summary

The work documented in this report had three primary parts: (1) a literature review; (2) laboratory testing of mixes for moisture resistance; and (3) a life cycle cost analysis and calculation of cost-benefit ratios. Surveys of paving materials producers and PennDOT personnel were also conducted, but low participation rates meant that the results had little significance.

The review of the literature concerning moisture damage and antistrip usage in asphalt concrete lead to several important findings. Pennsylvania has an unusually harsh environment for asphalt concrete and related materials; it is subject to a very large number of freeze thaw cycles, and also has a moderately high amount of precipitation. Pennsylvania is also more heavily populated than many other states and many of its roads see very heavy traffic. All of these factors tend to increase moisture damage to asphalt concrete pavements. A variety of test methods have been used to evaluate the susceptibility of asphalt concrete mixes to moisture damage; by far the most commonly used at this time is the modified Lottman test, AASHTO T 283. Various versions of this test are in use, the most common—and the one now in use by PennDOT—use relatively high levels of saturation (70 to 80 % in Pennsylvania) and includes a freeze-thaw cycle.

In discussing error rates for moisture resistance tests it is useful to categorize errors as either type I or type II; a type I error occurs when a mixture resistant to moisture damage is incorrectly identified as being susceptible. A type II error occurs when a mix that is susceptible to moisture damage is incorrectly identified as being resistant to damage. Based upon results reported in the literature, modified Lottman tests conducted at a high level of saturation tend to have a very low type I error rate, but a type II error rate of approximately 20 to 30 % for mixes containing aggregates highly susceptible to moisture damage. Although the modified Lottman test is far from perfect, it has been more thoroughly studied than any other method, and at this time is the accepted standard.

A variety of antistrip additives are available for improving the performance of asphalt concrete mixes containing aggregates susceptible to moisture damage. Hydrated lime—added to the aggregate as a slurry—is the most common type of antistrip. Liquid antistrips, surfactants that are often added to the asphalt binder at the refinery or terminal, are significantly cheaper and more convenient compared to hydrated lime, but there is evidence that the field performance of mixes treated with hydrated lime is in general significantly better compared to mixes treated with liquid antistrip.
saturation version of the modified Lottman test. The low-saturation version has no control over the level of saturation during specimen conditioning, and typically produces saturation levels between 30 and 67 %. This procedure was used in Pennsylvania between 2003 and October of 2014; the high-saturation method was used prior to 2003 and after October 2014. The high-saturation version of the modified Lottman procedure, as now used in Pennsylvania, requires specimen saturation levels between 70 and 80 %, and is more typical of testing performed by oth

Moisture damage in asphalt concrete is in part dependent on the type of aggregate used. Limestone and dolomite aggregates tend to produce mixes that are resistant to moisture damage, whereas granite and quartzite aggregates tend to produce mixes that are highly susceptible to moisture damage. Approximately 70 % of the aggregates produced in Pennsylvania for use in asphalt concrete are limestone and/or dolomite and for the most part produce mixes that are resistant to moisture damage. About 10 % of the aggregate used in asphalt concrete in Pennsylvania are crushed gravels; gravels tend to vary in moisture sensitivity, but in Pennsylvania most of the asphalt concrete produced with crushed gravel are highly susceptible to moisture damage. The balance of the aggregates produced in Pennsylvania for use in asphalt concrete vary in their susceptibility to moisture damage.

