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Impact of Construction Variability on Pavement Performance

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16. Abstract

The long term performance of hot mixed asphalt (HMA) pavements is significantly impacted by the properties of the HMA mixture. Regardless of how well the mix design and structural design have been prepared, the properties of the materials delivered to the job site, such as gradation, binder content, and the in-place compaction will ultimately control the behavior of the pavement under the combined action of traffic and environment. The job mix formula allows for certain tolerances in the HMA construction, this research studied the effect of construction variability on performance if the delivered product goes outside the tolerances range.

The construction variability was studied for the northern (Lockwood) and southern (Sloan) Nevada aggregate sources mixed with an unmodified AC-20 and AC-30, respectively. Forty two mixes were prepared for each source and tested for general strength using the resilient modulus, for rutting using the Asphalt Pavement Analyzer, for fatigue using the flexural beam fatigue and for thermal cracking using the Thermal Stress Restrained Specimen Test.

Construction variability has a significant impact on pavement performance regardless of the aggregate source and binder type. However, some laboratory prepared mixtures may provide better performance than the optimum mixture but such mixtures may be impractical in the field. If the contractor violates the specification limits, then there is 81% chance that the pavement section will have lower performance than the optimum mix, therefore quality control is recommended to keep the mixes within the specification limits.

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EXECUTIVE SUMMARY

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The construction variability was studied for the northern (Lockwood) and southern (Sloan) Nevada aggregate sources mixed with an unmodified AC-20 and AC-30, respectively. Forty two mixes were prepared for each source and tested for general strength using the resilient modulus, for rutting using the Asphalt Pavement Analyzer, for fatigue using the flexural beam fatigue and for thermal cracking using the Thermal Stress Restrained Specimen Test.

Construction variability has a significant impact on pavement performance regardless of the aggregate source and binder type. However, some laboratory prepared mixtures may provide better performance than the optimum mixture but such mixtures may be impractical in the field. If the contractor violates the specification limits, then there is 81% chance that the pavement section will have lower performance than the optimum mix, therefore quality control is recommended to keep the mixes within the specification limits.

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1 INTRODUCTION

The long-term performance of a hot mixed asphalt (HMA) pavement is significantly impacted by the properties of the HMA mixture. Regardless of how well the mix design and structural design have been prepared, the properties of the materials delivered to the job site, such as gradation, binder content, and the in-place compaction (i.e., air-voids) will ultimately control the behavior of the pavement under the combined action of traffic and environment. In order to control these critical factors, it is very important to understand how they impact the long-term performance of the pavement and assess their actual contributions toward performance.

1.1 Objective

The objective of this research was to evaluate the impact of construction variability in aggregate gradation, binder content, and in-place air-voids, on the performance of HMA pavements. The performance of HMA pavements was measured in terms of their resistance to rutting, fatigue cracking, and thermal cracking using advanced laboratory testing techniques. Materials were selected to cover common sources used in northern and southern Nevada and typical mix designs.

1.2 Scope

This research evaluated the HMA construction variability in terms of changes in aggregate gradation, binder content, and air-voids. Two aggregate sources were identified, one source in northern Nevada (Lockwood) and one source in southern Nevada (Sloan). Neat asphalt binders were used for each source. An AC-20 binder from Paramount Petroleum Company and an AC-30 binder from Koch Performance Asphalt (KPA) were used with the north aggregate and the south aggregate, respectively.

The gradation variability was defined in terms of violations on the # 4 and # 200 sieves. A total of four sources of variability in a given HMA mix when evaluated: gradation on # 4 sieve, gradation on # 200 sieve, binder content, and air-voids. Each variability source was simulated at three levels of: Low, medium, and high. The "medium" level represents the job mix formula (JMF) value while the "low" represents below the JMF level and the "high" represents above the JMF level. The following mixtures were considered impractical, and therefore, omitted from the study:

- Low binder content and low air-voids
- High binder content and high air-voids

In addition to the impractical mixes, the low level in the percent passing # 200 sieve was not achievable in the lab and was not present in any field project. Finally, a total of 84 HMA mixtures were evaluated for the two aggregate sources to assess the impact of construction variability on performance. All HMA mixtures were produced in the laboratory.

The impacts of construction variability on the performance of the HMA laboratory mixtures were measured using the resilient modulus and the Asphalt Pavement Analyzer (APA) for rutting resistance, the flexural beam fatigue for fatigue cracking resistance and the thermal stress restrained specimen test (TSRST) for the low temperature cracking resistance (TSRST was conducted on the northern mixtures only). In addition to the above direct measures, the performances of the HMA mixtures were assessed through their volumetric properties such as air-voids, voids in mineral aggregates (VMA), voids filled with asphalt (VFA), and asphalt film thickness (TF).

2 BACKGROUND

The design and construction of HMA mixtures represent the two critical steps in building HMA pavements. Usually, an HMA mixture is designed in the laboratory and a job mix formula (JMF) is produced for field implementation. Along with the JMF comes specification limits which control the acceptable ranges of the produced mixture. Specification limits are developed to recognize the inherent variability in the production and lay-down process; however, variations within these limits may still impact the long-term performance of the HMA pavement. The impact of these variations on performance can be positive toward one distress mode while negative toward another. For example, a reduction in the binder content can improve the resistance to rutting while it jeopardizes the mixture's resistance to cracking. Therefore, a meaningful assessment of the impact of construction variability must cover all prevailing failure modes, simultaneously.

Numerous research efforts have been conducted to assess the impact of construction variability on the performance of HMA pavements. Most recently, the WesTrack project evaluated the impact of construction variability on HMA mixtures designed with the Superpave volumetric mix design method (1). Direct implementation of the WesTrack data to Nevada's mixtures faces some problems:

- WesTrack used Superpave while Nevada uses the Hveem design,
- WesTrack gradations are significantly different than Nevada's gradations, and
- Failure modes at WesTrack do not resemble actual failure modes on Nevada's highways.

In summary, the sensitivity of HMA mixtures to construction variability is significantly impacted by local conditions represented by aggregate sources and gradations, mix design method, and binder type and grade. For example, an HMA mix with 6% passing # 200 sieve may be more sensitive to variations in the binder content than a mix with 4% passing # 200 sieve. Therefore, a true assessment of the impact of construction variability must consider the actual conditions of the HMA mixture where the results of the assessment will be implemented.

2.1 The WesTrack Project

WesTrack was a multimillion dollar accelerated pavement test facility constructed in Nevada approximately 60 miles southeast of Reno (1). The pavement test facility was designed, constructed, and operated by a team of private companies and universities (the WesTrack team) under contract to the U.S. Department of Transportation's Federal Highway Administration (FHWA) and the National Cooperative Highway Research Program (NCHRP). The test track, which included 26 HMA pavement test sections, was designed and constructed between October 1994 and October 1995. Traffic was initiated in March 1996 and was completed in February 1999. Five million equivalent single-axle loads (ESALs) were placed on the track during the trafficking period (1).
The objective of the WesTrack project was to evaluate the effect of variations in materials and construction quality of HMA mixtures on pavement performance under constant traffic and environmental conditions. The WesTrack experimental design is shown in Table 1. Three aggregate gradations, three asphalt binder contents and three in-place air-void contents were targeted. Since it is unlikely that hot-mix asphalt pavements will be placed at low asphalt binder contents and low air-voids or at high asphalt binder contents and high air-voids, these cells were not filled. Five replicate sections were included in the experimental design and they are reflected by the cells which have two numbers.

A non-modified asphalt binder was selected for use at WesTrack with a grade of PG 64-22, which can also be classified as an AC-20. A single primary aggregate source was selected for the project while three gradations were utilized as shown in Figure 1 and Table 2.

The Superpave volumetric mix design method was used to select the optimum binder contents for the various mixtures. The asphalt content was then varied by plus and minus 0.7 percent by total weight of mix (twm) from the optimum asphalt binder content for each of the gradations. The target asphalt binder content for each mixture was designated as "medium" while asphalt binder contents 0.7 below and 0.7 above the "medium" were designated as "low" and "high," respectively.

Three levels of in-place air-voids were selected. An eight percent air-void level was considered to be typical for HMA construction in the United States. Thus the 8% air-void was designated as the "medium" level. The other target air-voids selected were 4 and 12 percent and were designated as "low" and "high", respectively.

The main pavement performance measures were rut depth and percentage of the wheelpath area with fatigue cracking. Approximately 5 million ESALs were applied during the trafficking period. Several original sections failed early in the experiment; they were replaced with a mix that followed the coarse gradation, but changed from the crushed gravel used in the original sections to a more angular, quarried andesite aggregate. The total experiment yielded significantly different levels of permanent deformation and fatigue cracking among the various test sections.

2.1.a Performance Measurements

Rut depth was measured with the Dipstick, the Arizona DOT transverse profile device, and the laser transverse profile device developed by NATC (1). The frequency of testing was biweekly when the track was subjected to traffic. During periods of rapid rutting or fatigue cracking, testing frequency was increased. After 1.5 million ESALs, 5 sections failed in rutting and by the end of the trafficking period (5 million ESALs), only 15 of the original sections survived. Table 3 and Figure 2 summarize the rut depth data "peak to valley" obtained during the project after 1.5 million ESALs (3).

The presence of fatigue cracking was recorded during the visual condition survey (1). Fatigue cracking was also assessed biweekly when the track was subjected to traffic and more frequently during periods of rapid development of fatigue cracking. Fatigue cracking was reported as the percent of the wheelpath area with fatigue cracking. Table 4 and Figure 3 summarize the fatigue cracking data obtained after 2.8 million ESALs (3).

2.1.b Performance of various Mixtures in Rutting

The "fine" mixtures showed an increase in rut depth with an increase in initial in-place air-voids regardless of the asphalt binder content (2). A slight increase in rut depth was noted with increase in asphalt content. The rutting behavior of the "fine" mixture was not very sensitive to changes in asphalt binder content.

The "fine plus" mixtures showed a slight increase in rut depth as the initial in-place air-voids were increased (2). A large increase in rut depth was noted at the high binder content. The high binder content mixtures at both the medium and low air-void contents were removed after 1.5 million ESALs due to excessive rutting. The rutting behavior of the "fine plus" graded mixture was sensitive to changes in asphalt binder content at levels above the optimum asphalt binder content.

The "coarse" mixtures showed an increase in rut depth as the initial in-place air-voids were increased (2). The rut depth of this mixture at all asphalt binder contents was large. The high binder content mixtures at both the medium and low air-void contents were removed after 1.5 million ESALs due to excessive rutting.

The "coarse" graded mixtures experienced the highest rut depth (2). As the initial air-voids were decreased, the differences among the rutting of the "fine plus" and the "coarse" graded mixtures decrease. In general, higher rut depths were observed for the "coarse" graded mixtures as compared to the "fine" graded mixtures under all conditions available for comparisons. The rutting of the "fine plus" gradation mixture was between the "fine" and "coarse" graded mixture.

2.1.c Performance of various Mixtures in Fatigue

The "fine" mixtures showed a small amount of fatigue cracking in the section that was placed at the initial high air-void content (2). All measured fatigue cracking percentages in the "fine" mixtures were less than about 5 percent which is considered insignificant.

The "fine plus" mixtures showed a small amount of fatigue cracking in two of the sections having high initial air-void content and low asphalt binder content.

The "coarse" mixtures showed a significant amount of fatigue cracking at the medium and high initial air-void contents (2). The largest amount of fatigue cracking was associated with the mix having high air-void content. Significant amounts of fatigue cracking were also evident in the low asphalt content mixtures at medium and high initial air-void contents. An increase in the amount of fatigue cracking was evident at the lower binder contents. Fatigue cracking was not evident in the "coarse" mixtures with high asphalt contents as they were removed at 1.5 million ESALs due to excessive rutting. The "coarse" graded mixtures experienced the largest amount of fatigue cracking under all conditions of comparison (asphalt binder content and initial in-place air-voids) (2).

2.1.d Influence of Binder Content

The WesTrack experiment showed that the magnitude of the asphalt binder content influences the rutting and fatigue cracking performance of pavements. The coarse-graded Superpave mixtures appear to be more sensitive to changes in the asphalt binder content than the fine-graded mixtures. Thus, aggregate gradation influences the sensitivity of HMA mixtures to variations in the asphalt binder content.

2.1.e Influence of Aggregate Gradation

The WesTrack data showed significant differences in the performance of the fine- and coarse-graded Superpave mixtures (1). Differences in performance from both rutting and fatigue cracking were evident. The coarse-graded mixtures appeared to be more sensitive to asphalt binder content, percent passing the # 200 sieve, and in-place air-voids than the fine-graded mixtures. The coarse-graded mixtures placed at WesTrack must have low in-place air-voids and lower than Superpave design asphalt binder contents to perform at an acceptable level. The poor performance of the coarse mixtures appear to be contrary to highway agencies experiences with these two types of mixtures (at least in the pre-Superpave era).

2.1.f Influence of Air-Voids

A statistically significant separation of in-place air-voids was obtained during placement of the HMA mixtures at WesTrack (1). In general, the control of the in-place air-void content achieved by controlling the temperature of the mixture and the rolling patterns was good. The magnitude of the in-place air-voids influences the permanent deformation and fatigue cracking performance of the pavements placed at WesTrack. The coarse-graded Superpave mixtures appear to be more sensitive to the in-place air-void content than the fine-graded Superpave mixtures. Thus, aggregate gradation influences the sensitivity of an HMA mix to the in-place air-void content.

2.2 Other Studies on Rutting Sensitivity

Williams explored the relationships between HMA mixture properties and rutting susceptibility as measured under wheel-tracking devices (4). The overall conclusion of this analysis was that while many factors play a role in the rutting characteristics of HMA samples, regression procedures were unable to determine valid mathematical relationships; however, several important trends were documented. As VMA increases, so does rut depth. As the PG high temperature binder grade increases, rut depths decrease. Increases in the asphalt binder content and film thickness negatively impact the resistance of the HMA mixtures to rutting.

In 1999 Kandhal et al. suggested that the minimum VMA should be based on the minimum desirable asphalt film thickness instead of minimum asphalt binder content because the latter will be different for mixes with different gradations (5). Mixes with coarse gradation (and therefore, a low surface area) have difficulty meeting the minimum VMA requirement based on minimum asphalt binder content despite thick asphalt films. A rational approach based on a minimum asphalt film thickness was proposed and validated. The film thickness approach represented a more direct, equitable, and appropriate method of ensuring asphalt mix durability, and it encompasses various mix gradations.

In 2001 Anderson et al. evaluated the influence of changes in VMA on the performance-related properties of coarse and fine HMA mixtures (6). The effect of an increase in VMA on mixture properties at intermediate (fatigue cracking resistance) and high (rutting resistance) temperatures was studied. Laboratory testing indicated that the majority of properties generated from intermediate temperature stiffness and fatigue tests, and their associated analyses, showed no statistically significant difference between the fatigue properties of a mixture with 13 percent VMA and a mixture with 15 percent VMA. There also was no statistically significant difference between the fatigue properties of a coarse mixture and a fine mixture with the same VMA. Whereas high temperature testing indicated some statistically significant differences among HMA mixtures with different VMA and different gradations (coarse and fine). Shear test data suggested that an increase from 13 percent to 15 percent VMA significantly improves the shear fatigue characteristics of the fine mixture by 50 percent, while reducing the high temperature stiffness and rutting characteristics by no more than 30 percent. By contrast, increasing the VMA from 13 percent to 15 percent in the coarse mixture appears detrimental to its performance properties. This result can support industry concerns that higher VMA in coarse mixtures may be unnecessary and may lead to poor performance. The fine mixtures in this study exhibited less sensitivity to changes in VMA.

3 EXPERIMENTAL PROGRAM

In order to achieve widely applicable results, the impact of construction variability on the long-term performance of HMA pavements must be evaluated over a wide range of material sources and mix designs. This study evaluated two aggregate sources: one in the north (Lockwood) and one in the south (Sloan). Each source was sampled from the available stockpiles at the time of the conduct of research. Typical neat asphalt binders were used with each aggregate source obtained from common suppliers in the north and south.

3.1 North Aggregate Source

In December 2002, aggregates were sampled from the Lockwood quarry located approximately ten miles east of Reno, Nevada, along Interstate 80. Three hundred sacks were sampled from five different stockpiles. The five stockpiles as well as the weight of aggregate sampled from each are: 1" (5,000-lbs), ½" (3,000-lbs), 3/8" (4,000-lbs), Rock Dust (9,000-lbs) and Wadsworth Sand (3,000-lbs). The gradations of each stockpile are shown in Table 5 while the aggregate blend and the corresponding Type 2C requirements (7) are shown in Table 6. The aggregate properties are shown in Table 7.

The AC-20 asphalt binder was sampled from Paramount Petroleum Corporation, Fernley, Nevada. The binder was tested by the Nevada DOT, Materials Division and the results are shown in Table 8.

3.2 South Aggregate Source

In June 2003, aggregates were sampled from the Sloan quarry located south of Las Vegas, Nevada, along Interstate 15. Two hundred and fifty sacks were sampled from five different stockpiles. The five stockpiles as well as the weight of aggregate sampled from each are: 1" (2,000-lbs), ¾" (5,500-lbs), ¼" (3,500-lbs), Crushed Fines (3,500-lbs) and Washed Fines (4,500-lbs). The gradations of each stockpile are shown in Table 9 while the aggregate blend and the corresponding Type 2C requirements are shown in Table 10. The aggregate properties are shown in Table 11.

The AC-30 asphalt binder was sampled from Koch Performance Asphalt, Nevada. The binder was tested by the Nevada DOT, Materials Division and the results are shown in Table 12.

3.3 Experimental Limits

The first step in setting up the experiment design was to identify the limits to be used to simulate the field construction variability. As mentioned earlier, the objective of this study is to evaluate the impact of construction variability in gradation, air-voids, and asphalt binder content on the performance of HMA mixtures. Therefore, it is necessary to decide on the level of variations in these factors to be introduced in the HMA mixtures. This study used actual field data to identify the applicable variation limits for each of the three variables, i.e., gradations, air-voids, and asphalt binder content.

A group of six Type 2C projects that have experienced construction variability were identified by the Nevada Department of Transportation (NDOT). All records of field gradations, binder contents and the in-place air-voids for the six projects were obtained. One of the projects had four job mix formulas while the rest had only one each.

3.3.a Limits on Gradation

The NDOT Type 2C gradation has specification limits on eight sieves (1", ¾", ½", ⅜", # 4, # 10, # 40 and # 200). Field gradations are normally monitored based on the specification sieves. More than 160 gradations were evaluated from the six projects to examine the trend of violating the job mix formula. It was found that none of these gradations failed the low percent passing the # 200 sieve. Six gradation trends were identified based on the # 4 and # 200 sieves and they were labeled as LM, MM, HM, LH, MH, and HH, where L = Low, M = Medium, and H = High levels. The first letter represents the condition on sieve # 4 and the second letter represents the condition on sieve # 200.

The low and high violations on sieve # 4 and the high violations on sieve # 200 were analyzed in terms of their differences from the JMF. The differences were used since each project has its unique JMF, and therefore the actual values of the violations differ from one project to another. The mean and standard deviation (STD) were calculated for each group (i.e., low and high differences) as shown in Table 13. Finally, it was decided to use the mean ± 2×STD as the upper and lower limits for the violations on sieves # 4 and # 200. The mean ± 2×STD represents the range which covers 98 percent of the data.

The simulated six gradation trends for the north aggregate and south aggregate are shown in Tables 14 and 15, respectively along with the JMF and specification range for the MM gradation. The allowable tolerances for the JMF (7) are shown in Table 16. The job-mix range is obtained from the MM gradation ± the tolerances from Table 16 while the specification ranges are used as the absolute maximum/minimum allowable limits. In other words, if the job-mix range exceeds the specification range, then the specification range governs.

The six gradations curves for the Lockwood aggregate source are shown in Figures 4 and 5 for the medium and high percent passing # 200, respectively and Figures 6 and 7 show the Sloan aggregate source. The dotted lines represent the job-mix range for the MM gradation.

3.3.b Limits on Asphalt Content

The field binder content data were also obtained for the same projects that were evaluated for gradations. The violations in the binder content from the optimum AC ranged from – 0.9% by dry weight of aggregate (dwa) to + 0.7% by dwa from the optimum AC.

Knowing that there is a strong relationship between fatigue resistance and asphalt binder content, it was decided to use fatigue testing to select the variations limits. Four mixes were prepared: one at the mix design binder content of 4.3%, one at optimum – 0.3%, one at optimum – 0.5%, and one at optimum – 0.8%. All mixtures had the same mix design gradations and 7% air-voids. The four mixes were tested in the flexural beam fatigue test at 72°F and their behaviors are shown in Figure 8.

A statistical analysis was run on the data of the four mixes to check if the drop in the binder content would be significant on the fatigue life. Table 17 summarizes the fatigue data analysis where NS means the fatigue life wasn't significantly impacted and asterisk means the fatigue life was significantly impacted (more asterisk means more significant). The fatigue data showed that the changes of – 0.3, – 0.5, and – 0.8% in the binder content are all significant (except for Opt – 0.3% at low strain level). Based on this data, it was decided to use a range of ± 0.6% violations in the binder content. The ± 0.6% range was a good representation of the field data while producing practical mixtures in the laboratory (not too dry or too wet).

3.3.c Limits on Air-Voids

The Nevada DOT field density specifications states that the density of the field compacted HMA mix should be evaluated based on the results of 5 nuclear tests taken at randomly selected locations within a section as described in Test Method Nev. T335. The mean density of the 5 nuclear tests shall not be below 92% nor above 96% (with no single test below 90% nor above 97%) of the maximum theoretical density achieved in the DOT's Field Laboratory using Test method Nev. T324. In other words, the air-voids mean of 5 tests should be between 4% and 8% with no single test outside the range of 3 to 10%. Based on the six projects data, most of the air-voids violations were on the high side (10 to 11%) whereas few of them were on the low side (3%), therefore the three selected air-void levels were 3%, 7% and 11%.

3.4 Experimental Matrix

A total of six gradations, three asphalt binder content levels, and three air-voids levels were selected to be evaluated for the two aggregate and binder sources. As previously pointed out, some impractical mixtures were identified:

- Low binder content and low air-voids
- High binder content and high air-voids
- Low level for the percent passing # 200 sieve

This reduced the number of combinations to 42 for each aggregate and binder source as shown in Table 18, which will sum up to 84 combinations for the two aggregate sources.

Each mix was identified by four characters (two letters and two numbers). The first two letters refer to the gradation (passing # 4 and passing # 200 levels, respectively) and the last two numbers refer to the binder content level and air-voids level, respectively. The letters L, M, and H indicate low, medium, and high for the percent passing # 4 and passing # 200 levels, and the numbers 1, 2, and 3 indicate low, medium, and high for the binder content and air-voids levels. For example, the **LM21** is a mix which is **L**ow on percent passing # 4 sieve, **M**edium on percent passing # 200 sieve, **M**edium on asphalt binder content, and **L**ow on percent air-voids. The variability levels for the Lockwood and Sloan sources are summarized in Tables 19 and 20, respectively.

3.5 Measured Properties

The properties selected to measure the impact of construction variability on the performance of HMA mixtures are as follows:

- Resistance to rutting
- Resistance to fatigue cracking
- Resistance to low temperature cracking (north mixtures only)

In addition to the above direct measures, the performances of HMA mixtures can also be assessed through their volumetric properties such as air-voids, voids in mineral aggregates (VMA), and voids filled with asphalt (VFA).

