NDOT Research Report

Report No: RDT01-009

PERFORMANCE OF LIME IN HOT MIX ASPHALT PAVEMENTS

July 2001

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16. Abstract

The pavement community has recognized that moisture damage of hot mixed asphalt (HMA) mixtures has been a serious problem since the early 1960s. Numerous additives have been evaluated with the objective of reducing the potential of moisture damage in HMA mixtures. Lime has been one of the most common additives used to reduce the potential of moisture damage. The Nevada Department of Transportation (NDOT) has been using lime in HMA mixtures since the mid 1980s. The objective of this research is to quantify the improvements in pavement performance that have been realized through the addition of lime to HMA mixtures. The research used two methodologies: 1) quantify the effectiveness of lime on NDOT's HMA pavements through the evaluation of field pavements and 2) evaluate the various techniques of adding lime to HMA mixtures through laboratory testing. The evaluation of field pavements consisted of evaluating field samples and pavement performance data from untreated and lime-treated pavements. The evaluation of various techniques to add lime into HMA mixtures conducted laboratory evaluation of laboratory-mixed-laboratory-compacted HMA mixtures treated with lime using different techniques.

The properties of untreated and lime-treated mixtures from field projects in the southern and north-western parts of Nevada indicated that lime treatment of Nevada's aggregates significantly improves the moisture sensitivity of HMA mixtures. The study showed that lime-treated HMA mixtures become significantly more resistant to multiple freeze-thaw than the untreated mixtures. The long term pavement performance data indicated that under similar environmental and traffic conditions, the lime-treated mixtures provided better performing pavements with less requirements for maintenance and rehabilitation activities. The analysis of the impact of lime on pavement life indicated that lime treatment extends the performance life of HMA pavements by an average of 3 years. This represents an average increase of 38% in the expected pavement life. The laboratory portion of the study showed that lime improves the tensile strength and resilient modulus properties of the HMA mixtures after single and multiple freeze-thaw cycling. The portion of the laboratory study dealing with the evaluation of lime application indicated that all methods of application can produce similar results 80% of the time. In the other 20% of the time, the NDOT process for 48-hours marination showed to be the most effective. Based on the data generated in this experiment, the addition of lime on wet aggreagtes with 48-hours marination would be the most desirable method of lime application because it provides effective results and it is less susceptible to field problems than the addition of lime to wet aggregates without marination.

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I. INTRODUCTION

The Nevada Department of Transportation (NDOT) is responsible for the construction, maintenance and rehabilitation of over 5000 miles of pavements throughout the state. These pavements stretch over a wide range of environmental and traffic conditions where the southern part of the state is subjected to hot environment and heavy traffic, the north-western part of the state is subjected to cold environment and medium traffic while the north-eastern part of the state is subjected to cold environment and low traffic. Coupled with these changes in environmental and traffic conditions are the variations of aggregate sources which directly impact the performance of hot mixed asphalt (HMA) pavements.

The long-term performance of Nevada's pavements is crucial to the future of the entire state. The economic well-being of the state depends on the mobility of goods and tourism throughout the state. Good performance of a pavement is defined as a long service-life without major interruptions to the road users and surrounding businesses. A good performing pavement would show good resistance to the prevailing failure modes. Rutting failure is characterized by permanent depressions in the wheeltracks. Cracking failures are caused by three factors: fatigue, thermal, and aging. Fatigue cracking is characterized by longitudinal and interconnected cracks in the wheeltracks. Thermal cracking is characterized by transverse cracks across the pavement surface. Age cracking is characterized by block cracks covering the entire pavement surface. Raveling failure represents the separation of aggregate particles from the HMA mix. The advanced stages of raveling lead to the formation of potholes.

The resistance of HMA surfaces to these failures is dependent upon proper selection of materials (asphalt binder and aggregates), good mixture design, proper construction and adequate structural thickness design. The proper selection of materials and mixture design are very critical since they control the resistance of HMA mixtures to moisture damage. Moisture damage is not a failure mode by itself but it represents a conditioning process which could lead to any one of the failure modes that were described above. The presence of moisture damage can significantly accelerate the formation of the failure modes. The pavement community has recognized that moisture damage of HMA mixtures has been a serious problem since the early 1960s (1). Numerous additives have been evaluated with the objective of reducing the potential of moisture damage in HMA mixtures (2). Lime has been one of the most common additives used to reduce the potential of moisture damage (3).

I.1 Objectives

NDOT started using lime to reduce moisture damage of HMA mixtures since the mid 1980s, leading to significant improvements in the long-term performance of HMA pavements. The objective of this research is to quantify the improvements in pavement performance that have been realized through the addition of lime to HMA mixtures.

The research study was conducted over a three-year period and covered three distinct areas: a) review previous developments in the assessment of moisture damage and prevention techniques, b) quantify the effectiveness of lime on NDOT's HMA pavements through the evaluation of field pavements, and c) evaluate the various techniques of adding lime to HMA mixtures through laboratory testing.The work conducted under the first area has been documented in a report entitled: "Lime in Hot Mix Asphalt Pavements: A Synthesis of Information." (4) This current report summarizes the work completed under the second and third areas.

II. EVALUATION OF FIELD PAVEMENTS

This task concentrated on evaluating the performance of field pavement sections that have been subjected to various traffic and environmental conditions. Pavement sections in the southern and northern parts of the state were identified for evaluation. The overall objective was to compare the performance of HMA pavements that were treated with lime to the performance of HMA pavements that were not treated with lime. Two levels of investigations were conducted under this task: a) evaluate field projects through laboratory testing of field samples and b) evaluate field projects through the use of the pavement management system (PMS) data.

II.1 Pavements Evaluated through a Laboratory Program

The selection of candidate projects for this evaluation program recognized two important issues: a) aggregate source plays a major role in the resistance of HMA mixtures to moisture damage and b) aggregate properties from the same source change with time. Therefore, the main criterion of comparing the performance of lime-treated and untreated pavements consisted of comparing pavements constructed during the same two-year period with aggregates from the same source.

Table 1 summarizes the pavement sections that were evaluated under this program. Following the established criteria, it can be seen that in the southern part of the state, the performance of Pecos road can be compared with US 95, Russell Road with Sunset Road and SR 599, while the performance of Sahara Avenue cannot be compared to any of the other sections. In the northern part of the state, the performance of McCarran from Plumas to Greensboro and

Greensboro to Skyline can be compared to SR516 while the performance of Lakeside cannot be compared with any of the other sections.

II.1.a. Evaluation Program

As mentioned earlier, the evaluation program consisted of laboratory testing of field samples obtained from the pavement sections. The field sampling plan consisted of cutting cores from the wheelpath (WP) and between the wheelpath (BWP) of each section. The resilient modulus (Mr) and tensile strength (TS) properties of the cores were evaluated at the dry and moisture conditioned stages. Also the Mr property of some cores were evaluated after multiple freeze/thaw cycles. As mentioned earlier, the objective of the testing program was to evaluate the resistance of the HMA mixtures to moisture damage. The program assumed that the BWP cores can be used as a reference to evaluate the combined impact of moisture damage and traffic on HMA mixtures. In other words, by comparing the properties of the BWP cores with the properties of the WP cores, the impact of environment alone can be compared to the combined impact of environment and traffic.

The goal of this program is to compare the properties of the lime-treated and untreated mixtures at the dry and moisture conditioned stages under single and multiple freeze-thaw cycles. Replicate samples were tested from both the WP and BWP locations. Therefore, statistical analyses can be used to evaluate if there are significant differences among the various mixtures. The following process will be used to evaluate the performance of the mixtures from various pavements:

1. Group projects into South and North regions;

2. Compare the properties of WP and BWP mixtures within each project. This task will evaluate if there is a statistical difference between materials from the WP and BWP locations based on the Mr-dry and Mr-wet properties at 77°F;

3. Compare the properties of mixtures from projects using the same aggregates and constructed during the same two-year period. This task will evaluate the impact of lime on the following properties of field mixtures; Mr-dry and Mr-wet at 77°F, TS-dry and TS-wet at 77°F, and Mr-wet after multiple freeze-thaw cycles.

The Mr test is nondestructive which means that the sample is not damaged after the conduct of the test. Therefore, the Mr test is ideal to assess the impact of multiple freeze-thaw conditioning on HMA samples because the test can be conducted on the same sample at the dry stage and after any number of freeze-thaw cycles. This experiment evaluated the Mr property of the HMA mixtures at the dry stage and after freeze-thaw cycles of 1, 6, 8, 12, and 18. Each freeze-thaw cycle consists of saturating the HMA sample to a minimum of 75%, freeze the saturated sample for a minimum of 16 hours at -15°C, then thaw the sample for 24 hours in a water bath at 60°C.

The TS test is a destructive test which means that the sample is damaged after the conduct of the test. Therefore, the TS test cannot be conducted on the same sample before and after freeze-thaw cycling. This experiment evaluated the TS property of the HMA samples at the dry stage and after one freeze-thaw cycle. It should be noted that the dry and wet TS properties were evaluated on different sets of samples.

II.1.b. Projects from the South Region

Pecos Road Project: This project consisted of an HMA overlay constructed in 1993 over the pavement section on Pecos Road between Russell and Rawhide, Las Vegas, Nevada. The project was constructed for Clark County by Las Vegas Paving using aggregates from the Lone Mountain quarry. The HMA mix on this project used a design asphalt binder content of 4.8% and did not include lime. Tables 2 and 3 summarize the laboratory-evaluated properties of cores obtained from the Pecos Road project at the stages of dry, wet, and multiple freeze-thaw cycles.

Russell Road Project: This project consisted of an HMA overlay constructed in 1994 over the pavement section on Russell Road between Valley View and Procyon, Las Vegas, Nevada. The project was constructed for Clark County by Las Vegas Paving using aggregates from the Lone Mountain quarry. The HMA mix on this project used a design asphalt binder content of 4.5% and did not include lime. Tables 4 and 5 summarize the laboratory-evaluated properties of cores obtained from the Russell Road project at the stages of dry, wet, and multiple freeze-thaw cycles.

US 95 Project (2510): This project consisted of an overlay constructed in 1993 over the pavement section on US95 between CL MP76.00 and CL MP81.27, Las Vegas, Nevada. The project was constructed for the Nevada Department of Transportation (NDOT) by Las Vegas Paving using aggregates from the Lone Mountain quarry. The HMA mix on this project used a design asphalt binder content of 4.75% and 1.5% lime. Tables 6 and 7 summarize the laboratory-evaluated properties of cores obtained from the US 95 project at the stages of dry, wet, and multiple freeze-thaw cycles.

Sunset Road Project: This project consisted of an overlay constructed in 1994 over the pavement section on Sunset Road between Eastern and Las Vegas Boulevard, Las Vegas, Nevada. The project was constructed for the Nevada Department of Transportation (NDOT) by Las Vegas Paving using aggregates from the Lone Mountain quarry. The HMA mix on this project used a design asphalt binder content of 4.3% and 1.5% lime. Tables 8 and 9 summarize the laboratory-evaluated properties of cores obtained from the Sunset Road project at the stages of dry, wet, and multiple freeze-thaw cycles.

SR 599 Project (2588): This project consisted of an overlay constructed in 1994 over the pavement section on SR 599 between CL MP5.02 and CL MP12.56, Las Vegas, Nevada. The project was constructed for the Nevada Department of Transportation (NDOT) by Las Vegas Paving using aggregates from the Lone Mountain quarry. The HMA mix on this project used a design asphalt binder content of 4.5% and 1.5% lime. Tables 10 and 11 summarize the laboratory-evaluated properties of cores obtained from the SR 599 project at the stages of dry, wet, and multiple freeze-thaw cycles.

II.1.c. Projects from the North Region

McCarran, Plumas-Greensboro: This project consisted of widening McCarran Boulevard in 1987 between Plumas and Greensboro, Reno, Nevada. The project was constructed for the Regional Transportation Commission (RTC) by Eagle Valley Construction using aggregates from the Dayton quarry. The HMA mix on this project used a design asphalt binder content of 6.6% and did not include lime. Tables 12 and 13 summarize the laboratory evaluated properties of cores obtained from the Plumas-Greensboro project at the stages of dry, wet, and multiple freeze-thaw cycles.

McCarran, Greensboro-Skyline: This project consisted of widening McCarran Boulevard in 1988 between Greensboro and Skyline, Reno, Nevada. The project was constructed for the Regional Transportation Commission (RTC) by Eagle Valley Construction using aggregates from the Dayton quarry. The HMA mix on this project used a design asphalt binder content of 6.3% and did not include lime. Tables 14 and 15 summarize the laboratory-evaluated properties of cores obtained from the Greensboro-Skyline project at the stages of dry, wet, and multiple freeze-thaw cycles.

SR 516 Project (2261): This project consisted of an overlay constructed in 1988 over the pavement section on SR 516 between CC MP0.44 and CC MP2.45, Carson City, Nevada. The project was constructed for the Nevada Department of Transportation (NDOT) by Eagle Valley Construction using aggregates from the Dayton quarry. The HMA mix on this project used a design asphalt binder content of 4.75% and 1.5% lime. Tables 16 and 17 summarize the laboratory-evaluated properties of cores obtained from the SR 516 project at the stages of dry, wet, and multiple freeze-thaw cycles.

II.1.d. Analysis of Mixtures Properties

As outlined earlier, the objective of this analysis is to assess the impact of lime on the properties of field HMA mixtures. The following analyses will be conducted to achieve this objective.

Impact of Traffic and Environmental Stresses

This part of the analysis involves the comparison of the properties from the WP and BWP locations to assess the impact of traffic on the engineering properties of the HMA mixtures. This analysis assumes that the WP cores have been subjected to both traffic and environmental stresses while the BWP cores have been subjected to only the environmental stresses. Using the laboratory replicate data , statistical analyses were used to test whether there is a significant difference between the properties of the WP and BWP cores. The properties used in the statistical analyses were the dry Mr and wet Mr (after one freeze-thaw cycle) at 25°C.

Table 18 summarizes the results of the statistical analyses. An entry of "Yes" indicates that there is a significant difference between the properties of the WP and BWP cores while an entry of "No" indicates that there is no significant difference between the two locations. The data presented in table 18 indicate that there is no significant difference between the properties of cores from WP and BWP for seven out of eight projects. In the one project that there is a significant difference between the two locations, the values of the properties of the WP cores are significantly higher than those of the BWP cores. This indicates that, in general, the addition of lime did not significantly impact the properties of mixtures under the combined action of traffic and environmental stresses (WP) as compared to their performance under environmental stresses alone (BWP). The importance of this finding lies in the fact that the addition of lime has been thought of as increasing the initial properties of the HMA mixtures which may make them more susceptible to environment-caused aging distresses. This data showed that the addition of lime did not significantly change the response of the BWP mixtures indicating that the accelerated aging concept does not hold true. In addition, the SR599 project showed the opposite of this concept.

Another important finding of this analysis is that any set of cores can be used to conduct comparative analyses regardless of their location (WP or BWP) for seven out of eight projects. In the case of the SR599 project the WP cores will be used in comparative studies because they represent the combined actions of environment and traffic stresses.

Impact of Lime on Dry and Wet Properties

This part of the analysis evaluates the impact of lime on the dry properties and properties after one freeze-thaw cycle. As mentioned earlier, in order to compare the properties of mixtures from different projects, the projects should have the same aggregate source and should be constructed within the same time period (within two-years). Under these conditions, the Pecos Road project can be compared with the US95 project (table 19), the Russell Road project can be compared with Sunset and SR599 projects (table 20), and the McCarran projects can be compared with the SR516 project (table 21).

The data in tables 19, 20, and 21 show different trends among the various projects. The data from the Pecos Road and US95 projects (table 19) show that the untreated mixtures have higher dry properties but lower wet properties. The data from the Russell Road, Sunset Road, and SR 599 projects (table 20) show that the untreated mixtures have higher dry and wet properties. The data from the McCarrran and SR516 projects (table 21) show that the untreated mixtures have lower dry and wet properties. In general, the data show that the untreated mixtures experience more significant drop in their properties after one freeze-thaw cycle than the lime-treated mixtures. This observation was further investigated through subjecting the mixtures to multiple freeze-thaw cycles as discussed in the next section.

Impact of Lime on the Resistance of Mixtures to Multiple Freeze-Thaw Cycles

This part of the experiment was carried out to follow-up on the findings of the single freeze-thaw cycle experiment and to better simulate field conditions where HMA mixtures are subjected to multiple freeze-thaw cycles during their service lives. In this experiment, cores from each project were subjected to multiple freeze-thaw cycles following the process described earlier. Again, the same comparisons will be conducted here as under the one freeze-thaw cycle (previous section).

Figure 1, 2, and 3 compare the resistance of lime-treated and untreated mixtures to moisture damage caused through multiple freeze-thaw cycling. The resistance of HMA mixtures to multiple freeze-thaw damage can be assessed in two ways:

1. Rate of reduction in the Mr property as a function of freeze-thaw cycles;
2. The number of freeze-thaw cycles a mixture can withstand prior to failure.

Figure 1 compares the performance of Pecos Road (untreated) project with the US 95 (lime-treated) project. The data in figure 1 shows that the untreated mixtures exhibit higher dry Mr property but deteriorate at a faster rate than the lime-treated mixtures leading to a complete failure at the 10th cycle. The lime-treated mixtures start at lower dry Mr property but maintain good resistance to multiple freeze-thaw damage throughout the entire 18 cycles. Figure 2 also shows that the untreated mixtures experience drastic reduction in the Mr property as a function of multiple freeze-thaw cycles.

Figure 3 shows the resistance of the north region projects to multiple freeze-thaw damage by comparing the McCarran projects with the SR 516 project. The data in figure 3 show drastic differences between the resistance of untreated mixtures to multiple freeze-thaw damage and those of the lime-treated mixtures. The untreated mixtures exhibit complete failure after the 5th cycle while the lime-treated mixtures maintained good resistance to multiple freeze-thaw damage until the 13th cycle.

The data presented in figures 1, 2, and 3 show that lime treatment of aggregates improves the performance of HMA mixtures under multiple freeze-thaw damage. The impact of lime was significant when used with both the southern and northern aggregate sources. Regardless of whether the dry Mr property of the untreated mixture is higher (figure 1 and 2) or lower (figure 3), the lime treatment showed to significantly improve the mixtures resistance to moisture damage caused by multiple freeze-thaw cycles. As discussed earlier, the multiple freeze-thaw cycling process was selected to simulate the actual field conditions that HMA mixtures undergo, the data generated from this experiment indicate that lime treatment leads to better performing HMA mixtures under actual field conditions in both the southern and northern parts of Nevada.

II.1.e. Projects without Match-Ups

This group of projects consists of one pavement section located in the south (Sahara Ave.) and one pavement section located in the north (Lakeside Dr.) which do not have matching sections. Neither section included lime and it was difficult to match them up with sections that were constructed during the same period, using the same aggregate source and having lime. The evaluation program for these two projects included the following:

1. Evaluate the dry and wet properties of field cores;
2. Evaluate the properties of cores under multiple freeze-thaw cycles

Sahara Avenue Project: This project consisted of an HMA overlay constructed in 1996 over the pavement section on Sahara Avenue between Links and Tee, Las Vegas, Nevada. The project was constructed for Clark County by Industrial Company using aggregates from the Hendersen quarry. The HMA mix on this project used a design asphalt binder content of 4.8% and did not include lime. Tables 22 and 23 summarize the laboratory-evaluated properties of cores obtained from the Sahara Avenue project at the stages of dry, wet, and multiple freeze-thaw cycles.

Lakeside Drive Project: This project consisted of an overlay on Lakeside drive in 1987 between Moana and McCarran, Reno, Nevada. The project was constructed for the Regional Transportation Commission (RTC) by Helms Construction using aggregates from the Helms quarry. The HMA mix on this project used a design asphalt binder content of 6.6% and did not include lime. Tables 24 and 25 summarize the laboratory-evaluated properties of cores obtained from the Lakeside Drive project at the stages of dry, wet, and multiple freeze-thaw cycles.

Impact of Traffic and Environmental Stresses

This part of the analysis involves the comparison of the properties from the WP and BWP locations to assess the impact of traffic on the engineering properties of the HMA mixtures. This analysis assumes that the WP cores have been subjected to both traffic and environmental stresses while the BWP cores have been subjected to only the environmental stresses. Using the laboratory replicate data , statistical analyses were used to test whether there is a significant difference between the properties of the WP and BWP cores. The properties used in the statistical analyses were the dry Mr and wet Mr (after one freeze-thaw cycle) at 25°C.