A total of 45 asphalt concretes, all produced in Pennsylvania under PennDOT standards, were tested as part of this research. Sixteen of these mixes had known histories of moisture resistance: six had low potential for moisture damage, two had moderate potential and eight had a high potential for moisture damage. Two different procedures for evaluating HMA moisture resistance were used, a low-saturation version of the modified Lottman test, and a higher agency. The low-saturation method of testing failed to identify any mixes as being susceptible to moisture damage—that is, every mix passed this version of the test, even those with a known high potential for moisture damage. The high saturation method produced error rates consistent with those reported in the literature for Lottman tests of similar (level 2) severity: a type I error rate (good mixes that failed) of 0 % and a type II error rate (poor mixes that passed) of 50 % for mixes moderately susceptible to moisture damage and 25 % for mixes highly susceptible to moisture damage. Final, average error rates for the modified Lottman test as currently used in Pennsylvania (after October 2014, high-saturation or level 2 severity) were calculated by averaging values found in this study with those reported in the literature: type I error rate of 6 %; type II error rate of 62 % for mixes moderately susceptible to moisture damage; and a type II error rate of 23 % for mixes highly susceptible to moisture damage. These values were then used in the calculation of benefit/cost ratios. An important, consistent finding in the laboratory testing conducted in this project and reported in numerous other research projects is that modified Lottman testing tends to be reasonably accurate in differentiating between mixes with low and high susceptibility to moisture damage, but is poor at accurately identifying mixes with moderate susceptibility to moisture damage.

Standard PennDOT methodology was used in performing the life cycle cost analysis. However, a range of assumptions were used for critical variables in order to evaluate the sensitivity of the analysis to changes in these values. For example, two different discount rates were used, along with two different traffic growth rates. The analyses were also performed including and excluding user delay costs. It was assumed that highly susceptible mixes on average had half the life of mixes resistant to moisture damage along with increased maintenance costs. Use of antistrip was assumed to only partially restore the performance of mixes susceptible to moisture damage. The results of the analysis, as would be expected, showed increasing costs at higher levels of moisture susceptibility, and decreasing costs with the use of antistrip.

The cost/benefit analysis incorporated the results of the LCCA and the error rates estimated from the laboratory testing and literature review to calculate benefit/cost ratios for antistrip usage. The cost in this case is that of adding antistrip to the mix. The benefit is the partial increase in life and the reduced maintenance costs that result when antistrip is added to mixes susceptible to moisture damage. An important input into this analysis is the error rate of testing. Type I errors—where mixes resistant to moisture damage are incorrectly identified as susceptible—are associated with the minor cost of having to include antistrip when it is not needed. Type II errors—where mixes susceptible to moisture damage are incorrectly identified as resistant—are associated with a much higher cost, that of having a significantly shortened life and higher maintenance costs because antistrip was not included in the mix. Even considering the effect of these errors, the use of high-saturation moisture resistance testing in conjunction with liquid antistrip usage showed benefit/cost ratios that were always greater than one, usually much greater.

The low cost of type I errors in testing and the high cost of type II errors suggests an alternative approach to moisture resistance testing and treatment—the mandatory use of antistrip in all mixes. This is potentially cost effective because it greatly reduces or even eliminates the incidence of type II errors, since all mixes will contain antistrip. This approach was considered in the cost/benefit analysis, and the results—even when user delay costs are not considered and when the most optimistic performance assumptions are made—show savings compared to the approach where antistrip use is conditional upon the results of testing. Estimated potential savings from mandatory use of antistrip compared to conditional use range from several hundred thousand dollars per year to as much as six million dollars per year.

7.2. Practical Applications and Implementation.

One obvious, practical application of the results of this research is the abandonment of the low-saturation modified Lottman test and its replacement with the high-saturation method. Partly as a result of this research, this change was made in October of 2014. In all probability this change should result in an overall improvement in the performance of asphalt concrete pavements in the Commonwealth and substantial cost savings. Implementation of this change should prevent no significant problems, since the high-saturation test method (or a method nearly identical to it) was used in Pennsylvania prior to 2003.

The second application of the results of this research—mandatory use of antistrip—would also probably improve overall flexible pavement performance and also result in cost savings to PennDOT. However the projected cost savings are sensitive to several assumptions included the overall impact of moisture damage on pavement performance and the percentage of mixes in Pennsylvania subject to moisture damage. Implementation may also be difficult, since many producers that have traditionally not been required to use antistrip would now be required to use it. One approach to reducing this problem would be to only require mandatory antistrip usage in Districts where there are significant proportions of aggregate susceptible to moisture damage. It should be emphasized that mandatory use of antistrip does not mean that moisture resistance testing is not required; such testing is still necessary because the effect of antistrip on a particular combination of asphalt and aggregate tends to vary substantially among different additives. Furthermore, the FHWA has clearly stated opposition to the use of antistrip additives in asphalt concrete without appropriate moisture resistance testing.