3.5.1 Samples Preparation

The aggregate from the various stockpiles were dried at 230°F, blended, sieved into eight fractions and then samples were batched to the desired mass. The dried samples were mixed with four to five percent water for two minutes, then 1.5 percent hydrated lime by weight is added and remixed for an additional three minutes with the moistened aggregates. The lime-treated samples were then marinated for 48 hours in a sealed plastic container. After marination, the samples were dried and mixed with the corresponding binder content. The mixing temperature used was 315°F for both sources as obtained from the Temperature vs. Viscosity plot. After mixing, the samples were aged for 16 hours at 140°F.

The resilient modulus samples were compacted in the Hveem compactor at 230°F that imparts a kneading action type of consolidation by a series of individual impressions. The compaction efforts were adjusted for each mix to achieve the required air-void level; for example, the 3% air-voids mixes would take more tamps and more pressure than the 7% and 11% air-voids mixes for the same gradation and binder content. The compacted resilient modulus samples were 2.4" to 2.6" high and having a 4.0" diameter.

The asphalt pavement analyzer samples were compacted using the Superpave Gyratory Compactor (SGC). The compaction temperature used was 298°F. The compaction was done using the "Constant Height" option in the SGC, where the only factor that would change for the different combinations was the mass of the sample. A higher mass would be needed for a low air-void sample at a constant height, but it would require more gyrations to achieve the set height. The SGC ram pressure was 600 kPa (87 psi) for most of the mixes except for two where the pressure was 1 MPa (145 psi) since it took more than 600 gyrations at the 600 kPa pressure to get to the required height; therefore an increase in pressure was justified.

The beam fatigue samples were compacted in the kneading compactor. The compaction temperature used was 298°F or 325°F depending on the mix; the 325°F was needed for some mixes in order to achieve the required air-void level. The compacted beams were 16" long by 3" thick by 3" wide. The beams were cut using a diamond blade saw to 15" long by 2" thick by 2 ½" wide.

The thermal stress restrained specimen test (TSRST) samples were compacted similarly to the beam fatigue samples. The beams were cut to 10" long by 2" thick by 2" wide. The beams were conditioned overnight in the environmental chamber at 5°C before testing; which is the starting temperature of the TSRST test.

3.5.2 NDOT Hveem Mix Design

The basic concepts of the Hveem mix design method were originally developed by Francis Hveem when he was a Resident Engineer for the California Division of Highways in the late 1920s and 1930s. Currently, the Hveem method is used by several western states. The basic philosophy surrounding the Hveem method can be summarized in the following three points:

1. HMA requires enough asphalt binder to coat each aggregate particle to an optimum film thickness (allowing for its absorption into the aggregate).
2. HMA requires sufficient stability to resist traffic loading. This stability is generated by internal friction between aggregate particles and cohesion (or tensile strength) created by the binder.
3. HMA durability increases with thicker asphalt binder film thickness.

Based on this philosophy, the design asphalt content is selected as the one resulting in the highest durability without dropping below a minimum allowable stability. The "pyramid" method is a common method of selecting the optimum asphalt binder content. In addition to the specification on minimum stability, the NDOT has additional specifications on the percent air-voids and VMA at which the optimum binder content is selected. As a part of the NDOT Hveem mix design, the resistance of the compacted HMA mixture to moisture-induced damage is also checked.

3.5.3 Strength Test

Since the rutting resistance depends to a large extent on the stiffness of the mixture, the Mr test was used as a general strength test to give an indication of this rutting resistance.

The repeated-load indirect tension test (ASTM D 4123) for determining the resilient modulus (Mr) property of bituminous mixtures is conducted by applying compressive loads with a haversine waveform (loading = 0.1 sec and rest = 0.9 sec). The load is applied on the vertical diametral plane of a cylindrical specimen. The resulting instantaneous horizontal deformation of the specimen is measured. The testing temperature was 77°F with a loading frequency of 1 Hertz. Figure 9 shows the resilient modulus schematics along with the formula used to calculate the Mr from the measured deflection, load, and an assumed Poisson's ratio (μ) of 0.35.

3.5.4 Resistance to Rutting

Rutting is considered the most important distress that contributes to the failure of an HMA pavement. It is represented by a permanent deformation that develops gradually in the longitudinal direction under the wheel paths due to high traffic loads associated with high pavement temperatures. Rutting leads to safety problems when water collects in the ruts and creates dangerous driving conditions like hydroplaning and increased splash and spray.

This research evaluated the resistance of HMA mixtures to rutting using the APA which subjects the mixture to repeated wheel loads and measures the resulting permanent deformation at elevated temperatures.

The APA test is standardized under AASHTO TP63-03, where a loaded concave wheel travels along a pressurized rubber hose that rests upon the HMA sample. Four six-inch diameter cylindrical samples were compacted for each mix combination using the Superpave Gyratory Compactor to a height of 3". Samples are secured within form-fitting acrylic blocks during testing. The APA wheel load is 100-lb and the hose pressure is 100 psi. The samples were conditioned for four hours before being tested in the dry condition at 140°F under 8,000 cycles. A data acquisition program records rut depths at 2 points within each sample and their average is reported. Four specimens were tested for every mix making four replicates per combination. Figure 10 shows the schematics of the Asphalt Pavement Analyzer.

3.5.5 Resistance to Fatigue Cracking

Load-associated fatigue cracking of HMA pavements has remarkably increased with the recent changes in traffic volume, weight, and tire pressure. This type of distress is generally not considered as a safety hazard unless it becomes pronounced and severe but rather a structural distress that significantly affects ride quality and pavement smoothness.

The resistance of the HMA mixtures to fatigue cracking was evaluated using the flexural beam fatigue test "AASHTO T321-03: Determining the Fatigue Life of Compacted Hot-Mix Asphalt Subjected to Repeated Flexural Bending". The beam specimen is subjected to a 4-point bending with free rotation and horizontal translation at all load and reaction points. This produces a constant bending moment over the center portion of the specimen. In this research, the constant strain tests were conducted at different strain levels; using a repeated sinusoidal load at a frequency of 10 Hz, and a test temperature of 72°F. Initial flexural stiffness was measured at the 50th load cycle. Fatigue life or failure was defined as the number of cycles corresponding to a 50% reduction in the initial stiffness. The following model was used to characterize the fatigue behavior of the HMA mixtures:

$$N_f = k_1 \left(\frac{1}{\varepsilon_t} \right)^{k_2}$$

where N_f is the fatigue life (number of load repetitions to fatigue damage), ε_t is the applied tensile strain, and k_1 and k_2 are experimentally determined coefficients (10). Figure 11 shows the schematics of flexural beam fatigue.

3.5.6 Resistance to Thermal Cracking

Low temperature cracking of HMA pavements has been a serious concern to pavements/materials engineers for many years. The mechanism of low temperature cracking is very complex in nature due to the influence of material, structural and environmental conditions on the process.

The Thermal Stress Restrained Specimen Test (AASHTO TP10-93) was used in this research to determine the low-temperature cracking susceptibility of the HMA mixtures. The device cools down a beam specimen at a rate of 10°C/hour while restraining it from contracting. While the beam is being cooled down, tensile stresses are generated due to the ends being restrained. The HMA mixture would fracture as the internally generated stress exceeds its tensile strength. The temperature at which fracture occurs is referred to as "fracture temperature" and represents the field temperature under which the pavement will experience thermal cracking. Figure 12 shows the schematics of the TSRST.

3.5.7 Volumetric Properties

As indicated earlier, volumetric properties are evaluated as an indirect measure of the impact of construction variability on the performance of HMA mixtures. Standard AASHTO procedures are used to measure the volumetric properties of the HMA mixtures.

3.6 Statistical Analysis

Statistical analyses were conducted on the data to assess the impact of the individual factors and their combinations. Statistical techniques were used to identify the significant factors and their interactions while taking into consideration the repeatability of the various laboratory tests. Statistical analyses are valuable tools for this experiment in two aspects:

- Incorporate test methods variability, and
- Identify and evaluate interactions among factors.

Every test method has its associated level of repeatability. The repeatability of the test method becomes critical when comparing the properties of two HMA mixtures measured with the same test method. Statistical analyses are used to assess the difference in the measured properties in light of the expected repeatability of the testing method. With the help of the statistical analyses, the engineer will be able to decide whether the difference in the measured properties is a true difference or a difference caused by the repeatability of the test method.

The Analysis of Variance (ANOVA) was used to test the significance of the differences between the mix design (MM22) and the other mixtures. The statistical testing was conducted at an alpha level of 0.05, meaning that for each comparison reported as being significantly different; there is only a 5% chance that this is not true. The ANOVA is an inferential statistical technique which provides methods for comparing the means of two or more treatments by analyzing the variances of the measurements. The Dunnett method for treatment versus control comparison was used (9). All data were checked for violations in the outliers and normality assumptions.

The statistical analyses were performed using a SAS 8.02 macro-file called "Fixoneql" prepared by Dr. G. Fernandez from the "Department of Applied Economics and Statistics" at the "University of Nevada, Reno".

4 PERFORMANCE OF THE NORTH HMA MIXTURES

This section examines the impact of construction variability on the resistance of the north HMA mixtures to rutting, fatigue, and thermal cracking. The north HMA mixtures consist of the Lockwood aggregate source with the Paramount AC-20 binder.

4.1 NDOT Hveem Mix Design

The NDOT Hveem mix design was performed on the MM gradation (Type 2C) containing aggregate from the Lockwood quarry and an AC-20 binder from the Paramount Petroleum Corporation (Table 21). The Hveem stability, percent air-voids, unit weight, and percent voids in mineral aggregate versus the binder content are shown in Figures 13–16, respectively. The optimum binder content was selected at 4.3% by dry weight of aggregate (dwa). The mix properties and volumetrics at the design binder content are shown in Table 22.

As a part of the Hveem mix design, the resistance of the compacted HMA mixture to moisture-induced damage had to be checked using AASHTO T283. This test evaluates the ratio of the moisture-conditioned tensile strength over the dry tensile strength of the HMA mix. Moisture conditioning consists of saturating a compacted HMA sample to around 75% and subjecting it to one cycle of freeze/thaw. The results from this test as well as the NDOT specifications are shown in Table 23.

4.2 Resilient Modulus

The Mr property was evaluated for the 42 combinations of the north HMA source. It was performed on at least three replicates for each of the 42 combinations. Table 24 sorts the resilient modulus data in decreasing order where HH12 has the highest Mr and MH23 has the lowest. Note that the MM22 mix represents the optimum mix design conditions.

Table 25 summarizes the differences between the mean of the various mixtures and the MM22, simultaneous 95% confidence limits, and the significance denoted by (***) for the

41 mixes. The data in Table 25 show that 13 mixes have Mr properties that are not significantly different from the Mr property of the MM22 mix. Fifteen mixes had significantly higher Mr properties than the MM22 and thirteen mixes had significantly lower Mr properties than the MM22. It should be noted that higher Mr properties does not lead to better performance since a higher Mr may result in a brittle mix that experiences fatigue and thermal cracking.

4.3 Resistance to Rutting under the Asphalt Pavement Analyzer

The 42 mixes were tested for rutting resistance using the APA at 140°F. The average rutting, standard deviation, coefficient of variation and number of specimens are shown in Table 26. The AASHTO TP63 standard specifies that rut depth standard deviations greater than or equal to 2.0 mm indicates the presence of outliers. The data in Table 26 indicate that the highest standard deviation is 1.0 mm, and therefore, there are no outliers. The APA data show that as the binder content or the air-voids are increased, the rutting is increased indicating that the rutting resistance of the HMA mix is highly sensitive to these factors.

A statistical analysis was conducted to identify the mixes that are significantly different from the control mix MM22. The results are presented in Table 27 where 16 mixes were found to be similar to the MM22 mix and 12 mixes experienced significantly higher rut depths than the MM22 and 13 mixes had significantly lower rut depths than the MM22.

4.4 Resistance to Fatigue Cracking

The 42 mixes were tested for fatigue cracking. The coefficients k_1 and k_2, the fit parameter R^2, and the number of beams tested for the 29 mixes are shown in Table 28. Tables 29, 30, and 31 summarize the statistical comparisons of the various mixtures at the strain levels of 300, 500 and 800 microns. Note that all comparisons were conducted relative to the MM22 mix. The three strain levels were selected to represent thick, medium, and thin HMA layers under standard axle loads, or they can also represent the responses of a given HMA layer to various load levels.

At the 300 microns (Table 29), 10 mixes have significantly better fatigue life than the MM22 and 11 mixes have significantly worse fatigue life than the MM22, whereas 20 mixes were not significant. At the 500 microns (Table 30), 14 mixes have significantly better fatigue life than the MM22 and 18 mixes have significantly worse fatigue life than the MM22, whereas nine mixes were not significant. At the 800 microns (Table 31), 13 mixes have significantly better fatigue life than the MM22 and 15 mixes have significantly worse fatigue life than the MM22, whereas 13 mixes were not significant.

4.5 Resistance to Thermal Cracking

The low temperature cracking susceptibility of the HMA mixtures was evaluated using the TSRST. The lower the fracture temperature, the better resistance to thermal cracking the mix will have. The average, standard deviation, and coefficient of variation for the fracture temperatures as well as the number of beams tested for each of the 42 combinations are shown in Table 32.

The statistical analysis of the TSRST data is presented in Table 33 where the fracture temperatures of the various mixtures are compared to the fracture temperature of the MM22 mix. It is found that 20 mixes are similar to the MM22 mix. Six mixes had significantly colder fracture temperatures (better resistance to thermal cracking) than the MM22 mix and 15 mixes had significantly warmer fracture temperatures (worse resistance to thermal cracking) than the MM22 mix.

4.6 Volumetric Properties for the Lockwood Aggregate Source

Volumetric properties were evaluated as an indirect measure of the impact of construction variability on the performance of HMA mixtures. The binder content, air-void level, dust proportion (DP), voids in mineral aggregate (VMA), voids filled with asphalt (VFA), surface area (SA), and average film thickness (TF) were obtained for the 42 mixes (Table 34). The aggregate surface area is the highest for the mixes having high percent passing # 200, and therefore the average asphalt film thickness would be the lowest for these mixes for the same binder content. The dust proportion is the ratio of the percent passing # 200 to the effective binder content and it is an important parameter to consider in fatigue and thermal cracking resistance.

4.7 Performance Analysis

In summary, a total of 42 mixtures (including MM22) were tested for Mr at 77°F, rutting, fatigue, and thermal cracking resistance.

This analysis looked into the impacts of the individual and combined violations from the optimum design on the potential performance of the HMA mixtures. The Mr property was used as an indicator of the general quality of the mix. In addition to the performance properties, a compaction indicator was also included in the evaluation process. The inclusion of such an indicator was found necessary to represent the consequences of the various violations on the workability of the mixtures. For example, certain combinations of the violations may produce an HMA mix that exhibits good resistance to rutting, fatigue, and thermal cracking. However, the mix may require extremely high compaction efforts and high temperatures to produce it in the laboratory. Such mix will be impractical in the field and may never reach the properties measured in the laboratory. Mixtures that required unusual techniques, i.e., compaction efforts and/or temperatures, will be labeled as "impractical".

Table 35 shows the violations, mix ID, and the significance from the control mix (MM22) for the general strength Mr, rutting, fatigue at three strain levels, thermal cracking and compaction observations.

The first part of the analysis used the Mr to classify the mixtures into not significantly different (NS), significantly higher (S Higher), or significantly lower (S Lower) based on the comparison with the Mr property of the MM22 mix. For the rutting, fatigue, and thermal cracking properties, the mixtures were labeled as not significantly different (NS), significantly better (S Better), or significantly worse (S Worse) based on the comparison with the properties of the MM22 mix.

4.7.1 Violations in Single Factor

The LM22 mix represents an HMA mixture that is low on the # 4 sieve and meeting all specification limits on the # 200 sieve, binder content, and air-voids. This mix showed a lower Mr property than the optimum mix, MM22. Its resistance to rutting was not affected by such violation. Its fatigue life becomes better at low strain level, is unaffected at medium strain level, and becomes worse at high strain level. Its resistance to thermal cracking is not significantly different from the MM22 mix.

When the percent passing # 4 is violated on the low side, the mix would become slightly coarser, and therefore, would have a higher film thickness which justifies the drop in the Mr property. However, the increase in the film thickness is not significant enough to reduce the mixture's resistance to rutting or improve its resistance to fatigue and thermal cracking. The LM22 would not be a desirable mix due to its reduced general strength. Such a low strength will lead to durability and moisture sensitivity problems which will jeopardize the long-term performance of the HMA pavement.

The HM22 mix represents an HMA mixture that is high on the # 4 sieve and meeting all specification limits on the # 200 sieve, binder content, and air-voids. This mix showed an insignificant Mr property than the optimum mix, MM22. Its resistance to rutting was not affected by such violation. Its fatigue life becomes better at the three strain levels. Its resistance to thermal cracking becomes better than the MM22 mix.

The MH22 mix represents an HMA mixture that is high on the # 200 sieve and meeting all specification limits on the # 4 sieve, binder content, and air-voids. This mix showed an insignificant Mr property than the optimum mix, MM22. Its resistance to rutting becomes worse by such violation. Its fatigue life becomes worse at the three strain levels. Its resistance to thermal cracking is not significantly different from MM22 mix.

The MM12 mix represents an HMA mixture that is low on the binder content, and meeting the specification limits on the # 4 and # 200 sieves, and on the air-voids. This mix showed a higher Mr property than the optimum mix, MM22. Its resistance to rutting is unaffected by such violation. Its fatigue life becomes worse at the low, medium, and high strain levels. Its resistance to thermal cracking is not significantly different from MM22 mix.

The MM32 mix represents an HMA mixture that is high on the binder content, and meeting the specification limits on the # 4 and # 200 sieves, and on the air-voids. This mix showed insignificance in the Mr property. Its resistance to rutting becomes worse by such violation. Its fatigue life is unaffected at low strain level, becomes better at medium and high strain levels. Its resistance to thermal cracking becomes better than the MM22 mix.

The MM21 mix represents an HMA mixture that is low on the air-voids, and meeting the specification limits on the # 4 and # 200 sieves, and on the binder content. This mix showed a higher Mr property than the optimum mix, MM22. Its resistance to rutting becomes better by such violation. Its fatigue life is unaffected at low and medium strain levels, and becomes better at high strain level. Its resistance to thermal cracking becomes better for such violation. This mix is considered as "impractical" due to the high compaction effort and high temperature required to reach the 3% air-void level.

The MM23 mix represents an HMA mixture that is high on the air-voids, and meeting the specification limits on the # 4 and # 200 sieves, and on the binder content. This mix showed insignificance in the Mr property. Its resistance to rutting becomes worse by such violation. Its fatigue life is unaffected at low strain level, becomes worse at medium and high strain levels. Its resistance to thermal cracking is unaffected by such violation.

4.7.2 Violations in Two Factors

The LH22 mix represents an HMA mixture that is low on the # 4 sieve and high on # 200 sieve and meeting all specification limits on the binder content, and air-voids. This mix showed insignificance in the Mr property. Its resistance to rutting becomes worse by such violation. Its fatigue life is unaffected at low strain level, becomes worse at medium and high strain levels. Its resistance to thermal cracking is unaffected by such violations.

The HH22 mix represents an HMA mixture that is high on the # 4 and # 200 sieves and meeting all specification limits on the binder content, and air-voids. This mix showed a higher Mr property than the optimum mix, MM22. Its resistance to rutting becomes better by such violations. Its fatigue life is unaffected at low strain level, becomes worse at medium strain level, and is unaffected at high strain level. Its resistance to thermal cracking becomes worse than the MM22 mix.

When the percent passing # 4 and # 200 are violated on the high side, the mix becomes finer, and therefore, would have a thinner film thickness which justifies the increase in the Mr property. This increase in the Mr property increased its resistance to rutting, but reduced the fatigue and thermal cracking resistance.

The LM12 mix represents an HMA mixture that is low on the # 4 sieve, low on binder content and meeting all specification limits on the # 200 sieve, and air-voids. This mix showed an insignificant Mr property than the optimum mix, MM22. Its resistance to rutting was not affected by such violation. Its fatigue life becomes worse at the three strain levels. Its resistance to thermal cracking becomes worse than the MM22 mix.

The LM32 mix represents an HMA mixture that is low on the # 4 sieve, high on binder content and meeting all specification limits on the # 200 sieve, and air-voids. This mix showed a lower Mr property than the optimum mix, MM22. Its resistance to rutting becomes worse by such violations. Its fatigue life is unaffected at low strain level, becomes better at medium and high strain levels. Its resistance to thermal cracking is not significantly different from MM22 mix.

The violation of percent passing # 4 on the low side, and the violation of binder content on the high side produce a mix having the highest film thickness which justifies the drop in Mr property, and therefore, in rutting resistance. On the other hand, it would increase the fatigue cracking resistance.

The HM12 mix represents an HMA mixture that is high on the # 4 sieve, low on binder content and meeting all specification limits on the # 200 sieve, and air-voids. This mix showed a higher Mr property than the optimum mix, MM22. Its resistance to rutting becomes better by such violations. Its fatigue life is unaffected at low strain level, becomes worse at medium and high strain levels. Its resistance to thermal cracking becomes worse than the MM22 mix. This mix is considered as "impractical" due to the high compaction effort and high temperature required to reach the 7% air-void level.

The violations of percent passing # 4 on the high side and of the binder content on the low side produce a very stiff mix which justifies the increase in the Mr property, and therefore, an increase in the rutting resistance. However, a drop in the binder content would jeopardize the fatigue and thermal cracking resistance and made the mix unworkable.

The HM32 mix represents an HMA mixture that is high on the # 4 sieve, high on binder content and meeting all specification limits on the # 200 sieve, and air-voids. This mix showed an insignificant Mr property than the optimum mix, MM22. Its resistance to rutting was not affected by such violation. Its fatigue life becomes better at the three strain levels. Its resistance to thermal cracking becomes better than the MM22 mix.

The LM21 mix represents an HMA mixture that is low on the # 4 sieve, low on air-voids and meeting all specification limits on the # 200 sieve, and binder content. This mix showed a higher Mr property than the optimum mix, MM22. Its resistance to rutting becomes better by such violations. Its fatigue life becomes better at low and medium strain levels, and is unaffected at high strain level. Its resistance to thermal cracking is not significantly different from the MM22 mix.

A higher compaction effort of the LM22 mix would produce the LM21 mix. The LM22 mix had lower Mr property, whereas the LM21 has higher Mr property than the optimum mix MM22. The increase in stiffness is due to the reduction in air-voids.

The LM23 mix represents an HMA mixture that is low on the # 4 sieve, high on air-voids and meeting all specification limits on the # 200 sieve, and binder content. This mix showed a lower Mr property than the optimum mix, MM22. Its resistance to rutting becomes worse by such violations. Its fatigue life becomes better at low and medium strain levels, and is unaffected at high strain level. Its resistance to thermal cracking is not significantly different from MM22 mix.

The LM23 mix was not compacted in order to obtain the 11% air-voids, which justifies the low Mr property, and therefore a worse rutting resistance.

The HM21 mix represents an HMA mixture that is high on the # 4 sieve, low on air-voids and meeting all specification limits on the # 200 sieve, and binder content. This mix showed a high Mr property than the optimum mix, MM22. Its resistance to rutting becomes better by such violations. Its fatigue life is unaffected at low, medium, and high strain level. Its resistance to thermal cracking is not significantly different from MM22 mix. This mix is considered as "impractical" due to the very high compaction effort and high temperature required to reach the 3% air-void level.

The HM23 mix represents an HMA mixture that is high on the # 4 sieve, high on air-voids and meeting all specification limits on the # 200 sieve, and binder content. This mix showed a lower Mr property than the optimum mix, MM22. Its resistance to rutting is unaffected by such violations. Its fatigue life is unaffected at low strain level, becomes better at medium and high strain levels. Its resistance to thermal cracking is not significantly different from the MM22 mix.