Table 26 summarizes the results of the statistical analyses. An entry of "Yes" indicates that there is a significant difference between the properties of the WP and BWP cores while an entry of "No" indicates that there is no significant difference between the two locations. The data presented in table 26 indicate that there is no significant difference between the properties of cores from WP and BWP for the Sahara Avenue project while there is a significant difference between the properties of cores from WP and BWP for the Lakeside Drive project.

The dry properties of the BWP cores from the two projects were very close. However, the mixture from the Lakeside project experienced more damage in two aspects:

1. The WP mixtures of the Lakeside project show more damage than their BWP counterparts;
2. The properties after one freeze-thaw cycle showed a more drastic reduction.

Even though the Sahara and Lakeside projects cannot be directly compared because of the differences in aggregate source, binder, and locations, the data indicate that the Lakeside mixtures would be classified as more susceptible to moisture damage than the Sahara mixtures. It should be recognized that the location of the Lakeside project subjects it to more severe environmental conditions.

Figures 4 and 5 show the impact of multiple freeze-thaw on the Mr property of the mixtures from the Sahara and Lakeside projects, respectively. The multiple freeze-thaw data indicate that neither mixture survived the full 18 cycles which is consistent with other untreated projects that were evaluated earlier. However, the multiple freeze-thaw data also indicate that the Lakeside mixtures exhibit severe moisture damage.

II.2 Pavements Evaluated through PMS Data

This part of the evaluation consisted of comparing the field performance of projects that were constructed using untreated and lime-treated mixtures. Table 27 lists the projects that have been selected for this part of the evaluation. As can be seen from table 27, the untreated projects were constructed during the 1980s while the lime-treated projects were constructed during the 1990s. The common feature among the two types of projects is that they were constructed on the same highway facility which implies that they received the same traffic and environmental stresses.

The performance of the projects are compared in terms of their present serviceability index (PSI) as measured by the NDOT PMS. The PSI is a performance indicator that was developed based on data from the AASHTO road test. It expresses pavement performance in terms of roughness, rutting, and cracking. The PSI is presented on a scale of 0 to 5 with a 4.2 rating representing brand new flexible pavement and a PSI rating below 2.0 indicating a rough road in need of major rehabilitation.

Figures 6 through 11 show the PSI as a function of number of years in service for the north and south projects. Each figure is divided into two parts: untreated and lime-treated mixtures. The NDOT PMS measures the PSI at each milepost. Therefore, there are multiple PSI measurements for each project depending on the length of the project (i.e. a ten mile long project will have 10 PSI measurements). The PSI data are plotted in terms of the section average and lowest PSI throughout the section. Both measures need to be evaluated in order to assess the true performance of the mixtures; the average PSI reflects all the NDOT maintenance efforts while the lowest PSI of the section shows the occurrence of failures within the project. The performance of the pavement should be evaluated in terms of the change in PSI as a function of year and not in terms of the initial PSI level. For example, the data in figure 6 shows the average and low PSI values for the untreated and treated mixtures on I-15. The fact that the untreated mixtures had an initial PSI of 3.5 as compared to the initial PSI of 4.2 for the lime-treated mixtures should not indicate that the untreated mixtures are inferior to the lime-treated mixtures. As discussed earlier, the performance of these two mixtures should be evaluated in terms of the changes in the average PSI and low PSI values as a function of their years in service. An inspection of the data in figure 6 shows that the untreated mixture maintains a stable average PSI value but experiences a more frequent occurrence of low PSI values than the lime-treated mixture. This observation indicates that NDOT needed to conduct more maintenance activities on the untreated mixtures than on the lime-treated mixtures in order to keep the pavement sections at an acceptable level of serviceability (average PSI).

Based on the above discussion, evaluating the performance of the untreated versus lime-treated pavement sections will be accomplished using the following criteria:

1. Compare the change in the average PSI value;
2. Compare the occurrence of the low PSI values;
3. Compare the impact of the occurrence of the low PSI value on the average PSI value.

The principles behind criteria 1 and 2 have been discussed earlier. Criteria 3 has been introduced to assess whether the occurrence of a low PSI is an isolated event or if it is a predominant one. For example, if the occurrence of the low PSI value did not impact the average PSI then the low PSI value existed on an isolated milepost within the project and it does not represent the conditions of the majority of the project. However, if the occurrence of the low PSI value impacts the average PSI, then the low PSI value existed on the majority of the mileposts within the project. This concept is clearly identified in figure 9 (the second I-80 north project) where the occurrence of a low PSI value significantly impacted the average PSI for the untreated mixture while, in the case of the lime-treated mixture, the occurrence of a low PSI value did not impact the average PSI. This indicates that the low PSI value represents the conditions of the majority of the mileposts of the untreated mixtures while the low PSI value on the lime-treated mixtures represents only an isolated milepost within the entire project.

Table 28 summarizes the review of figures 6 through 11. The performance of the untreated and lime-treated mixtures are evaluated in terms of the three established criteria. The data in table 28 should be evaluated on the basis that a good-performing pavement section would have zero or little to moderate reduction in the average PSI, zero or little to moderate occurrence of low PSI, and an insignificant impact of the low PSI.

Evaluating the PMS data presented in Figures 6 through 11 and the summary presented in table 28, it can be concluded that the lime-treated mixtures performed better than the untreated mixtures under all three criteria and for all the evaluated projects. Based on these findings it can be concluded that lime treatment of HMA mixtures in Nevada resulted in better-performing HMA mixtures.

II.3 Impact of Lime on Pavement Life

The last step in evaluating the performance of lime in HMA mixtures is to quantify its impact on actual pavement life. In order to achieve this task, the data generated from evaluating field sections will be used. The PMS data will be used to verify the recommendations of the pavement life impact study.

The laboratory study evaluated the resilient modulus of field cores from lime-treated and untreated projects under multiple freeze-thaw cycling. This analysis uses the impact of freeze-thaw cycling on the Mr property to evaluate the corresponding reduction in the layer coefficient (a_1) used in the AASHTO Design Guide of Pavement Structures. The reduction in the a_1 is then translated into a reduction in the expected pavement life using the AASHTO pavement design approach. This analysis is based on the following three assumptions:

1. The sixth freeze-thaw cycle is selected to represent the critical stage for the damage of HMA mixtures. This assumption is supported by the data presented in figures 1 through 5 which show that the reduction in the Mr property flattens out after the sixth cycle.

2. The percent reduction in the Mr property is proportional to the percent reduction in the a_1 coefficient up to a certain critical level. This indicates that the percent reduction in the Mr property after the 6^{th} cycle will be used to estimate the reduction in the a_1 coefficient except in the cases where the HMA cores completely fail after

the 6^{th} cycle (Plumas-Greens-untreated, figure3). In these cases, the a_1 will be assigned a minimum value of 0.01.

3. The reduced Mr property exists over four month of the year (33% of the time). This indicates that a weighted a_1 coefficient should be used to represent the relative strength of the HMA layer.

Using the above assumptions along with the AASHTO design method for flexible pavements, the following procedure was devised:

1. Assume a typical pavement structure with the following properties:

HMA layer:	6" and a_1 (to be determined for each mix)
Gravel base layer:	12" and $a_2 = 0.1$
Borrow layer:	12" and $a_3 = 0.07$
Subgrade:	Mr = 10,000 psi

2. Use the sixth freeze-thaw cycle data to evaluate the reduced a_1 based on a normal a_1 value of 0.35 as recommended in the NDOT Pavement Structural Design and Policy Manual.

3. Use the reduced a_1 value to determine the weighted a_1 coefficient for the untreated and lime-treated sections.

4. Use the weighted a_1 values to determine the structural number (SN) for the untreated and lime-treated sections.

5. Use the SN values in the AASHTO Design Guide to evaluate the expected pavement life in terms of the equivalent single axle loads (ESAL) based on the following properties:

$PSI_{initial}$ =	4.2
$PSI_{terminal}$ =	2.5
Reliability=	90%
So =	0.45

6. Convert the reductions in ESALs into pavement life in years.

Table 29 summarizes the data generated from the above analysis. The step of converting the increase in ESALs into pavement life assumes that NDOT expects an eight-year life from untreated

HMA mixtures, and therefore, any percentage increase in the ESALs due to lime treatment is directly converted into increase in pavement life over the eight-years period. The data presented in table 29 show that the expected increase in pavement life due to lime treatment ranges between 1and 6 years. This recommendation can be checked by looking at the PMS data presented in figures 6 through 11. All these figures show that the untreated sections have experienced reductions in the PSI that are more significant than the lime-treated sections. Figure 7 shows that the untreated section is experiencing a continuous decrease in the PSI since construction while the lime-treated section held a steady PSI level. Figure 8 shows that a major rehabilition was needed on the untreated section after six years in service while the lime-treated section held a good level of PSI throughout. Figure 9 shows that the untreated section got on a downward trend after the 3rd year in service while the lime-treated section held up real well. Figures 10 and 11 both show that the untreated sections experienced a downward trend in PSI soon after construction while it is still too early to observe the corresponding lime-treated sections.

Based on the data generated from the AASHTO Design Guide analysis, and the trends shown by the PMS data, it can be safely assumed that lime treatment of Nevada's HMA mixture would increase the pavement life by an average of 3 years. This represents an average increase of 38% in the expected pavement life. The percent increase in pavement life of 38% compares very favorably with the percent increase in the cost of HMA mixtures of 12% ($4/ton) due to lime treatment.

III. EVALUATION OF LABORATORY MIXTURES

This task concentrated on evaluating the impact of lime treatment on the moisture sensitivity of laboratory-prepared mixtures. The experiment evaluated several methods of adding lime into HMA mixtures which were produced using two sources of aggregates. This section of the report summarizes the data developed through the laboratory evaluation program.

III.1 Materials

Two sources of aggregates were evaluated in this program: the Lockwood source in north-western Nevada and the Lone Mountain source in southern Nevada. The Lockwood source uses five stockpiles while the Lone Mountain source uses four stockpiles. Tables 30 and 31 summarize the gradations of the Lockwood and Lone Mountain stockpiles, respectively. The objective of the program was to evaluate a NDOT Type 2C mixture. Therefore, the Lockwood and Lone Mountain sources were each blended individually to create mixtures meeting the NDOT Type 2C specifications as shown in table 32. Figure 12 presents the gradations for the two sources along with the NDOT specifications. The properties of the coarse and fine portions of the blended aggregates from each source were evaluated and are summarized in table 33.

Three asphalt binders were used in the evaluation program: two binders were used with the Lockwood source; AC-20P and PG 64-34, and one binder was used with the Lone Mountain source; AC-30. The AC-20P is a polymer-modified binder commonly used in northern Nevada and the PG 64-34 binder is a performance-graded binder which meets the 98% reliability for north-western Nevada. The AC-30 is a neat asphalt binder commonly used in southern Nevada. Tables

34, 35, and 36 summarize the properties of the three binders used in this study which show that all binders meet their respective specification limits.

III.2 Lime Treatments

The main objective of this task is to evaluate the effectiveness of lime in reducing the moisture sensitivity of Nevada's HMA mixtures and to identify the most effective method of adding lime to HMA mixtures. Therefore, the experiment evaluated the following five methods of adding lime to HMA mixtures:

1. no lime is added (No Lime)
2. dry lime added to wet aggregate without marination (NDOT 0-hr)
3. dry lime added to wet aggregate with 48 hours marination (NDOT 48-hr)
4. lime slurry added to aggregate without marination (L. S. 0-hour)
5. lime slurry added to aggregate with 48 hours marination (L. S. 48-hour)

The abbreviations in the parenthesis will be used throughout the report to identify the lime treatments used.

III.3 Mix Designs

The NDOT Hveem design method for HMA mixtures was used to identify the optimum asphalt binder contents for all mixtures. A total of 15 mix designs were developed: (three combinations of aggregate source and asphalt binder) x (five lime treatments). Tables 37, 38, and 39 summarize the mix designs for the mixtures evaluated in this study. Table 40 summarizes the selected optimum asphalt binder contents using the NDOT Hveem mix design criteria.

III.4 Data Analysis

The laboratory program evaluated the following properties for each of the 15 mixtures.

- dry tensile strength at 77°F
- tensile strength at 77°F after one freeze-thaw cycle
- tensile strength at 77°F after 18 freeze-thaw cycles
- dry resilient modulus at 77°F
- resilient modulus at 77°F after one freeze-thaw cycle
- resilient modulus at 77°F after 6 freeze-thaw cycles
- resilient modulus at 77°F after 12 freeze-thaw cycles
- resilient modulus at 77°F after 18 freeze-thaw cycles

Tables 41 and 42 summarize the data generated from this experiment. Figures 13 through 24 compare the properties of the various mixtures. There are four figures (two sets of two figures) for each mixture: two figures presenting the tensile strength property and two figures presenting the resilient modulus property. The first figure of each set of two shows the graphical comparison of the property (TS or Mr) along with the pooled standard deviation and standard error and the second figure of each set presents the statistical comparison of the various treatments. The graphical presentations display the average property (TS or Mr) and a vertical bar showing the range of the average plus one least significant difference (LSD). The range is used to statistically compare any two cases. If the range of one case overlaps the average of the other case, then the two cases are statistically the same (S), otherwise the two cases are statistically different (D).

By looking at the data in each of these figures, the reader should be able to compare the tensile strength and resilient modulus properties for the three types of mixtures using the five types of lime treatments and various methods of moisture conditioning. The graphical presentations show the physical comparisons while the statistical analyses indicate whether any set of two mixtures have similar (S) or different (D) properties when conditioned using the same process. For example, in figure 14 looking across from the unconditioned no lime under the no lime with 1 F-T cycle, the reader would find "D" which indicates the tensile strength of the no lime mixture at the unconditioned stage is statistically different than the tensile strength of the no lime mixture after one cycle of freeze-thaw conditioning. On the other hand, looking across from the unconditioned NDOT 48-hr under the NDOT 48-hr with 1 F-T cycle, the reader would find an "S" which indicates the tensile strength of the NDOT 48-hr at the unconditioned stage is statistically the same as the tensile strength of the NDOT 48-hr after one cycle of freeze-thaw conditioning.

The above examples explain the one part of the statistical figures which compares the similar mixtures as they are subjected to different conditioning processes. The other part of the statistical figures compares the properties of different mixtures as they are subjected to similar conditioning processes. For example, in figure 14 looking across from the unconditioned no lime under the unconditioned NDOT 0-hr mixture, the reader would find "S" which indicates the tensile properties of the unconditioned no lime and unconditioned NDOT 0-hr lime-treated mixtures are statistically the same.

Statistical analyses are used to differentiate among the various mixtures and conditioning processes because such analyses take into consideration the variability of the test method when assessing the similarity in the measured properties. The objective of presenting figures 13 through 24 is to provide the engineer with a quick reference to evaluate the impact of lime additive and method of application on the moisture sensitivity of typical Nevada's HMA mixtures. For example, if the engineer would like to assess the potential benefit of lime on the tensile strength of HMA mixtures in the northern part of the state using a PG graded binder, then figures 17 and 18 may be consulted. Figure 17 shows the graphical comparison of the impact of lime on the tensile strength property under the various conditioning processes and application methods while figure 18 shows the statistical comparison of the same data. In this case the engineer would make the following observations:

- at the unconditioned stage, all the mixtures have the same TS properties.
- after one freeze-thaw cycle the no-lime mixture exhibits lower TS while all the lime- treated mixtures, except the L.S. 0-hr, maintained the same TS properties;
- after 18 cycles of freeze-thaw, all mixtures exhibit lower TS properties than the unconditioned stage;
- after one freeze-thaw cycle, all the lime-treated mixtures exhibit the same TS properties which are higher than the TS property for the no-lime mixture, except for the L.S. 48-hr mixture;
- after 18 cycles of freeze-thaw, all the lime-treated mixtures had similar TS properties which are higher than the no-lime mixtures.

Evaluating the data presented in figures 13-24, in light of the study objective to assess the effectiveness of lime in improving the moisture resistance of Nevada's HMA mixtures using various application techniques, the following summaries were prepared.

Impact of Lime Treatment

The objective of this analysis is to assess the impact of adding lime on the TS and Mr properties of the NDOT mixtures regardless of the method of application. This analysis will try to answer the question of whether lime is effective in reducing the moisture sensitivity of Nevada's mixtures irrespective of which application method is used. Tables 43, 44 and 45 summarizes the statistically-based comparisons of the untreated versus lime-treated mixtures. The data presented in these tables show that, in the majority of the cases, the untreated mixtures had similar TS and

Mr properties at the unconditioned stage but exhibit lower TS and Mr properties after the 1 cycle or 18 cycles of freeze-thaw conditioning. The following conclusions can be drawn:

TS Property Comparison

- In 12 out of 12 cases of the unconditioned stage, the untreated mixtures had the same TS property as the lime-treated mixtures.
- In 11 out of 12 cases of the 1 freeze-thaw cycle conditioning stage, the untreated mixtures had lower TS property than the lime-treated mixtures. In 1 out of 12 cases, the untreated mixtures had the same TS property as the lime-treated mixtures.
- In 12 out of 12 cases of the 18 freeze-thaw cycles conditioning stage, the untreated mixtures had lower TS property than the lime-treated mixtures.

Mr Property Comparison

- In 11 out of 12 cases of the unconditioned stage, the untreated mixtures had the same Mr property as the lime-treated mixtures. In 1 out of 12 cases, the untreated mixtures had lower Mr property than the lime-treated mixtures.
- In 10 out of 12 cases of the 1 freeze-thaw cycle conditioning stage, the untreated mixtures had lower Mr property than the lime-treated mixtures. In 2 out of 12 cases, the untreated mixtures had the same Mr property as the lime-treated mixtures.
- In 12 out of 12 cases of the 18 freeze-thaw cycles conditioning stage, the untreated mixtures had lower Mr property than the lime-treated mixtures.

In summary, the laboratory data show that at the unconditioned stage, the untreated mixtures exhibit TS and Mr properties which are similar to the lime-treated properties, however, when the mixtures are conditioned either with 1 or 18 freeze-thaw cycles, the TS and Mr properties of the unconditioned mixtures become significantly lower than the properties of the lime-treated mixtures. Based on these data, it can be concluded that lime treatment of Nevada's aggregates is highly effective in reducing the moisture sensitivity of Nevada's mixtures.

Impact of Lime Application Method

The objective of this analysis is to assess the impact of lime application method on the TS and Mr properties of the NDOT's HMA mixtures. This analysis will try to answer the question of whether the method of applying lime to the HMA mixture makes a significant difference in reducing the moisture sensitivity of Nevada's mixtures. The data presented in Figures 13-24 will be used to assess the impact of the method of lime application. Figures 25, 26, and 27 show the graphical comparison among the Mr properties at the various freeze-thaw cycles for the three HMA mixtures. The data in these figures show that there is a clear difference between the Mr properties of the untreated mixtures and the lime-treated mixtures. However, when it comes to comparing the Mr properties among the various methods of lime application, statistical analyses are needed to identify the significant differences among the various methods.

Table 46 summarizes the results of the statistically-based comparisons among the various methods of lime application. The data show that in 85 out of 108 possible cases, the method of lime application did not make a significant difference in the moisture sensitivity of Nevada's HMA mixtures. In the 22 cases that the method of lime application made a significant difference, in the majority of these cases, the NDOT 48-hr method showed higher properties than the other methods. In summary, this analysis shows that, 80% of the time, the method of lime application does not make a significant impact in the moisture sensitivity of Nevada's HMA mixtures as measured by the TS and Mr properties under 1 and 18 freeze-thaw cycles.

IV. SUMMARY AND RECOMMENDATIONS

The objectives of this study were to assess the effectiveness of lime in reducing the moisture sensitivity of NDOT's HMA mixtures. In order to meet these objectives, an experimental program was conducted which covered both field and laboratory evaluations. The field evaluation consisted of laboratory testing of field samples from untreated and lime-treated in-service projects and the analysis of pavement performance data as collected through the NDOT PMS. The laboratory evaluation consisted of laboratory testing of laboratory-prepared mixtures using different sources of aggregates and binders and treated with various lime application methods.

The overall program evaluated samples from 10 field projects, analyzed PMS data for 12 in-service projects, and conducted laboratory preparation and testing for 15 HMA mixtures. The program assessed the impact of lime treatment on field projects and laboratory mixtures that are typically used by NDOT in the southern and north-western part of the state.