A third potential application of the results of this research is the potential use of hydrated lime as an antistrip additive in Pennsylvania. The literature review revealed that hydrated lime is in fact the most commonly used antistrip additive in the U.S., and appears to provide for a superior level of field performance compared to liquid antistrip additives when used in susceptible mixes. It is however significantly more expensive than liquid antistrip and not as convenient, since it must be added at the plant, most commonly as a slurry sprayed onto the aggregate prior to mixing. Implementation of the use of hydrated lime would probably meet with significant opposition from producers because of the increased cost and complexity compared to liquid antistrip. Also, since it has not been used in Pennsylvania it is difficult to say with certainty that it would result in improved performance in susceptible mixes. A reasonable first step in implementation would therefore be construction of several pilot projects using hydrated lime. These projects should include control sections produced with liquid antistrip so that the performance of the two approaches can be directly compared. Incentives could be provided to the successful bidder for these pilot projects to ensure that they were adequately compensated for the cost and inconvenience of using hydrated lime in the mixes.

8. CONCLUSIONS AND RECOMMENDATIONS

Based upon the results of this research as documented in this report, the following conclusions and recommendations are made:

- Although there have been several efforts to develop improved procedures for evaluating the moisture resistance of asphalt concrete mixes, various versions of the modified Lottman procedure remain the most widely used such test method in the U.S.
- When the modified Lottman procedure is used with moderately high saturation levels (55 to 80 %), it is reasonably good at identifying mixes that are resistant to moisture damage and highly susceptible to moisture damage, but poor at identifying mixes with intermediate resistance to moisture damage.
- Hydrated lime is the most commonly used antistrip additive in the U.S. There is substantial evidence that the use of hydrated lime results in improved field performance in mixes susceptible to moisture damage compared to liquid antistrip. However, hydrated lime is substantially more expensive and less convenient to use than liquid antistrip.
- Two versions of the modified Lottman test have been recently used in Pennsylvania. In the low-saturation method, specimens are “saturated” by applying a 254-mm vacuum for 30 minutes. In this study, this resulted in saturation levels ranging from 30 to 67 %, with an average of 43 %. In the high-saturation method, the strength of the vacuum and saturation time are not specified, but the final saturation level of the specimens must be between 70 and 80 %.
- In this study, 48 mixes were tested using both the low-saturation and high-saturation procedures. Sixteen of the 48 mixes had known moisture resistance levels so that the accuracy of the two procedures could be evaluated. All of the mixes tested passed the low-saturation method, indicating that this procedure has little or no ability to detect mixes susceptible to moisture damage. The error rate for the high-saturation test method were very similar to those reported in the literature for this and similar procedures. The type I error rate (“good” mixes that fail the test) was 0 %, and the type II error rate (mixes susceptible to moisture damage that pass the test) was 25 % for mixtures with low resistance to moisture damage, and 50 % for mixes with moderate resistance to moisture damage. Partly in response to the result of this research, as of October 2014 the low-saturation method is no longer used in Pennsylvania, which has returned to using the high-saturation version of modified Lottman testing.
- Benefit/cost ratios were calculated using a variety of assumptions to evaluate the sensitivity of the results to changes in the values of critical variables such as discount rate, traffic growth rate and overall level of moisture damage. Ratios were calculated with and without user delay costs. Costs were calculated using

standard PennDOT methodology with some modifications because of the nature of the study. Because the low-saturation test method fails to identify any mixes susceptible to moisture damage, the benefit/cost ratio for this method is zero. For the high-saturation test method, the benefit/cost ratio is always greater than one, and usually much greater, indicating that the test procedure and the associated use of antistrip additives in mixes that fail the test are a cost-effective approach to improving the performance of asphalt concrete mixes susceptible to moisture damage.