The MH12 mix represents an HMA mixture that is high on the # 200 sieve, low on binder content and meeting the specification limits on the # 4 sieve, and on the air-voids. This mix showed a higher Mr property than the optimum mix, MM22. Its resistance to rutting becomes better by such violations. Its fatigue life becomes worse at low, medium, and high strain levels. Its resistance to thermal cracking becomes worse by such violations.

The MH12 mix has one of the lowest asphalt film thicknesses making it stiff for rutting resistance, but at the same time this would jeopardize the fatigue and thermal cracking resistance.

The MH32 mix represents an HMA mixture that is high on the # 200 sieve, high on binder content and meeting the air-voids and the # 4 specification limits. This mix showed an insignificant Mr property. Its resistance to rutting becomes worse by such violations. Its fatigue life is unaffected at low, medium, and high strain levels. Its resistance to thermal cracking is not significantly different from MM22 mix.

The MH21 mix represents an HMA mixture that is high on the # 200 sieve, low on air-voids and meeting the specification limits on the # 4 sieve, and on the binder content. This mix showed a higher Mr property than the optimum mix, MM22. Its resistance to rutting becomes better by such violations. Its fatigue life is unaffected at low, medium, and high strain levels. Its resistance to thermal cracking becomes worse by such violations. This mix is considered as "impractical" due to the high compaction effort and high temperature required to reach the 3% air-void level.

The MH23 mix represents an HMA mixture that is high on the # 200 sieve, high on air-voids and meeting the specification limits on the # 4 sieve, and on the binder content. This mix showed a lower Mr property than the optimum mix, MM22. Its resistance to rutting becomes worse by such violations. Its fatigue life is unaffected at low strain level, and becomes worse at medium and high strain levels. Its resistance to thermal cracking becomes worse by such violations.

The MM13 mix represents an HMA mixture that is low on binder content, high on air-voids, and meeting all specification limits on the # 4 and # 200 sieves. This mix showed an insignificant Mr property than the optimum mix, MM22. Its resistance to rutting becomes worse by such violation. Its fatigue life becomes worse at the three strain levels. Its resistance to thermal cracking is not significantly different from MM22 mix.

The MM31 mix represents an HMA mixture that is high on the binder content, low on the air-voids and meeting the specification limits on the # 4 and # 200 sieves. This mix showed a higher Mr property than the optimum mix, MM22. Its resistance to rutting is unaffected by such violations. Its fatigue life is unaffected at low strain level, becomes better at medium and high strain levels. Its resistance to thermal cracking is not significantly different from the MM22 mix.

4.7.3 Violations in Three Factors

The HH12 mix represents an HMA mixture that is high on the # 4 and # 200 sieves, low on binder content and meeting the air-voids specification limits. This mix showed the highest Mr property among the 42 mixes. Its resistance to rutting becomes better by such violations. Its fatigue life becomes worse at low, medium, and high strain levels. Its resistance to thermal cracking becomes worse than the MM22 mix. This mix is considered as "impractical" due to the high compaction effort and high temperature required to reach the 7% air-void level.

The HH gradation has the highest surface area and if combined with low binder content, then it would produce a mix having the lowest film thickness, which justifies the increase in the Mr property and in the rutting resistance. On the other hand, the low film thickness jeopardizes the fatigue and thermal cracking resistance.

The HH32 mix represents an HMA mixture that is high on the # 4 and # 200 sieves, high on binder content and meeting the specification limits on air-voids. This mix showed an insignificant Mr property than the optimum mix, MM22. Its resistance to rutting was not affected by such violation. Its fatigue life becomes better at the three strain levels. Its resistance to thermal cracking is not significantly different from the MM22 mix.

The LH12 mix represents an HMA mixture that is low on the # 4 sieve, high on # 200 sieve, low on binder content and meeting the air-voids specification limits. This mix showed an insignificant Mr property. Its resistance to rutting is unaffected by such violations. Its fatigue life becomes worse at low and medium strain levels, and is unaffected at high strain level. Its resistance to thermal cracking becomes worse for such violations.

The LH32 mix represents an HMA mixture that is low on the # 4 sieve, high on the # 200 sieve, high on binder content and meeting the air-voids specification limits. This mix showed a lower Mr property than the optimum mix, MM22. Its resistance to rutting becomes worse by such violations. Its fatigue life is unaffected at low, medium, and high strain levels. Its resistance to thermal cracking is not significantly different from MM22 mix. This mix required minimal compaction to reach the 7% air-voids level.

The difference between the LH32 and the LM32 mixes is that LH32 has an additional 4% passing # 200 sieve than the LM32, which reflects the non-significance in fatigue life for LH32 while the LM32 mix had a better fatigue life than the optimum mix MM22. This implies that an increase in passing # 200 sieve would reduce the fatigue life for most of the mixes.

The HH21 mix represents an HMA mixture that is high on the # 4 and # 200 sieves, low on air-voids and meeting the binder content specification limits. This mix showed a higher Mr property than the optimum mix, MM22. Its resistance to rutting becomes better by such violations. Its fatigue life becomes worse at low and medium strain levels, and is unaffected at high strain level. Its resistance to thermal cracking becomes better for such violations. This mix is considered as "impractical" due to the very high compaction effort and high temperature required to reach the 3% air-void level.

The increase in percent passing # 200 sieve with a drop in percent air-voids would significantly increase the Mr property, and therefore an increase in rutting resistance is expected. The HH21 mix is very brittle to deflect, which jeopardizes the fatigue life of this mix since the fatigue testing is performed at a constant strain (deflection) mode. The drop in air-voids increases the thermal cracking resistance.

The HH23 mix represents an HMA mixture that is high on the # 4 and # 200 sieves, high on air-voids and meeting the binder content specification limits. This mix showed a lower Mr property than the optimum mix, MM22. Its resistance to rutting is unaffected by such violations. Its fatigue life becomes better at low strain level, and is unaffected at medium and high strain levels. Its resistance to thermal cracking becomes worse for such violations.

The increase in air-voids significantly drops the Mr property, but the fine gradation recovered some of the fatigue life. The air-void level dominates to a high extent the thermal cracking resistance, which justifies the warmer temperature at which the HH23 mix fractured.

The LH21 mix represents an HMA mixture that is low on the # 4 sieve, high on the # 200 sieve, low on air-voids and meeting the binder content specification limits. This mix showed a higher Mr property than the optimum mix, MM22. Its resistance to rutting becomes better by such violations. Its fatigue life is unaffected at low, medium, and high strain levels. Its resistance to thermal cracking becomes worse for such violations.

When the air voids level is violated on the low side, then the mix becomes stiffer, which would increase the Mr property and the rutting resistance but jeopardizes the thermal cracking.

The LH23 mix represents an HMA mixture that is low on the # 4 sieve, high on the # 200 sieve, high on air-voids and meeting the binder content specification limits. This mix showed a lower Mr property than the optimum mix, MM22. Its resistance to rutting becomes worse by such violations. Its fatigue life becomes worse at low strain level, is unaffected at medium strain level, and becomes better at high strain level. Its resistance to thermal cracking becomes worse by such violations. The LH23 mix required minimal compaction in order to obtain the 11% air-voids, which justifies the low Mr property, and therefore a worse rutting resistance.

The LM13 mix represents an HMA mixture that is low on the # 4 sieve, low on binder content, and high on air-voids and meeting the percent passing # 200 specification limits. This mix showed a lower Mr property than the optimum mix, MM22. Its resistance to rutting is unaffected by such violations. Its fatigue life is unaffected at low strain level, and becomes worse at medium and high strain levels. Its resistance to thermal cracking becomes worse by such violations.

The binder content is an important factor for the fatigue and thermal cracking resistance, and a drop in the AC level would jeopardize this kind of performance.

The HM31 mix represents an HMA mixture that is high on the # 4 sieve, high on binder content, and low on air-voids and meeting the percent passing # 200 specification limits. This mix showed a higher Mr property than the optimum mix, MM22. Its resistance to rutting becomes better by such violations. Its fatigue life becomes better at low, medium, and high strain levels. Its resistance to thermal cracking is not significantly different from the MM22 mix. This mix is considered as "impractical" due to the high compaction effort and high temperature required to reach the 3% air-void level.

The LM31 mix represents an HMA mixture that is low on the # 4 sieve, high on binder content, low on air-voids and meeting the #200 sieve specification limits. This mix showed an insignificant Mr property. Its resistance to rutting is unaffected by such violations. Its fatigue life becomes better at low and medium strain levels, and is unaffected at high strain level. Its resistance to thermal cracking becomes better for such violations.

The HM13 mix represents an HMA mixture that is high on the # 4 sieve, low on binder content, and high on air-voids and meeting the percent passing # 200 specification limits. This mix showed a lower Mr property than the optimum mix, MM22. Its resistance to rutting is unaffected by such violations. Its fatigue life becomes better at low strain level, and becomes worse at medium and high strain levels. Its resistance to thermal cracking is not significantly different from the MM22 mix.

The increase in percent passing # 4 sieve combined with a drop in binder content, made the HM13 mix better in rutting resistance.

The MH31 mix represents an HMA mixture that is high on the # 200 sieve, high on the binder content, low on the air-voids and meeting the # 4 sieve specification limits. This mix showed a higher Mr property than the optimum mix, MM22. Its resistance to rutting becomes better by such violations. Its fatigue life is unaffected at low strain level, and becomes better at medium and high strain levels. Its resistance to thermal cracking is not significantly different from MM22 mix.

The MH13 mix represents an HMA mixture that is high on the # 200 sieve, low on the binder content, high on the air-voids and meeting the # 4 sieve specification limits. This mix showed a lower Mr property than the optimum mix, MM22. Its resistance to rutting is unaffected by such violations. Its fatigue life becomes worse at low, medium, and high strain levels. Its resistance to thermal cracking becomes worse for such violations.

The presence of the high on # 200 sieve combined with the low binder content jeopardizes the fatigue and thermal cracking resistance for most of the mixes, while being not significant for the rutting resistance.

4.7.4 Violations in Four Factors

The LH13 mix represents an HMA mixture that is low on the # 4 sieve, high on the # 200 sieve, low on binder content, and high on air-voids. This mix showed a lower Mr property than the optimum mix, MM22. Its resistance to rutting is unaffected by such violations. Its fatigue life is unaffected at low strain level, and becomes worse at medium and high strain levels. Its resistance to thermal cracking becomes worse for such violations.

The LH13 is one of the worst combinations that may occur in the field, since the increase in passing # 200 sieve, with a drop in binder content, and an increase in air-voids would jeopardize the Mr property, the fatigue and thermal cracking resistance. However, the increase in passing # 200 sieve with a reduction in the binder content made the rutting resistance unaffected.

The LH31 mix represents an HMA mixture that is low on # 4 sieve, high on # 200 sieve, high on the binder content, and low on air-voids. This mix showed insignificance in the Mr property. Its resistance to rutting becomes worse by such violation. Its fatigue life is unaffected at low strain level, becomes better at medium and high strain levels. Its resistance to thermal cracking is unaffected by such violations.

The HH31 mix represents an HMA mixture that is high on the # 4 and # 200 sieves, high on binder content, and low on air-voids. This mix showed a higher Mr property than the optimum mix, MM22. Its resistance to rutting becomes better by such violations. Its fatigue life is unaffected at low strain level, and becomes better at medium and high strain levels. Its resistance to thermal cracking is not significantly different from the MM22 mix. This mix is considered as "impractical" due to the high compaction effort and high temperature required to reach the 3% air-void level.

The HH13 mix represents an HMA mixture that is high on the # 4 and # 200 sieves, low on binder content, and high on air-voids. This mix showed a lower Mr property than the optimum mix, MM22. Its resistance to rutting is unaffected by such violations. Its fatigue life becomes worse at low and medium strain levels, and is unaffected at high strain levels. Its resistance to thermal cracking becomes worse by such violations. The same observations of the LH13 apply to the HH13 mix.

5 PERFORMANCE OF THE SOUTH HMA MIXTURES

This section examines the relationship among construction variability and the resistance of the south HMA mixtures to rutting, and fatigue cracking. TSRST testing was not performed on these mixtures since this failure mode is not common in southern Nevada. The south HMA mixtures consist of the Sloan aggregate source with the KPA AC-30 binder.

5.1 NDOT Hveem Mix Design

The NDOT Hveem mix design was performed on the MM gradation (Type 2C) containing aggregate from the Sloan quarry and an AC-30 binder from KPA (Table 36). The Hveem stability, percent air-voids, unit weight, and voids in mineral aggregate versus the binder content are shown in Figures 17–20, respectively. The optimum binder content was selected at 3.8% by dwa. The mix properties and volumetrics at the design binder content are shown in Table 37.

The resistance of the compacted HMA mixture to moisture-induced damage was evaluated using AASHTO T283. The results from this test are shown in Table 38.

5.2 Resilient Modulus

The Mr property was evaluated for the 42 combinations of the south HMA source. Table 39 sorts the resilient modulus data in decreasing order where HM21 has the highest Mr and LH23 has the lowest.

Table 40 summarizes the differences between the mean of the various mixtures and the MM22. The level of significance is denoted by number of "*" for the 41 mixes. The data in Table 40 show that 13 mixes have Mr properties that are not significantly different than the Mr property of the MM22 mix. Five mixes had significantly higher Mr properties than the MM22 and 23 mixes had significantly lower Mr properties than the MM22.

5.3 Resistance to Rutting under the Asphalt Pavement Analyzer

The 42 mixes were tested for rutting resistance using the APA at 140°F. The average rutting, standard deviation, coefficient of variation and number of specimens are shown in Table 41.

A statistical analysis was conducted to identify the mixes that are significantly different from the control mix MM22. The results are presented in Table 42 where 14 mixes were found to be similar to the MM22 mix and 10 mixes experienced significantly higher rut depths than the MM22 and 17 mixes had significantly lower rut depths than the MM22.

5.4 Resistance to Fatigue Cracking

The 42 mixes were tested for fatigue cracking. The coefficients k_1 and k_2, the fit parameter R^2, and the number of beams tested are shown in Table 43.

Tables 44 and 45 summarize the statistical comparisons of the various mixtures at the strain levels of 300 and 500 microns. Note that there is no comparison at the high strain level of 800 microns. The 800 micro-strain level is considered unrealistic for these mixtures due to their high Mr properties.

At the 300 microns (Table 44), 8 mixes have significantly better fatigue life than the MM22 and 23 mixes have significantly worse fatigue life than the MM22, whereas 10 mixes were not significant. At the 500 microns (Table 45), 6 mixes have significantly better fatigue life than the MM22 and 21 mixes have significantly worse fatigue life than the MM22, whereas 14 mixes were not significant.

5.5 Volumetric Properties for the Sloan Aggregate Source

Volumetric properties were evaluated as an indirect measure of the impact of construction variability on the performance of HMA mixtures. The binder content, air-voids level, dust proportion, voids in mineral aggregate, voids filled with asphalt, surface area, and average film thickness were obtained for the 42 mixes (Table 46).

5.6 Performance Analysis

In summary, a total of 42 mixtures (including MM22) were tested for Mr at 77°F, rutting, and fatigue cracking resistance.

As for the Lockwood mixtures, the Sloan mixtures had also a compaction indicator to represent the consequences of the various violations on the workability of the mixtures. Some of the mixes were considered impractical since they required high compaction effort to produce in the laboratory, and may never be realized in the field.

Table 47 shows the violations, mix ID, and the significance from the control mix (MM22) for the general strength Mr, rutting, fatigue at two strain levels, and compaction observations.

The Mr property was classified into not significantly different (NS), significantly higher (S Higher), or significantly lower (S Lower) based on the comparison with the Mr property of the MM22 mix.

For the rutting, and fatigue cracking properties, the mixtures were labeled as not significantly different (NS), significantly better (S Better), or significantly worse (S Worse) based on the comparison with the properties of the MM22 mix.

5.6.1 Violations in Single Factor

The LM22 mix represents an HMA mixture that is low on the # 4 sieve and meeting all specification limits on the # 200 sieve, binder content, and air-voids. This mix showed a lower Mr property than the optimum mix, MM22. Its resistance to rutting was not affected by such violation. Its fatigue life becomes worse at low and medium strain levels.

When the percent passing # 4 is violated on the low side, the mix would become slightly coarser, and therefore, would have a higher film thickness which justifies the drop in the Mr property. However, the increase in the film thickness is not significant enough to reduce the mixture's resistance to rutting. Whenever the passing # 4 sieve is violated on the low side, then the fatigue life would be worse or not significant from that of the optimum unless the mix has high asphalt film thickness or low air-voids.

The HM22 mix represents an HMA mixture that is high on the # 4 sieve and meeting all specification limits on the # 200 sieve, binder content, and air-voids. This mix showed an insignificant Mr property. Its resistance to rutting becomes better by such violation. Its fatigue life becomes better at low and medium strain levels.

The MH22 mix represents an HMA mixture that is high on the # 200 sieve and meeting all specification limits on the # 4 sieve, binder content, and air-voids. This mix showed an insignificant Mr property. Its resistance to rutting was not affected by such violation. Its fatigue life becomes worse at low and medium strain levels.

The MM12 mix represents an HMA mixture that is low on binder content and meeting all specification limits on the # 4 and #200 sieves, and air-voids. This mix showed an insignificant Mr property. Its resistance to rutting becomes better by such violation. Its fatigue life becomes worse at low and medium strain levels.

The MM32 mix represents an HMA mixture that is high on the binder content, and meeting the specification limits on the # 4 and # 200 sieves, and on the air-voids. This mix showed a lower Mr property than the optimum mix, MM22. Its resistance to rutting becomes worse by such violation. Its fatigue life is unaffected at low strain level, and becomes better at medium strain level.

The MM21 mix represents an HMA mixture that is low on the air-voids, and meeting the specification limits on the # 4 and # 200 sieves, and on the binder content. This mix showed a higher Mr property than the optimum mix, MM22. Its resistance to rutting becomes better by such violation. Its fatigue life is unaffected at low and medium strain levels. This mix is considered as "impractical" due to the high compaction effort required to reach the 3% air-void level.

The MM23 mix represents an HMA mixture that is high on the air-voids, and meeting the specification limits on the # 4 and # 200 sieves, and on the binder content. This mix showed a lower Mr property than the optimum mix, MM22. Its resistance to rutting becomes worse by such violation. Its fatigue life becomes worse at low and medium strain levels.

5.6.2 Violations in Two Factors

The LH22 mix represents an HMA mixture that is low on the # 4 sieve, high on the # 200 sieve and meeting all specification limits on the binder content, and air-voids. This mix showed a lower Mr property than the optimum mix, MM22. Its resistance to rutting is unaffected by such violations. Its fatigue life is unaffected at low and medium strain levels.

The HH22 mix represents an HMA mixture that is high on the # 4 and # 200 sieves and meeting all specification limits on the binder content, and air-voids. This mix showed an insignificant Mr property. Its resistance to rutting becomes better by such violations. Its fatigue life is unaffected at low and medium strain levels.

The LM12 mix represents an HMA mixture that is low on the # 4 sieve, low on binder content and meeting all specification limits on the # 200 sieve, and air-voids. This mix showed a lower Mr property than the optimum mix, MM22. Its resistance to rutting becomes better by such violations. Its fatigue life becomes worse at low and medium strain levels.

The LM12 and LH12 mixes are the only mixes having significantly lower Mr properties, and at the same time having better rutting resistance than the optimum mix MM22. This is due to the presence of the coarse gradation and the low binder content in these mixtures. The LM12 mix jeopardizes the fatigue life since it is coarse and has a low film thickness.

The LM32 mix represents an HMA mixture that is low on the # 4 sieve, high on binder content and meeting all specification limits on the # 200 sieve, and air-voids. This mix showed a lower Mr property than the optimum mix, MM22. Its resistance to rutting becomes worse by such violations. Its fatigue life is becomes better at low and medium strain levels.

The violation of percent passing # 4 on the low side, and the violation of binder content on the high side produce a mix having the highest film thickness which justifies the drop in Mr property, and therefore, in rutting resistance. On the other hand, it would increase the fatigue cracking resistance.

The HM12 mix represents an HMA mixture that is high on # 4 sieve, low on binder content and meeting all specification limits on #200 sieve, and air-voids. This mix showed an insignificant Mr property. Its resistance to rutting becomes better by such violations. Its fatigue life becomes worse at low and medium strain levels. This mix is considered as "impractical" due to the high compaction effort required to reach the 7% air-void level.

The HM32 mix represents an HMA mixture that is high on the # 4 sieve, high on binder content and meeting all specification limits on the # 200 sieve, and air-voids. This mix showed a lower Mr property than the optimum mix, MM22. Its resistance to rutting is unaffected by such violations. Its fatigue life is becomes better at low and medium strain levels.

The failure of the passing # 4 sieve on the high side makes the mix finer, which would require a higher binder content to coat the particles. The failure in the binder content on the high side provides this additional binder content making it not significant in the rutting resistance. The HM32 mix has a higher film thickness than MM22 making it better in fatigue resistance.

The LM21 mix represents an HMA mixture that is low on the # 4 sieve, low on air-voids and meeting all specification limits on the # 200 sieve, and binder content. This mix showed a higher Mr property than the optimum mix, MM22. Its resistance to rutting becomes better by such violations. Its fatigue life is unaffected at low and medium strain levels.

A comparison between the LM22 and the LM21 mixes show that a drop in air-voids would increase the Mr property, the rutting resistance, and the fatigue life for the LM gradation.

The LM23 mix represents an HMA mixture that is low on the # 4 sieve, high on air-voids and meeting all specification limits on the # 200 sieve, and binder content. This mix showed a lower Mr property than the optimum mix, MM22. Its resistance to rutting becomes worse by such violations. Its fatigue life becomes worse at low and medium strain levels.

The LM23 mix was not compacted in order to obtain the 11% air-voids, which justifies the low Mr property, and therefore a worse rutting resistance.

The HM21 mix represents an HMA mixture that is high on the # 4 sieve, low on air-voids and meeting all specification limits on the # 200 sieve, and binder content. This mix showed higher Mr property than the optimum mix, MM22. Its resistance to rutting becomes better by such violations. Its fatigue life is unaffected at low and medium strain levels. This mix is considered as "impractical" due to the very high compaction effort required to reach the 3% air-void level.

The HM23 mix represents an HMA mixture that is high on the # 4 sieve, high on air-voids and meeting all specification limits on the # 200 sieve, and binder content. This mix showed a lower Mr property than the optimum mix, MM22. Its resistance to rutting is unaffected by such violations. Its fatigue life is unaffected at low and medium strain levels.
All the Sloan mixes with high air-voids have significantly lower Mr property than that of the optimum mix MM22. Most of these mixes have significantly lower fatigue life than MM22.

The MH12 mix represents an HMA mixture that is high on # 200 sieve, low on binder content and meeting all specification limits on #4 sieve, and air-voids. This mix showed an insignificant Mr property. Its resistance to rutting becomes better by such violations. Its fatigue life becomes worse at low and medium strain levels.

The MH32 mix represents an HMA mixture that is high on the # 200 sieve, high on binder content and meeting the specification limits on the # 4 sieve, and on the air-voids. This mix showed a lower Mr property than the optimum mix, MM22. Its resistance to rutting becomes worse by such violations. Its fatigue life is unaffected at low strain level and becomes better at medium strain level.

The MH32 mix required minimal compaction to reach the 7% air-void level, which justifies the lower Mr property, and therefore the rutting resistance.

The MH21 mix represents an HMA mixture that is high on # 200 sieve, low on air-voids and meeting all specification limits on #4 sieve, and binder content. This mix showed an insignificant Mr property. Its resistance to rutting becomes better by such violations. Its fatigue life becomes worse at low and medium strain levels.