Based on the three components of the overall evaluation program, the following recommendations can be made:

- The properties of untreated and lime-treated mixtures from field projects in the southern and north-western parts of Nevada indicated that lime treatment of Nevada's aggregates significantly improves the moisture sensitivity of HMA mixtures. The study showed that lime-treated HMA mixtures become significantly more resistant to multiple freeze-thaw than the untreated mixtures. Lime-treated HMA mixtures showed excellent properties in the wheel path and in the between wheel path locations which indicates that lime treatment helps HMA mixtures in resisting the combined action of environmental and traffic stresses. The untreated mixtures experienced very severe damage when subjected to multiple freeze-thaw cycling which explains their poor performance in the north-western part of the state (Reno area) since such conditioning simulates the environmental conditions of this part of the state. All of the lime-treated mixtures survived the damage induced by multiple freeze-thaw cycling which would indicate good long term pavement performance;

- The long term pavement performance data of the 12 in-service pavements clearly showed the superior performance of the lime-treated HMA mixtures. The present serviceability index (PSI) was used as the performance indicator for the untreated and lime-treated HMA pavements. The effectiveness of lime treatment was evaluated by comparing the performance of projects constructed on the same route which provided similar environmental and traffic conditions for both untreated and lime-treated mixtures. The long term pavement performance data indicated that under similar environmental and traffic conditions, the lime-treated mixtures provided better performing pavements with less requirements for maintenance and rehabilitation activities. In summary, NDOT was able to maintain a better average PSI on pavement sections built with lime-treated mixtures with less maintenance activities than for untreated HMA mixtures. Also, the pavements constructed with untreated HMA mixtures showed a wider-spread reduction in PSI than the lime-treated HMA mixtures (i.e. lower PSI over more locations within the project);

- The analysis of the impact of lime on pavement life indicated that lime treatment extends the performance life of HMA pavements by an average of 3 years. This represents an average increase of 38% in the expected pavement life. The percent increase in pavement life of 38% compares very favorably with the percent increase in the cost of HMA mixtures of 12% ($4/ton) due to lime treatment. Therefore, NDOT's policy requiring lime treatment of HMA mixtures has been very effective based on both the performance and life cycle cost of flexible pavements in the state of Nevada;

- The portion of the laboratory study dealing with the evaluation of lime treatments of Nevada's aggregates indicated that the addition of lime improved the tensile strength and resilient modulus properties of the HMA mixtures after single and multiple freeze-thaw cycling. The untreated mixtures showed drastic reductions in the tensile strength and resilient modulus properties after 1 freeze-thaw cycle and, in some cases, complete disintegration after multiple freeze-thaw cycling. In summary, this part of the laboratory experiment showed that adding lime to Nevada's aggregate is very effective in reducing the moisture sensitivity of HMA mixtures regardless of the method of lime application;

- The portion of the laboratory study dealing with the evaluation of method of lime application indicated that all four methods of application can produce similar results 80 % of the time. In the other 20% of the time, the NDOT process for 48-hours marination showed to be the most effective. The data generated in this laboratory experiment showed that the addition of lime to wet aggregate without marination (NDOT 0-hr) can be as effective as the addition of lime to wet aggregate with 48 hours marination and the use of lime slurry with and without marination. However, it should be recognized that these observations were all made under ideal laboratory conditions where the lime is always added to perfectly-wetted aggregates and thoroughly mixed to ensure uniform distribution and coating. Such ideal conditions are impossible to maintain under field applications especially when dealing with the addition of lime to wet aggregate without marination. Therefore, based on the data generated in this experiment, the addition of lime to wet aggregates with 48 hours marination (NDOT 48-hr) would be the most desirable method of lime application because it provides effective results and it is less susceptible to field problems than the addition of lime to wet aggregates without marination. It is recommended that NDOT continue requiring the addition of lime to wet aggregates with 48 hours marination

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Table 1. Summary of the pavement sections evaluated under the laboratory program.

State Region	Project Location	Agency	Condition	Aggregate Source	Year of Construction
South: Las Vegas Area	Pecos Rd: Russell to Rawhide	Clark County	Untreated	Lone Mountain	1993
	Russell Rd: Valley View to Procyon	Clark County	Untreated	Lone Mountain	1994
	Sahara Av: Links to Tee	Clark County	Untreated	Hendersen	1996
	US 95: CL MP76.00 to MP81.27 (2510)	NDOT	Lime-treated	Lone Mountain	1993
	Sunset Rd: Eastern to Las Vegas Blvd.	NDOT	Lime-treated	Lone Mountain	1994
	SR 599: CL MP5.02 to MP12.56 (2588)	NDOT	Lime-treated	Lone Mountain	1994
North: Reno Area	Lakeside Dr: Moana to McCarran	RTC	Untreated	Helms	1986
	McCarran Blvd: Plumas to Greensboro	RTC	Untreated	Dayton	1987
	McCarran Blvd: Greensboro to Skyline	RTC	Untreated	Dayton	1988
	SR516: CC MP0.44 to MP2.45 (2261)	NDOT	Lime-treated	Dayton	1988

Table 2. Summary of properties of HMA mixtures from the Pecos Road project.

Cores from the WP Location										
	Replicates							Avg	STD	CV
Air Voids (%)	4.5	4.4	4.6					4.5	0.1	2
Mr dry @ 77°F, ksi	1956	1764	1953					1891	110	6
Mr wet @ 77°F, ksi	678	650	660					663	14	2
Cores from the BWP Location										
	Replicates							**Avg**	**STD**	**CV**
Air Voids (%)	5.3	4.4	5.1	4.4	3.3	4.0	3.2	4.2	0.8	20
Mr dry @ 77°F, ksi	1768	1960	1727	1797	1738	1809	1777	1797	78	4
Mr wet @ 77°F, ksi	658	651	656					655	4	1
TS Dry @77°F, psi				293	290	295	292	293	2	1
TS wet @ 77°F, psi	165		162					164	2	1

Table 3. Summary of the multiple freeze-thaw properties of HMA mixtures from the Pecos Road project.

Number of Freeze-Thaw Cycles	**Air Voids (%)**			
	4.4	4.5	4.4	4.6
	Mr @ 77°F (ksi)			
0	1960	1956	1764	1953
1	651	678	650	660
6	103	109	100	105
8	70	63	61	72
12	failed at 11th cycle	failed at 9th cycle	failed at 9th cycle	failed at 11th cycle

Table 4. Summary of properties of HMA mixtures from the Russell Road project.

Cores from the WP Location									
	Replicates						Avg	STD	CV
Air Voids (%)	7.7	7.7	7.4	7.3			7.5	0.2	3
Mr dry @ 77°F, ksi	1845	1927	1872	1939			1896	45	2
Mr wet @ 77°F, ksi	1503	1544	1521	1500			1517	20	1
TS wet @ 77°F, psi	219	221	220				220	1	1
Cores from the BWP Location									
	Replicates						Avg	STD	CV
Air Voids (%)	7.3	6.2	6.4	7.9	8.0	7.2	7.2	0.7	10
Mr dry @ 77°F, ksi	1863	1837	1917	1845	1892	1930	1881	38	2
Mr wet @ 77°F, ksi		1218	1394	1502		1434	1387	121	9
TS Dry @77°F, psi	254				267		261	9	3
TS wet @ 77°F, psi				216			216	na	na

Table 5. Summary of the multiple freeze-thaw properties of HMA mixtures from the Russell Road project.

Number of Freeze-Thaw Cycles	**Air Voids (%)**		
	6.2	7.3	7.2
	Mr @ 77°F (ksi)		
0	1837	1940	1930
1	1218	1500	1434
6	258	290	261
8	171	187	179
12	98	104	failed at 10th cycle
18	failed at 16th cycle	failed at 16th cycle	

Table 6. Summary of properties of HMA mixtures from the US 95 project (NDOT #2510).

Cores from the WP Location												
	Replicates									Avg	STD	CV
Air Voids (%)	3.5	3.4	3.7	5.0	4.9	4.8				4.2	0.8	19
Mr dry @ 77°F, ksi	1232	1124	1091	1127	1056	1111				1124	59	5
Mr wet @ 77°F, ksi	1017	1004	1016	1027						1016	9	1
TS dry @ 77°F, psi					183	185				184	1	1
TS wet @ 77°F, psi	158	154								156	3	2
Cores from the BWP Location												
	Replicates									Avg	STD	CV
Air Voids (%)	5.4	5.9	3.5	3.7	4.2	4.1	5.0	4.2	4.5	4.5	0.8	18
Mr dry @ 77°F, ksi	1158	1171	1198	1134	1116	1017	1011	1145	1173	1125	67	6
Mr wet @ 77°F, ksi	1060	1086	1034				901	907	965	992	79	8
TS Dry @77°F, psi				225	208	190				208	18	9
TS wet @ 77°F, psi	166	167	172							168	3	2

Table 7. Summary of the multiple freeze-thaw properties of HMA mixtures from the US 95 project (NDOT #2510).

Number of freeze-Thaw Cycles	**Air Voids (%)**				
	3.7	5.0	4.2	4.5	5.0
	Mr @ 77°F (ksi)				
0	1091	1011	1145	1173	1127
1	1016	901	907	965	1027
6	503	430	436	453	490
8	350	221	233	251	341
12	126	88	92	105	118
18	68	failed at 15th cycle	failed at 15th cycle	failed at 15th cycle	52

Table 8. Summary of properties of HMA mixtures from the Sunset Road project.

Cores from the WP Location											
	Replicates								Avg	STD	CV
Air Voids (%)	6.3	6.6	5.4	6.6	5.9	4.8	6.3	6.6	6.1	0.7	11
Mr dry @ 77°F, ksi	1034	1141	1035	988	1047	1026	1208	1162	1080	79	7
Mr wet @ 77°F, ksi	618	587	619	572	632		586	570	598	25	4
TS dry @ 77°F, psi						168			168	na	na
TS wet @ 77°F, psi		129		127			128	125	127	2	2
Cores from the BWP Location											
	Replicates								Avg	STD	CV
Air Voids (%)	4.3	5.0	5.9	4.5					4.9	0.7	14
Mr dry @ 77°F, ksi	1031	1035	1045	1016					1032	12	1
Mr wet @ 77°F, ksi			625						625	na	na
TS Dry @77°F, psi	173	175		151					166	13	8

Table 9. Summary of the multiple freeze-thaw properties of HMA mixtures from the Sunset Road project.

Number of Freeze-Thaw Cycles	**Air Voids (%)**			
	6.3	5.4	5.9	5.9
	Mr @ 77°F (ksi)			
0	1034	1035	1047	1045
1	618	619	632	625
6	189	191	197	193
8	115	128	132	132
12	73	76	81	78
18	49	51	57	54

Table 10. Summary of properties of HMA mixtures from the SR 599 project (NDOT #2588).

Cores from the WP Location												
	Replicates									Avg	STD	CV
Air Voids (%)	5.8	5.7	5.7	4.1	4.2	4.0	3.4	3.4	3.9	4.5	1.0	22
Mr dry @ 77°F, ksi	1292	1327	1324	1072	977	1010	1166	1114	1075	1151	134	12
Mr wet @ 77°F, ksi	647	664		610	491	598	633	627	619	611	53	9
TS dry @ 77°F, psi			252							252	na	na
TS wet @ 77°F, psi				148	141	145	152		151	148	5	3
Cores from the BWP Location												
	Replicates									Avg	STD	CV
Air Voids (%)	2.9	2.9	3.0	2.8	3.0	3.3	4.4			3.2	0.6	19
Mr dry @ 77°F, ksi	692	753	793	966	897	835	888			832	94	11
Mr wet @ 77°F, ksi	355	371	393	500	480		471			428	63	15
TS Dry @77°F, psi						203				203	na	na
TS wet @ 77°F, psi	112	120	126	139	129		127			126	9	7

Table 11. Summary of the multiple freeze-thaw properties of HMA mixtures from the SR 599 project (NDOT #2588).

Number of Freeze-Thaw Cycles	Air Voids (%)		
	5.8	5.7	3.4
	Mr @ 77°F (ksi)		
0	1292	1327	1114
1	647	665	627
6	32	365	317
8	23	264	228
12	158	161	149
18	86	91	83

Table 12. Summary of properties of HMA mixtures from the McCarran Boulevard, Plumas-Greensboro project.

Cores from the WP Location												
	Replicates									Avg	STD	CV
Air Voids (%)	5.6	6.0	6.2	5.9	5.9	6.8				6.1	0.4	7
Mr dry @ 77°F, ksi	979	995	978	948	917	967				964	28	3
Mr wet @ 77°F, ksi	720	736	714	758	748	748				737	17	2
TS wet @ 77°F, psi	168	174	167	178	174	174				173	4	2
Cores from the BWP Location												
	Replicates									**Avg**	**STD**	**CV**
Air Voids (%)	8.1	8.2	8.3	8.9	9.2	8.5	9.2	8.9	9.0	8.7	0.4	5
Mr dry @ 77°F, ksi	926	956	908	927	938	942	957	969	980	945	31	3
Mr wet @ 77°F, ksi				711	717	719	729	742	756	729	17	2
TS Dry @77°F, psi	254	251	238							248	9	4
TS wet @ 77°F, psi				141	142	143				142	1	1

Table 13. Summary of the multiple freeze-thaw properties of HMA mixtures from the McCarran Boulevard, Plumas-Greensboro project.

Number of Freeze-Thaw Cycles	**Air Voids (%)**		
	9.2	8.9	9.0
	Mr @ 77°F (ksi)		
0	957	969	980
1	729	742	756
6	failed at 5th cycle	failed at 5th cycle	failed at 5th cycle
8			
12			
18			

Table 14. Summary of properties of HMA mixtures from the McCarran Boulevard, Greensboro-Skyline project.

Cores from the WP Location												
	Replicates									Avg	STD	CV
Air Voids (%)	6.0	6.6	6.7	6.4	6.5	7.2				6.6	0.4	6
Mr dry @ 77°F, ksi	924	945	943	959	956	958				948	13	1
Mr wet @ 77°F, ksi	856	843	858	794	787	783				820	36	4
TS wet @ 77°F, psi	185	187	188	149	145	144				166	22	13
Cores from the BWP Location												
	Replicates									Avg	STD	CV
Air Voids (%)	8.4	8.5	8.6	8.7	8.3	8.4	8.7	8.1	7.8	8.4	0.3	4
Mr dry @ 77°F, ksi	856	880	854	943	940	938	925	915	896	905	35	4
Mr wet @ 77°F, ksi				825	818	811	625	607	593	714	115	16
TS Dry @77°F, psi	220	228	219							222	5	2
TS wet @ 77°F, psi				142	242	240				141	1	1

Table 15. Summary of the multiple freeze-thaw properties of HMA mixtures from the McCarran Boulevard, Greensboro-Skyline project.

Number of Freeze-Thaw Cycles	**Air Voids (%)**		
	8.7	8.1	7.8
	Mr @ 77°F (ksi)		
0	925	915	896
1	625	607	593
6	failed at 5th cycle	failed at 5th cycle	failed at 5th cycle
8			
12			
18			

Table 16. Summary of properties of HMA mixtures from the SR 516 project (NDOT #2261).

Cores from the WP Location												
	Replicates									Avg	STD	CV
Air Voids (%)	5.3	6.1	6.5	6.2	5.9	5.9	5.5	6.1	5.2	5.9	0.4	7
Mr dry @ 77°F, ksi	1762	1625	1723	1349	1318	1369	1749	1574	1249	1524	204	13
Mr wet @ 77°F, ksi	1123	1006	1071	862			1089	978	813	992	117	12
TS dry @ 77°F, psi					313	335				324	16	5
TS wet @ 77°F, psi				205			223	207	190	206	14	7
Cores from the BWP Location												
	Replicates									Avg	STD	CV
Air Voids (%)	5.9	5.3	5.6	5.3	5.9	5.6	5.7	5.5	5.9	5.6	0.2	4
Mr dry @ 77°F, ksi	1343	1633	1541	1578	1593	1702	1166	1519	1607	1520	166	11
Mr wet @ 77°F, ksi		1107	1041	1080	1093	1104	765	965	1000	1019	115	11
TS Dry @77°F, psi	322									322	na	na
TS wet @ 77°F, psi		214	209	208	210	220	181	207	211	208	11	5

Table 17. Summary of the multiple freeze-thaw properties of HMA mixtures from the SR 516 project (NDOT #2261).

Number of Freeze-Thaw Cycles	**Air Voids (%)**		
	5.3	6.1	6.5
	Mr @ 77°F (ksi)		
0	1762	1625	1723
1	1123	1006	1071
6	409	364	376
8	267	220	243
12	94	79	84
18	failed at 13th cycle	failed at 13th cycle	failed at 13th cycle

Table 18. Comparison of properties from the WP and BWP locations.

State Region	Project Location	Significant Difference Between WP and BWP Cores	
		Based on Dry Mr at 25°C	Based on wet Mr at 25°C
South: Las Vegas Area	Pecos Rd: Russell to Rawhide	No	No
	Russell Rd: Valley View to Procyon	No	No
	US95: CL MP76.00 to MP81.27	No	No
	Sunset Rd: Eastern to Las Vegas Blvd.	No	No
	SR599: CL MP5.02 to MP12.56	Yes	Yes
North: Reno Area	McCarran Blvd: Plumas to Greensboro	No	No
	McCarran Blvd: Greensboro to Skyline	No	No
	SR516: CC MP0.44 to MP2.45	No	No

Table 19. Comparison of untreated (Pecos Road) and lime-treated mixtures (US 95).

Property	Pecos Road Project	US 95 Project
Mr dry @ 77°F, ksi	1844	1125
Mr wet @ 77°F, ksi	659	1004
TS dry @ 77°F, psi	293	196
TS wet @77°F, psi	164	162

Table 20. Comparison of untreated (Russell Road) and lime-treated mixtures (Sunset Road and SR 599).

Property	Russell Road Project	Sunset Road Project	SR 599 Project
Mr dry @ 77°F, ksi	1889	1056	1151
Mr wet @ 77°F, ksi	1452	612	611
TS dry @ 77°F, psi	261	167	252
TS wet @77°F, psi	218	127	148

Table 21. Comparison of untreated (McCarran) and lime-treated mixtures (SR 516).

Property	McCarran: Plumas-Greensboro	McCarran: Greensboro-Skyline	SR 516 Project
Mr dry @ 77°F, ksi	955	927	1522
Mr wet @ 77°F, ksi	733	767	1006
TS dry @ 77°F, psi	248	222	223
TS wet @77°F, psi	158	154	207

Table 22. Summary of properties of HMA mixtures from the Sahara Avenue project.

Cores from the WP Location											
	Replicates								Avg	STD	CV
Air Voids (%)	3.3	4.6	3.5	4.7					4	0.7	18
Mr dry @ 77°F, ksi	1162	1169	1199	1142					1168	24	2
Mr wet @ 77°F, ksi		1109	1003	1098					1070	58	5
TS dry @ 77°F, psi	288								288	na	na
TS wet @ 77°F, psi			251						251	na	na
Cores from the BWP Location											
	Replicates								Avg	STD	CV
Air Voids (%)	3.8	4.8	3.1	4.4	2.4	3.7	2.3	3.8	3.5	0.9	26
Mr dry @ 77°F, ksi	1199	1178	1190	1186	1179	1204	1194	1146	1185	18	2
Mr wet @ 77°F, ksi	1012	1119		1003		1023		1020	1035	47	5
TS Dry @77°F, psi			291		289		291		290	1	0
TS Wet @77°F, psi	253			250		257			253	4	2

Table 23. Summary of the multiple freeze-thaw properties of HMA mixtures from the Sahara Avenue project.

Number of Freeze-Thaw Cycles	**Air Voids (%)**			
	4.6	4.8	4.7	3.8
	Mr @ 77°F (ksi)			
0	1169	1178	1142	1146
1	1109	1119	1098	1020
6	350	191	347	341
8	192	failed at 7th cycle	214	206
12	failed at 10th cycle		failed at 10th cycle	failed at 10th cycle
18				

Table 24. Summary of properties of HMA mixtures from the Lakeside Drive project.