- The cost/benefit analysis indicated that the mandatory use of antistrip—regardless of the outcome of moisture resistance testing—would probably result in significant savings to the Commonwealth. This is because even with the high-saturation procedure, a significant number of mixes susceptible to moisture damage are not identified as such. Mandatory antistrip usage would ensure that all susceptible mixes contained antistrip additive, resulting in significant improvements in pavement performance at relative small cost.
- Since the majority of aggregates used in hot mix in Pennsylvania have been found to have low susceptibility to moisture related damage, it may be prudent to consider mandatory usage of antistrip material on an individual District basis.
- The use of hydrated lime as an antistrip agent should be evaluated in several pilot projects in which companion test sections of pavement potentially susceptible to moisture damage are treated with liquid antistrip and with hydrated lime. Hydrated lime in general has proven to be more effective than liquid antistrip in improving the performance of mixes prone to moisture damage.

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APPENDIX: REPAIR AND MAINTENANCE ASSUMPTIONS FOR LIFE CYCLE COST ANALYSIS

Scenario C

Year	Life	R&M Activities
0	12	Full Depth Patching, 2% of pavement area
		Mill wearing course
		Leveling Course, 60 PSY
		Bituminous Overlay, 1.5" or 2.0"
		Type 7 Paved Shoulders
		Adjust guide rail and drainage structures, if necessary
		Maintenance and Protection of Traffic
		User Delay
1		
2		
3		
4		
5		
6	6	Clean and Seal, 25% of longitudinal joints
		Crack Seal,500 lineal feet per mile
		Seal Coat or Micro Surface shoulders, if Type 1, 1S, 3, 4, 6 or 6S
		Maintenance and Protection of Traffic
		User Delay
7		
8		
9		
10		
11		
12	12	Full Depth Patching, 2% of pavement area
		Mill wearing course
		Bituminous Inlay, 1.5" or 2.0"
		Maintenance and Protection of Traffic
		User Delay
13		
14		
15		
16		
17		
18	6	Clean and Seal, 25% of longitudinal joints
		Crack Seal, 500 lineal feet per mile
		Seal Coat or Micro Surface shoulders, if Type 1, 1S, 3, 4, 6 or 6S
		Maintenance and Protection of Traffic
		User Delay
19		
20		
21		
22		
23		
24		

Scenario RHN

Year	Life	R&M Activities
0	6	Full Depth Patching, 2% of pavement area
		Mill wearing course
		Leveling Course, 60 PSY
		Bituminous Overlay, 1.5" or 2.0"
		Type 7 Paved Shoulders
		Adjust guide rail and drainage structures, if necessary
		Maintenance and Protection of Traffic
		User Delay
1		
2		
3	3	Clean and Seal, 25% of longitudinal joints
		Crack Seal,500 lineal feet per mile
		Seal Coat or Micro Surface shoulders, if Type 1, 1S, 3, 4, 6 or 6S
		Maintenance and Protection of Traffic
		User Delay
4		
5		
6	6	Full Depth Patching, 2% of pavement area
		Mill wearing course
		Bituminous Inlay, 1.5" or 2.0"
		Maintenance and Protection of Traffic
		User Delay
7		
8		
9	3	Clean and Seal, 25% of longitudinal joints
		Crack Seal, 500 lineal feet per mile
		Seal Coat or Micro Surface shoulders, if Type 1, 1S, 3, 4, 6 or 6S
		Maintenance and Protection of Traffic
		User Delay
10		
11		
12	6	Full Depth Patching, 4% of pavement area
		Mill wearing course
		Leveling Course, 60 PSY
		Bituminous Overlay, 1.5" or 2.0"
		Type 7 Paved Shoulders
		Adjust guide rail and drainage structures, if necessary
		Maintenance and Protection of Traffic
		User Delay
13		