The MH23 mix represents an HMA mixture that is high on the # 200 sieve, high on air-voids and meeting the specification limits on the # 4 sieve, and on the binder content. This mix showed a lower Mr property than the optimum mix, MM22. Its resistance to rutting becomes worse by such violations. Its fatigue life becomes worse at low and medium strain levels.

The MM13 mix represents an HMA mixture that is low on the binder content, high on the air-voids and meeting the specification limits on the # 4 and # 200 sieves. This mix showed a lower Mr property than the optimum mix, MM22. Its resistance to rutting is unaffected by such violations. Its fatigue life becomes worse at low and medium strain levels.

The violation in low binder content and high air-voids significantly jeopardizes the fatigue life.

The MM31 mix represents an HMA mixture that is high on the binder content, low on air-voids and meeting all specification limits on the # 4 and # 200 sieves. This mix showed an insignificant Mr property. Its resistance to rutting becomes better by such violations. Its fatigue life is unaffected at low and medium strain levels.

5.6.3 Violations in Three Factors

The HH12 mix represents an HMA mixture that is high on # 4 and # 200 sieves, low on binder content and meeting the specification limits on air-voids. This mix showed an insignificant Mr property. Its resistance to rutting becomes better by such violations. Its fatigue life becomes worse at low and medium strain levels. This mix is considered as "impractical" due to the very high compaction effort required to reach the 7% air-void level.

The HH32 mix represents an HMA mixture that is high on the # 4 and # 200 sieves, high on binder content and meeting the air-voids specification limits. This mix showed lower Mr property than the optimum mix, MM22. Its resistance to rutting is unaffected by such violations. Its fatigue life is unaffected at low and medium strain levels.

The LH12 mix represents an HMA mixture that is low on the # 4 sieve, high on the # 200 sieve, low on binder content and meeting the air-voids specification limits. This mix showed a lower Mr property than the optimum mix, MM22. Its resistance to rutting becomes better by such violations. Its fatigue life becomes worse at low and medium strain levels.

The LH12 mix has one of the lowest asphalt film thicknesses due to the high passing # 200 along with the low binder content making the fatigue life significantly worse than the optimum mix.

The LH32 mix represents an HMA mixture that is low on the # 4 sieve, high on the # 200 sieve, high on binder content and meeting the air-voids specification limits. This mix showed a lower Mr property than the optimum mix, MM22. Its resistance to rutting becomes worse by such violations. Its fatigue life becomes worse at low and medium strain levels. This mix just required a leveling load to reach the 7% air-voids level.

The HH21 mix represents an HMA mixture that is high on the # 4 and # 200 sieves, low on air-voids and meeting the binder content specification limits. This mix showed a higher Mr property than the optimum mix, MM22. Its resistance to rutting becomes better by such violations. Its fatigue life becomes worse at low and medium strain levels.

This mix is considered as "impractical" due to the very high compaction effort required to reach the 3% air-void level.

The increase in percent passing # 200 sieve with a drop in percent air-voids would significantly increase the Mr property, and therefore an increase in rutting resistance is expected. The HH21 mix is very brittle to deflect, which jeopardizes the fatigue life of this mix since the fatigue testing is performed at a constant strain (deflection) mode.

The HH23 mix represents an HMA mixture that is high on the # 4 and # 200 sieves, high on air-voids and meeting the binder content specification limits. This mix showed a lower Mr property than the optimum mix, MM22. Its resistance to rutting becomes worse by such violations. Its fatigue life becomes worse at low and medium strain levels. The LH21 mix represents an HMA mixture that is low on # 4 sieve, high on # 200 sieve, low on air-voids and meeting the specification limits on binder content. This mix showed an insignificant Mr property. Its resistance to rutting becomes better by such violations. Its fatigue life becomes worse at low strain level and unaffected at medium strain levels.

The LH23 mix represents an HMA mixture that is low on the # 4 sieve, high on the # 200 sieve, high on air-voids and meeting the binder content specification limits. This mix showed a lower Mr property than the optimum mix, MM22. Its resistance to rutting becomes worse by such violations. Its fatigue life becomes worse at low strain level, and is unaffected at medium strain level. The LH23 mix was not compacted in order to obtain the 11% air-voids, which justifies the low Mr property, and therefore a worse rutting resistance.

The LM13 mix represents an HMA mixture that is low on the # 4 sieve, low on binder content, and high on air-voids and meeting the percent passing # 200 specification limits. This mix showed a lower Mr property than the optimum mix, MM22. Its resistance to rutting becomes worse by such violations. Its fatigue life becomes worse at low and medium strain levels.

The LM13 required minimal compaction to reach the 11% air-voids, which justifies the low Mr property, and therefore a worse rutting resistance.

The HM31 mix represents an HMA mixture that is high on # 4 sieve, high on binder content, low on air-voids and meeting the specification limits on # 200 sieve. This mix showed an insignificant Mr property. Its resistance to rutting becomes better by such violations. Its fatigue life becomes better at low strain level and unaffected at medium strain levels. This mix is considered as "impractical" due to the high compaction effort required to reach the 3% air-void level.

The LM31 mix represents an HMA mixture that is low on the # 4 sieve, high on binder content, low on air-voids and meeting the specification limits on the # 4 sieve. This mix showed an insignificant Mr property. Its resistance to rutting is unaffected by such violations. Its fatigue life becomes better at low and medium strain levels.

The HM13 mix represents an HMA mixture that is high on the # 4 sieve, low on binder content, and high on air-voids and meeting the percent passing # 200 specification limits. This mix showed a lower Mr property than the optimum mix, MM22. Its resistance to rutting is unaffected by such violations. Its fatigue life becomes worse at low and medium strain levels.

The MH31 mix represents an HMA mixture that is high on # 200 sieve, high on binder content, low on air-voids and meeting the specification limits on # 4 sieve. This mix showed an insignificant Mr property. Its resistance to rutting is unaffected by such violations. Its fatigue life becomes better at low strain level and unaffected at medium strain levels.

The MH13 mix represents an HMA mixture that is high on the # 200 sieve, low on the binder content, high on the air-voids and meeting the # 4 sieve specification limits. This mix showed a lower Mr property than the optimum mix, MM22. Its resistance to rutting is unaffected by such violations. Its fatigue life becomes worse at low and medium strain levels.

The presence of the high on # 200 sieve with the low binder content jeopardizes the fatigue cracking resistance for most of the mixes, while being not significant or better for the rutting resistance.

5.6.4 Violations in Four Factors

The LH13 mix represents an HMA mixture that is low on the # 4 sieve, high on the # 200 sieve, low on binder content, and high on air-voids. This mix showed a lower Mr property than the optimum mix, MM22. Its resistance to rutting is unaffected by such violations. Its fatigue life becomes worse at low and medium strain levels.

The LH31 mix represents an HMA mixture that is low on the # 4 sieve, high on the # 200 sieve, high on binder content, and low on air-voids. This mix showed a lower Mr property than the optimum mix, MM22. Its resistance to rutting is unaffected by such violations. Its fatigue life becomes better at low strain level, and is unaffected at medium strain level.

The HH31 mix represents an HMA mixture that is high on the # 4 and # 200 sieves, high on binder content, and low on air-voids. This mix showed a higher Mr property than the optimum mix, MM22. Its resistance to rutting becomes better by such violations. Its fatigue life becomes better at low strain level, and is unaffected at medium strain level. This mix is considered as "impractical" due to the high compaction effort and high temperature required to reach the 3% air-void level.

The HH13 mix represents an HMA mixture that is high on the # 4 and # 200 sieves, low on binder content, and high on air-voids. This mix showed a lower Mr property than the optimum mix, MM22. Its resistance to rutting is unaffected by such violations. Its fatigue life becomes worse at low and medium strain levels.

6 COMPARISON OF THE NORTH AND SOUTH HMA MIXTURES

This section compares the performance of the north and south HMA mixtures. Nine of the 11 mixes (82%) that ranked better than MM22 for the Lockwood aggregate source ranked also better for the Sloan aggregate source. Twenty nine out the 30 mixes (97%) that ranked lower than MM22 for the Lockwood aggregate source ranked also worse for the Sloan aggregate. Many of these mixes had similar relative performances (i.e. as compared to their corresponding MM22 mix) under the Mr, APA, beam fatigue, and TSRST indicating that the relative performance is independent on the source of the material used but it depends on the variations that occur in the field.

6.1 Ranking of the North and South HMA Mixtures

The various mixtures were ranked based on their performance in rutting, fatigue cracking, thermal cracking (northern source only), and general strength. If the performance was significantly lower (S Lower) or significantly worse (S Worse) than that of the optimum mix MM22, then a score of 1 is assigned for the corresponding performance measure, if the performance is not significant (NS) then a score of 2 is assigned, and if the performance is significantly higher (S Higher) or significantly better (S Better) then a score of 3 is assigned. The sums of all scores are then calculated for each mix and are summarized in Table 48. The mix with the highest score is ranked first while the mix with the lowest score is ranked last. Note that the scores are not consistent between the two sources since the Lockwood source was tested for thermal cracking and for beam fatigue at high strain level, while the Sloan source was not.

All the mixes that ranked higher than the optimum mix had a not significant or a significantly better performance than the MM22 for all performance tests. The impractical mixes that required high compaction effort or high temperature to reach the required air-voids are also identified in Table 48; these impractical mixes might never be realized in the field. In the case of the North aggregate, 4 out of the 11 mixtures that ranked better than the MM22 mix were classified as impractical. In the case of the South aggregate source, 4 out of the 10 mixtures that ranked better than the MM22 mix were classified as impractical. The data generated in this research indicate that there is about 79% chance for the North aggregate source, and about 82% chance for the South aggregate source that the mixes will have worse performance than the optimum mix MM22 if the there are violations in the construction specification limits.

None of the mixes that ranked better than MM22 for the two sources had low binder or high air-voids level. Many of these mixes have low air-voids combined with medium or high binder content. These mixes might experience further compaction and bleeding under early traffic leading to rutting failures in the field. This aspect of the performance was not evaluated in this research.

Some of the practical mixtures that ranked better than the MM22 were further evaluated in the Superpave Shear Tester (SST) under the repeated shear constant height (RSCH) test for both aggregate sources. The RSCH subjects the HMA to a simple shear stress and measures its permanent shear strain as a function of stress repetitions. This test condition represents the mix within the top 2" of the HMA layer. Table 49 summarizes the RSCH plastic shear strain for these mixes along with the APA rut depth. The data in Table 49 show that there is a full agreement between the RSCH and the APA indicating that these mixtures are actually better in rutting resistance than the MM22 mix.

None of the mixes that violated the binder content on the low side performed better than the optimum mix, especially in the fatigue or thermal cracking resistance.
In general, mixtures that had high percent passing # 200 were always worse than the MM22 unless a higher binder content was introduced. This indicates that anytime a high percent passing # 200 mix is produced, it will require more binder.

All mixtures that were low on the # 4 sieve and high on the # 200 sieve performed worse than the MM22 mix.

6.2 Contribution of the Mix Property toward Performance

Volumetric properties such as VMA, VFA, air-voids, and binder content, as well as the gradation, dust proportion, and asphalt film thickness have an effect on the performance. Some of these properties could be significant on rutting or Mr but not significant on fatigue or thermal cracking. Tables 50 and 51 summarize the percent contribution of each property toward the mixtures performance for the Lockwood and Sloan mixes, respectively. The percent represents the likelihood that the property could impact the performance. The higher the percent, the more significant the impact of the property would be. A positive (+) label indicates a direct relationship with performance while a negative (–) label indicates an inverse relationship. For example the VMA has a 54 percent impact on the Mr for the Lockwood source with a negative label (–) indicating that an increase in the VMA would result in a decrease in the Mr 54% of the time.

The VMA, air-voids, VFA and the percent passing # 4 have the highest impact on the Mr property for both sources. The Mr, VMA, air-voids, VFA, and passing # 4 have the highest impact on rutting performance. In addition to the strain, the asphalt film thickness, dust proportion, and binder content have the highest impact on the fatigue performance. The dust proportion, asphalt film thickness and binder content have the highest impact on the thermal cracking performance.

6.3 Impact of the Single Factor Violations on the Performance

The impact of the single factor violations on the performance was studied further as shown in Tables 52 and 53. The impacts of the various factors are represented by the percent change that the specific violation has introduced relative to the properties of the

MM22 mix. The percent change is also coupled with a label of (+) or (–). A (+) label indicates an improvement in the performance indicator and a (–) label indicates a reduction in the performance indicator. For example the violation of "Low on #4-sieve" generates a 20% reduction in the Mr property relative to the Mr property of the MM22 mix. A not significant (NS) indicates that the change is not significant enough to affect the performance.

The data from both aggregate sources show that all of the violations, except the high on #4 sieve will jeopardize the performance of the HMA mix. This indicates that a gradation that is finer on the #4 sieve may lead to improved performance.

6.4 Correlation Trends for the Performance Tests

The correlation between the performance tests and the important mix parameters are plotted in figures 21 through 31 for the two aggregate sources.

Figures 21 and 27 show that the resilient modulus Mr decreases as the VMA increases and also show that mixes that are high on the # 4 sieve have higher Mr than the mixes that are low on #4-sieve.

Figures 22 through 24 and 28 through 30 show that higher rutting occurs as the VMA increases and the mixes that are high on # 4 sieve have the lowest rutting.

In general, the fatigue life increases as the asphalt film becomes thicker as shown in figures 25 and 31. As the percent passing # 200 sieve increases, the fatigue life decreases.

As the dust proportion increases, the TSRST fracture temperature becomes warmer (less thermal resistance) as shown in Figure 26 for the Lockwood aggregate source.

7 CONCLUSIONS AND RECOMMENDATIONS

This research evaluated the performance of laboratory produced HMA mixtures under rutting, fatigue, and thermal cracking using state of the art testing technologies. Based on the analysis of the data generated from the laboratory testing of 42 mixtures from each of the two aggregate sources; north and south, the following conclusions and recommendations can be made.

- Construction variability has a significant impact on pavement performance regardless of the aggregate source and binder type.

- Some laboratory prepared mixtures may provide better performance than the optimum mixture but such mixtures may be impractical in the field.

- Mixtures that were low on the # 4 sieve and high on the # 200 sieve never achieved a performance that is equivalent to or better than the MM22 mix.

- In general, mixtures that had high percent passing # 200 were always worse than MM22 unless higher binder content was introduced.

- None of the mixes that violated the binder content on the low side performed better than the optimum mix especially in the fatigue or thermal cracking resistance.

- None of the mixes that ranked better than MM22 for the two sources had low binder content or high air-voids level.

- If the contractor violates the specification limits, then there is 81% chance that the pavement section will have lower performance than the optimum mix MM22, therefore strict quality control is recommended to keep the mixes within the specification limits.

- The majority of the mixtures that performed better than the optimum mix had low air-voids combined with medium or high binder content. This critical combination of low air-voids and high binder content leads to premature bleeding and rutting under traffic loads. Eventhough this research did not evaluate this specific aspect of the performance, such mixtures should not be permitted.

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Table 1 Experiment Design for Original 26 WesTrack Sections.

Design Air-void Content	Aggregate Gradation Designation								
	Fine (Above Restricted Zone)			Fine Plus (Above Restricted Zone)			Coarse (Below Restricted Zone)		
	Design Asphalt Contents								
	Low	Opt.	High	Low	Opt.	High	Low	Opt.	High
Low	■	04	18	■	12	09/12	■	23	25
Medium	02	01/15	14	22	11/19	13	08	05/24	07
High	03/16	17	■	10	20	■	26	06	■

Table 2 WesTrack Mixture Gradations (Fine, Fine Plus, Coarse).

Sieve Size		Fine Gradation	Fine Plus Gradation	Coarse Gradation
(US)	(mm)			
1"	25	100	100	100
3/4"	19	99.9	99.9	99.9
1/2"	12.5	88.5	88.8	82.4
3/8"	9.5	75.4	76.1	64.6
# 4	4.75	48.9	50.4	41.2
# 8	2.36	38.4	40.2	27.8
# 16	1.18	33.9	35.8	19.7
# 30	0.6	27.6	29.7	14.6
# 50	0.3	15.7	18.2	10.8
# 100	0.15	6.8	9.6	7.7
# 200	0.075	3.5	6.4	5

Table 3 WesTrack Rut Depth Summary after 1.5×10^6 ESALs.

Section Number	Designations		Rut Depth (mm)	ESALs ×10^6	Status
	Gradation	AC/AV Content			
01	Fine	MM1	9	1.5	In Service
02	Fine	LM	6	1.5	In Service
03	Fine	LH	10	1.5	In Service
04	Fine	ML	7	1.5	In Service
05	Coarse	MM1	17	1.5	In Service
06	Coarse	MH	21	1.5	In Service
07	Coarse	HM	36	1.5	Out of Service
08	Coarse	LM	17	1.5	In Service
09	Fine Plus	HL2	30	1.5	Out of Service
10	Fine Plus	LH	13	1.5	In Service
11	Fine Plus	MM2	8	1.5	In Service
12	Fine Plus	ML	9	1.5	In Service
13	Fine Plus	HM	20	1.5	Out of Service
14	Fine	HM	13	1.5	In Service
15	Fine	MM2	8	1.5	In Service
16	Fine	LH2	9	1.5	In Service
17	Fine	MH	12	1.5	In Service
18	Fine	HL	9	1.5	In Service
19	Fine Plus	MM1	13	1.5	In Service
20	Fine Plus	MH	17	1.5	In Service
21	Fine Plus	HL1	35	1.5	Out of Service
22	Fine Plus	LM	9	1.5	In Service
23	Coarse	ML	13	1.5	In Service
24	Coarse	MM2	22	1.5	In Service
25	Coarse	HL	27	1.5	Out of Service
26	Coarse	LH	15	1.5	In Service

Table 4 WesTrack Fatigue Cracking Summary after 2.8×10^6 ESALs.

Section Number	Designations		Fatigue Cracking, (% of Wheel Path)	ESALs $\times10^6$	Status
	Gradation	AC/AV Content			
01	Fine	MM1	0	2.8	In Service
02	Fine	LM	0	2.8	In Service
03	Fine	LH	5	2.8	In Service
04	Fine	ML	0	2.8	In Service
05	Coarse	MM1	50	2.8	Out of Service
06	Coarse	MH	100	2.8	Out of Service
07	Coarse	HM	0	1.5	Out of Service
08	Coarse	LM	98	2.8	Out of Service
09	Fine Plus	HL2	0	1.5	Out of Service
10	Fine Plus	LH	34	2.8	In Service
11	Fine Plus	MM2	1	2.8	In Service
12	Fine Plus	ML	1	2.8	In Service
13	Fine Plus	HM	0	2.8	Out of Service
14	Fine	HM	0	2.8	In Service
15	Fine	MM2	0	2.8	In Service
16	Fine	LH2	1	2.8	In Service
17	Fine	MH	3	2.8	In Service
18	Fine	HL		2.8	In Service
19	Fine Plus	MM1	0	2.8	In Service
20	Fine Plus	MH	0	2.8	In Service
21	Fine Plus	HL1	0	1.5	Out of Service
22	Fine Plus	LM	0	2.8	In Service
23	Coarse	ML	0	2.8	In Service
24	Coarse	MM2	0	2.8	Out of Service
25	Coarse	HL	0	1.5	Out of Service
26	Coarse	LH	69	2.8	Out of Service

Table 5 Gradation of the Lockwood Stockpiles.

Sieve Size		1" Agg. (22%)	½" Agg. (13%)	3/8" Agg. (17%)	Rock Dust (38%)	Wadsworth Sand (10%)
(US)	(mm)					
1"	25	100.0	100.0	100.0	100.0	100.0
3/4"	19	61.3	100.0	100.0	100.0	100.0
1/2"	12.5	7.3	99.9	100.0	100.0	100.0
3/8"	9.5	0.5	53.4	100.0	100.0	99.8
# 4	4.75	0.3	0.9	22.9	96.4	98.8
# 8	2.36	0.3	0.7	0.7	68.8	97.5
# 10	2.00	0.3	0.6	0.6	61.3	97.0
# 16	1.18	0.3	0.6	0.5	43.1	94.2
# 30	0.6	0.3	0.5	0.4	28.0	77.4
# 40	0.425	0.3	0.5	0.4	23.1	59.4
# 50	0.3	0.3	0.4	0.4	19.5	39.3
# 100	0.15	0.3	0.4	0.3	14.7	11.6
# 200	0.075	0.3	0.4	0.3	11.1	2.9

Table 6 North Aggregate (Lockwood) Blend and Type 2C Requirements.

Sieve Size		Blend	Type 2C Specs
(US)	(mm)		
1"	25	100	100
3/4"	19	93	88 – 95
1/2"	12.5	80	70 – 85
3/8"	9.5	73	60 – 78
# 4	4.75	51	43 – 60
# 8	2.36	36	
# 10	2.00	33	30 – 44
# 16	1.18	26	
# 30	0.6	19	
# 40	0.425	16	12 – 22
# 50	0.3	12	
# 100	0.15	8	
# 200	0.075	6	3 – 8

Table 7 Properties of the Lockwood Aggregate.

Surface Area m^2/kg (ft^2/lb)	5.8 (28.3)	Specifications
Sand Equivalent	65	
Calif. Apparent Specific Gravity	2.73	
Coarse Agg. Bulk Specific Gravity	2.66	2.85 Max
Fine Agg. Bulk Specific Gravity	2.55	2.85 Max
+ # 4 Water Absorption	1.9	5% Max
SS Soundness Coarse (%)	3	12% Max
SS Soundness Fines (%)	RD: 5; W. Sand: 3	15% Max
Liquid Limit (Before Marination)	RD: 20; W. Sand: 21	35 Max
Plasticity Index (Before Marination)	RD: NP; W. Sand: NP	10 Max
LA Abrasion (%)	12.6	37% Max
Fracture Face Count (%)	100	80% Min

Table 8 Properties of the Paramount AC-20 Binder.

Test Performed	Test Results	Nevada Specifications
Original Viscosity @ 140°F, 300 mm Hg, Poises	2033	1600 – 2400 Poises
Residue Viscosity @ 140°F, 300 mm Hg, Poises	4668	Maximum 8000 Poises
Original Kinematic Viscosity @ 275°F, cSt	413	Minimum 300 cSt
Original Penetration @ 77°F, 100 g, 5 sec, dmm	75	Minimum 60 dmm
Flash Point, °F, C.O.C.	465+	Minimum 450°F
Original Ductility @ 39.2°F, 1 cm/min, cm	7+	Minimum 5 cm
Loss on Heating, %	0.102	Maximum 0.5 %

Table 9 Gradation of the Sloan Stockpiles.

Sieve Size		1" Agg. (10%)	¾" Agg. (31%)	¼" Agg. (18%)	Crushed Fines (18%)	Washed Fines (23%)
(US)	(mm)					
1"	25	99.0	100.0	100.0	100.0	100.0
3/4"	19	19.0	97.6	100.0	100.0	100.0
1/2"	12.5	1.3	55.1	100.0	100.0	100.0
3/8"	9.5	1.0	16.7	99.9	100.0	100.0
No. 4	4.75	1.0	4.1	65.4	97.4	100.0
No. 8	2.36	1.0	3.5	12.6	78.6	91.2
No. 10	2.00	1.0	3.4	7.9	73.0	83.0
No. 16	1.18	1.0	3.3	3.5	59.6	60.0
No. 30	0.6	1.0	3.2	1.7	46.0	35.9
No. 40	0.425	1.0	3.2	1.4	40.4	25.4
No. 50	0.3	1.0	3.1	1.2	35.0	15.9
No. 100	0.15	0.9	2.9	1.0	25.4	5.2
No. 200	0.075	0.8	2.5	0.8	18.9	2.9

Table 10 South Aggregate (Sloan) Blend and Type 2C Requirements.