Cores from the WP Location									
	Replicates						Avg	STD	CV
Air Voids (%)	4.0	4.2	4.0	6.4	6.6	6.1	5.2	1.3	25
Mr dry @ 77°F, ksi	1033	1052	1087	968	957	949	1008	57	6
Mr wet @ 77°F, ksi	795	803	809	663	647	643	727	83	11
TS wet @ 77°F, psi	163	164	168	126	124	121	144	23	16
Cores from the BWP Location									
	Replicates						**Avg**	**STD**	**CV**
Air Voids (%)	6.0	6.3	6.1	5.9	6.2	5.9	6.1	0.2	3
Mr dry @ 77°F, ksi	794	787	793	783	772	765	782	12	2
Mr wet @ 77°F, ksi				629	615	624	623	7	11
TS Dry @77°F, psi	231	201	214				215	15	7
TS Wet @77°F, psi				131	129	131	130	1	1

Table 25. Summary of the multiple freeze-thaw properties of HMA mixtures from the Lakeside Drive project.

Number of Freeze-Thaw Cycles	**Air Voids (%)**		
	5.9	6.0	6.7
	Mr @ 77°F (ksi)		
0	796	791	798
1	624	625	640
6	74	75	75
8	failed at 7th cycle	failed at 7th cycle	failed at 7th cycle
12			
18			

Table 26. Comparison of properties from the WP and BWP locations.

State Region	**Project Location**	**Significant Difference Between WP and BWP Cores**	
		Based on Dry Mr at 25°C	**Based on wet Mr at 25°C**
South: Las Vegas Area	Sahara Av.: Links to Tee	No	No

North:Reno Area	Lakeside Dr: Moana to McCarran	Yes	Yes

Table 27. Summary of projects evaluated based on NDOT PMS data.

State Region	Route	County	Mixture	Mileposts	Year of Construction
South: Las Vegas Area	I-15	CL	Untreated	0.00 - 9.20	1984
	I-15	CL	Lime-treated	0.00 - 16.35	1992
	US-95	CL	Untreated	19.00 - 26.00	1986
	US-95	CL	Lime-treated	19.00 - 26.00	1996
North: Reno Area	I-80	WA	Untreated	0.00 - 4.46	1983
	I-80	WA	Lime-treated	0.00 - 6.30	1990
	I-80	WA	Untreated	4.46 - 12.49	1984
	I-80	WA	Lime-treated	0.00 - 12.47	1994
	US-395	WA	Untreated	19.57 - 22.08	1983
	US-395	WA	Lime-treated	20.33 - 23.31	1996
	SR-663	WA	Untreated	0.00 - 2.48	1983
	SR-663	WA	Lime-treated	0.00 - 2.46	1996

Table 28. Summary of PSI evaluations.

State Region	Route	County	Mixture	Mileposts	Year of Const.	Reduction In Average PSI	Occurrence of Low PSI	Impact of Low PSI
South: Las Vegas Area	I-15	CL	Untreated	0.00 - 9.20	1984	Moderate (after 4th year)	frequent	insignificant
	I-15	CL	Lime-treated	0.00 - 16.35	1992	none	none	insignificant
	US-95	CL	Untreated	19.00 - 26.00	1986	Severe	frequent	significant
	US-95	CL	Lime-treated	19.00 - 26.00	1996	none	infrequent	insignificant
North: Reno Area	I-80	WA	Untreated	0.00 - 4.46	1983	Severe (years 3, 5, 6)	frequent	significant
	I-80	WA	Lime-treated	0.00 - 6.30	1990	Moderate (years 3 and 6)	moderate	insignificant
	I-80	WA	Untreated	4.46 - 12.49	1984	Moderate (years 2 and 5)	frequent	significant
	I-80	WA	Lime-treated	0.00 - 12.47	1994	none	frequent	insignificant
	US-395	WA	Untreated	19.57 - 22.08	1983	Severe (years 3, 4, 6, 7)	frequent	significant
	US-395	WA	Lime-treated	20.33 - 23.31	1996	none	moderate	insignificant
	SR-663	WA	Untreated	0.00 - 2.48	1983	Severe (years 2, 6,7)	frequent	significant
	SR-663	WA	Lime-treated	0.00 - 2.46	1996	none	moderate	insignificant

Table 29. Impact of lime treatment on pavement life based on AASHTO Design Guide.

Project	Uncond. Mr (ksi)	6th Cycle Mr (ksi)	Reduced a_1	Weighted a_1	SN	ESALs	Increase in ESALs (%)	Increase in Pav. Life (yr)
Pecos-untreated	1900	104	0.02	0.24	3.44	1,850,000		
US 95-treated	1100	460	0.15	0.28	3.74	3,120,000	70	6**
Russell-untreated	1900	270	0.05	0.25	3.54	2,210,000		
Sunset-treated	1050	193	0.07	0.26	3.60	2,415,000	14*	1
SR 599-treated	1250	345	0.10	0.27	3.64	2,600,000		
Plumas-Greens-untreated	970	0	0.01	0.23	3.44	1,850,000		
Greens-Skyline-untreated	910	0	0.01	0.23	3.44	1,850,000		
SR 516-treated	1700	383	0.08	0.26	3.64	2,600,000	40	3

* Average percent increase in ESALs for the two lime-treated projects as compared to the untreated project.

** Increase in pavement life is based on average of 8-year life for untreated projects.

Table 30. Gradation of the Lockwood stockpile aggregates.

Sieve Size	1" by 1/2" Stockpile	1/2" Stockpile	3/8" Stockpile	Rock Dust	Blend Sand
1"	100				
3/4"	57.9				
1/2"	12.8	100	100		
3/8"	4.1	48.4	99.8	100	
#4	0.5	0.7	23.7	97.3	100
#8	0.4	0.5	1.6	67.3	99.3
#16	0.4	0.5	0.8	43.4	96.4
#30	0.3	0.4	0.7	29.6	79.6
#50	0.3	0.4	0.6	21.1	35.4
#100	0.3	0.4	0.5	16.6	8.5
#200	0.3	0.3	0.4	13.4	1.9

Table 31. Gradation of the Lone Mountain stockpile aggregates.

Sieve Size	1" by 1/2" Stockpile	1/2" Stockpile	Crusher Fines	Washed Sand
1"	100			
3/4"	71.3	100		
1/2"	7.3	99.8		
3/8"	1.5	86.3	100	100
#4	1.0	28.5	98.9	99.9
#8	0.9	6.0	72.2	90.8
#16	0.9	2.9	47.4	59.8
#30	0.8	2.3	32.5	31.8
#50	0.8	2.0	23.3	16.2
#100	0.7	1.8	18.0	7.2
#200	0.5	1.5	11.8	1.8

Table 32. Gradation of the blended aggregates for NDOT Type 2C mix.

Sieve Size	Lockwood Mixture Blend	Lone Mountain Mixture Blend	NDOT Specifications Type 2c
1"	100.0	100.0	100
3/4"	88.2	91.5	88-95
1/2"	75.6	77.5	70-85
3/8"	62.8	69.0	60-78
#4	44.5	51.5	43-60
#8	32.5	39.5	
#10			30-44
#16	24.2	28.5	
#30	18.0	20.5	
#40			12-22
#50	12.0	14.0	
#100	7.5	8.5	
#200	4.8	5.0	3-8

Table 33. Properties of the blended aggregates.

Property	Lockwood Aggregate		Lone Mountain Agg.	
	Material Passing #4	Material Retained #4	Material Passing #4	Material Retained #4
Bulk Specific Gravity (Dry)	2.708	2.603	2.761	2.799
Bulk Specific Gravity (SSD)	2.794	2.659	2.805	2.811
Apparent Specific Gravity	2.962	2.755	2.890	2.833
Absorption (%)	3.17	2.12	1.63	0.435

Table 34. Properties of the AC-20P viscosity-graded asphalt binder.

Test Performed On Original Binder	AC-20P	NDOT SPEC
Viscosity 60 C 300mm Hg Pa.s	210+	210 Min.
Viscosity 135 C mm^2/s	488	475-3000 mm^2/s
Flash Point COC Degrees C	268	Min. 232 C
Ductility 4C (5cm/min) cm	65	Min. 50 C
Toughness Nm	18.5	Min. 12.43 Nm
Tenacity Nm	16.5	Min. 8.47 Nm
Test Performed On Residue after RTFO		
Viscosity 60 C 300mm Hg Pa.s	429	Min. 300 Pa.s
Ductility 4C (5cm/min) cm	43	Min. 25 cm
Loss on Heating %	0.30	Max 0.5%

Table 35. Properties of the PG 64-34 performance-graded asphalt binder.

		SUPERPAVE PG-Grade
Contract Number	NDOT	
AC Sample Number	KOCK	
Asphalt Type	Polymer Modified	PG 64-34
Mass Loss, %	0.455	
Brookfield Vis., Pas	1.75	
Flash Pt., C	296	
Limiting Temp. for Tmax, C	69.3	
Limiting Temp. for Tint, C	8.1	
Limiting Temp. for Tmin, C	-27.9	

DSR-Original						DSR-RTFOT					
Temp, C	Plate Diam., mm	Strain, %	G*, KPa	Phase angle δ	G*/sinδ kPa	Temp, C	Plate Diam., mm	Strain, %	G*, KPa	Phase angle δ	G*/sinδ kPa
70	25	12	1.149	60.68	1.3	70	25	10	1.806	59.32	2.1
64	25	12	1.764	60.88	2.0	64	25	10	2.751	58.07	3.2
58	25	12	2.826	61.08	3.2	58	25	10	4.378	58.02	5.2
52	25	12	4.641	61.15	5.3	52	25	10	7.196	57.79	8.5

DSR-PAV						BBR-PAV			DT-PAV		
Temp, C	Plate Diam., mm	Strain, %	G*, KPa	Phase angle δ	G*sinδ kPa	Temp, C	S(t), MPa	m	Temp, C	Avg. F. Strain %	Avg. F. Stress Pa
16	8	1	2.327	48.6	1.8	-24	158.1	0.342			
19	8	1	1.562	50.1	1.2	-30	269.4	0.309			
22	8	1	1.026	51.5	0.8						
25	8	1	0.6638	52.4	0.5						

Original: Tmax
Temperature at which G*/sinδ = 1.0 kPa is 73.6

RTFOT: Tmax
Temperature at which G*/sinδ = 2.2 kPa is 69.3

DSR-PAV: Tint
Temperature at which G*/sinδ = 5.0 MPa is 8.1

BBR-PAV: Tmin
Temperature at which S(t) = 300.0 MPa is 28.3
Temperature at which m = 0.3 is 27.9

OR

BBR-PAV & DT-PAV: Tmin
Temperature at which S(t) = 600.0 MPa is ______
Temperature at which m = 0.3 is ______
Temperature at which % Strain = 1.0 % is ______

Table 36. Properties of the AC-30 viscosity-graded asphalt binder.

Test Performed On Original Binder	AC-30	NDOT SPEC
Viscosity 60 C 300mm Hg Pa.s	339	240-360
Viscosity 135 C mm^2/s	558	Min. 350
Flash Point COC Degrees C	310	Min. 232 C
Penetration 25C, 100g, 5s	60	Min. 50
Test Performed On Residue after RTFO		
Viscosity 60 C 300mm Hg Pa.s	847	Max. 1200 Pa.s
Loss on Heating %	0.42	Max 0.5%

Table 37. Properties of the Hveem mixtures for the Lockwood aggregate and AC-20P asphalt binder.

Mixture Type: No Lime			
Binder Content % by DWA	Hveem Stability	Air Voids %	VMA %
3.5	51	6.8	15.1
4.0	51	4.3	13.9
4.5	46	3.4	14.1
5.0	32	1.8	13.7
5.5	20	1.8	14.6

Mixture Type: NDOT Lime - 0 Hour Marination			
Binder Content % by DWA	Hveem Stability	Air Voids %	VMA %
3.5	44	5.9	14.2
4.0	44	4.3	13.8
4.5	34	3.1	13.7
5.0	21	2.5	14.2

Mixture Type: NDOT Lime - 48 Hour Marination			
Binder Content % by DWA	Hveem Stability	Air Voids %	VMA %
3.5	44	7.1	15.5
4.0	40	4.5	14.1
4.5	30	3.6	14.3
5.0	24	3.2	14.9

Mixture Type: Lime Slurry - 0 Hour Marination			
Binder Content % by DWA	Hveem Stability	Air Voids %	VMA %
3.5	42	7.3	15.3
4.0	41	5.2	14.4
4.5	36	3.5	13.8
5.0	--	3.5	14.9

Mixture Type: Lime Slurry - 48 Hour Marination			
Binder Content % by DWA	Hveem Stability	Air Voids %	VMA %
3.5	48	9.1	17.2
4.0	42	5.1	14.6
4.5	31	3.8	14.4
5.0	19	3.7	15.3

Table 38. Properties of the Hveem mixtures for the Lockwood aggregate and PG 64-34 asphalt binder.

Mixture Type: No Lime			
Binder Content % by DWA	Hveem Stability	Air Voids %	VMA %
3.5	51	8.2	16.4
4.0	52	6.3	15.7
4.5	53	6.7	16.0
5.0	42	4.4	16.0
5.5	20	2.5	15.3

Mixture Type: NDOT Lime - 0 Hour Marination			
Binder Content % by DWA	Hveem Stability	Air Voids %	VMA %
3.5	50	10.3	18.6
4.0	54	8.7	18.1
4.5	51	6.7	17.2
5.0	51	3.8	15.6
5.5	29	1.4	14.5

Mixture Type: NDOT Lime - 48 Hour Marination			
Binder Content % by DWA	Hveem Stability	Air Voids %	VMA %
3.5	61	9.8	18.1
4.0	57	9.0	18.3
4.5	56	6.9	17.4
5.0	52	5.4	17.0
5.5	42	3.8	16.6

Mixture Type: Lime Slurry - 0 Hour Marination			
Binder Content % by DWA	Hveem Stability	Air Voids %	VMA %
3.5	54	10.0	18.1
4.0	47	7.0	16.3
4.5	56	8.3	18.5
5.0	46	3.9	15.5
5.5	--	0.7	13.7

Mixture Type: Lime Slurry - 48 Hour Marination			
Binder Content % by DWA	Hveem Stability	Air Voids %	VMA %
3.5	50	9.4	17.7
4.0	53	7.0	16.4
4.5	43	5.1	15.8
5.0	45	4.3	15.9
5.5	--	1.0	14.0

Table 39. Properties of the Hveem mixtures for the Lone Mountain aggregate and AC-30 asphalt binder.

Mixture Type: No Lime			
Binder Content % by DWA	Hveem Stability	Air Voids %	VMA %
3.0	59	8.6	14.8
3.5	51	5.1	12.7
4.0	45	3.8	12.5
4.5	37	2.4	12.3

Mixture Type: NDOT Lime - 0 Hour Marination			
Binder Content % by DWA	Hveem Stability	Air Voids %	VMA %
3.0	45	7.9	14.7
3.5	45	4.8	12.9
4.0	20	1.6	11.0
4.5	--	0.7	11.3

Mixture Type: NDOT Lime - 48 Hour Marination			
Binder Content % by DWA	Hveem Stability	Air Voids %	VMA %
3.0	38	9.4	15.8
3.5	45	4.7	12.5
4.0	42	3.8	12.8
4.5	--	1.5	11.7

Mixture Type: Lime Slurry - 0 Hour Marination			
Binder Content % by DWA	Hveem Stability	Air Voids %	VMA %
3.0	57	9.2	15.9
3.5	54	4.4	12.5
4.0	37	2.9	12.2
4.5	--	0.8	11.4

Mixture Type: Lime Slurry - 48 Hour Marination			
Binder Content % by DWA	Hveem Stability	Air Voids %	VMA %
3.0	50	10	16.1
3.5	53	7.4	14.7
4.0	48	4.7	13.4
4.5	18	1.2	11.3

Table 40. Optimum binder contents for the evaluated mixes.

Aggregate Source	Asphalt Binder	Lime Treatment	Optimum Binder (%)	Hveem Stability	Air Voids (%)	VMA (%)
Lockwood	AC-20P	No Lime	4.2	49.0	4.0	13.7
Lockwood	AC-20P	NDOT 0 Hr	4.1	38.0	4.0	13.7
Lockwood	AC-20P	NDOT 48 Hr	4.1	37.0	4.5	14.2
Lockwood	AC-20P	Lime Slurry 0 hr	4.3	38.0	4.0	14.0
Lockwood	AC-20P	Lime Slurry 48 hr	4.2	37.0	4.4	14.4
Lockwood	PG 64-34	No Lime	4.9	42	4.0	15.6
Lockwood	PG 64-34	NDOT 0 Hr	4.9	47	4.2	16.1
Lockwood	PG 64-34	NDOT 48 Hr	5.3	46	4.0	16.7
Lockwood	PG 64-34	Lime Slurry 0 hr	5.0	37	4.0	15.7
Lockwood	PG 64-34	Lime Slurry 48 hr	5.1	37	4.0	15.0
Lone Mountain	AC-30	No Lime	3.8	48	4.0	12.3
Lone Mountain	AC-30	NDOT 0 Hr	3.6	39	3.9	12.2
Lone Mountain	AC-30	NDOT 48 Hr	3.8	45	4.0	12.4
Lone Mountain	AC-30	Lime Slurry 0 hr	3.7	49	4.0	12.4
Lone Mountain	AC-30	Lime Slurry 48 hr	4.1	42	3.9	13.0

Table 41. Tensile strength at 77°F data for all mixtures.

Mix	Lime Treatment	Dry TS		TS after one F-T Cycle			TS after 18 F-T Cycles		
		Air Voids (%)	TS (psi)	Air Voids (%)	TS (psi)	Ratio (%)	Air Voids (%)	TS (psi)	Ratio (%)
Lockwood AC-20P	No Lime	7.1	123	7.2	49	40	7.3	0	0
	NDOT 0-hour	7.3	104	7.3	113	100	7.3	81	78
	NDOT 48-hour	7.2	143	7.2	139	97	7.2	112	78
	Lime Slurry 0-hour	7.2	111	7.2	111	100	7.2	79	71
	Lime Slurry 48-hour	7.2	125	7.2	135	100	7.0	113	90
Lockwood PG 64-34	No Lime	7.1	95	7.1	65	69	7.1	18	19
	NDOT 0-hour	6.9	103	6.9	92	90	6.9	78	76
	NDOT 48-hour	6.9	86	6.9	83	97	6.9	70	81
	Lime Slurry 0-hour	7.4	102	7.4	86	84	7.4	75	74
	Lime Slurry 48-hour	7.0	84	6.9	78	93	7.0	65	77
Lone Mountain AC-30	No Lime	6.7	150	6.7	53	35	6.5	10	7
	NDOT 0-hour	6.7	123	6.7	129	100	6.5	62	50
	NDOT 48-hour	6.4	113	6.3	124	100	6.3	55	49
	Lime Slurry 0-hour	6.4	127	6.4	131	100	6.4	65	51
	Lime Slurry 48-hour	6.7	115	6.6	121	100	6.6	48	42

Table 42. Resilient modulus at 77°F data for all mixtures.

Mix	Lime Treatment	Air Voids (%)	Mr, Dry, ksi	Mr @ 1 F-T		Mr @ 6 F-T		Mr @ 12 F-T		Mr @ 18 F-T	
				Mr, ksi	Ratio, %	Mr, ksi	Ratio, %	Mr, ksi	Ratio, %	Mr, ksi	Ratio, %
Lockwood AC-20P	No Lime	7.3	259	73	28	0	0	0	0	0	0
	NDOT 0-hour	7.3	214	118	55	127	59	99	46	112	52
	NDOT 48-hour	7.2	281	234	83	224	80	207	74	182	64
	Lime Slurry 0-hour	7.2	236	112	47	132	56	124	53	94	40
	Lime Slurry 48-hour	7.0	261	163	62	176	67	176	67	160	61
Lockwood PG64-34	No Lime	7.1	115	43	37	23	20	14	12	9	8
	NDOT 0-hour	6.9	109	69	63	58	53	60	55	48	44
	NDOT 48-hour	6.9	98	93	95	65	66	74	76	56	57
	Lime Slurry 0-hour	7.4	102	80	78	58	57	59	58	58	57
	Lime Slurry 48-hour	7.0	91	80	88	45	49	49	54	38	42
Lone Mountain AC-30	No Lime	6.5	509	121	24	43	8	16	3	0	0
	NDOT 0-hour	6.5	532	415	78	429	81	301	57	225	42
	NDOT 48-hour	6.3	457	327	72	322	70	234	51	189	41
	Lime Slurry 0-hour	6.4	704	426	61	458	65	371	53	261	37
	Lime Slurry 48-hour	6.6	459	325	71	308	67	188	41	161	35

Table 43. Statistically-based comparisons of the Lockwood AC-20P HMA mixtures.