Scenario RHN (continued)

Year	Life	R&M Activities
14		
15	3	Clean and Seal, 25% of longitudinal joints
		Crack Seal, 500 lineal feet per mile
		Seal Coat or Micro Surface shoulders, if Type 1, 1S, 3, 4, 6 or 6S
		Maintenance and Protection of Traffic
		User Delay
16		
17		
18	6	Full Depth Patching, 4% of pavement area
		Mill wearing course
		Bituminous Inlay, 1.5" or 2.0"
		Maintenance and Protection of Traffic
		User Delay
19		
20		
21	3	Clean and Seal, 25% of longitudinal joints
		Crack Seal, 500 lineal feet per mile
		Seal Coat or Micro Surface shoulders, if Type 1, 1S, 3, 4, 6 or 6S
		Maintenance and Protection of Traffic
		User Delay
22		
23		
24		

Scenario RHS

Year	Life	R&M Activities
0	8	Full Depth Patching, 2% of pavement area
		Mill wearing course
		Leveling Course, 60 PSY
		Bituminous Overlay, 1.5" or 2.0"
		Type 7 Paved Shoulders
		Adjust guide rail and drainage structures, if necessary
		Maintenance and Protection of Traffic
		User Delay
1		
2		
3		
4	4	Clean and Seal, 25% of longitudinal joints
		Crack Seal,500 lineal feet per mile
		Seal Coat or Micro Surface shoulders, if Type 1, 1S, 3, 4, 6 or 6S
		Maintenance and Protection of Traffic
		User Delay
5		
6		
7		
8	8	Full Depth Patching, 2% of pavement area
		Mill wearing course
		Bituminous Inlay, 1.5" or 2.0"
		Maintenance and Protection of Traffic
		User Delay
9		
10		
11		
12	4	Clean and Seal, 25% of longitudinal joints
		Crack Seal, 500 lineal feet per mile
		Seal Coat or Micro Surface shoulders, if Type 1, 1S, 3, 4, 6 or 6S
		Maintenance and Protection of Traffic
		User Delay
13		

Scenario RHS (continued)		
Year	Life	R&M Activities
14		
15		
16	8	Full Depth Patching, 4% of pavement area
		Mill wearing course
		Leveling Course, 60 PSY
		Bituminous Overlay, 1.5" or 2.0"
		Type 7 Paved Shoulders
		Adjust guide rail and drainage structures, if necessary
		Maintenance and Protection of Traffic
		User Delay
17		
18		
19		
20	4	Clean and Seal, 25% of longitudinal joints
		Crack Seal, 500 lineal feet per mile
		Seal Coat or Micro Surface shoulders, if Type 1, 1S, 3, 4, 6 or 6S
		Maintenance and Protection of Traffic
		User Delay
21		
22		
23		
24		

Scenario RMN

Year	Life	R&M Activities
0	8	Full Depth Patching, 2% of pavement area
		Mill wearing course
		Leveling Course, 60 PSY
		Bituminous Overlay, 1.5" or 2.0"
		Type 7 Paved Shoulders
		Adjust guide rail and drainage structures, if necessary
		Maintenance and Protection of Traffic
		User Delay
1		
2		
3		
4	4	Clean and Seal, 25% of longitudinal joints
		Crack Seal,500 lineal feet per mile
		Seal Coat or Micro Surface shoulders, if Type 1, 1S, 3, 4, 6 or 6S
		Maintenance and Protection of Traffic
		User Delay
5		
6		
7		
8	8	Full Depth Patching, 2% of pavement area
		Mill wearing course
		Bituminous Inlay, 1.5" or 2.0"
		Maintenance and Protection of Traffic
		User Delay
9		
10		
11		
12	4	Clean and Seal, 25% of longitudinal joints
		Crack Seal, 500 lineal feet per mile
		Seal Coat or Micro Surface shoulders, if Type 1, 1S, 3, 4, 6 or 6S
		Maintenance and Protection of Traffic
		User Delay
13		
14		