Sieve Size		Blend	Type 2C Specs
(US)	(mm)		
1"	25	99.9	100
3/4"	19	91.2	88 – 95
1/2"	12.5	76.2	70 – 85
3/8"	9.5	64.3	60 – 78
No. 4	4.75	53.7	43 – 60
No. 8	2.36	38.6	
No. 10	2.00	34.8	30 – 44
No. 16	1.18	26.3	
No. 30	0.6	17.9	
No. 40	0.425	14.5	12 – 22
No. 50	0.3	11.2	
No. 100	0.15	6.9	
No. 200	0.075	5.1	3 – 8

Table 11 Properties of the Sloan Aggregate.

Surface Area m^2/kg (ft^2/lb)	5.6 (27.3)	Specifications
Sand Equivalent	72	
Calif. Apparent Specific Gravity	2.81	
Coarse Agg. Bulk Specific Gravity	2.75	2.85 Max
Fine Agg. Bulk Specific Gravity	2.72	2.85 Max
+ # 4 Water Absorption	0.5	4% Max
SS Soundness Coarse	0	12% Max
SS Soundness Fines	0	15% Max
Liquid Limit (Before Marination)	1":16; ¾":12; CF:12; WF:15.	35 Max
Plasticity Index (Before Marination)	1":NP; ¾":NP; CF:NP; WF:NP.	10 Max
LA Abrasion	28.3	37% Max
Fracture Face Count	100	80% Min

Table 12 Properties of the KPA AC-30 Binder.

Test Performed	Test Results	Nevada Specifications
Original Viscosity @ 140°F, 300 mm Hg, Poises	2937	2400 – 3600 Poises
Residue Viscosity @ 140°F, 300 mm Hg, Poises	7044	Maximum 12000 Poises
Original Kinematic Viscosity @ 275°F, cSt	474	Minimum 350 cSt
Residue Kinematic Viscosity @ 275°F, cSt	689	N/A
Original Penetration @ 77°F, 100 g, 5 sec, dmm	56	Minimum 50 dmm
Residue Penetration @ 77°F, 100 g, 5 sec, dmm	33	N/A
Original Penetration @ 39.2°F, 200 g, 60 sec, dmm	17	N/A
Residue Penetration @ 39.2°F, 200 g, 60 sec, dmm	13	N/A
Flash Point, °F, C.O.C.	630	Minimum 450°F
Original Ductility @ 39.2°F, 1 cm/min, cm	9	N/A
Loss on Heating, %	0.049	Maximum 0.5 %
Solubility, %	99.95	Minimum 99.0%
Specific Gravity	1.037	N/A
Sieve Test	Pass	Pass

Table 13 Variation of the Field Gradations from the Medium Level.

Sieve Size	Average Difference (%)	Count	Standard Deviation	Av. ± 2 Std.
Low on ¾”	– 3.1	69	2.0	– 7.0
High on ¾”	3.4	80	2.1	7.6
Low on ½”	– 6.0	101	3.4	– 12.9
High on ½”	4.5	57	2.2	9.0
Low on ⅜”	– 5.1	97	3.4	– 12.0
High on ⅜”	5.5	65	2.9	11.4
Low on # 4	**– 4.3**	**82**	**2.8**	**– 10.0**
High on # 4	**4.8**	**66**	**2.9**	**10.6**
Low on # 10	– 3.5	88	1.9	– 7.3
High on # 10	3.4	68	1.9	7.2
Low on # 40	– 2.1	43	1.0	– 4.0
High on # 40	3.2	95	1.9	7.0
Low on # 200	**– 1.1**	**53**	**0.3**	**– 1.8**
High on # 200	**2.0**	**58**	**1.0**	**4.0**

Table 14 North Aggregate Simulated Field Gradations.

Sieve Size	25mm (1")	19mm (¾")	12.5mm (½")	9.5mm (⅜")	**4.75mm (#4)**	2.0mm (#10)	425mm (#40)	**75mm (#200)**
% Passing	100	93	80	73	51	33	16	6
Job Mix Range	100	88	73	66	44	30	12	4
	100	95	85	78	58	37	20	8
Spec Range	100	88	70	60	43	30	12	3
	100	95	85	78	60	44	22	8
1- LM	100	86	71	63	**41**	30	16	**6**
2- MM	100	93	80	73	**51**	33	16	**6**
3- HM	100	98	89	82	**61**	37	16	**6**
4- LH	100	86	71	63	**41**	32	21	**10**
5- MH	100	93	80	73	**51**	36	21	**10**
6- HH	100	98	89	82	**61**	40	21	**10**

Table 15 South Aggregate Simulated Field Gradations.

Sieve Size	25mm (1")	19mm (¾")	12.5mm (½")	9.5mm (⅜")	**4.75mm (#4)**	2.0mm (#10)	425mm (#40)	**75mm (#200)**
% Passing	100	91	77	68	54	37	17	5
Job Mix Range	100	88	70	61	47	33	13	3
	100	95	84	75	60	41	21	7
Spec Range	100	88	70	60	43	30	12	3
	100	95	85	78	60	44	22	8
1- LM	100	84	68	58	**44**	33	17	**5**
2- MM	100	91	77	68	**54**	37	17	**5**
3- HM	100	98	86	78	**64**	41	17	**5**
4- LH	100	84	68	58	**44**	37	22	**9**
5- MH	100	91	77	68	**54**	39	22	**9**
6- HH	100	98	86	78	**64**	44	22	**9**

Table 16 Job-Mix Formula Range Tolerances.

Aggregate passing the 4.75 mm (# 4) and larger sieves	± 7%
Aggregate passing the 2.36 mm to 150 µm (# 8 to # 100) sieves	± 4%
Aggregate passing the 75 µm (# 200) sieve	± 2%
Bitumen Content (by dry mass of aggregate)	± 0.4%

Table 17 Statistical Analysis of the Fatigue Life of the Lockwood Aggregate

	Fatigue Life		
	300 µStrain	500 µStrain	800 µStrain
Opt – 0.3%	NS	****	****
Opt – 0.5%	*	****	**
Opt – 0.8%	****	****	****

Table 18 Experimental Matrix.

Asphalt Content	**Air-voids**	**Passing # 4**								
		L			**M**			**H**		
		Passing # 200			**Passing # 200**			**Passing # 200**		
		L	**M**	**H**	**L**	**M**	**H**	**L**	**M**	**H**
1 – Target-0.6%	1: 3%									
2 – Target			LM21	LH21		MM21	MH21		HM21	HH21
3 – Target+0.6%			LM31	LH31		MM31	MH31		HM31	HH31
1 – Target-0.6%	2: 7%		LM12	LH12		MM12	MH12		HM12	HH12
2 – Target			LM22	LH22		MM22	MH22		HM22	HH22
3 – Target+0.6%			LM32	LH32		MM32	MH32		HM32	HH32
1 – Target-0.6%	3: 11%		LM13	LH13		MM13	MH13		HM13	HH13
2 – Target			LM23	LH23		MM23	MH23		HM23	HH23
3 – Target+0.6%										

Table 19 Variability Levels for the Lockwood Aggregate Source.

Percent Passing # 4 Sieve		Percent Passing # 200 Sieve		Percent AC (by dwa)		Percent AV	
L	41%	L	---	1	3.7%	1	3%
M	51%	M	6%	2	4.3%	2	7%
H	61%	H	10%	3	4.9%	3	11%

Table 20 Variability Levels for the Sloan Aggregate Source.

Percent Passing # 4 Sieve		Percent Passing # 200 Sieve		Percent AC (by dwa)		Percent AV	
L	44%	L	---	1	3.2%	1	3%
M	54%	M	5%	2	3.8%	2	7%
H	64%	H	9%	3	4.4%	3	11%

Table 21 Hveem Mix Design for the Lockwood Aggregate Source.

Binder Content, % by dwa	3.5	4.0	4.5	5.0	PROJECT SPECS (TYPE 2C)	
Max. Specific Gravity	2.545	2.526	2.508	2.490		
Bulk Specific Gravity	2.353	2.364	2.418	2.449		
Density, PCF	146.8	147.5	150.9	152.8	Min	Max
Hveem Value	42	44	39	21	37	
% Air-voids	7.5	6.4	3.6	1.6	4	7
% VMA	15.6	15.7	14.1	13.4	12	22

Table 22 Mix Properties at the Optimum AC for the Lockwood Aggregate Source.

Binder Content, % by dwa	**4.3**	PROJECT SPECS (TYPE 2C)	
Max. Specific Gravity	2.514		
Unit Weight, PCF	149		
% Air-voids	4.9		
Hveem Value	42	Min. 37	
% VMA	14.9	12	22

Table 23 Moisture Sensitivity Properties of the Lockwood Aggregate Source.

Test	Result	Requirements
Indirect Tensile Strength (Unconditioned)	120 psi	Min. 65 psi
Indirect Tensile Strength (Conditioned)	93 psi	
Indirect Tensile Strength (Retained Strength)	78%	Min. 70%

Table 24 Resilient Modulus Properties of the Lockwood Aggregate Source.

Mix ID	Resilient Modulus at 77°F (ksi)	Standard Deviation	Coefficient of Variation (%)	Count
HH12	1,021	28	2.7	4
MH21	1,019	10	1.0	3
HH21	970	52	5.4	4
HH31	886	43	4.9	3
HM21	831	42	5	4
HM12	778	48	6.2	3
MH31	759	24	3.2	3
HM31	700	36	5.1	4
MM21	694	32	4.6	4
MH12	671	45	6.7	4
HH22	669	38	5.6	4
LM21	628	30	4.9	4
MM12	623	13	2.1	3
MM31	610	32	5.2	4
LH21	609	16	2.6	4
HM22	560	15	2.7	5
HH32	528	22	4.2	4
LM12	511	16	3.2	4
Control MM22	**504**	**35**	**6.9**	**5**
MH22	490	27	5.6	4
LH12	478	30	6.3	4
HM32	472	17	3.6	5
LM31	472	35	7.4	4
MM13	469	20	4.4	3
LH22	468	25	5.3	3
LH31	460	17	3.8	3
MM23	447	11	2.5	3
MH32	445	17	3.7	4
MM32	445	32	7.3	4
HM13	408	10	2.3	5
LM22	405	25	6.2	4
HH13	401	1	0.2	3
LM32	399	32	8.0	3
HH23	392	16	4.2	4
LH32	387	15	3.8	3
HM23	381	17	4.6	4
LH13	378	47	12.4	3
LH23	352	6	1.7	3
LM13	352	26	7.5	3
MH13	319	23	7.2	4
LM23	318	22	6.8	4
MH23	298	24	7.9	3

Table 25 Comparison of the Mr Properties of the Various Mixtures for the Lockwood Aggregate Source.

#	Treatment Comparison	Difference between Means	Simultaneous 95% Confidence Limits		Significance = ***
1	HH12 – Control	517.45	457.01	577.89	***
2	MH21 – Control	515.53	449.73	581.34	***
3	HH21 – Control	465.7	405.26	526.14	***
4	HH31 – Control	382.2	316.4	448	***
5	HM21 – Control	327.45	267.01	387.89	***
6	HM12 – Control	273.87	208.06	339.67	***
7	MH31 – Control	255.53	189.73	321.34	***
8	HM31 – Control	195.7	135.26	256.14	***
9	MM21 – Control	189.95	129.51	250.39	***
10	MH12 – Control	167.2	106.76	227.64	***
11	HH22 – Control	165.2	104.76	225.64	***
12	LM21 – Control	123.95	63.51	184.39	***
13	MM12 – Control	118.87	53.06	184.67	***
14	MM31 – Control	106.2	45.76	166.64	***
15	LH21 – Control	104.7	44.26	165.14	***
1	HM22 – Control	55.8	-1.19	112.79	Not Significant from MM22 in Mr
2	HH32 – Control	24.2	-36.24	84.64	
3	LM12 – Control	6.7	-53.74	67.14	
	Control MM22	0			
4	MH22 – Control	-14.05	-74.49	46.39	
5	LH12 – Control	-25.55	-85.99	34.89	
6	LM31 – Control	-31.55	-91.99	28.89	
7	HM32 – Control	-31.8	-88.79	25.19	
8	MM13 – Control	-34.47	-100.27	31.34	
9	LH22 – Control	-36.13	-101.94	29.67	
10	LH31 – Control	-43.8	-109.6	22	
11	MM23 – Control	-56.8	-122.6	9	
12	MM32 – Control	-58.8	-119.24	1.64	
13	MH32 – Control	-59.3	-119.74	1.14	
1	HM13 – Control	-96.2	-153.19	-39.21	***
2	LM22 – Control	-98.8	-159.24	-38.36	***
3	HH13 – Control	-102.8	-168.6	-37	***
4	LM32 – Control	-105.13	-170.94	-39.33	***
5	HH23 – Control	-111.55	-171.99	-51.11	***
6	LH32 – Control	-116.47	-182.27	-50.66	***
7	HM23 – Control	-123.3	-183.74	-62.86	***
8	LH13 – Control	-125.8	-191.6	-60	***
9	LH23 – Control	-151.8	-217.6	-86	***
10	LM13 – Control	-152.13	-217.94	-86.33	***
11	MH13 – Control	-184.55	-244.99	-124.11	***
12	LM23 – Control	-185.55	-245.99	-125.11	***
13	MH23 – Control	-205.8	-271.60	-140	***

Table 26 APA Results for the Lockwood Aggregate Source.

Mix ID	Rut Depth (mm)	Standard Deviation	Coefficient of Variation (%)	Count
HH21	0.9	0.1	9.1	4
HM21	1.1	0.2	18.9	4
MH21	1.1	0.0	2.2	4
HH31	1.2	0.3	27.9	4
HH12	1.4	0.1	9.9	4
MM21	1.6	0.4	24.1	4
HM12	1.7	0.3	14.6	4
HM31	1.8	0.5	26.9	4
MH12	1.9	0.1	7.6	4
LM21	2.1	0.4	18.7	4
HH22	2.4	0.3	12.9	4
MH31	2.4	0.3	13.7	4
LH21	2.5	0.2	9.1	4
MM12	2.8	0.8	27.5	4
HM13	2.9	0.2	7.2	4
HM22	3.0	0.4	14.4	4
HH13	3.3	0.2	7.1	4
MH13	3.5	0.4	10.6	4
HM32	3.5	0.8	24.2	4
LH12	3.7	0.4	11.3	3
LM12	3.8	0.2	5.7	3
Control MM22	**3.9**	**0.4**	**10.3**	**4**
HH23	3.9	0.3	6.9	4
LM22	4.1	0.5	12.2	4
MM31	4.2	0.7	17.7	4
LM31	4.2	0.6	13.2	4
LH13	4.3	0.5	12.0	4
HM23	4.6	0.5	11.2	4
HH32	4.6	0.6	13.9	4
LM13	4.7	0.3	6.3	4
MM32	5.1	0.6	11.9	4
MM13	5.2	1.0	19.9	5
MH23	5.4	0.4	7.3	4
MH22	5.5	0.6	11.0	4
LH23	5.9	0.3	4.6	4
LH31	6.0	0.9	15.0	4
MM23	6.4	0.5	8.5	4
MH32	6.4	0.3	4.4	4
LH22	6.4	0.7	11.0	4
LM23	7.1	0.5	7.1	4
LH32	7.3	0.4	4.8	4
LM32	7.4	0.5	6.4	4

Table 27 Comparison of the APA Rut Depth of the Various Mixtures for the Lockwood Aggregate Source.

#	Treatment Comparison	Difference between Means	Simultaneous 95% Confidence		Significance = ***
1	HH21 – Control (Imp)	-2.9813	-4.0725	-1.89	***
2	HM21 – Control (Imp)	-2.7826	-3.8739	-1.6913	***
3	MH21 – Control (Imp)	-2.7512	-3.8424	-1.6599	***
4	HH31 – Control (Imp)	-2.6835	-3.7748	-1.5922	***
5	HH12 – Control (Imp)	-2.435	-3.5263	-1.3437	***
6	MM21 – Control (Imp)	-2.3021	-3.3934	-1.2108	***
7	HM12 – Control (Imp)	-2.1363	-3.2275	-1.045	***
8	HM31 – Control (Imp)	-2.0381	-3.1294	-0.9468	***
9	MH12 – Control	-1.9796	-3.0709	-0.8883	***
10	LM21 – Control	-1.7883	-2.8795	-0.697	***
11	HH22 – Control	-1.4519	-2.5432	-0.3606	***
12	MH31 – Control	-1.4125	-2.5038	-0.3212	***
13	LH21 – Control	-1.3914	-2.4827	-0.3001	***
1	MM12 – Control	-1.0221	-2.1134	0.0692	Not Significant from MM22 in Rutting
2	HM13 – Control	-0.9516	-2.0429	0.1397	
3	HM22 – Control	-0.852	-1.9433	0.2393	
4	HH13 – Control	-0.5205	-1.6118	0.5708	
5	MH13 – Control	-0.3724	-1.4637	0.7189	
6	HM32 – Control	-0.3428	-1.434	0.7485	
7	LH12 – Control	-0.1713	-1.35	1.0074	
8	LM12 – Control	-0.0418	-1.2205	1.1369	
	Control MM22	**0**			
9	HH23 – Control	0.014	-1.0773	1.1053	
10	LM22 – Control	0.2679	-0.8234	1.3592	
11	MM31 – Control	0.3295	-0.7618	1.4208	
12	LM31 – Control	0.3824	-0.7089	1.4737	
13	LH13 – Control	0.4801	-0.6112	1.5714	
14	HM23 – Control	0.6953	-0.396	1.7865	
15	HH32 – Control	0.7608	-0.3305	1.852	
16	LM13 – Control	0.8525	-0.2388	1.9438	
1	MM32 – Control	1.2686	0.1773	2.3599	***
2	MM13 – Control	1.3775	0.3422	2.4128	***
3	MH23 – Control	1.5078	0.4165	2.599	***
4	MH22 – Control	1.6754	0.5841	2.7667	***
5	LH23 – Control	2.0793	0.988	3.1705	***
6	LH31 – Control	2.1908	1.0995	3.282	***
7	MM23 – Control	2.5506	1.4593	3.6419	***
8	MH32 – Control	2.5618	1.4705	3.653	***
9	LH22 – Control	2.5856	1.4943	3.6769	***
10	LM23 – Control	3.207	2.1157	4.2983	***
11	LH32 – Control	3.4229	2.3316	4.5142	***
12	LM32 – Control	3.5623	2.471	4.6535	***

(Imp) = Field Impractical Mixes

Table 28 Fatigue Properties of the Lockwood Aggregate Source.

Mix ID	k_1	k_2	Fit R^2 (%)	Count
HH12	3.450E-14	5.097	98.43	6
HH13	3.261E-09	3.756	97.93	5
HH21	7.153E-11	4.280	98.38	7
HH22	1.288E-10	4.233	98.70	7
HH23	1.525E-16	6.120	99.21	5
HH31	3.860E-08	3.624	99.91	5
HH32	7.006E-11	4.493	99.88	4
HM12	7.350E-13	4.903	98.21	5
HM13	6.983E-21	7.319	99.07	6
HM21	1.509E-13	5.207	99.11	4
HM22	1.197E-09	4.098	99.67	4
HM23	5.403E-09	3.911	97.46	7
HM31	9.157E-10	4.145	98.71	6
HM32	5.813E-08	3.655	99.98	5
LH12	5.292E-07	3.127	100.00	4
LH13	5.730E-17	6.093	99.21	4
LH21	2.538E-09	3.923	99.75	5
LH22	1.405E-13	5.141	99.63	4
LH23	4.137E-04	2.288	99.39	6
LH31	5.582E-09	3.875	99.46	4
LH32	9.699E-10	4.065	99.50	9
LM12	4.924E-16	5.715	96.57	4
LM13	9.797E-16	5.798	99.04	5
LM21	1.081E-13	5.330	98.88	5
LM22	5.720E-16	5.936	99.25	7
LM23	5.430E-14	5.416	99.62	5
LM31	4.939E-13	5.126	99.20	4
LM32	2.876E-08	3.693	99.14	5
MH12	8.636E-14	5.083	99.98	4
MH13	6.715E-15	5.433	98.25	6
MH21	1.787E-13	5.136	99.68	5
MH22	5.133E-11	4.309	99.92	4
MH23	2.377E-15	5.655	99.10	5
MH31	5.471E-09	3.875	98.88	5
MH32	1.245E-11	4.642	99.66	4
MM12	8.910E-11	4.227	98.46	5
MM13	1.065E-12	4.805	99.86	4
MM21	4.536E-08	3.563	99.50	4
Control MM22	**9.513E-11**	**4.335**	**99.86**	**4**
MM23	2.853E-13	5.046	100.00	4
MM31	1.774E-07	3.425	98.37	5
MM32	5.933E-07	3.293	99.98	5

Table 29 Comparisons of the Fatigue Properties of the Lockwood Aggregate Source at the 300 microns Strain Level.

#	Treatment Comparison	Difference between Ln Means	Adjusted P	Significance
1	LM23 – Control	1.2892	<.0001	****
2	LM21 – Control	1.2549	0.0014	**
3	LM31 – Control	1.1307	0.0008	***
4	HH23 – Control	1.1103	0.0002	***
5	HH32 – Control	0.9723	0.0002	***
6	LM22 – Control	0.9461	<.0001	****
7	HM32 – Control	0.9017	0.0001	***
8	HM13 – Control	0.8472	0.0013	**
9	HM31 – Control	0.6974	0.0156	*
10	HM22 – Control	0.6049	0.0415	*
1	HM21 – Control	0.6102	0.0747	Not Significant in Fatigue from MM22 at 300 Microns Strain Level
2	HM23 – Control	0.5559	0.0548	
3	LM32 – Control	0.489	0.4198	
4	MH32 – Control	0.4495	0.2266	
5	LM13 – Control	0.3641	0.652	
6	LH31 – Control	0.3312	0.6368	
7	MH31 – Control	0.3021	0.8801	
8	MM32 – Control	0.2941	0.7755	
9	HH31 – Control	0.2399	0.972	
10	MH21 – Control	0.2114	0.9963	
11	LH32 – Control	0.1251	1	
12	MM31 – Control	0.1187	1	
13	MH23 – Control	0.08795	1	
14	LH22 – Control	0.01697	1	
	Control MM22	**0**		
15	MM23 – Control	-0.04146	1	
16	LH21 – Control	-0.05432	1	
17	LH13 – Control	-0.08298	1	
18	MM21 – Control	-0.1013	1	
19	HM12 – Control	-0.2856	0.7947	
20	HH22 – Control	-0.5512	0.0903	
1	MH13 – Control	-0.6705	0.005	**
2	MM13 – Control	-0.6838	0.0111	*
3	HH21 – Control	-0.7401	0.0009	***
4	MH22 – Control	-0.8286	0.0003	***
5	MH12 – Control	-0.9327	<.0001	****
6	MM12 – Control	-0.958	<.0001	****
7	LM12 – Control	-0.9957	<.0001	****
8	LH12 – Control	-1.1671	<.0001	****
9	HH13 – Control	-1.1878	<.0001	****
10	LH23 – Control	-1.3208	<.0001	****
11	HH12 – Control	-1.7478	<.0001	****

Table 30 Comparisons of the Fatigue Properties of the Lockwood Aggregate Source at the 500 microns Strain Level.