Comparison Based on TS Property of Untreated versus Lime-Treated Mixtures			
Condition	**Lower**	**Same**	**Higher**
Unconditioned		4	
1 Freeze-Thaw Cycle	4		
18 Freeze-Thaw Cycles	4		
Comparison Based on Mr Property of Untreated versus Lime-Treated Mixtures			
Condition	**Lower**	**Same**	**Higher**
Unconditioned		4	
1 Freeze-Thaw Cycle	2	2	
18 Freeze-Thaw Cycles	4		

Table 44. Statistically-based comparisons of the Lockwood PG64-34 HMA mixtures.

Comparison Based on TS Property of Untreated versus Lime-Treated Mixtures			
Condition	**Lower**	**Same**	**Higher**

Unconditioned		4	
1 Freeze-Thaw Cycle	3	1	
18 Freeze-Thaw Cycles	4		
Comparison Based on Mr Property of Untreated versus Lime-Treated Mixtures			
Condition	**Lower**	**Same**	**Higher**
Unconditioned		4	
1 Freeze-Thaw Cycle	3	1	
18 Freeze-Thaw Cycles	4		

Table 45. Statistically-based comparisons of the Lone Mountain AC-30 HMA mixtures.

Comparison Based on TS Property of Untreated versus Lime-Treated Mixtures			
Condition	**Lower**	**Same**	**Higher**
Unconditioned		4	
1 Freeze-Thaw Cycle	4		
18 Freeze-Thaw Cycles	4		

Comparison Based on Mr Property of Untreated versus Lime-Treated Mixtures			
Condition	**Lower**	**Same**	**Higher**
Unconditioned	1	3	
1 Freeze-Thaw Cycle	4		
18 Freeze-Thaw Cycles	4		

Table 46. Comparison of the various methods of lime application.

Property	Total cases	Number of same cases	Number of different cases	Different cases
	Lockwood AC-20P Mixture			
Tensile Strength (TS)	18	11	2 @ unconditioned 1@1 F-T Cycle 4@ 18 F-T Cycles	NDOT 48-hr >NDOT 0-hr NDOT 48-hr > L.S. 0-hr NDOT 48-hr > L.S. 0-hr NDOT 48-hr > NDOT 0-hr NDOT 48-hr > L.S. 0-hr L.S. 48-hr > L.S. 0-hr L.S. 48-hr > NDOT 0-hr
Resilient Modulus (Mr)	18	11	1@ unconditioned 3@ 1 F-T Cycle 3@ 18 F-T Cylces	NDOT 48-hr > NDOT 0-hr NDOT 48-hr > NDOT 0-hr NDOT 48-hr > L.S. 0-hr NDOT 48-hr > L.S. 48-hr NDOT 48-hr > NDOT 0-hr NDOT 48-hr > L.S. 0-hr L.S. 48-hr > L.S. 0-hr
Property	**Lockwood PG 64-34 Mixture**			

Tensile Strength (TS)	18	13	4@ unconditioned 1@ 1 F-T Cycle	NDOT 0-hr > NDOT 48-hr L.S. 0-hr > NDOT 48-hr NDOT 0-hr > L.S. 48-hr L.S. 0-hr > L.S. 48-hr NDOT 0-hr > L.S. 48-hr
Resilient Modulus (Mr)	18	18		
Property	**Lone Mountain AC-30 Mixture**			
Tensile Strength (TS)	18	17	1@ 18 F-T Cycles	L.S. 0-hr > L.S. 48-hr
Resilient Modulus (Mr)	18	15	3@ unconditioned	L.S. 0-hr > NDOT 48-hr L.S. 0-hr > L.S. 48-hr L.S. 0-hr > NDOT 0-hr

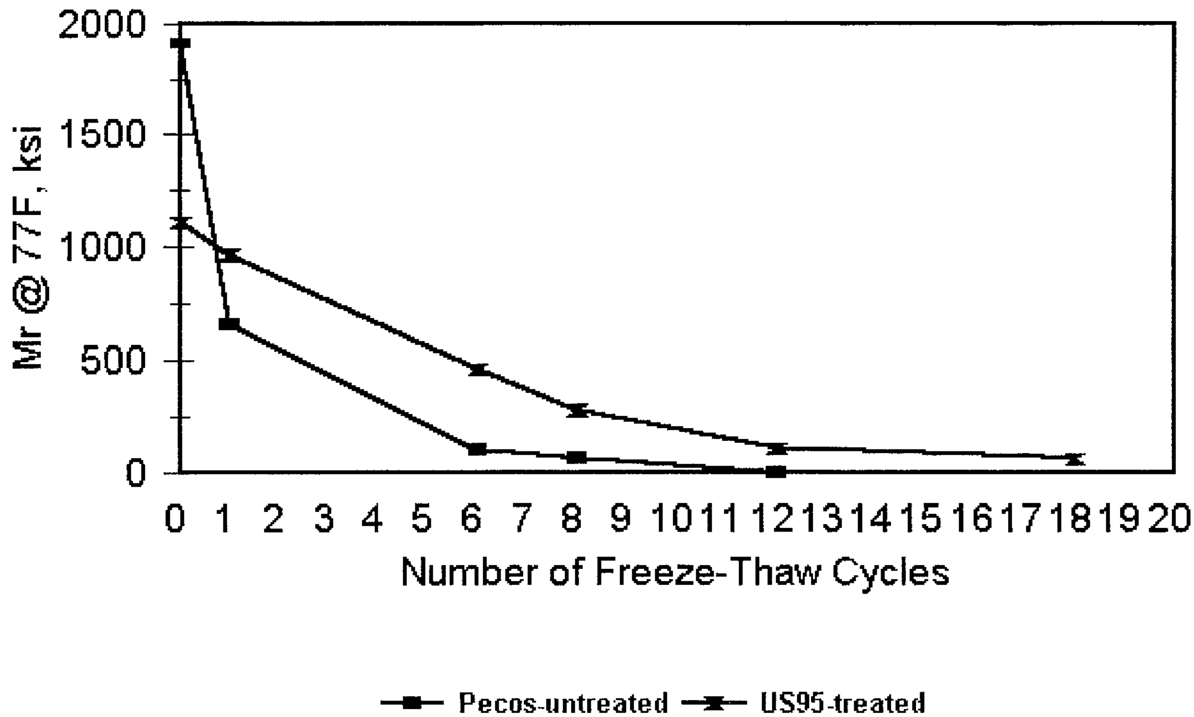


Figure 1. Mr property of field cores at various freeze-thaw cycles for the Pecos road and US 95 projects.

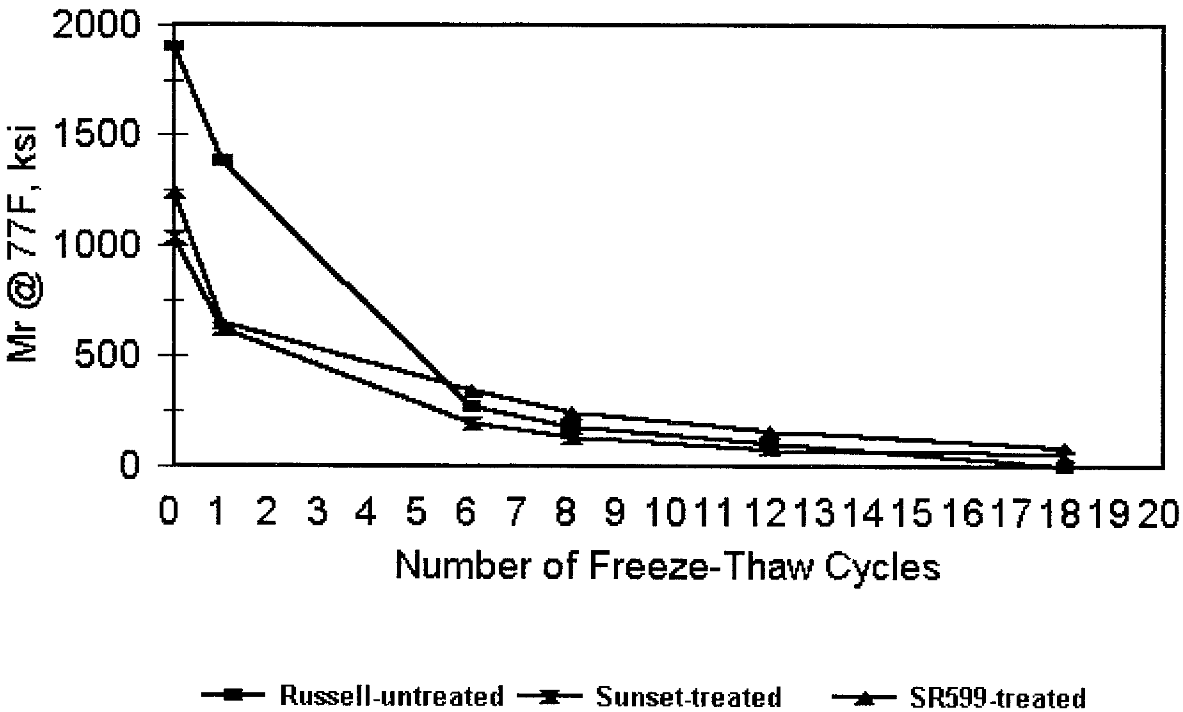


Figure 2. Mr property of field cores at various freeze-thaw cycles for the Russell Road, Sunset Road, and SR 599 projects.

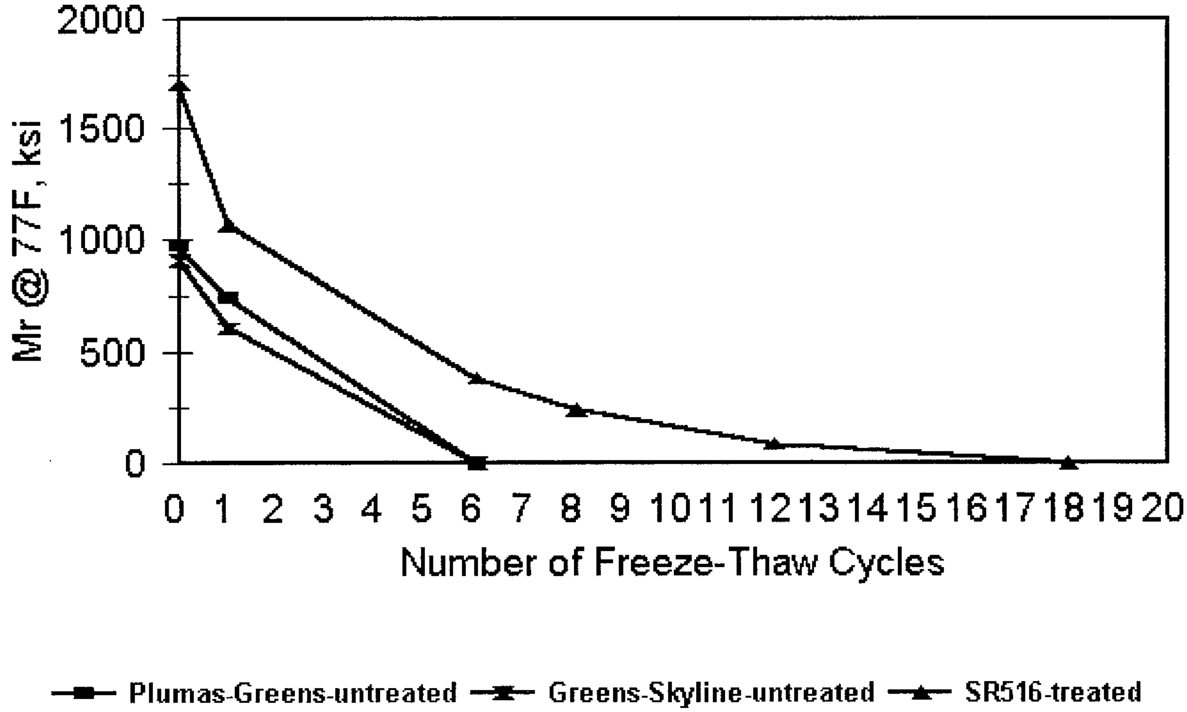


Figure 3. Mr property of field cores at various freeze-thaw cycles for the McCarran Boulevard and SR 516 projects.

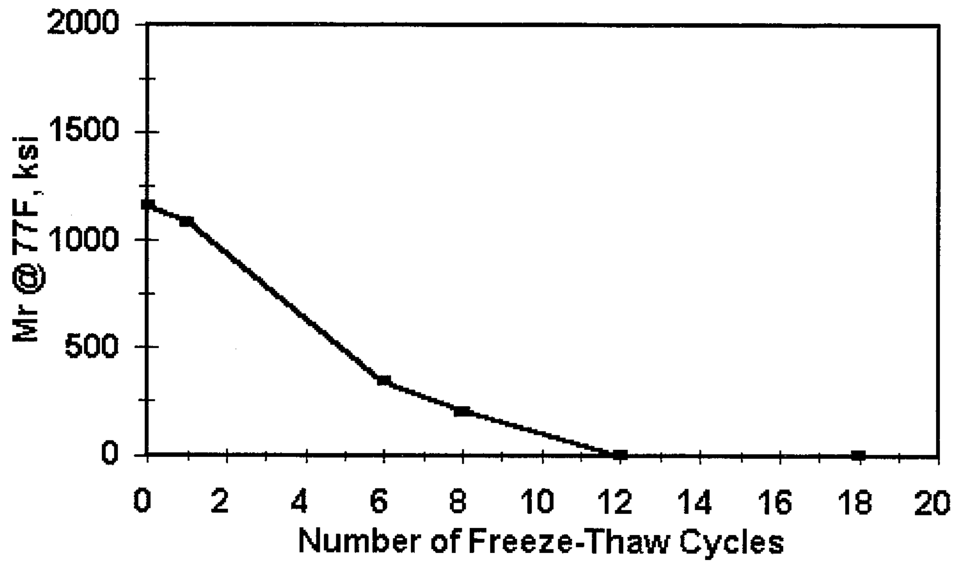


Figure 4. Mr property of field cores at various freeze-thaw cycles for the Sahara Avenue project.

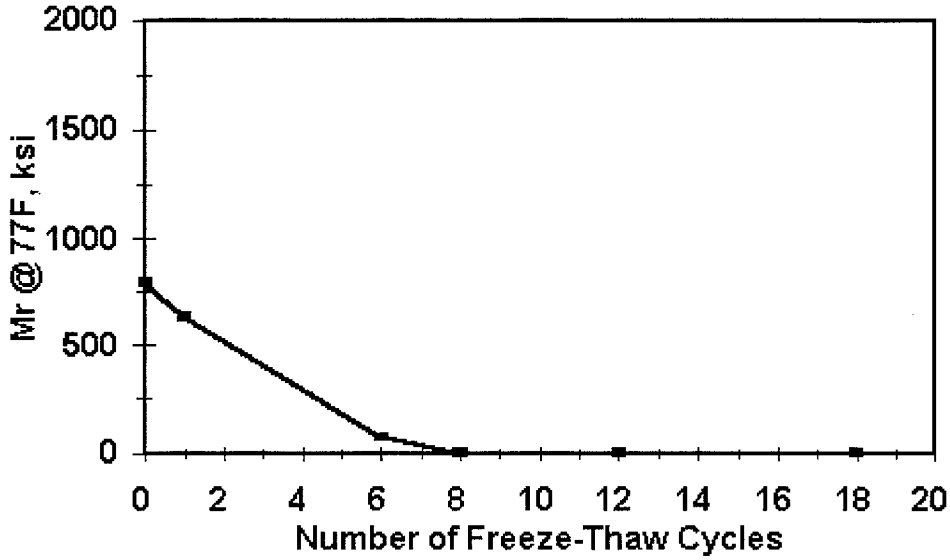
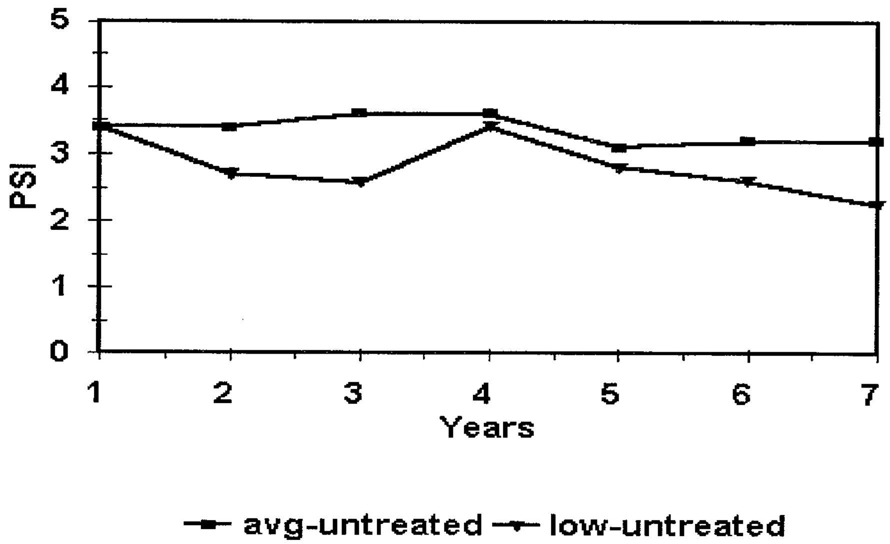


Figure 5. Mr property of field cores at various freeze-thaw cycles for the Lakeside Drive project.



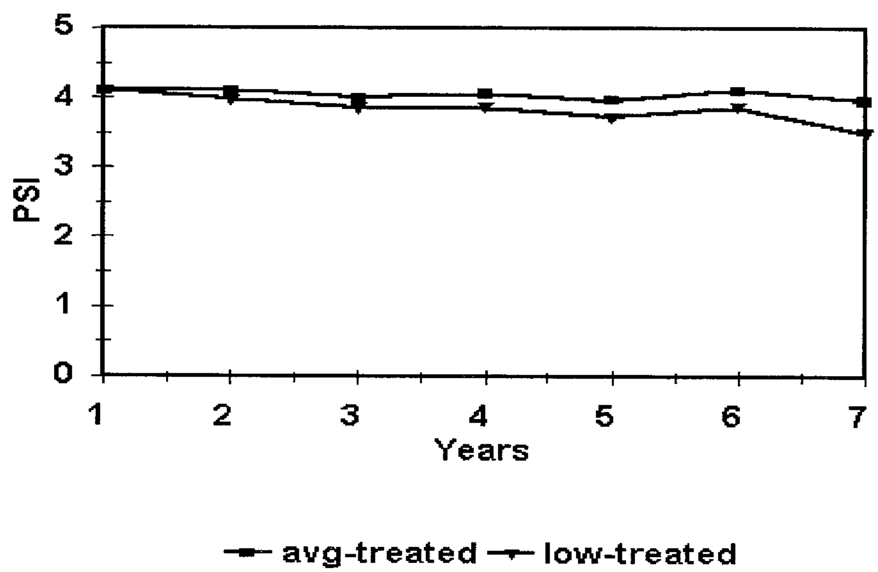
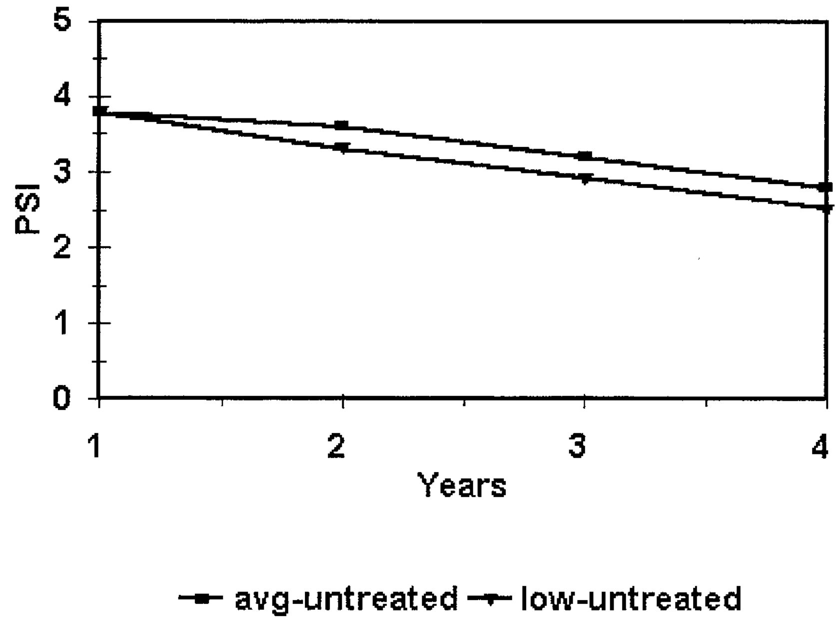


Figure 6.
Average and low values of PSI for untreated and lime-treated mixtures on I-15 in southern Nevada.