Scenario RMN (continued)

Year	Life	R&M Activities
15		
16	8	Full Depth Patching, 2% of pavement area
		Mill wearing course
		Leveling Course, 60 PSY
		Bituminous Overlay, 1.5" or 2.0"
		Type 7 Paved Shoulders
		Adjust guide rail and drainage structures, if necessary
		Maintenance and Protection of Traffic
		User Delay
17		
18		
19		
20	4	Clean and Seal, 25% of longitudinal joints
		Crack Seal, 500 lineal feet per mile
		Seal Coat or Micro Surface shoulders, if Type 1, 1S, 3, 4, 6 or 6S
		Maintenance and Protection of Traffic
		User Delay
21		
22		
23		
24		

Scenario RMS

Year	Life	R&M Activities
0	12	Full Depth Patching, 2% of pavement area
		Mill wearing course
		Leveling Course, 60 PSY
		Bituminous Overlay, 1.5" or 2.0"
		Type 7 Paved Shoulders
		Adjust guide rail and drainage structures, if necessary
		Maintenance and Protection of Traffic
		User Delay
1		
2		
3		
4		
5		
6	6	Clean and Seal, 25% of longitudinal joints
		Crack Seal,500 lineal feet per mile
		Seal Coat or Micro Surface shoulders, if Type 1, 1S, 3, 4, 6 or 6S
		Maintenance and Protection of Traffic
		User Delay
7		
8		
9		
10		
11		
12	12	Full Depth Patching, 2% of pavement area
		Mill wearing course
		Bituminous Inlay, 1.5" or 2.0"
		Maintenance and Protection of Traffic
		User Delay
13		
14		
15		
16		

Scenario RMS (continued)		
Year	Life	R&M Activities
17		
18	6	Clean and Seal, 25% of longitudinal joints
		Crack Seal, 500 lineal feet per mile
		Seal Coat or Micro Surface shoulders, if Type 1, 1S, 3, 4, 6 or 6S
		Maintenance and Protection of Traffic
		User Delay
19		
20		
21		
22		
23		
24		

Scenario OHN

Year	Life	R&M Activities
0	8	Full Depth Patching, 2% of pavement area
		Mill wearing course
		Leveling Course, 60 PSY
		Bituminous Overlay, 1.5" or 2.0"
		Type 7 Paved Shoulders
		Adjust guide rail and drainage structures, if necessary
		Maintenance and Protection of Traffic
		User Delay
1		
2		
3		
4	4	Clean and Seal, 25% of longitudinal joints
		Crack Seal,500 lineal feet per mile
		Seal Coat or Micro Surface shoulders, if Type 1, 1S, 3, 4, 6 or 6S
		Maintenance and Protection of Traffic
		User Delay
5		
6		
7		
8	8	Full Depth Patching, 2% of pavement area
		Mill wearing course
		Bituminous Inlay, 1.5" or 2.0"
		Maintenance and Protection of Traffic
		User Delay
9		
10		
11		
12	4	Clean and Seal, 25% of longitudinal joints
		Crack Seal, 500 lineal feet per mile
		Seal Coat or Micro Surface shoulders, if Type 1, 1S, 3, 4, 6 or 6S
		Maintenance and Protection of Traffic
		User Delay
13		
14		

Scenario OHN (continued)

Year	Life	R&M Activities
15		
16	8	Full Depth Patching, 4% of pavement area
		Mill wearing course
		Leveling Course, 60 PSY
		Bituminous Overlay, 1.5" or 2.0"
		Type 7 Paved Shoulders
		Adjust guide rail and drainage structures, if necessary
		Maintenance and Protection of Traffic
		User Delay
17		
18		
19		
20	4	Clean and Seal, 25% of longitudinal joints
		Crack Seal, 500 lineal feet per mile
		Seal Coat or Micro Surface shoulders, if Type 1, 1S, 3, 4, 6 or 6S
		Maintenance and Protection of Traffic
		User Delay
21		
22		
23		
24		