#	Treatment Comparison	Difference between Ln Means	Adjusted P	Significance
1	HM32 – Control	1.2458	<.0001	****
2	HH32 – Control	0.8916	<.0001	****
3	LM32 – Control	0.8294	<.0001	****
4	MM32 – Control	0.8225	<.0001	****
5	HM23 – Control	0.8197	<.0001	****
6	HM31 – Control	0.8183	<.0001	****
7	LM21 – Control	0.775	<.0001	****
8	LM23 – Control	0.7454	<.0001	****
9	LM31 – Control	0.7452	<.0001	****
10	HM22 – Control	0.7298	<.0001	****
11	MM31 – Control	0.6085	<.0001	****
12	HH31 – Control	0.6011	<.0001	****
13	LH31 – Control	0.5736	<.0001	****
14	MH31 – Control	0.5557	<.0001	****
1	MH32 – Control	0.2982	0.0791	Not Significant in Fatigue from MM22 at 500 Microns Strain Level
2	MM21 – Control	0.2982	0.1122	
3	LH32 – Control	0.2702	0.057	
4	HH23 – Control	0.2216	0.3179	
5	HM21 – Control	0.1858	0.6895	
6	LH21 – Control	0.1575	0.8946	
7	LM22 – Control	0.1493	0.8326	
	Control MM22	**0**		
8	MH21 – Control	-0.1916	0.6414	
9	LH23 – Control	-0.2726	0.1228	
1	LM13 – Control	-0.357	0.0147	*
2	LH22 – Control	-0.3876	0.0096	**
3	MM23 – Control	-0.407	0.003	**
4	HH22 – Control	-0.474	<.0001	****
5	HM12 – Control	-0.5335	<.0001	****
6	LH12 – Control	-0.5542	0.0105	*
7	MH23 – Control	-0.5621	<.0001	****
8	HM13 – Control	-0.6431	<.0001	****
9	HH21 – Control	-0.68	<.0001	****
10	MH22 – Control	-0.8165	<.0001	****
11	HH13 – Control	-0.8558	<.0001	****
12	MM12 – Control	-0.8729	<.0001	****
13	MM13 – Control	-0.923	<.0001	****
14	LH13 – Control	-0.9583	<.0001	****
15	MH13 – Control	-1.1849	<.0001	****
16	MH12 – Control	-1.317	<.0001	****
17	LM12 – Control	-1.6028	<.0001	****
18	HH12 – Control	-2.0984	<.0001	****

Table 31 Comparisons of the Fatigue Properties of the Lockwood Aggregate Source at the 800 microns Strain Level.

#	Treatment Comparison	Difference between Ln Means	Adjusted P	Significance
1	HM32 – Control	1.5629	<.0001	****
2	MM32 – Control	1.3094	<.0001	****
3	LM32 – Control	1.1431	<.0001	****
4	HM23 – Control	1.0627	<.0001	****
5	MM31 – Control	1.0598	<.0001	****
6	HH31 – Control	0.934	<.0001	****
7	HM31 – Control	0.9298	<.0001	****
8	HM22 – Control	0.845	0.0003	***
9	HH32 – Control	0.8172	<.0001	****
10	LH31 – Control	0.797	0.0001	***
11	MH31 – Control	0.7894	0.0001	***
12	LH23 – Control	0.6935	0.0034	**
13	MM21 – Control	0.6664	0.0002	***
1	LH32 – Control	0.4039	0.261	Not Significant in Fatigue from MM22 at 800 Microns Strain Level
2	LM31 – Control	0.3899	0.4157	
3	LH21 – Control	0.3526	0.8783	
4	LM21 – Control	0.3327	0.9553	
5	LM23 – Control	0.2442	0.9557	
6	MH32 – Control	0.1587	1	
7	LH12 – Control	0.01052	1	
	Control MM22	**0**		
8	HM21 – Control	-0.2054	0.9999	
9	HH22 – Control	-0.4028	0.2826	
10	HH13 – Control	-0.5499	0.0635	
11	MH21 – Control	-0.563	0.3136	
12	HH23 – Control	-0.5973	0.0662	
13	HH21 – Control	-0.6246	0.0833	
1	LM22 – Control	-0.585	0.0263	*
2	MM23 – Control	-0.7438	0.0005	***
3	LH22 – Control	-0.7604	0.0065	**
4	HM12 – Control	-0.762	0.0046	**
5	MM12 – Control	-0.7944	0.0219	*
6	MH22 – Control	-0.8054	0.0012	**
7	LM13 – Control	-1.0215	0.0006	***
8	MM13 – Control	-1.1434	<.0001	****
9	MH23 – Control	-1.1612	<.0001	****
10	MH13 – Control	-1.659	<.0001	****
11	MH12 – Control	-1.6712	<.0001	****
12	LH13 – Control	-1.7649	<.0001	****
13	HM13 – Control	-2.0164	<.0001	****
14	LM12 – Control	-2.1623	<.0001	****
15	HH12 – Control	-2.4215	<.0001	****

Table 32 Thermal Cracking Properties of the Lockwood Aggregate Source.

Mix ID	Fracture Temperature (°C)			Count
	Average	Standard Deviation	Coefficient of Variation (%)	
HM22	-30.6	1.3	4.4	3
MM32	-29.5	1.8	6.1	3
HH21	-29.1	0.3	1.0	3
HM32	-29.0	0.4	1.5	3
LM31	-28.8	0.2	0.6	3
MM21	-28.3	1.3	4.6	3
MM31	-28.1	0.5	1.8	3
MH31	-27.9	1.0	3.4	3
LM32	-27.4	0.7	2.4	3
HM21	-27.4	1.7	6.2	4
HM31	-27.3	0.4	1.5	3
HM23	-27.0	0.7	2.5	4
HH32	-26.8	0.9	3.4	3
LM22	-26.7	0.6	2.3	3
LH32	-26.5	0.7	2.8	4
LM21	-26.3	1.5	5.7	5
HM13	-26.3	1.0	3.9	3
MH22	-26.1	0.6	2.4	3
HH31	-26.0	0.3	1.1	4
MM23	-25.9	0.4	1.7	3
LM23	-25.8	2.2	8.5	3
LH31	-25.7	1.6	6.2	3
Control MM22	**-25.6**	**1.0**	**4.0**	**4**
LH22	-25.4	0.5	2.1	3
MM13	-24.6	1.3	5.3	3
MH32	-24.6	0.9	3.7	3
MM12	-23.4	1.7	7.2	3
LM12	-22.5	0.3	1.5	3
LH12	-21.4	1.3	5.9	3
MH21	-21.0	1.0	4.8	3
LH21	-20.6	1.4	6.8	4
HH22	-20.6	0.3	1.2	3
HH23	-20.2	1.7	8.4	3
HM12	-19.9	0.4	2.1	3
LM13	-19.4	0.8	4.3	3
MH13	-19.4	0.9	4.9	3
MH12	-19.2	1.2	6.1	3
MH23	-18.6	0.3	1.7	3
HH12	-15.9	0.7	4.3	3
LH23	-14.4	0.3	1.8	3
HH13	-13.9	1.3	9.2	4
LH13	-13.9	1.4	10.3	3

Table 33 Comparison of the Thermal Cracking Properties of the Lockwood Aggregate Source.

#	Treatment Comparison	Difference between Means	Simultaneous 95% Confidence		Significance = ***
1	HM22 – Control	-4.9	-7.6	-2.3	***
2	MM32 – Control	-3.9	-6.5	-1.3	***
3	HH21 – Control	-3.4	-6.1	-0.8	***
4	HM32 – Control	-3.3	-6.0	-0.7	***
5	LM31 – Control	-3.2	-5.8	-0.6	***
6	MM21 – Control	-2.7	-5.3	-0.1	***
1	MM31 – Control	-2.5	-5.1	0.2	Not Significant in Thermal Resistance from MM22
2	MH31 – Control	-2.3	-4.9	0.4	
3	LM32 – Control	-1.8	-4.4	0.8	
4	HM21 – Control	-1.8	-4.2	0.6	
5	HM31 – Control	-1.6	-4.3	1.0	
6	HM23 – Control	-1.4	-3.8	1.0	
7	HH32 – Control	-1.2	-3.8	1.5	
8	LM22 – Control	-1.1	-3.7	1.5	
9	LH32 – Control	-0.9	-3.4	1.5	
10	LM21 – Control	-0.7	-3.0	1.6	
11	HM13 – Control	-0.6	-3.3	2.0	
12	MH22 – Control	-0.5	-3.1	2.1	
13	HH31 – Control	-0.4	-2.8	2.1	
14	MM23 – Control	-0.3	-2.9	2.4	
15	LM23 – Control	-0.2	-2.8	2.4	
	Control MM22	**0.0**			
16	LH31 – Control	0.0	-2.7	2.6	
17	LH22 – Control	0.3	-2.4	2.9	
18	MM13 – Control	1.0	-1.6	3.6	
19	MH32 – Control	1.1	-1.6	3.7	
20	MM12 – Control	2.2	-0.4	4.9	
1	LM12 – Control	3.2	0.5	5.8	***
2	LH12 – Control	4.2	1.6	6.8	***
3	MH21 – Control	4.6	2.0	7.3	***
4	LH21 – Control	5.0	2.6	7.4	***
5	HH22 – Control	5.1	2.4	7.7	***
6	HH23 – Control	5.5	2.9	8.1	***
7	HM12 – Control	5.8	3.1	8.4	***
8	LM13 – Control	6.2	3.6	8.8	***
9	MH13 – Control	6.3	3.6	8.9	***
10	MH12 – Control	6.4	3.8	9.0	***
11	MH23 – Control	7.0	4.4	9.7	***
12	HH12 – Control	9.7	7.1	12.4	***
13	LH23 – Control	11.2	8.6	13.9	***
14	HH13 – Control	11.7	9.3	14.1	***
15	LH13 – Control	11.8	9.1	14.4	***

Table 34 Volumetric Properties for the Lockwood Aggregate Source.

Mix ID	Pb (% dwa)	Air-Voids (%)	DP	VMA (%)	VFA (%)	Surface Area		Average Film Thickness (microns)
						(ft^2/lb)	(m^2/kg)	
HH12	3.7	7.0	4.4	15.9	56.1	40.5	8.3	2.8
HH13	3.7	11.0	4.4	19.5	43.7			2.8
HH21	4.3	3.0	3.5	13.6	77.9			3.6
HH22	4.3	7.0	3.5	17.1	59.2			3.6
HH23	4.3	11.0	3.5	20.7	46.9			3.6
HH31	4.9	3.0	2.9	14.8	79.8			4.3
HH32	4.9	7.0	2.9	18.3	61.8			4.3
HM12	3.7	7.0	2.6	15.9	56.1	28.7	5.9	4.0
HM13	3.7	11.0	2.6	19.5	43.7			4.0
HM21	4.3	3.0	2.1	13.6	77.9			5.0
HM22	4.3	7.0	2.1	17.1	59.2			5.0
HM23	4.3	11.0	2.1	20.7	46.9			5.0
HM31	4.9	3.0	1.8	14.8	79.8			6.1
HM32	4.9	7.0	1.8	18.3	61.8			6.1
LH12	3.7	7.0	3.9	15.5	54.8	39.6	8.1	3.3
LH13	3.7	11.0	3.9	19.1	42.5			3.3
LH21	4.3	3.0	3.2	13.1	77.1			4.0
LH22	4.3	7.0	3.2	16.7	58.1			4.0
LH23	4.3	11.0	3.2	20.3	45.8			4.0
LH31	4.9	3.0	2.7	14.4	79.1			4.8
LH32	4.9	7.0	2.7	17.9	60.9			4.8
LM12	3.7	7.0	2.3	15.5	54.8	27.9	5.7	4.7
LM13	3.7	11.0	2.3	19.1	42.5			4.7
LM21	4.3	3.0	1.9	13.1	77.1			5.7
LM22	4.3	7.0	1.9	16.7	58.1			5.7
LM23	4.3	11.0	1.9	20.3	45.8			5.7
LM31	4.9	3.0	1.6	14.4	79.1			6.8
LM32	4.9	7.0	1.6	17.9	60.9			6.8
MH12	3.7	7.0	4.1	15.7	55.4	40.1	8.2	3.1
MH13	3.7	11.0	4.1	19.3	43.1			3.1
MH21	4.3	3.0	3.3	13.3	77.5			3.8
MH22	4.3	7.0	3.3	16.9	58.6			3.8
MH23	4.3	11.0	3.3	20.5	46.3			3.8
MH31	4.9	3.0	2.8	14.6	79.5			4.5
MH32	4.9	7.0	2.8	18.1	61.4			4.5
MM12	3.7	7.0	2.5	15.7	55.4	28.3	5.8	4.4
MM13	3.7	11.0	2.5	19.3	43.1			4.4
MM21	4.3	3.0	2.0	13.3	77.5			5.4
MM22	**4.3**	**7.0**	**2.0**	**16.9**	**58.6**			**5.4**
MM23	4.3	11.0	2.0	20.5	46.3			5.4
MM31	4.9	3.0	1.7	14.6	79.5			6.4
MM32	4.9	7.0	1.7	18.1	61.4			6.4

Table 35 Performance Analysis of the Lockwood Aggregate Source.

Violations	Mix ID	General Strength MR	Rutting	Beam Fatigue			Thermal Cracking	Compaction Observations
				300 µStrain	500 µStrain	800 µStrain		
Low on # 4-Sieve	LM22	S Lower	NS	S Better	NS	S Worse	NS	
High on # 4-Sieve	HM22	NS	NS	S Better	S Better	S Better	S Better	
High on # 200-Sieve	MH22	NS	S Worse	S Worse	S Worse	S Worse	NS	
Low on Percent AC	MM12	S Higher	NS	S Worse	S Worse	S Worse	NS	
High on Percent AC	MM32	NS	S Worse	NS	S Better	S Better	S Better	
Low on Percent AV	MM21	S Higher	S Better	NS	NS	S Better	S Better	High Compaction Effort – High temp
High on Percent AV	MM23	NS	S Worse	NS	S Worse	S Worse	NS	
Low on # 4 & High on # 200-Sieves	LH22	NS	S Worse	NS	S Worse	S Worse	NS	
High on # 4 & High on # 200-Sieves	HH22	S Higher	S Better	NS	S Worse	NS	S Worse	
Low on # 4 & Low on Percent AC	LM12	NS	NS	S Worse	S Worse	S Worse	S Worse	
Low on # 4 & High on Percent AC	LM32	S Lower	S Worse	NS	S Better	S Better	NS	Minor Compaction
High on # 4 & Low on Percent AC	HM12	S Higher	S Better	NS	S Worse	S Worse	S Worse	High Compaction Effort – High temp
High on # 4 & High on Percent AC	HM32	NS	NS	S Better	S Better	S Better	S Better	
Low on # 4 & Low on Percent AV	LM21	S Higher	S Better	S Better	S Better	NS	NS	
Low on # 4 & High on Percent AV	LM23	S Lower	S Worse	S Better	S Better	NS	NS	Not Compacted – Just Leveled

Table 35 Performance Analysis of the Lockwood Aggregate Source (Continued)

Violations	Mix ID	General Strength MR	Rutting	Beam Fatigue			Thermal Cracking	Compaction Observations
				300 μStrain	500 μStrain	800 μStrain		
High on # 4 & Low on Percent AV	HM21	S Higher	S Better	NS	NS	NS	NS	Very High Compaction Effort – High temp
High on # 4 & High on Percent AV	HM23	S Lower	NS	NS	S Better	S Better	NS	
High on # 200 & Low on Percent AC	MH12	S Higher	S Better	S Worse	S Worse	S Worse	S Worse	
High on # 200 & High on Percent AC	MH32	NS	S Worse	NS	NS	NS	NS	
High on # 200 & Low on Percent AV	MH21	S Higher	S Better	NS	NS	NS	S Worse	High Compaction Effort – High temp
High on # 200 & High on Percent AV	MH23	S Lower	S Worse	NS	S Worse	S Worse	S Worse	
Low on Percent AC & High on Percent AV	MM13	NS	S Worse	S Worse	S Worse	S Worse	NS	
High on Percent AC & Low on Percent AV	MM31	S Higher	NS	NS	S Better	S Better	NS	
High on # 4, High on # 200 & Low on Percent AC	HH12	S Higher	S Better	S Worse	S Worse	S Worse	S Worse	High Compaction Effort – High temp
High on # 4, High on # 200 & High on Percent AC	HH32	NS	NS	S Better	S Better	S Better	NS	
Low on # 4, High on # 200 & Low on Percent AC	LH12	NS	NS	S Worse	S Worse	NS	S Worse	
Low on # 4, High on # 200 & High on Percent AC	LH32	S Lower	S Worse	NS	NS	NS	NS	Minor Compaction
High on # 4, High on # 200 & Low on Percent AV	HH21	S Higher	S Better	S Worse	S Worse	NS	S Better	Very High Compaction Effort – High temp
High on # 4, High on # 200 & High on Percent AV	HH23	S Lower	NS	S Better	NS	NS	S Worse	
Low on # 4, High on # 200 & Low on Percent AV	LH21	S Higher	S Better	NS	NS	NS	S Worse	

Table 35 Performance Analysis of the Lockwood Aggregate Source (Continued).

Violations	Mix	General Strength MR	Rutting	Beam Fatigue			Thermal Cracking	Compaction Observations
				300 µStrain	500 µStrain	800 µStrain		
Low on # 4, High on # 200 & High on Percent AV	LH23	S Lower	S Worse	S Worse	NS	S Better	S Worse	Not Compacted – Just Leveled
Low on # 4, Low on % AC & High on % AV	LM13	S Lower	NS	NS	S Worse	S Worse	S Worse	
High on # 4, High on % AC & Low on % AV	HM31	S Higher	S Better	S Better	S Better	S Better	NS	High Compaction Effort – High temp
Low on # 4, High on % AC & Low on % AV	LM31	NS	NS	S Better	S Better	NS	S Better	
High on # 4, Low on % AC & High on % AV	HM13	S Lower	NS	S Better	S Worse	S Worse	NS	
High on # 200, High on % AC & Low on % AV	MH31	S Higher	S Better	NS	S Better	S Better	NS	
High on # 200, Low on % AC & High on % AV	MH13	S Lower	NS	S Worse	S Worse	S Worse	S Worse	
Low # 4, High # 200, Low % AC & High % AV	LH13	S Lower	NS	NS	S Worse	S Worse	S Worse	
Low # 4, High # 200, High % AC & Low % AV	LH31	NS	S Worse	NS	S Better	S Better	NS	
High # 4, High # 200, High % AC & Low % AV	HH31	S Higher	S Better	NS	S Better	S Better	NS	High Compaction Effort – High temp
High # 4, High # 200, Low % AC & High % AV	HH13	S Lower	NS	S Worse	S Worse	NS	S Worse	

Table 36 Hveem Mix Design for the Sloan Aggregate Source.

Binder Content, % by dwa	3.0	3.5	4.0	4.5	PROJECT SPECS (TYPE 2C)	
Max. Specific Gravity	2.659	2.639	2.620	2.601		
Bulk Specific Gravity	2.447	2.510	2.543	2.552		
Density, PCF	152.7	156.6	158.7	159.3	Min	Max
Hveem Value	53	52	37	18	37	
% Air-voids	8.0	4.9	2.9	1.9	4	7
% VMA	14.6	12.8	12.1	12.2	12	22

Table 37 Mix Properties at the Optimum AC for the Sloan Aggregate Source.

Binder Content, % by dwa	**3.8**	PROJECT SPECS (TYPE 2C)	
Max. Specific Gravity	2.627		
Unit Weight, PCF	158.1		
% Air-voids	3.6		
Hveem Value	44	Min. 37	
% VMA	12.3	12	22

Table 38 Moisture Sensitivity Properties of the Sloan Aggregate Source.

Test	Result	Requirements
Indirect Tensile Strength (Unconditioned)	144 psi	Min. 65 psi
Indirect Tensile Strength (Conditioned)	108 psi	
Indirect Tensile Strength (Retained Strength)	75%	Min. 70%

Table 39 Resilient Modulus Properties of the Sloan Aggregate Source.

Mix ID	Resilient Modulus at 77°F (ksi)	Standard Deviation	Coefficient of Variation (%)	Count
HM21	1,431	81	5.7	4
HH21	1,399	22	1.6	4
MM21	1,359	35	2.6	3
HH31	1,272	49	3.8	3
LM21	1,203	126	10.5	4
MH21	1,140	141	12.3	4
HM31	1,135	63	5.5	4
MM12	1,133	19	1.7	3
HM12	1,133	46	4.1	4
MM31	1,125	62	5.5	3
HH22	1,088	12	1.1	3
LH21	1,045	57	5.5	3
HH12	1,023	51	4.9	4
HM22	1,021	18	1.7	3
MM22 Control	**1,020**	**43**	**4.2**	**4**
MH31	1,006	47	4.7	4
MH12	947	9	0.9	3
LM31	934	45	4.8	4
MH22	906	43	4.8	3
LH31	846	66	7.8	3
HM32	827	56	6.8	4
HM13	792	46	5.8	4
LM22	785	33	4.2	4
HH32	781	38	4.9	4
MM23	778	19	2.5	4
HM23	739	22	3.0	4
LM12	722	30	4.2	3
MM32	691	9	1.3	3
LM13	669	49	7.4	3
HH13	650	47	7.2	3
MH32	646	64	9.9	4
MM13	614	27	4.4	3
LM32	609	33	5.4	4
LH12	574	43	7.4	3
LH32	560	46	8.2	3
LH22	555	82	14.8	3
LM23	548	52	9.6	4
HH23	536	54	10.1	3
MH23	534	39	7.3	4
LH13	523	6	1.1	3
MH13	494	31	6.4	3
LH23	420	56	13.3	4

Table 40 Comparison of the Mr Properties of the Various Mixtures for the Sloan Aggregate Source.

No.	Treatment Comparison	Difference between Means	Simultaneous 95% Confidence Limits		Significance = ***
1	HM21 – Control	411	288.29	533.71	***
2	HH21 – Control	379.5	256.79	502.21	***
3	MM21 – Control	339.5	206.96	472.04	***
4	HH31 – Control	252.17	119.63	384.71	***
5	LM21 – Control	183	60.29	305.71	***
1	MH21 – Control	120.5	-2.21	243.21	Not Significant from MM22 in Mr
2	HM31 – Control	115.5	-7.21	238.21	
3	MM12 – Control	113.83	-18.71	246.37	
4	HM12 – Control	113.75	-8.96	236.46	
5	MM31 – Control	105.5	-27.04	238.04	
6	HH22 – Control	68.5	-64.04	201.04	
7	LH21 – Control	25.83	-106.71	158.37	
8	HH12 – Control	3.75	-118.96	126.46	
9	HM22 – Control	1.5	-131.04	134.04	
	Control MM22	**0**			
10	MH31 – Control	-13.25	-135.96	109.46	
11	MH12 – Control	-72.5	-205.04	60.04	
12	LM31 – Control	-86	-208.71	36.71	
13	MH22 – Control	-113.17	-245.71	19.37	
1	LH31 – Control	-173.5	-306.04	-40.96	***
2	HM32 – Control	-192.5	-315.21	-69.79	***
3	HM13 – Control	-227.75	-350.46	-105.04	***
4	LM22 – Control	-234.5	-357.21	-111.79	***
5	HH32 – Control	-238.5	-361.21	-115.79	***
6	MM23 – Control	-241.25	-363.96	-118.54	***
7	HM23 – Control	-280.75	-403.46	-158.04	***
8	LM12 – Control	-297.5	-430.04	-164.96	***
9	MM32 – Control	-328.5	-461.04	-195.96	***
10	LM13 – Control	-350.5	-483.04	-217.96	***
11	HH13 – Control	-369.5	-502.04	-236.96	***
12	MH32 – Control	-373.25	-495.96	-250.54	***
13	MM13 – Control	-405.5	-538.04	-272.96	***
14	LM32 – Control	-410.75	-533.46	-288.04	***
15	LH12 – Control	-445.17	-577.71	-312.63	***
16	LH32 – Control	-459.17	-591.71	-326.63	***
17	LH22 – Control	-464.5	-597.04	-331.96	***
18	LM23 – Control	-471.75	-594.46	-349.04	***
19	HH23 – Control	-483.17	-615.71	-350.63	***
20	MH23 – Control	-485.75	-608.46	-363.04	***
21	LH13 – Control	-496.5	-629.04	-363.96	***
22	MH13 – Control	-525.83	-658.37	-393.29	***
23	LH23 – Control	-599.25	-721.96	-476.54	***

Table 41 APA Results for the Sloan Aggregate Source.