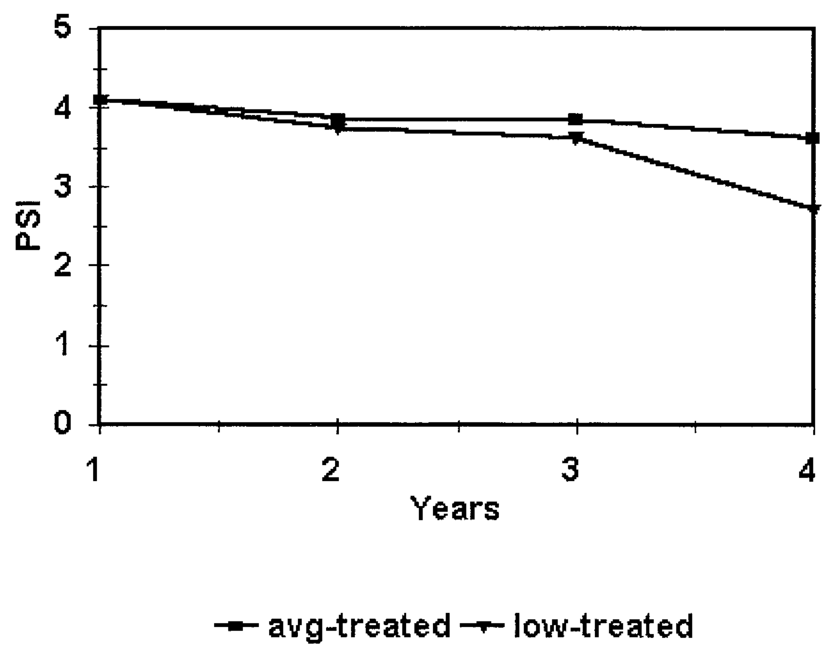
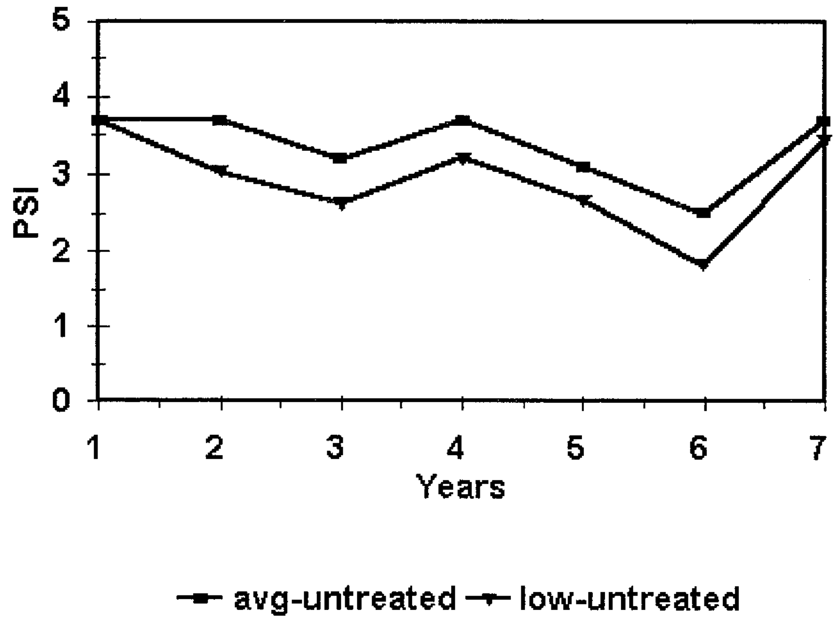


Figure 7. Average and low values of PSI for untreated and lime-treated mixtures on US 95 in southern Nevada.



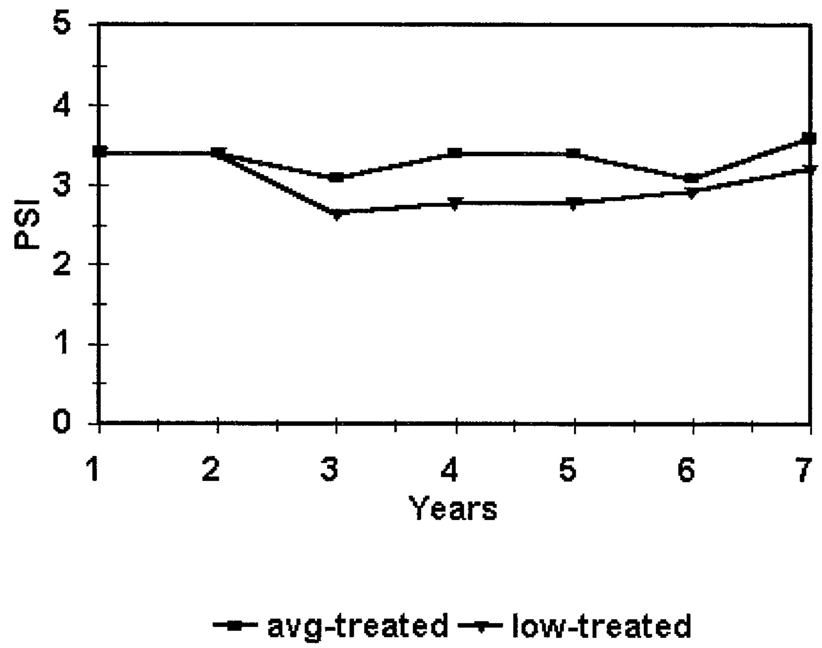
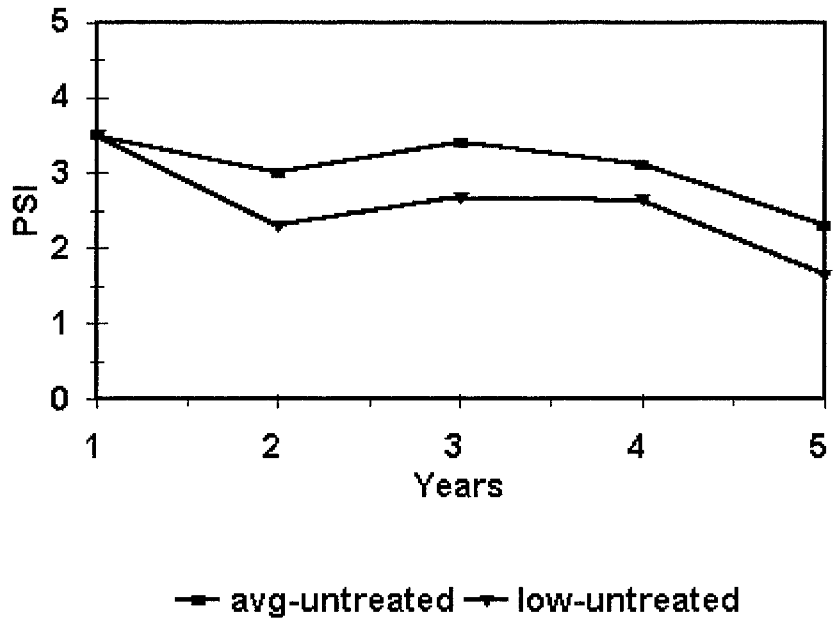


Figure 8. Average and low values of PSI for untreated and lime-treated mixtures on I-80 (1) in north-western Nevada.



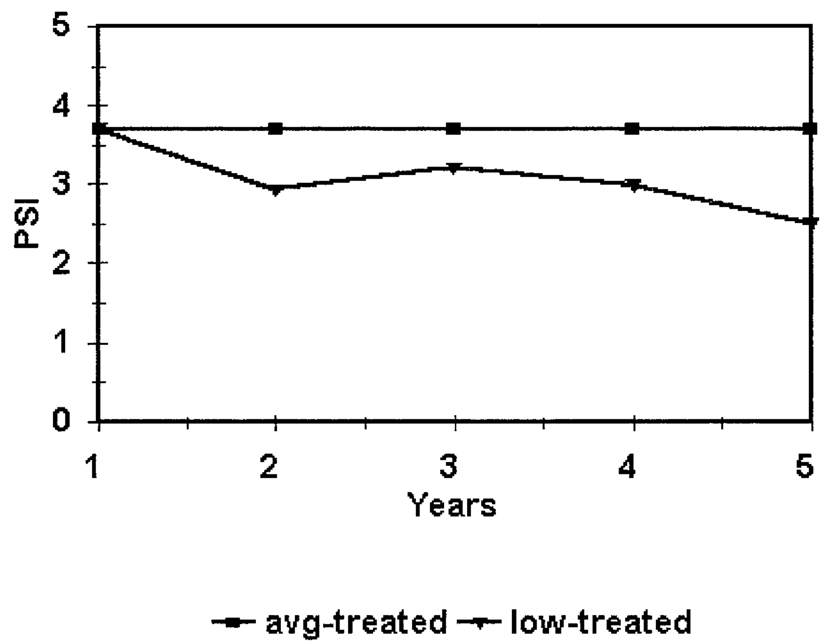
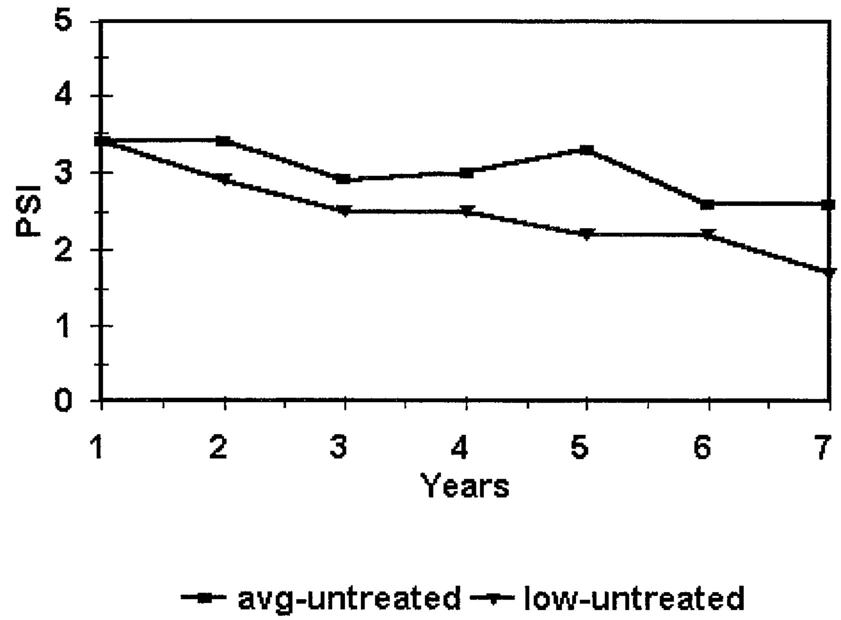


Figure 9. Average and low values of PSI for untreated and lime-treated mixtures on I-80 (2) in north-western Nevada.



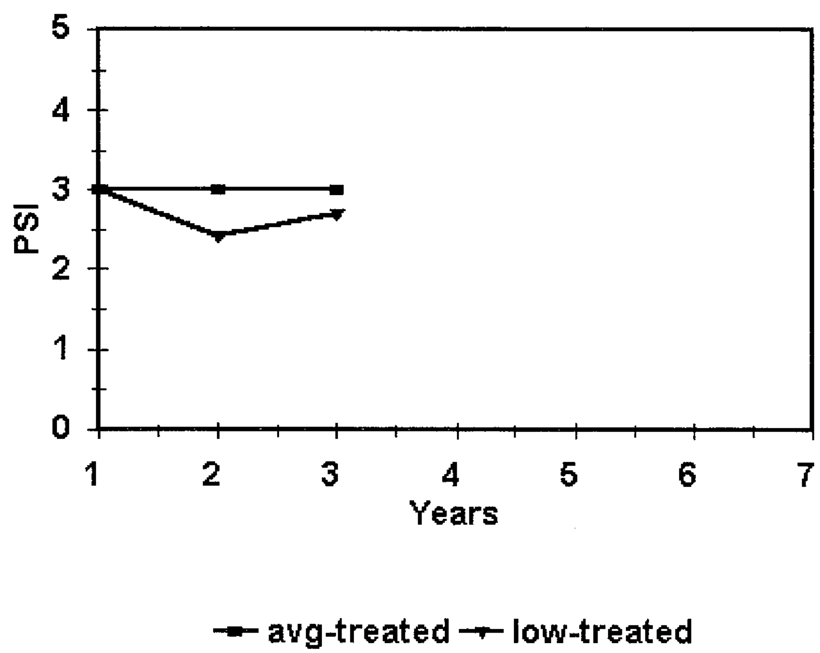
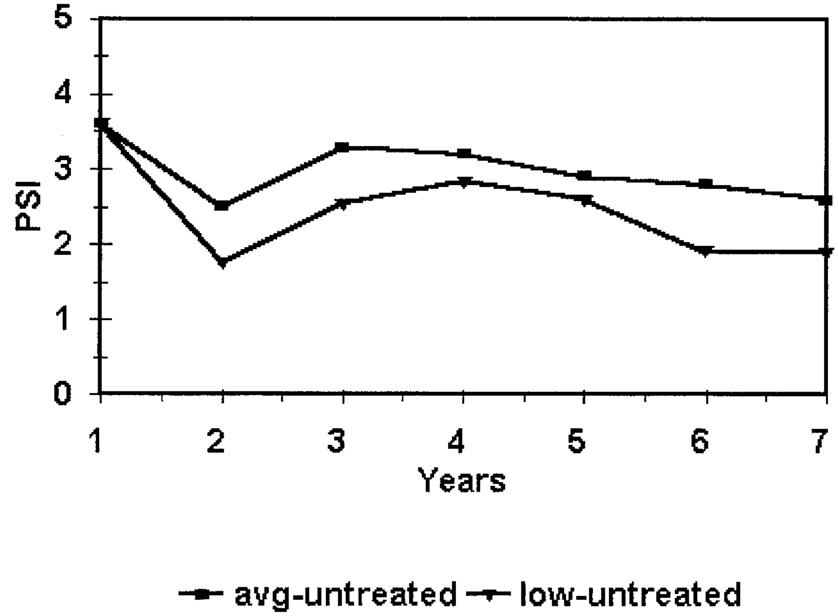


Figure 10. Average and low values of PSI for untreated and lime-treated mixtures on US 395 in northwestern Nevada.



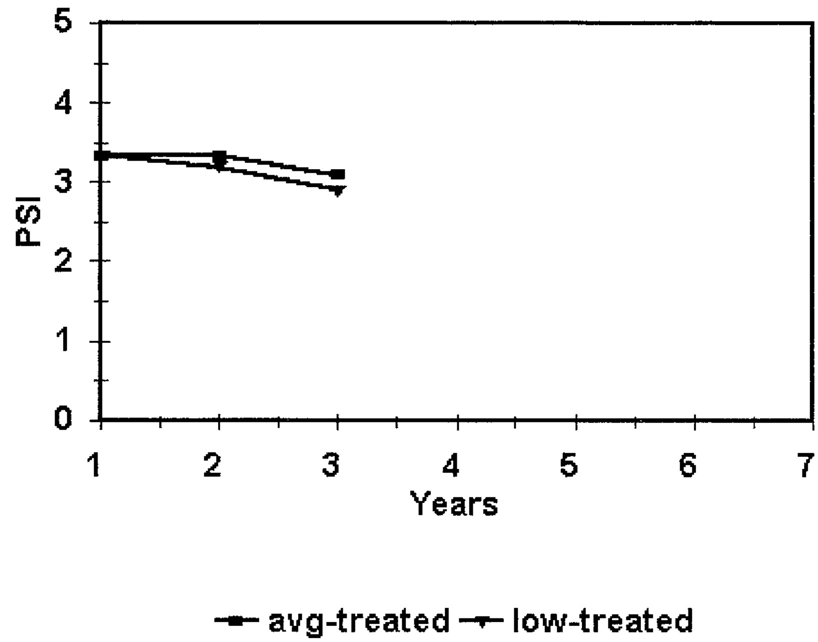


Figure 11. Average and low values of PSI for untreated and lime-treated mixtures on SR 663 in northwestern Nevada.

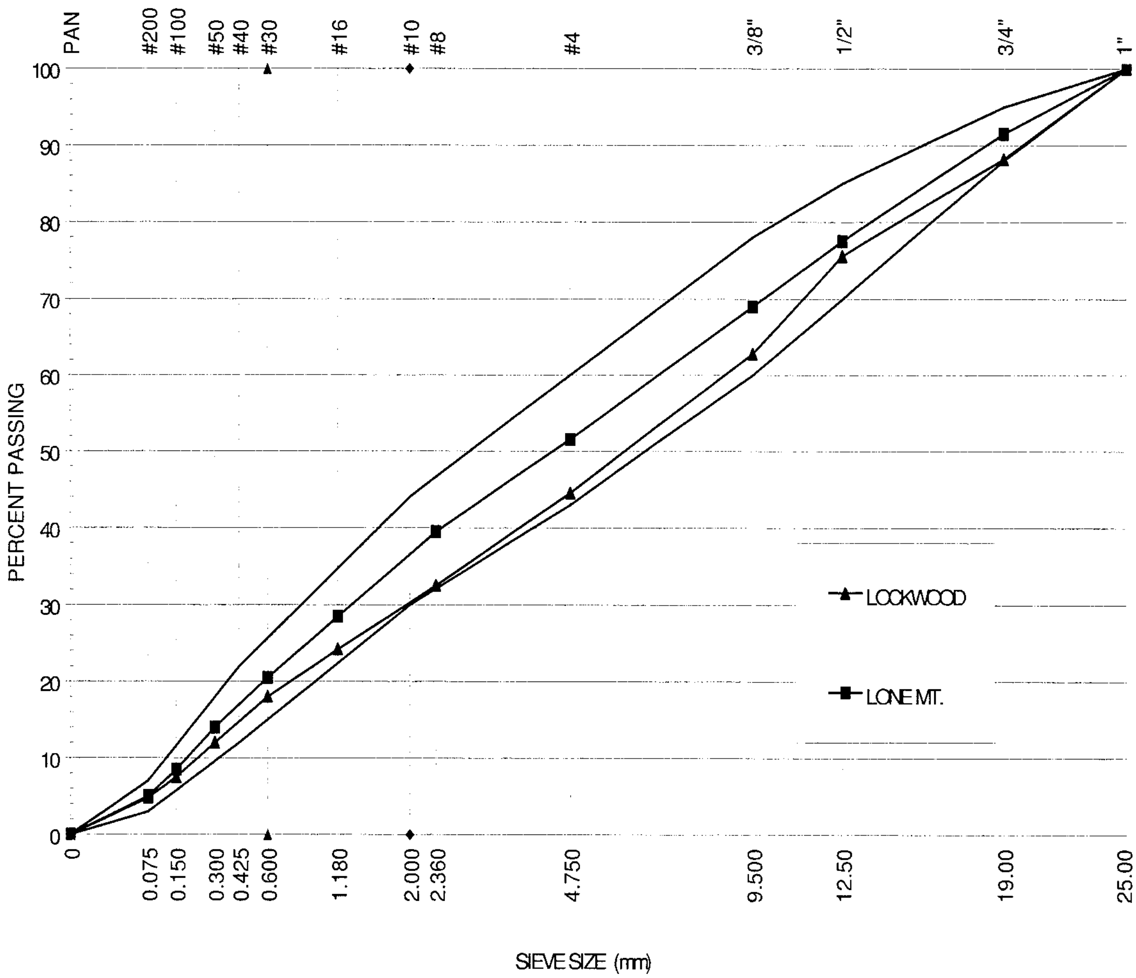


Figure 12. Gradation curves for the Lockwood and Lone Mountain aggregate sources in comparison to the NDOT Type 2C gradation specifications.