Scenario OHS

Year	Life	R&M Activities
0	12	Full Depth Patching, 2% of pavement area
		Mill wearing course
		Leveling Course, 60 PSY
		Bituminous Overlay, 1.5" or 2.0"
		Type 7 Paved Shoulders
		Adjust guide rail and drainage structures, if necessary
		Maintenance and Protection of Traffic
		User Delay
1		
2		
3		
4		
5		
6	6	Clean and Seal, 25% of longitudinal joints
		Crack Seal,500 lineal feet per mile
		Seal Coat or Micro Surface shoulders, if Type 1, 1S, 3, 4, 6 or 6S
		Maintenance and Protection of Traffic
		User Delay
7		
8		
9		
10		
11		
12	12	Full Depth Patching, 4% of pavement area
		Mill wearing course
		Bituminous Inlay, 1.5" or 2.0"
		Maintenance and Protection of Traffic
		User Delay
13		
14		
15		
16		
17		
18	6	Clean and Seal, 25% of longitudinal joints
		Crack Seal, 500 lineal feet per mile
		Seal Coat or Micro Surface shoulders, if Type 1, 1S, 3, 4, 6 or 6S
		Maintenance and Protection of Traffic
		User Delay
19		
20		
21		
22		
23		
24		

Scenario OMN

Year	Life	R&M Activities
0	12	Full Depth Patching, 2% of pavement area
		Mill wearing course
		Leveling Course, 60 PSY
		Bituminous Overlay, 1.5" or 2.0"
		Type 7 Paved Shoulders
		Adjust guide rail and drainage structures, if necessary
		Maintenance and Protection of Traffic
		User Delay
1		
2		
3		
4		
5		
6	6	Clean and Seal, 25% of longitudinal joints
		Crack Seal,500 lineal feet per mile
		Seal Coat or Micro Surface shoulders, if Type 1, 1S, 3, 4, 6 or 6S
		Maintenance and Protection of Traffic
		User Delay
7		
8		
9		
10		
11		
12	12	Full Depth Patching, 2% of pavement area
		Mill wearing course
		Bituminous Inlay, 1.5" or 2.0"
		Maintenance and Protection of Traffic
		User Delay
13		
14		
15		
16		
17		
18	6	Clean and Seal, 25% of longitudinal joints
		Crack Seal, 500 lineal feet per mile
		Seal Coat or Micro Surface shoulders, if Type 1, 1S, 3, 4, 6 or 6S
		Maintenance and Protection of Traffic
		User Delay
19		
20		
21		
22		
23		
24		

Scenario OMS

Year	Life	R&M Activities
0	12	Full Depth Patching, 2% of pavement area
		Mill wearing course
		Leveling Course, 60 PSY
		Bituminous Overlay, 1.5" or 2.0"
		Type 7 Paved Shoulders
		Adjust guide rail and drainage structures, if necessary
		Maintenance and Protection of Traffic
		User Delay
1		
2		
3		
4		
5		
6	6	Clean and Seal, 25% of longitudinal joints
		Crack Seal,500 lineal feet per mile
		Seal Coat or Micro Surface shoulders, if Type 1, 1S, 3, 4, 6 or 6S
		Maintenance and Protection of Traffic
		User Delay
7		
8		
9		
10		
11		
12	12	Full Depth Patching, 2% of pavement area
		Mill wearing course
		Bituminous Inlay, 1.5" or 2.0"
		Maintenance and Protection of Traffic
		User Delay
13		
14		
15		
16		
17		
18	6	Clean and Seal, 25% of longitudinal joints
		Crack Seal, 500 lineal feet per mile
		Seal Coat or Micro Surface shoulders, if Type 1, 1S, 3, 4, 6 or 6S
		Maintenance and Protection of Traffic
		User Delay
19		
20		
21		
22		
23		
24		