Mix ID	Rut Depth (mm)	Standard Deviation	Coefficient of Variation (%)	Count
HH21	1.1	0.2	18.4	4
MM21	1.3	0.2	14.1	4
HH31	1.4	0.1	10.7	4
HM21	1.4	0.4	24.8	4
HM31	1.9	0.1	7.0	4
HM12	1.9	0.2	11.7	4
HH12	1.9	0.4	23.0	4
MH21	2.0	0.3	17.0	4
MH12	2.2	0.4	17.3	4
LM21	2.3	0.3	15.0	4
MM12	2.4	0.2	10.4	4
LH12	2.5	0.4	15.2	4
HM22	2.6	0.5	19.0	4
MM31	2.8	0.6	20.6	4
LM12	2.8	0.3	9.4	4
LH21	2.8	0.4	15.0	4
HH22	2.8	0.2	6.3	4
HM13	3.0	0.2	5.2	4
HH13	3.1	0.4	12.1	4
HH32	3.1	0.5	17.0	4
LH22	3.1	0.2	7.2	4
MH31	3.2	0.3	8.2	3
HM32	3.6	0.6	15.8	4
MH22	3.7	0.7	19.9	4
Control MM22	**3.8**	**0.6**	**15.0**	**7**
LM31	4.1	0.6	15.6	4
MH13	4.1	0.6	15.2	4
MM13	4.2	0.6	15.3	4
HM23	4.2	0.4	10.5	4
LH31	4.3	0.7	15.4	4
LH13	4.5	0.7	15.1	4
LM22	4.5	0.3	6.4	4
HH23	5.1	0.5	9.9	4
MM32	5.2	0.3	5.2	4
MM23	5.3	0.5	9.5	4
LH23	5.6	0.3	4.7	4
MH23	5.8	0.3	4.8	4
LM13	6.1	0.6	10.2	4
MH32	6.4	0.5	7.4	4
LM32	7.1	0.2	3.2	4
LH32	7.6	0.3	4.0	4
LM23	8.5	0.6	7.2	4

Table 42 Comparison of the APA Rut Depth of the Various Mixtures for the Sloan Aggregate Source.

#	Treatment Comparison	Difference between Means	Simultaneous 95% Confidence		Significance = ***
1	HH21 – Control (Imp)	-2.7076	-3.5943	-1.8208	***
2	MM21 – Control (Imp)	-2.5401	-3.4268	-1.6533	***
3	HH31 – Control (Imp)	-2.4904	-3.3772	-1.6037	***
4	HM21 – Control (Imp)	-2.4042	-3.2909	-1.5174	***
5	HM31 – Control (Imp)	-1.9942	-2.8809	-1.1074	***
6	HM12 – Control (Imp)	-1.9436	-2.8303	-1.0568	***
7	HH12 – Control (Imp)	-1.9281	-2.8148	-1.0413	***
8	MH21 – Control	-1.8443	-2.7311	-0.9575	***
9	MH12 – Control	-1.6291	-2.5158	-0.7423	***
10	LM21 – Control	-1.5829	-2.4697	-0.6962	***
11	MM12 – Control	-1.4856	-2.3723	-0.5988	***
12	LH12 – Control	-1.3586	-2.2453	-0.4718	***
13	HM22 – Control	-1.2832	-2.1699	-0.3964	***
14	MM31 – Control	-1.0629	-1.9497	-0.1762	***
15	LM12 – Control	-1.0593	-1.9461	-0.1725	***
16	LH21 – Control	-1.0272	-1.9139	-0.1404	***
17	HH22 – Control	-0.9999	-1.8867	-0.1132	***
1	HM13 – Control	-0.8268	-1.7136	0.06	Not Significant in Rutting from MM22
2	HH13 – Control	-0.7724	-1.6592	0.1143	
3	HH32 – Control	-0.7143	-1.6011	0.1725	
4	LH22 – Control	-0.7023	-1.5891	0.1845	
5	MH31 – Control	-0.6928	-1.6691	0.2835	
6	HM32 – Control	-0.2486	-1.1353	0.6382	
7	MH22 – Control	-0.1008	-0.9876	0.786	
	Control MM22	**0**			
8	LM31 – Control	0.2442	-0.6426	1.131	
9	MH13 – Control	0.2839	-0.6028	1.1707	
10	MM13 – Control	0.3139	-0.5728	1.2007	
11	HM23 – Control	0.3523	-0.5344	1.2391	
12	LH31 – Control	0.4272	-0.4596	1.314	
13	LH13 – Control	0.6458	-0.2409	1.5326	
14	LM22 – Control	0.6691	-0.2177	1.5558	
1	HH23 – Control	1.2586	0.3718	2.1453	***
2	MM32 – Control	1.3667	0.4799	2.2535	***
3	MM23 – Control	1.4571	0.5703	2.3438	***
4	LH23 – Control	1.7718	0.8851	2.6586	***
5	MH23 – Control	1.9086	1.0218	2.7953	***
6	LM13 – Control	2.2549	1.3682	3.1417	***
7	MH32 – Control	2.5623	1.6756	3.4491	***
8	LM32 – Control	3.2139	2.3272	4.1007	***
9	LH32 – Control	3.7142	2.8274	4.601	***
10	LM23 – Control	4.6178	3.7311	5.5046	***

(Imp) = Field Impractical Mixes

Table 43 Fatigue Properties of the Sloan Aggregate Source.

Mix ID	k_1	k_2	Fit R^2 (%)	Count
HH12	1.145E-14	5.167	99.34	4
HH13	2.212E-17	5.972	98.92%	6
HH21	2.855E-21	7.054	98.41%	6
HH22	3.085E-14	5.204	99.27	5
HH23	1.350E-13	4.886	98.10%	6
HH31	4.555E-11	4.339	99.87%	6
HH32	1.514E-13	5.017	97.79%	6
HM12	9.484E-12	4.412	99.90	4
HM13	2.780E-13	4.790	99.51%	5
HM21	1.593E-09	3.886	99.76%	5
HM22	1.233E-10	4.261	99.92	4
HM23	9.419E-09	3.640	98.34%	8
HM31	3.855E-14	5.254	98.88	4
HM32	2.000E-08	3.658	99.11%	6
LH12	9.132E-16	5.426	99.68%	4
LH13	4.333E-21	6.882	97.55%	4
LH21	4.097E-09	3.672	99.52	4
LH22	1.014E-11	4.512	99.37%	4
LH23	6.967E-10	3.873	97.06%	5
LH31	2.555E-13	4.983	98.65%	6
LH32	1.221E-14	5.230	98.44%	6
LM12	1.987E-09	3.656	99.70%	4
LM13	2.050E-20	6.709	97.74%	6
LM21	4.076E-13	4.867	99.73%	5
LM22	4.278E-15	5.360	99.29%	4
LM23	2.109E-30	9.545	99.79%	4
LM31	2.442E-09	3.943	99.43	4
LM32	5.380E-14	5.259	97.64%	6
MH12	4.957E-11	4.125	99.77	5
MH13	1.925E-26	8.181	98.26%	6
MH21	7.120E-11	4.141	98.99	4
MH22	9.954E-19	6.270	99.96	4
MH23	4.056E-12	4.424	98.99%	4
MH31	7.372E-12	4.599	99.41	5
MH32	8.994E-06	2.792	99.82%	4
MM12	2.050E-22	7.353	99.87	4
MM13	7.380E-13	4.729	98.02%	5
MM21	2.776E-08	3.526	99.13%	5
Control MM22	**1.516E-09**	**3.847**	**99.91%**	**6**
MM23	8.017E-14	5.011	99.92%	5
MM31	2.573E-11	4.389	99.66	4
MM32	7.945E-08	3.397	98.64%	7

Table 44 Comparisons of the Fatigue Properties of the Sloan Aggregate Source at the 300 microns Strain Level.

#	Treatment Comparison	Difference between Ln Means	Adjusted P	Significance
1	LM31 – Control	1.2439	<.0001	****
2	LM32 – Control	1.1628	<.0001	****
3	HM32 – Control	1.0385	<.0001	****
4	HM22 – Control	0.8455	<.0001	****
5	HM31 – Control	0.8174	<.0001	****
6	MH31 – Control	0.7641	<.0001	****
7	LH31 – Control	0.5053	0.0085	**
8	HH31 – Control	0.4794	0.0013	**
1	LH22 – Control	0.3761	0.7704	Not Significant in Fatigue from MM22 at 300 Microns Strain Level
2	HM21 – Control	0.36	0.1844	
3	MM31 – Control	0.3127	0.8402	
4	MM32 – Control	0.3053	0.0631	
5	MM21 – Control	0.3016	0.1795	
6	HH32 – Control	0.2596	0.3107	
7	HH22 – Control	0.192	0.9945	
8	MH32 – Control	0.1338	0.9986	
9	HM23 – Control	0.1305	0.9939	
10	LM21 – Control	0.04731	1	
	Control MM22	0		
1	MM23 – Control	-0.4083	0.006	**
2	LH21 – Control	-0.4232	0.0104	*
3	HM12 – Control	-0.4923	0.001	***
4	MM13 – Control	-0.4924	0.0007	***
5	LM22 – Control	-0.5052	0.0006	***
6	LH32 – Control	-0.5139	<.0001	****
7	LH23 – Control	-0.5691	<.0001	****
8	MH21 – Control	-0.6843	<.0001	****
9	HH13 – Control	-0.8117	<.0001	****
10	HH23 – Control	-0.8969	<.0001	****
11	HM13 – Control	-0.9527	<.0001	****
12	HH21 – Control	-0.9748	<.0001	****
13	HH12 – Control	-1.0859	<.0001	****
14	MH12 – Control	-1.1652	<.0001	****
15	MM12 – Control	-1.2015	<.0001	****
16	MH23 – Control	-1.2374	<.0001	****
17	LM12 – Control	-1.2734	<.0001	****
18	MH22 – Control	-1.4971	<.0001	****
19	LH12 – Control	-1.5164	<.0001	****
20	LM13 – Control	-1.8025	<.0001	****
21	LM23 – Control	-1.8109	<.0001	****
22	LH13 – Control	-1.9567	<.0001	****
23	MH13 – Control	-3.7197	<.0001	****

Table 45 Comparisons of the Fatigue Properties of the Sloan Aggregate Source at the 500 microns Strain Level.

#	Treatment Comparison	Difference between Ln Means	Adjusted P	Significance
1	LM31 – Control	1.2049	<.0001	****
2	HM32 – Control	1.1498	<.0001	****
3	MH32 – Control	0.6725	0.0083	**
4	HM22 – Control	0.6345	0.0061	**
5	MM32 – Control	0.5568	0.0088	**
6	LM32 – Control	0.5042	0.0092	**
1	MM21 – Control	0.4791	0.0764	Not Significant in Fatigue from MM22 at 500 Microns Strain Level
2	MH31 – Control	0.3929	0.3685	
3	HM21 – Control	0.3433	0.5031	
4	HM23 – Control	0.2655	0.685	
5	HH31 – Control	0.23	0.9268	
6	HM31 – Control	0.1282	1	
7	LH22 – Control	0.04947	1	
8	MM31 – Control	0.04232	1	
	Control MM22	**0**		
9	LH31 – Control	-0.04148	1	
10	HH32 – Control	-0.2821	0.8659	
11	LH21 – Control	-0.327	0.9494	
12	LM21 – Control	-0.4678	0.1229	
13	HH22 – Control	-0.4824	0.1262	
14	LH23 – Control	-0.5262	0.3948	
1	HM12 – Control	-0.7799	0.0046	**
2	MH21 – Control	-0.8143	0.0008	***
3	MM13 – Control	-0.8958	<.0001	****
4	MM23 – Control	-1.0014	<.0001	****
5	LM12 – Control	-1.1722	<.0001	****
6	LH32 – Control	-1.179	<.0001	****
7	LM22 – Control	-1.2594	<.0001	****
8	MH12 – Control	-1.3039	<.0001	****
9	HH23 – Control	-1.381	<.0001	****
10	HM13 – Control	-1.4236	<.0001	****
11	MH23 – Control	-1.5105	<.0001	****
12	HH12 – Control	-1.7436	<.0001	****
13	HH13 – Control	-1.864	<.0001	****
14	LH12 – Control	-2.3146	<.0001	****
15	HH21 – Control	-2.5547	<.0001	****
16	MH22 – Control	-2.7328	<.0001	****
17	MM12 – Control	-2.9862	<.0001	****
18	LM13 – Control	-3.1865	<.0001	****
19	LH13 – Control	-3.4202	<.0001	****
20	LM23 – Control	-4.7085	<.0001	****
21	MH13 – Control	-5.8589	<.0001	****

Table 46 Volumetric Properties for the Sloan Aggregate Source.

Mix ID	Pb (% dwa)	Air-Voids (%)	DP	VMA (%)	VFA (%)	Surface Area		Average Film Thickness (microns)
						(ft^2/lb)	(m^2/kg)	
HH12	3.2	7.0	3.7	14.5	51.9	39.5	8.1	3.0
HH13	3.2	11.0	3.7	18.2	39.6			3.0
HH21	3.8	3.0	3.0	12.2	75.4			3.7
HH22	3.8	7.0	3.0	15.8	55.7			3.7
HH23	3.8	11.0	3.0	19.4	43.4			3.7
HH31	4.4	3.0	2.5	13.5	77.7			4.4
HH32	4.4	7.0	2.5	17.0	58.9			4.4
HM12	3.2	7.0	2.1	14.5	51.9	27.7	5.7	4.3
HM13	3.2	11.0	2.1	18.2	39.6			4.3
HM21	3.8	3.0	1.7	12.2	75.4			5.3
HM22	3.8	7.0	1.7	15.8	55.7			5.3
HM23	3.8	11.0	1.7	19.4	43.4			5.3
HM31	4.4	3.0	1.4	13.5	77.7			6.3
HM32	4.4	7.0	1.4	17.0	58.9			6.3
LH12	3.2	7.0	3.6	14.2	50.6	38.7	7.9	3.1
LH13	3.2	11.0	3.6	17.9	38.4			3.1
LH21	3.8	3.0	2.9	11.8	74.6			3.9
LH22	3.8	7.0	2.9	15.4	54.7			3.9
LH23	3.8	11.0	2.9	19.1	42.3			3.9
LH31	4.4	3.0	2.5	13.1	77.1			4.6
LH32	4.4	7.0	2.5	16.7	58.0			4.6
LM12	3.2	7.0	2.0	14.2	50.6	26.9	5.5	4.5
LM13	3.2	11.0	2.0	17.9	38.4			4.5
LM21	3.8	3.0	1.6	11.8	74.6			5.6
LM22	3.8	7.0	1.6	15.4	54.7			5.6
LM23	3.8	11.0	1.6	19.1	42.3			5.6
LM31	4.4	3.0	1.4	13.1	77.1			6.6
LM32	4.4	7.0	1.4	16.7	58.0			6.6
MH12	3.2	7.0	3.6	14.4	51.2	39.0	8.0	3.1
MH13	3.2	11.0	3.6	18.0	39.0			3.1
MH21	3.8	3.0	3.0	12.0	75.0			3.8
MH22	3.8	7.0	3.0	15.6	55.2			3.8
MH23	3.8	11.0	3.0	19.3	42.9			3.8
MH31	4.4	3.0	2.5	13.3	77.4			4.5
MH32	4.4	7.0	2.5	16.8	58.4			4.5
MM12	3.2	7.0	2.0	14.4	51.2	27.3	5.6	4.4
MM13	3.2	11.0	2.0	18.0	39.0			4.4
MM21	3.8	3.0	1.6	12.0	75.0			5.4
MM22	**3.8**	**7.0**	**1.6**	**15.6**	**55.2**			**5.4**
MM23	3.8	11.0	1.6	19.3	42.9			5.4
MM31	4.4	3.0	1.4	13.3	77.4			6.5
MM32	4.4	7.0	1.4	16.8	58.4			6.5

Table 47 Performance Analysis of the Sloan Aggregate Source.

Violations	Mix ID	General Strength Mr	Rutting	Beam Fatigue		Compaction Observations
				300 μStrain	500 μStrain	
Low on # 4-Sieve	LM22	S Lower	NS	S Worse	S Worse	
High on # 4-Sieve	HM22	NS	S Better	S Better	S Better	
High on # 200-Sieve	MH22	NS	NS	S Worse	S Worse	
Low on Percent AC	MM12	NS	S Better	S Worse	S Worse	
High on Percent AC	MM32	S Lower	S Worse	NS	S Better	Minor Compaction
Low on Percent AV	MM21	S Higher	S Better	NS	NS	High Compaction Effort
High on Percent AV	MM23	S Lower	S Worse	S Worse	S Worse	Minor Compaction
Low on # 4 & High on # 200-Sieves	LH22	S Lower	NS	NS	NS	
High on # 4 & High on # 200-Sieves	HH22	NS	S Better	NS	NS	
Low on # 4 & Low on Percent AC	LM12	S Lower	S Better	S Worse	S Worse	
Low on # 4 & High on Percent AC	LM32	S Lower	S Worse	S Better	S Better	Not Compacted – Just Leveled
High on # 4 & Low on Percent AC	HM12	NS	S Better	S Worse	S Worse	High Compaction Effort
High on # 4 & High on Percent AC	HM32	S Lower	NS	S Better	S Better	
Low on # 4 & Low on Percent AV	LM21	S Higher	S Better	NS	NS	
Low on # 4 & High on Percent AV	LM23	S Lower	S Worse	S Worse	S Worse	Not Compacted – Just Leveled
High on # 4 & Low on Percent AV	HM21	S Higher	S Better	NS	NS	Very High Compaction Effort
High on # 4 & High on Percent AV	HM23	S Lower	NS	NS	NS	
High on # 200 & Low on Percent AC	MH12	NS	S Better	S Worse	S Worse	
High on # 200 & High on Percent AC	MH32	S Lower	S Worse	NS	S Better	Minor Compaction
High on # 200 & Low on Percent AV	MH21	NS	S Better	S Worse	S Worse	
High on # 200 & High on Percent AV	MH23	S Lower	S Worse	S Worse	S Worse	Minor Compaction
Low on Percent AC & High on Percent AV	MM13	S Lower	NS	S Worse	S Worse	
High on Percent AC & Low on Percent AV	MM31	NS	S Better	NS	NS	

Table 47 Performance Analysis of the Sloan Aggregate Source (Continued).

Violations	Mix ID	General Strength Mr	Rutting	Beam Fatigue		Compaction Observations
				300 µStrain	500 µStrain	
High on # 4, High on # 200 & Low on Percent AC	HH12	NS	S Better	S Worse	S Worse	Very High Compaction Effort
High on # 4, High on # 200 & High on Percent AC	HH32	S Lower	NS	NS	NS	
Low on # 4, High on # 200 & Low on Percent AC	LH12	S Lower	S Better	S Worse	S Worse	
Low on # 4, High on # 200 & High on Percent AC	LH32	S Lower	S Worse	S Worse	S Worse	Not Compacted – Just Leveled
High on # 4, High on # 200 & Low on Percent AV	HH21	S Higher	S Better	S Worse	S Worse	Very High Compaction Effort
High on # 4, High on # 200 & High on Percent AV	HH23	S Lower	S Worse	S Worse	S Worse	
Low on # 4, High on # 200 & Low on Percent AV	LH21	NS	S Better	S Worse	NS	
Low on # 4, High on # 200 & High on Percent AV	LH23	S Lower	S Worse	S Worse	NS	Not Compacted – Just Leveled
Low on # 4, Low on % AC & High on % AV	LM13	S Lower	S Worse	S Worse	S Worse	Minor Compaction
High on # 4, High on % AC & Low on % AV	HM31	NS	S Better	S Better	NS	High Compaction Effort
Low on # 4, High on % AC & Low on % AV	LM31	NS	NS	S Better	S Better	
High on # 4, Low on % AC & High on % AV	HM13	S Lower	NS	S Worse	S Worse	
High on # 200, High on % AC & Low on % AV	MH31	NS	NS	S Better	NS	
High on # 200, Low on % AC & High on % AV	MH13	S Lower	NS	S Worse	S Worse	
Low # 4, High # 200, Low % AC & High % AV	LH13	S Lower	NS	S Worse	S Worse	
Low # 4, High # 200, High % AC & Low % AV	LH31	S Lower	NS	S Better	NS	
High # 4, High # 200, High % AC & Low % AV	HH31	S Higher	S Better	S Better	NS	High Compaction Effort
High # 4, High # 200, Low % AC & High % AV	HH13	S Lower	NS	S Worse	S Worse	

Table 48 Ranking of the Lockwood and Sloan Aggregate Sources.

Lockwood Aggregate Source				Sloan Aggregate Source			
Mix ID	**Score**	**Rank**	**Impractical Mixes**	**Mix ID**	**Score**	**Rank**	**Impractical Mixes**
HM31	17	1	Impractical	HH31	11	1	Impractical
HH31	16	2	Impractical	HM22	11	1	
HM22	16	2		HM21	10	2	Impractical
HM32	16	2		LM21	10	2	
LM21	16	2		MM21	10	2	Impractical
MH31	16	2		HM31	10	2	Impractical
MM21	16	2	Impractical	LM31	10	2	
HH32	15	3		HH22	9	3	
LM31	15	3		MM31	9	3	
MM31	15	3		MH31	9	3	
HM21	14	4	Impractical	**MM22**			
MM22				HM32	9	3	
MM32	14	4		LH31	8	4	
HH21	13	5	Impractical	LH21	8	4	
HM23	13	5		LM32	8	4	
LH21	13	5		HH21	8	4	Impractical
LH31	13	5		HH32	7	5	
MH21	13	5	Impractical	HM23	7	5	
HH22	12	6		LH22	7	5	
LM23	12	6		MH32	7	5	
LM32	12	6		MM32	7	5	
HH23	11	7		HH12	7	5	Impractical
HM12	11	7	Impractical	HM12	7	5	Impractical
LM22	11	7		MH12	7	5	
MH32	11	7		MH21	7	5	
HH12	10	8	Impractical	MM12	7	5	
HM13	10	8		MH22	6	6	
LH32	10	8		LH12	6	6	
MH12	10	8		LM12	6	6	
MM12	10	8		LH23	5	7	
LH12	9	9		LM22	5	7	
LH22	9	9		HH13	5	7	
LH23	9	9		HM13	5	7	
MM23	9	9		LH13	5	7	
HH13	8	10		MH13	5	7	
LH13	8	10		MM13	5	7	
LM12	8	10		HH23	4	8	
LM13	8	10		LH32	4	8	
MH22	8	10		LM13	4	8	
MM13	8	10		LM23	4	8	
MH13	7	11		MH23	4	8	
MH23	7	11		MM23	4	8	

Table 49 Superpave Shear Tester – Repeated Shear Constant Height @ 50°C

	Lockwood (North)		**Sloan (South)**	
	Plastic Shear Strain (%)	APA Rut Depth (mm)	Plastic Shear Strain (%)	APA Rut Depth (mm)
Control MM22	4.4	3.9	4.0	3.8
LM21	2.5	2.1	2.5	2.3
MH31	2.3	2.4		

Table 50 Contribution of the Mix Property toward Performance for the Lockwood Mixes.