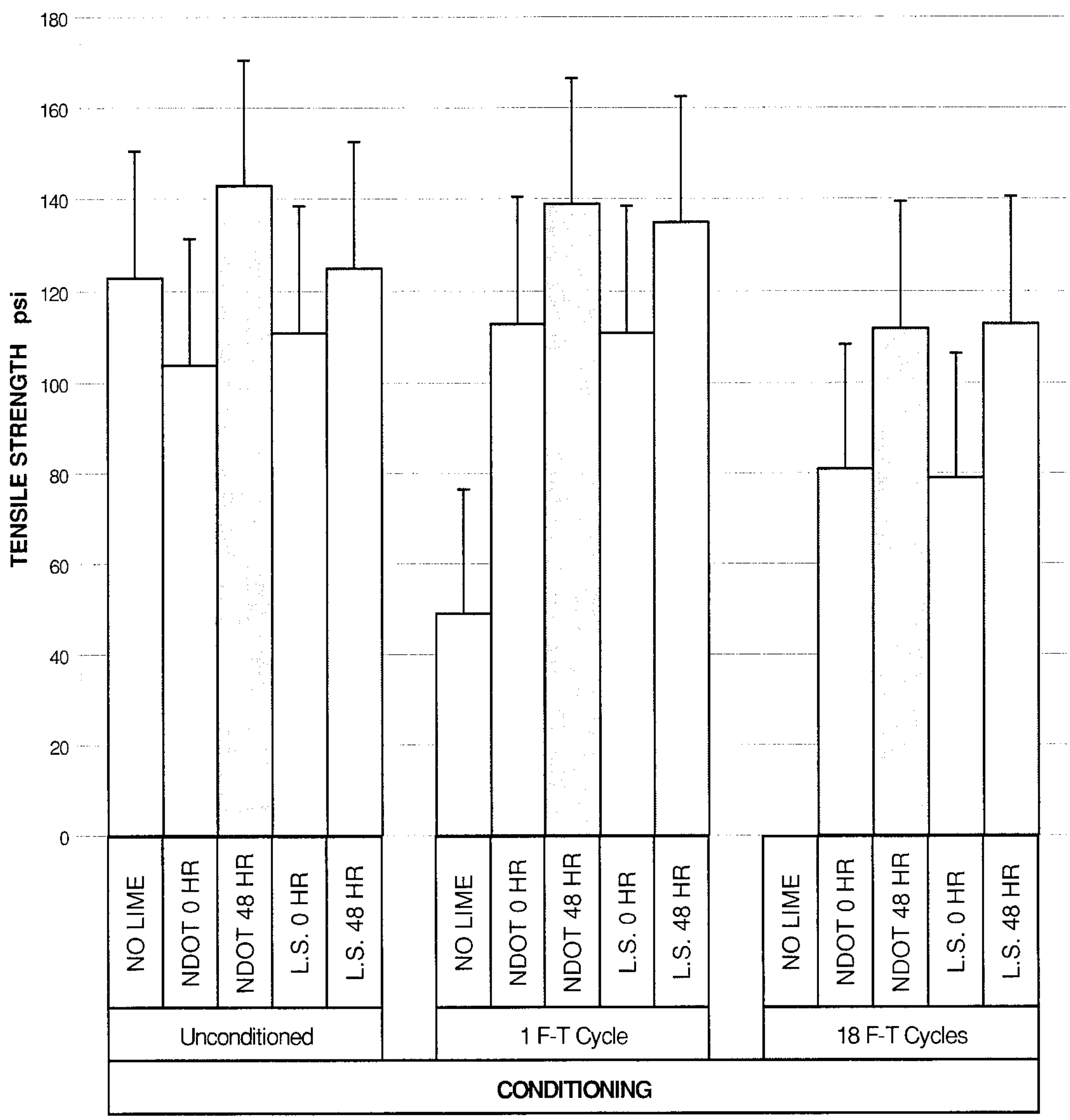


Figure 13. Average tensile strength property of the Lockwood AC-20P mixtures, vertical bars indicate the range of average value plus one least significant difference.

LOCKWOOD AC-20P		Unconditioned						1 F-T Cycle						18 F-T Cycles				
		NO LIME	NDOT 0 HR	NDOT 48 HR	L.S. 0 HR	L.S. 48 HR		NO LIME	NDOT 0 HR	NDOT 48 HR	L.S. 0 HR	L.S. 48 HR		NO LIME	NDOT 0 HR	NDOT 48 HR	L.S. 0 HR	L.S. 48 HR
Unconditioned	NO LIME		S	S	S	S		D						D				
	NDOT 0 HR			D	S	S			S						S			
	NDOT 48 HR				D	S				S						D		
	L.S. 0 HR					S					S						D	
	L.S. 48 HR											S						S
1 F-T Cycle	NO LIME								D	D	D	D		D				
	NDOT 0 HR									S	S	S			D			
	NDOT 48 HR										D	S				S		
	L.S. 0 HR											S					D	
	L.S. 48 HR																	S
18 F-T Cycles	NO LIME														D	D	D	D
	NDOT 0 HR															D	S	D
	NDOT 48 HR																D	S
	L.S. 0 HR																	D
	L.S. 48 HR																	

S = The mixtures are statistically the same.
D = The mixtures are statistically different.

Figure 14. Statistically-based comparisons of the tensile strength property for the Lockwood AC-20P mixtures.

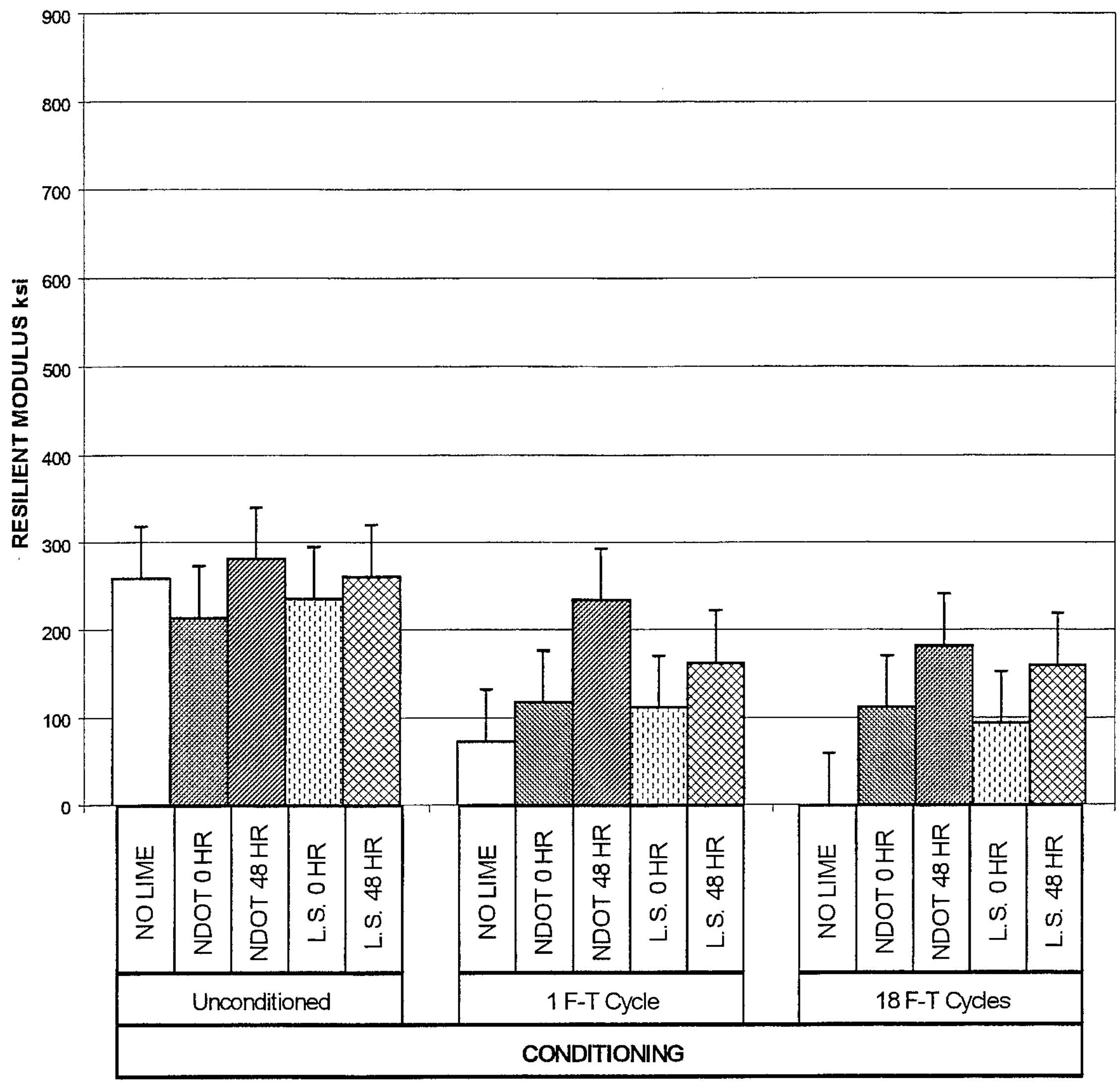


Figure 15. Average resilient modulus property of the Lockwood AC-20P mixtures, vertical bars indicate the range of average value plus one least significant difference.

LOCKWOOD AC-20P		Unconditioned						1 F-T Cycle						18 F-T Cycles				
		NO LIME	NDOT 0 HR	NDOT 48 HR	L.S. 0 HR	L.S. 48 HR		NO LIME	NDOT 0 HR	NDOT 48 HR	L.S. 0 HR	L.S. 48 HR		NO LIME	NDOT 0 HR	NDOT 48 HR	L.S. 0 HR	L.S. 48 HR
Unconditioned	NO LIME		S	S	S	S		D						D				
	NDOT 0 HR			D	S	S			D						D			
	NDOT 48 HR				S	S				S						D		
	L.S. 0 HR					S					D						D	
	L.S. 48 HR											D						D
1 F-T Cycle	NO LIME								S	D	S	D		D				
	NDOT 0 HR									D	S	S			S			
	NDOT 48 HR										D	D				S		
	L.S. 0 HR											S					S	
	L.S. 48 HR																	S
18 F-T Cycles	NO LIME														D	D	D	D
	NDOT 0 HR															D	S	S
	NDOT 48 HR																D	S
	L.S. 0 HR																	D
	L.S. 48 HR																	

S = The mixtures are statistically the same.
D = The mixtures are statistically different.

Figure 16. Statistically-based comparisons of the resilient modulus property for the Lockwood AC-20P mixtures.

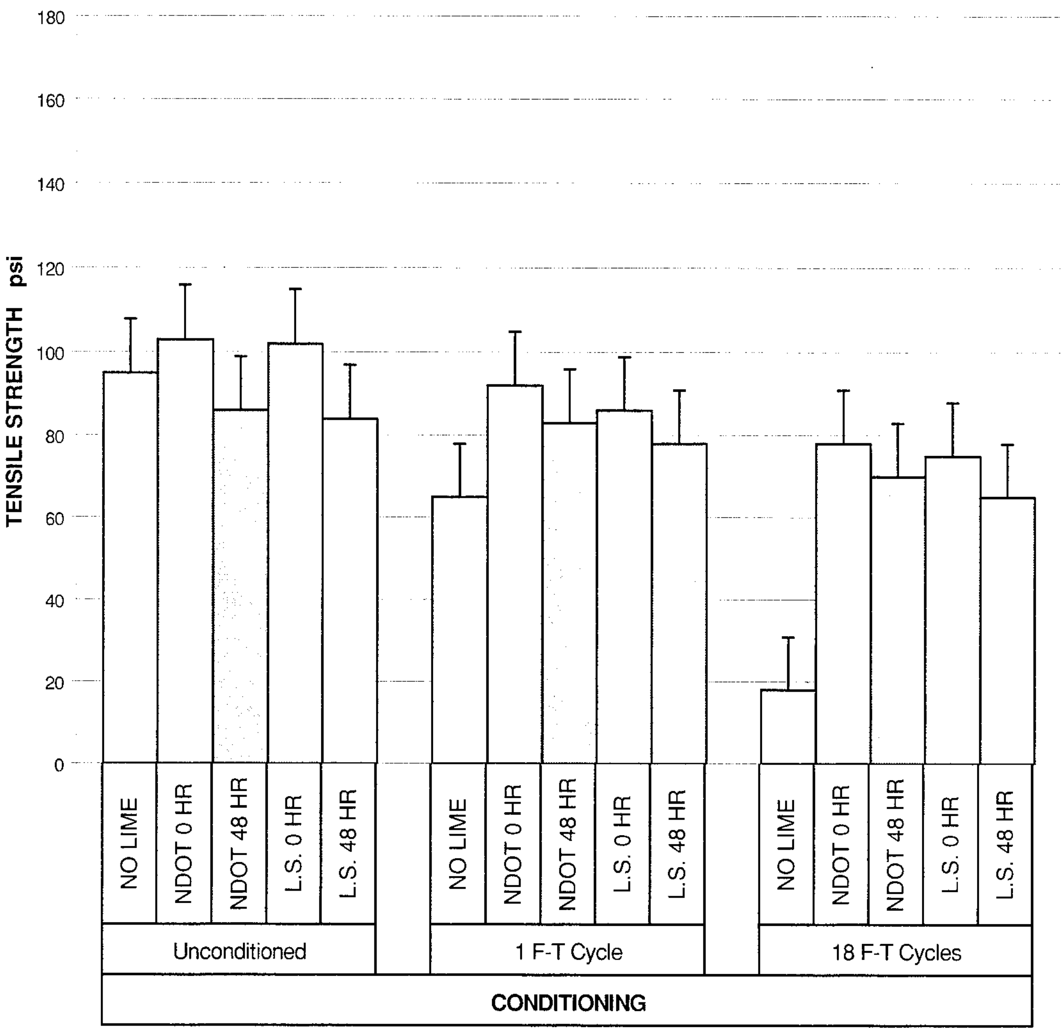


Figure 17. Average tensile strength property of the Lockwood PG 64-34 mixtures, vertical bars indicate the range of average value plus one least significant difference.

LOCKWOOD PG 64-34		Unconditioned						1 F-T Cycle						18 F-T Cycles				
		NO LIME	NDOT 0 HR	NDOT 48 HR	L.S. 0 HR	L.S. 48 HR		NO LIME	NDOT 0 HR	NDOT 48 HR	L.S. 0 HR	L.S. 48 HR		NO LIME	NDOT 0 HR	NDOT 48 HR	L.S. 0 HR	L.S. 48 HR
Unconditioned	NO LIME		S	S	S	S		D						D				
	NDOT 0 HR			D	S	D			S						D			
	NDOT 48 HR				D	S				S						D		
	L.S. 0 HR					D					D						D	
	L.S. 48 HR											S						D
1 F-T Cycle	NO LIME								D	D	D	S		D				
	NDOT 0 HR									S	S	D			D			
	NDOT 48 HR										S	S				S		
	L.S. 0 HR											S					S	
	L.S. 48 HR																	S
18 F-T Cycles	NO LIME														D	D	D	D
	NDOT 0 HR															S	S	S
	NDOT 48 HR																S	S
	L.S. 0 HR																	S
	L.S. 48 HR																	

S = The mixtures are statistically the same.
D = The mixtures are statistically different.

Figure 18. Statistically-based comparisons of the tensile strength property for the Lockwood PG 64-34 mixtures.

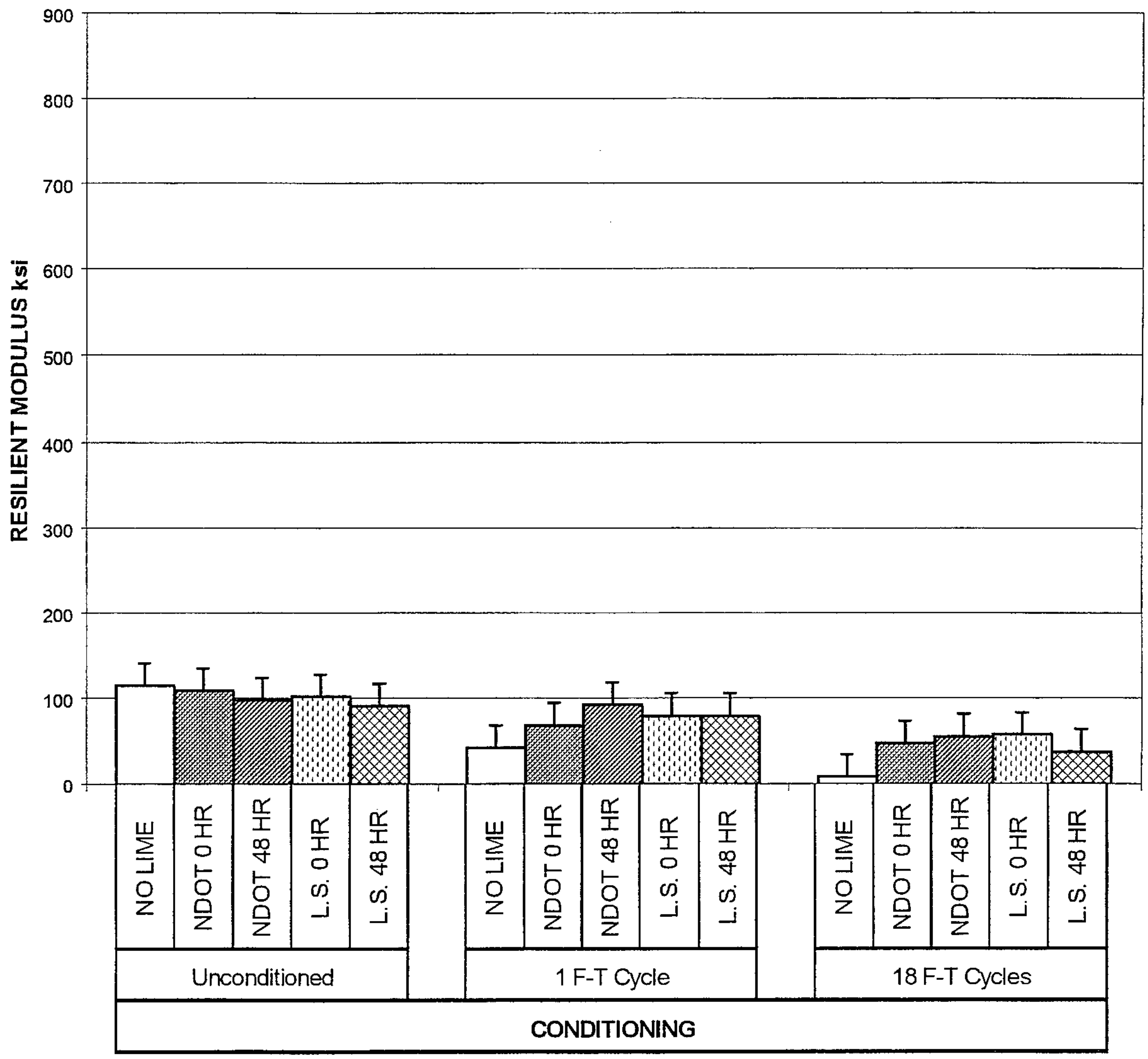


Figure 19. Average resilient modulus property of the Lockwood PG 64-34 mixtures, vertical bars indicate the range of average value plus one least significant difference.

LOCKWOOD PG 64-34		Unconditioned						1 F-T Cycle						18 F-T Cycles				
		NO LIME	NDOT 0 HR	NDOT 48 HR	L.S. 0 HR	L.S. 48 HR		NO LIME	NDOT 0 HR	NDOT 48 HR	L.S. 0 HR	L.S. 48 HR		NO LIME	NDOT 0 HR	NDOT 48 HR	L.S. 0 HR	L.S. 48 HR
Unconditioned	NO LIME		S	S	S	S		D						D				
	NDOT 0 HR			S	S	S			D						D			
	NDOT 48 HR				S	S				S						D		
	L.S. 0 HR					S					S						D	
	L.S. 48 HR											S						D
1 F-T Cycle	NO LIME								S	D	D	D		D				
	NDOT 0 HR									S	S	S			S			
	NDOT 48 HR										S	S				D		
	L.S. 0 HR											S					S	
	L.S. 48 HR																	D
18 F-T Cycles	NO LIME														D	D	D	D
	NDOT 0 HR															S	S	S
	NDOT 48 HR																S	S
	L.S. 0 HR																	S
	L.S. 48 HR																	

S = The mixtures are statistically the same.
D = The mixtures are statistically different.

Figure 20. Statistically-based comparisons of the resilient modulus property for the Lockwood PG 64-34 mixtures.

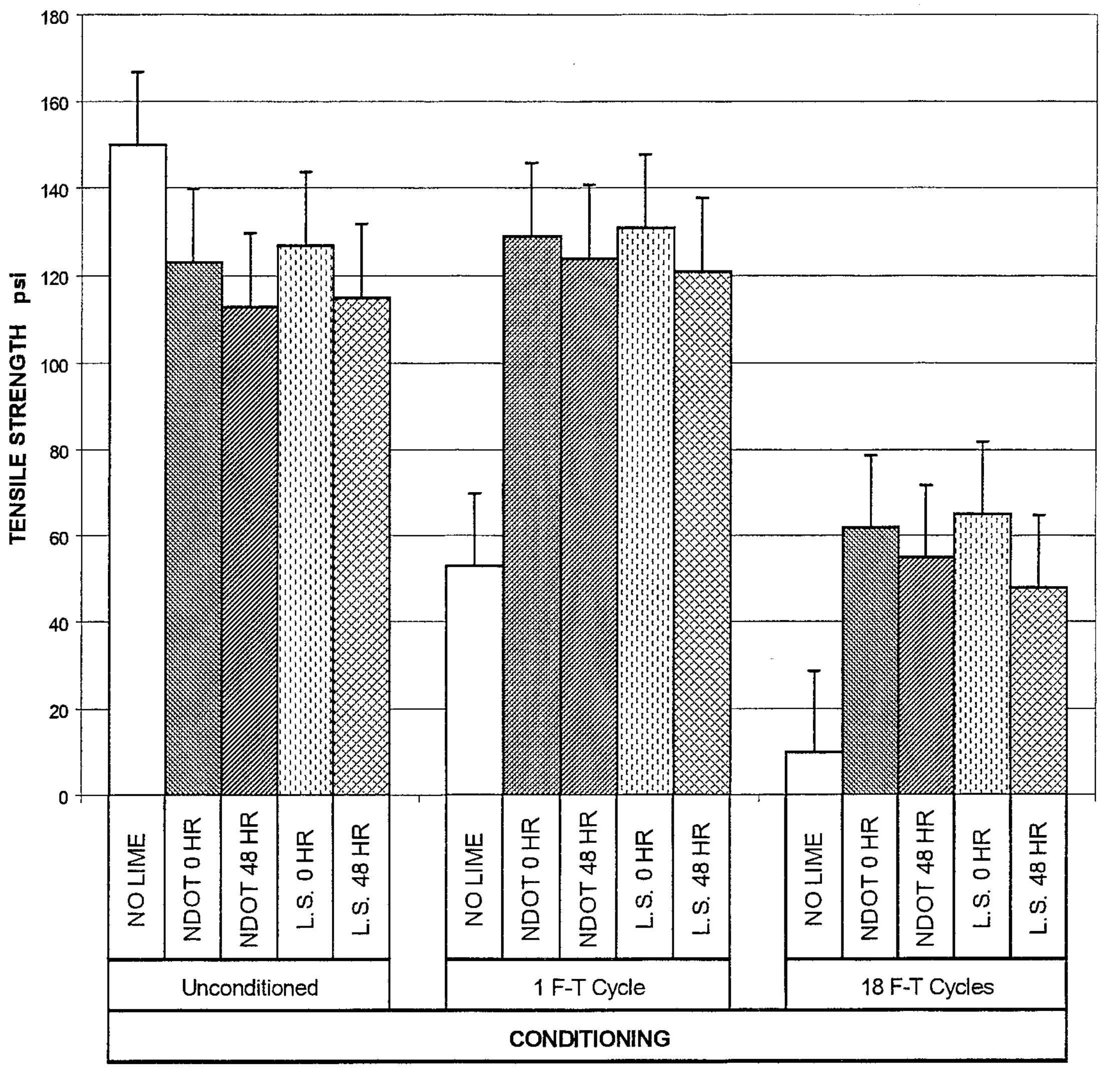


Figure 21. Average tensile strength property of the Lone Mountain AC-30 mixtures, vertical bars indicate the range of average value plus one least significant difference.

LONE MOUNTAIN AC-30		Unconditioned					1 F-T Cycle					18 F-T Cycles				
		NO LIME	NDOT 0 HR	NDOT 48 HR	L.S. 0 HR	L.S. 48 HR	NO LIME	NDOT 0 HR	NDOT 48 HR	L.S. 0 HR	L.S. 48 HR	NO LIME	NDOT 0 HR	NDOT 48 HR	L.S. 0 HR	L.S. 48 HR
Unconditioned	NO LIME		D	D	D	D	D					D				
	NDOT 0 HR			S	S	S		S					D			
	NDOT 48 HR				S	S			S					D		
	L.S. 0 HR					S				S					D	
	L.S. 48 HR										S					D
1 F-T Cycle	NO LIME							D	D	D	D	D				
	NDOT 0 HR								S	S	S		D			
	NDOT 48 HR									S	S			D		
	L.S. 0 HR										S				D	
	L.S. 48 HR															D
18 F-T Cycles	NO LIME												D	D	D	D
	NDOT 0 HR													S	S	S
	NDOT 48 HR														S	S
	L.S. 0 HR															D
	L.S. 48 HR															

S = The mixtures are statistically the same.
D = The mixtures are statistically different.

Figure 22. Statistically-based comparisons of the tensile strength property for the Lone Mountain AC-30 mixtures.

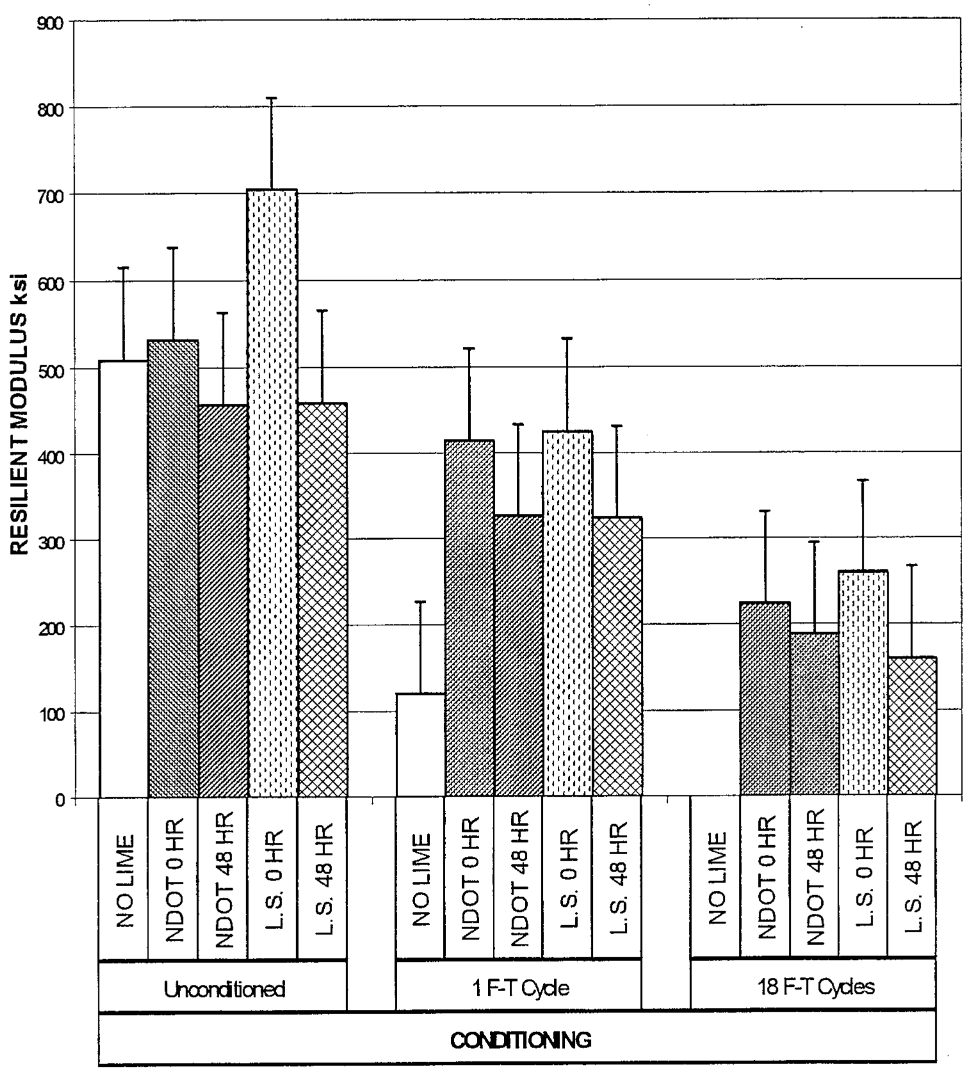


Figure 23. Average resilient modulus property of the Lone Mountain AC-30 mixtures, vertical bars indicate the range of average value plus one least significant difference.

LONE MOUNTAIN AC-30		Unconditioned						1 F-T Cycle						18 F-T Cycles				
		NO LIME	NDOT 0 HR	NDOT 48 HR	L.S. 0 HR	L.S. 48 HR		NO LIME	NDOT 0 HR	NDOT 48 HR	L.S. 0 HR	L.S. 48 HR		NO LIME	NDOT 0 HR	NDOT 48 HR	L.S. 0 HR	L.S. 48 HR
Unconditioned	NO LIME		S	S	D	S		D						D				
	NDOT 0 HR			S	D	S			D						D			
	NDOT 48 HR				D	S				D						D		
	L.S. 0 HR					D					D						D	
	L.S. 48 HR											D						D
1 F-T Cycle	NO LIME								D	D	D	D		D				
	NDOT 0 HR									S	S	S			D			
	NDOT 48 HR										S	S				D		
	L.S. 0 HR											S					D	
	L.S. 48 HR																	D
18 F-T Cycles	NO LIME														D	D	D	D
	NDOT 0 HR															S	S	S
	NDOT 48 HR																S	S
	L.S. 0 HR																	S
	L.S. 48 HR																	

S = The mixtures are statistically the same.
D = The mixtures are statistically different.

Figure 24. Statistically-based comparisons of the resilient modulus property for the Lone Mountain AC-30 mixtures.

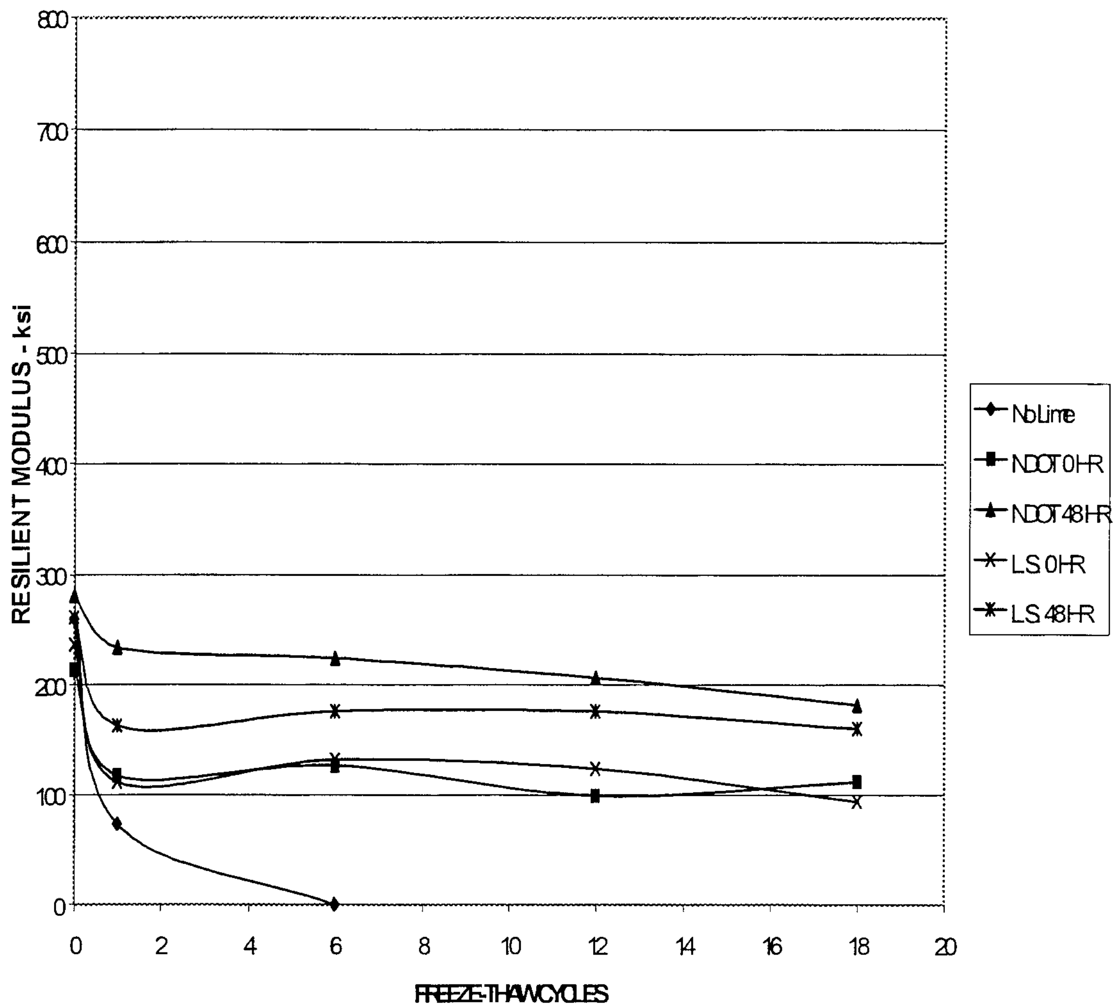


Figure 25. Resilient modulus property of the Lockwood AC-20P mixtures at various freeze-thaw cycles.

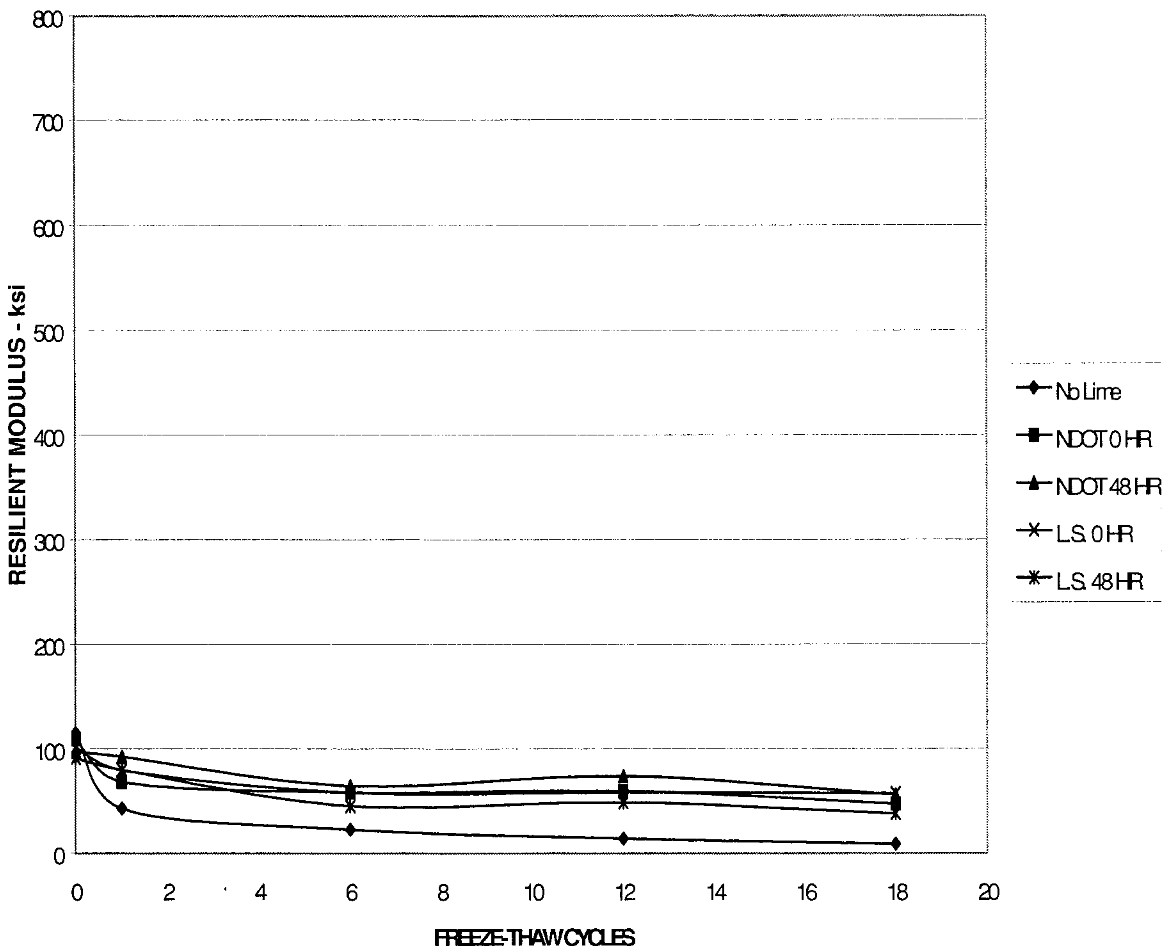


Figure 26. Resilient modulus property of the Lockwood PG 64-34 mixtures at various freeze-thaw cycles.

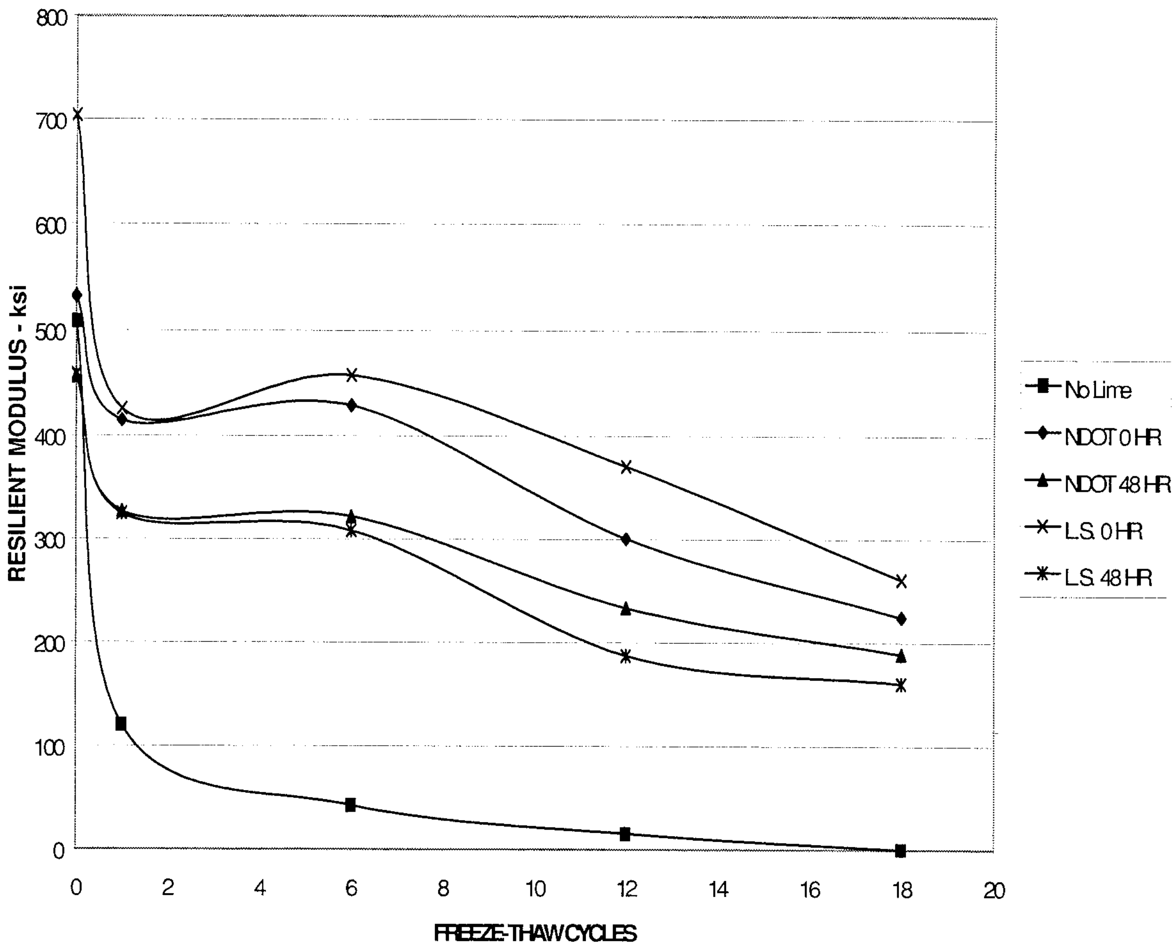


Figure 27. Resilient modulus property of the Lone Mountain AC-30 mixtures at various freeze-thaw cycles.