Property	Label	Strength Mr	Rutting	Fatigue Life	Thermal Cracking Temp
Air Voids	AV	47% (–)	23% (–)	1% (–)	23% (–)
VMA	VMA	54% (–)	36% (–)	0%	9% (–)
VFA	VFA	40% (+)	18% (+)	4% (+)	27% (+)
Percent Passing No. 4	P4	18% (+)	28% (+)	0%	1% (+)
Percent Passing No. 200	P200	2% (+)	0%	15% (–)	25% (–)
Binder Content	Pb	0 %	7% (–)	24% (+)	39% (+)
Effective Asphalt Content	Pbe	1% (–)	16% (–)	22% (+)	32% (+)
Surface Area	SA	2% (+)	0%	15% (–)	24% (–)
Average Film Thickness	TF	3% (–)	8% (–)	36% (+)	51% (+)
Dust Proportion	DP	2% (+)	5% (+)	32% (–)	54% (–)
Resilient Modulus	Mr	NA	61% (+)	4% (–)	1% (+)

Table 51 Contribution of the Mix Property toward Performance for the Sloan Mixes.

Property	Label	Strength Mr	Rutting	Fatigue Life
Air Voids	AV	59% (–)	31% (–)	23% (–)
VMA	VMA	63% (–)	47% (–)	7% (–)
VFA	VFA	53% (+)	21% (+)	30% (+)
Percent Passing No. 4	P4	17% (+)	23% (+)	1% (+)
Percent Passing No. 200	P200	0%	0%	10% (–)
Binder Content	Pb	2% (+)	5% (–)	51% (+)
Effective Asphalt Content	Pbe	1% (+)	6% (–)	49% (+)
Surface Area	SA	3% (–)	0%	9% (–)
Average Film Thickness	TF	4% (+)	4% (–)	49% (+)
Dust Proportion	DP	6% (–)	2% (+)	31% (–)
Resilient Modulus	Mr	NA	57% (+)	5% (+)

Table 52 Impact of the Single Factor Violations on the Lockwood Aggregate Source.

Violations	Mix ID	General Strength MR	Rutting	Beam Fatigue			Thermal Cracking
				300 µStrain	500 µStrain	800 µStrain	
Low on # 4-Sieve	LM22	-20%	-7% NS	+158%	+16% NS	-44%	+4% NS
High on # 4-Sieve	HM22	+11% NS	+22% NS	+83%	+107%	+133%	+20%
High on # 200-Sieve	MH22	-3% NS	-43%	-56%	-56%	-55%	+2% NS
Low on Percent AC	MM12	+24%	+27% NS	-62%	-58%	-55%	-9% NS
High on Percent AC	MM32	-12% NS	-33%	+34% NS	+128%	+270%	+15%
Low on Percent AV	MM21	+38%	+60%	-10% NS	35% NS	95%	+11%
High on Percent AV	MM23	-11% NS	-66%	-4% NS	-33%	-52%	+1% NS

Table 53 Impact of the Single Factor Violations on the Sloan Aggregate Source.

Violations	Mix ID	General Strength Mr	Rutting	Beam Fatigue	
				300 µStrain	500 µStrain
Low on # 4-Sieve	LM22	-23%	-18% NS	-40%	-72%
High on # 4-Sieve	HM22	0% NS	+32%	+133%	+89%
High on # 200-Sieve	MH22	-11% NS	+3% NS	-78%	-93%
Low on Percent AC	MM12	+11% NS	+37%	-70%	-95%
High on Percent AC	MM32	-32%	-37%	+36% NS	+75%
Low on Percent AV	MM21	+33%	+66%	+35% NS	+61% NS
High on Percent AV	MM23	-24%	-39%	-34%	-63%

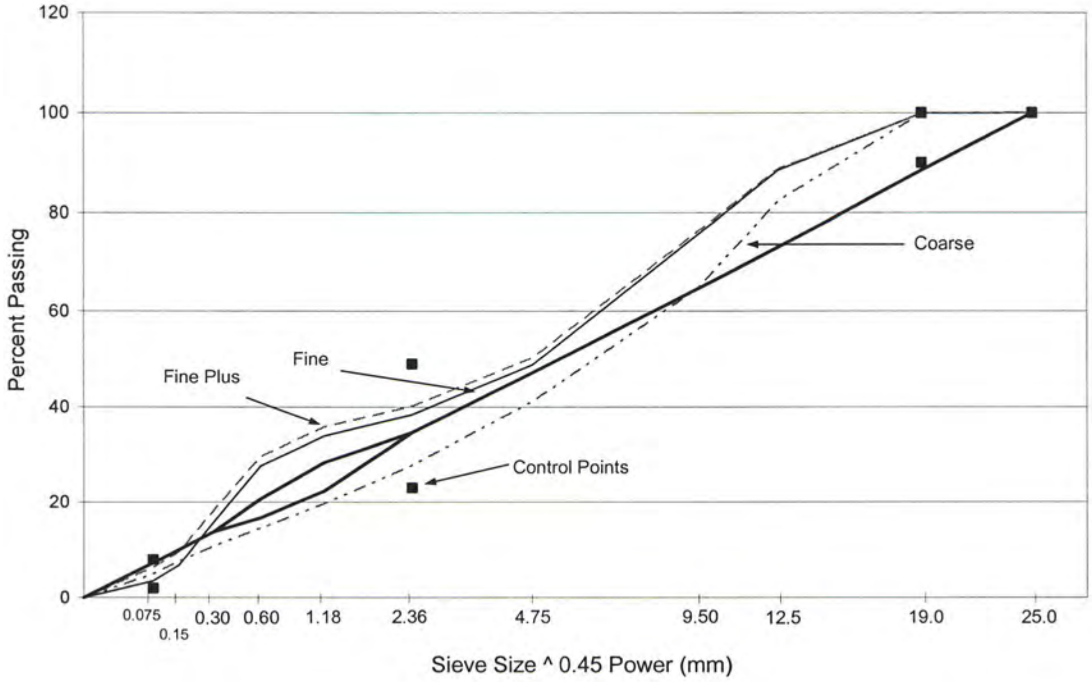


Figure 1 WesTrack Mixture Gradations (Fine, Fine Plus, Coarse).

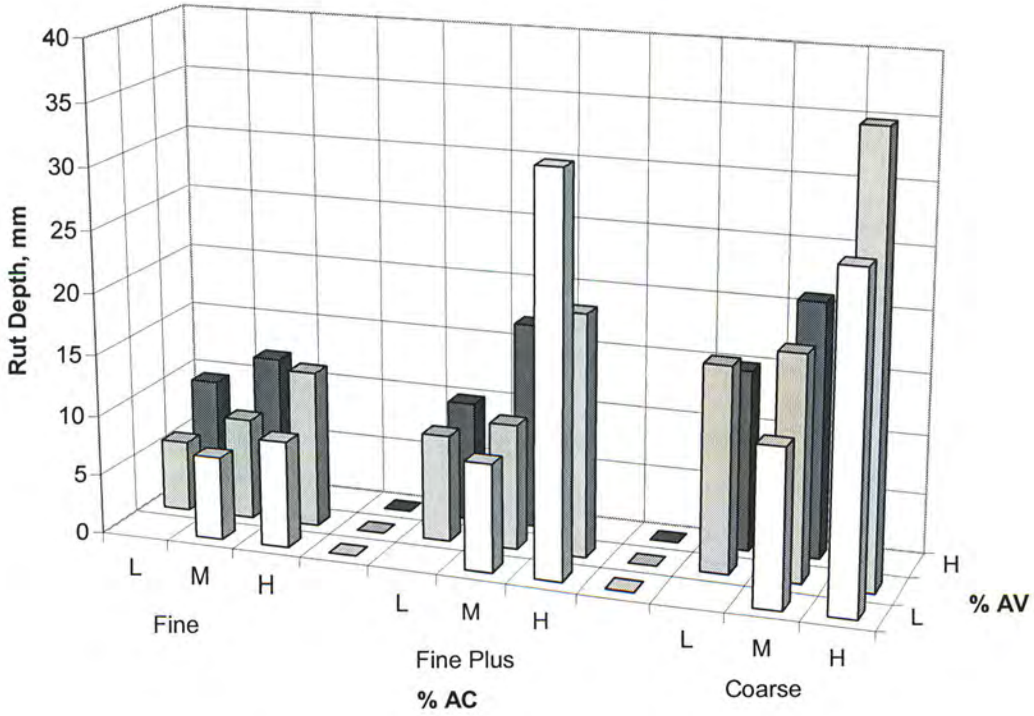


Figure 2 WesTrack Rut Depth after 1.5 Million ESALs.

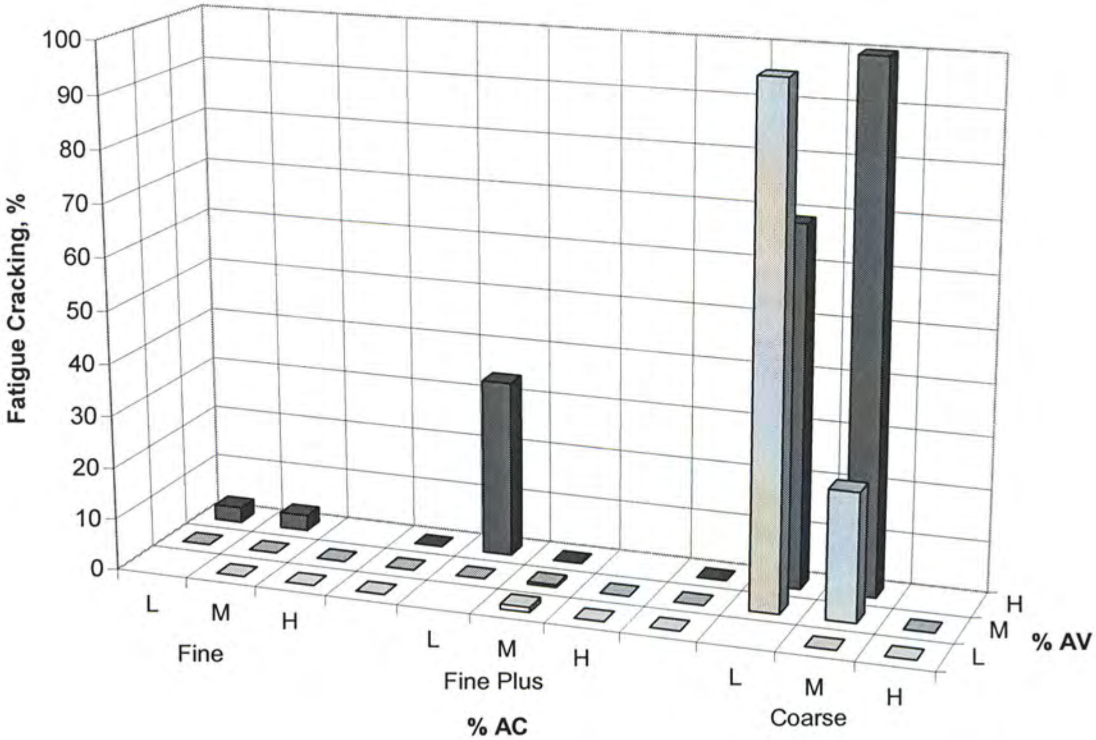


Figure 3 WesTrack Fatigue Data after 2.8 Million ESALs.

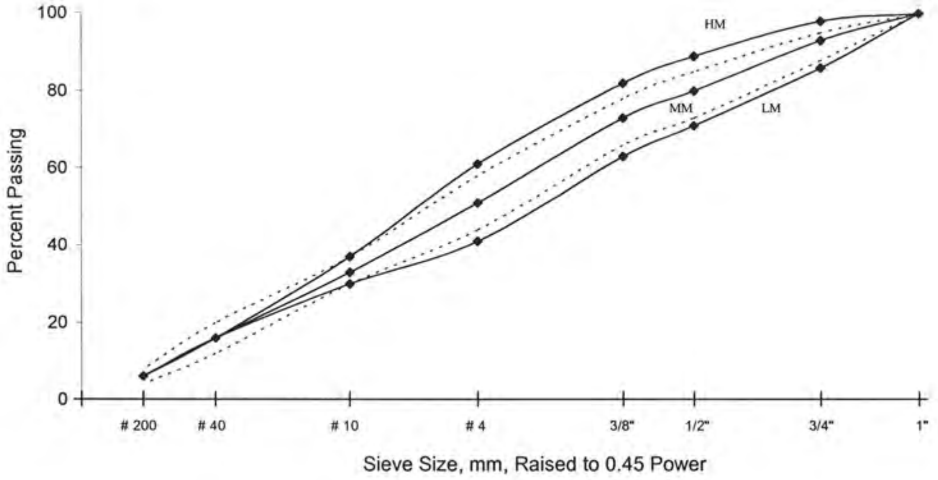


Figure 4 North Aggregate Gradations Passing the # 200 Sieve at the Medium Level .

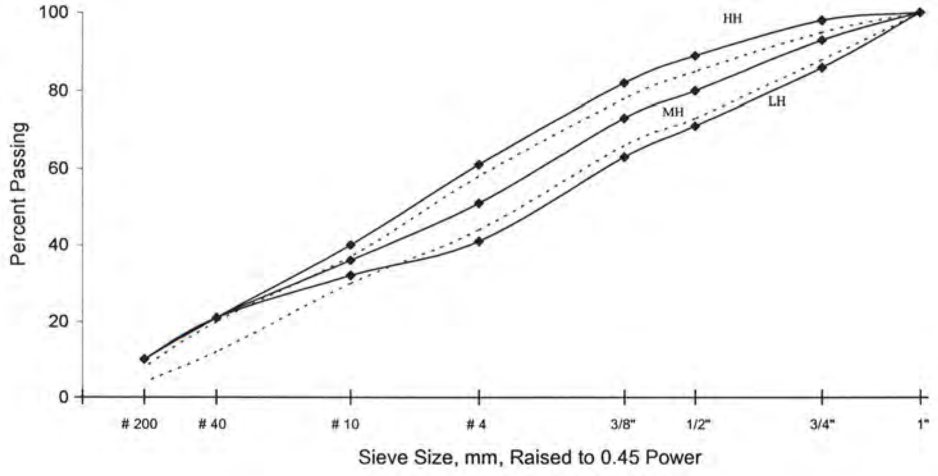


Figure 5 North Aggregate Gradations Passing the # 200 Sieve at the High Level.

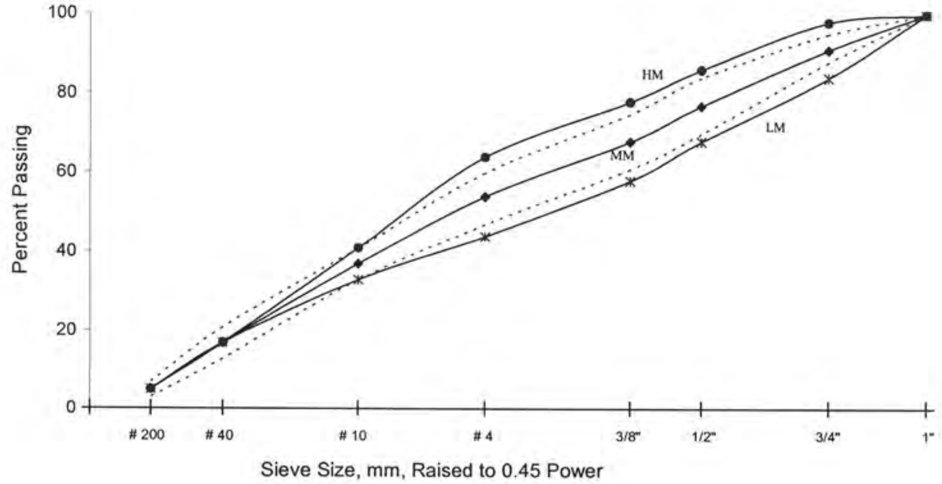


Figure 6 South Aggregate Gradations Passing the # 200 Sieve at the Medium Level .

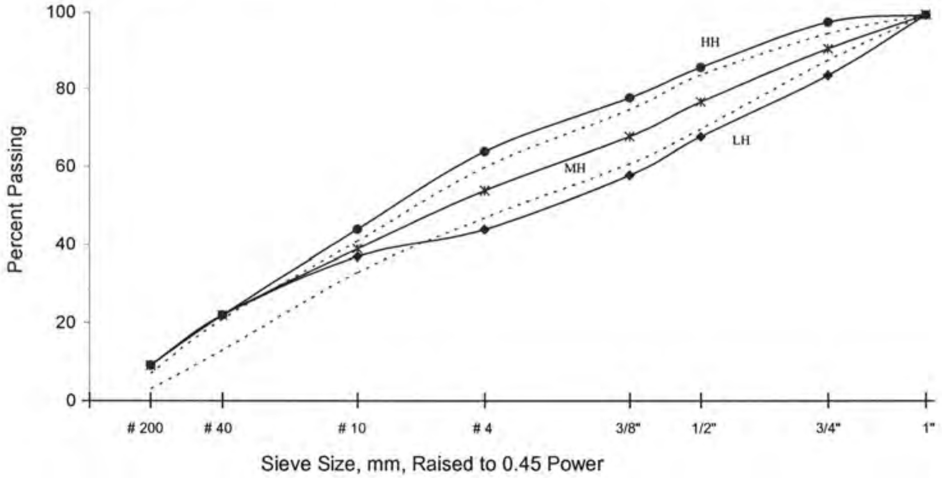


Figure 7 South Aggregate Gradations Passing the # 200 Sieve at the High Level.

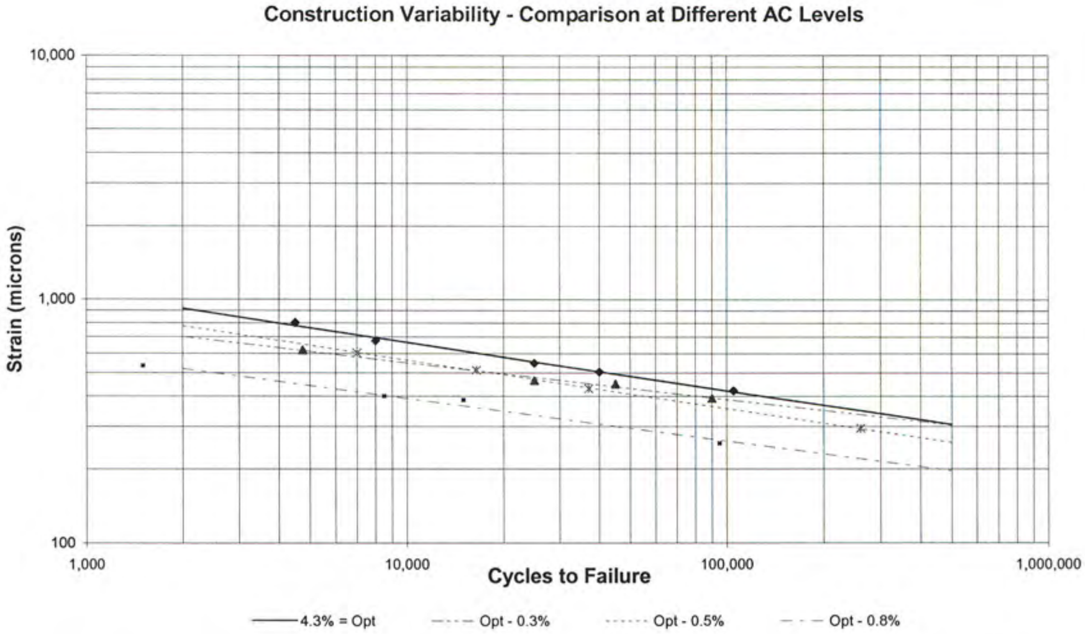
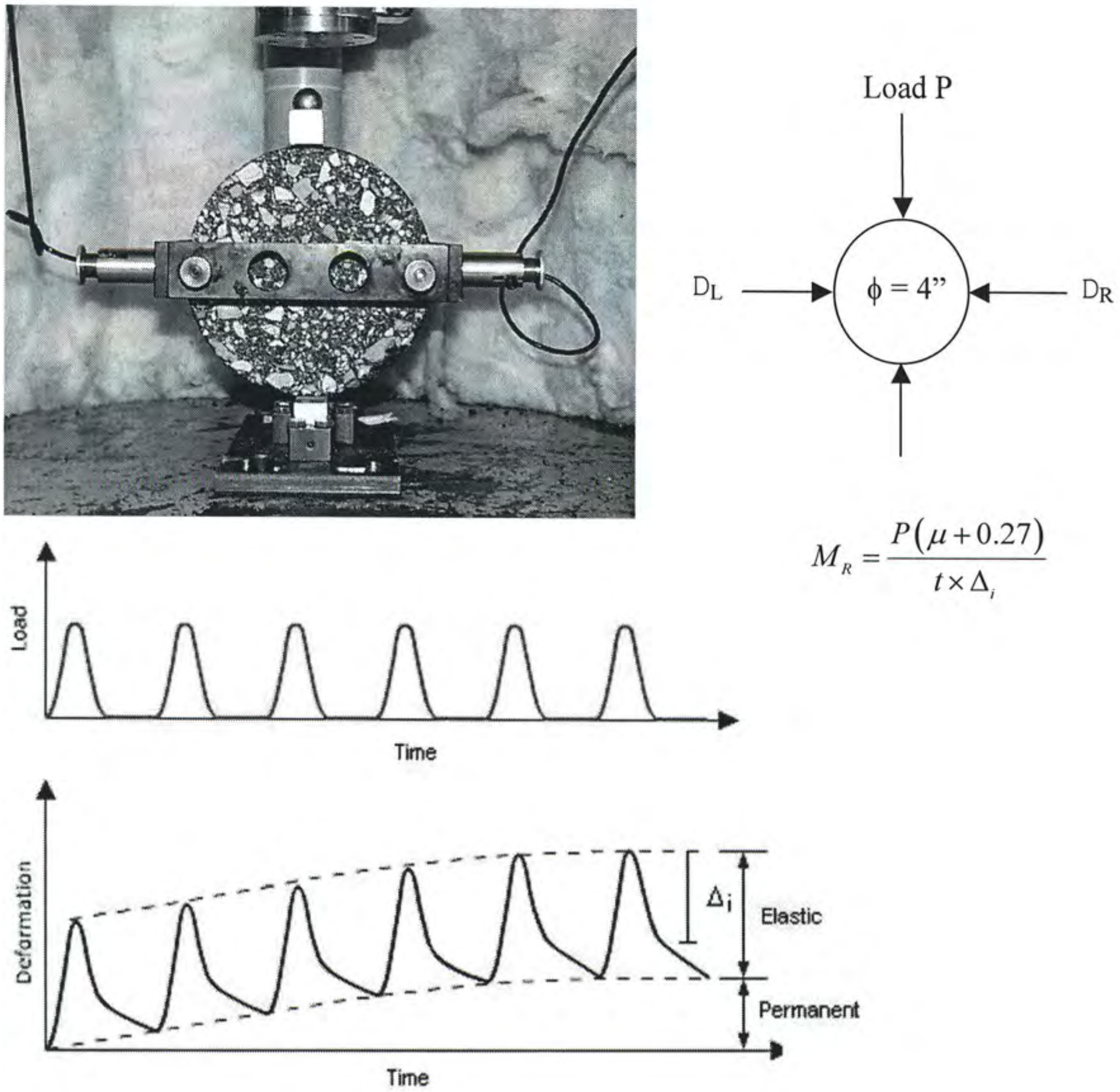


Figure 8 Comparison of Fatigue Life of the Lockwood Source at Different AC Levels.



$$M_R = \frac{P(\mu + 0.27)}{t \times \Delta_i}$$

Figure 9 Schematics of the Resilient Modulus Test.

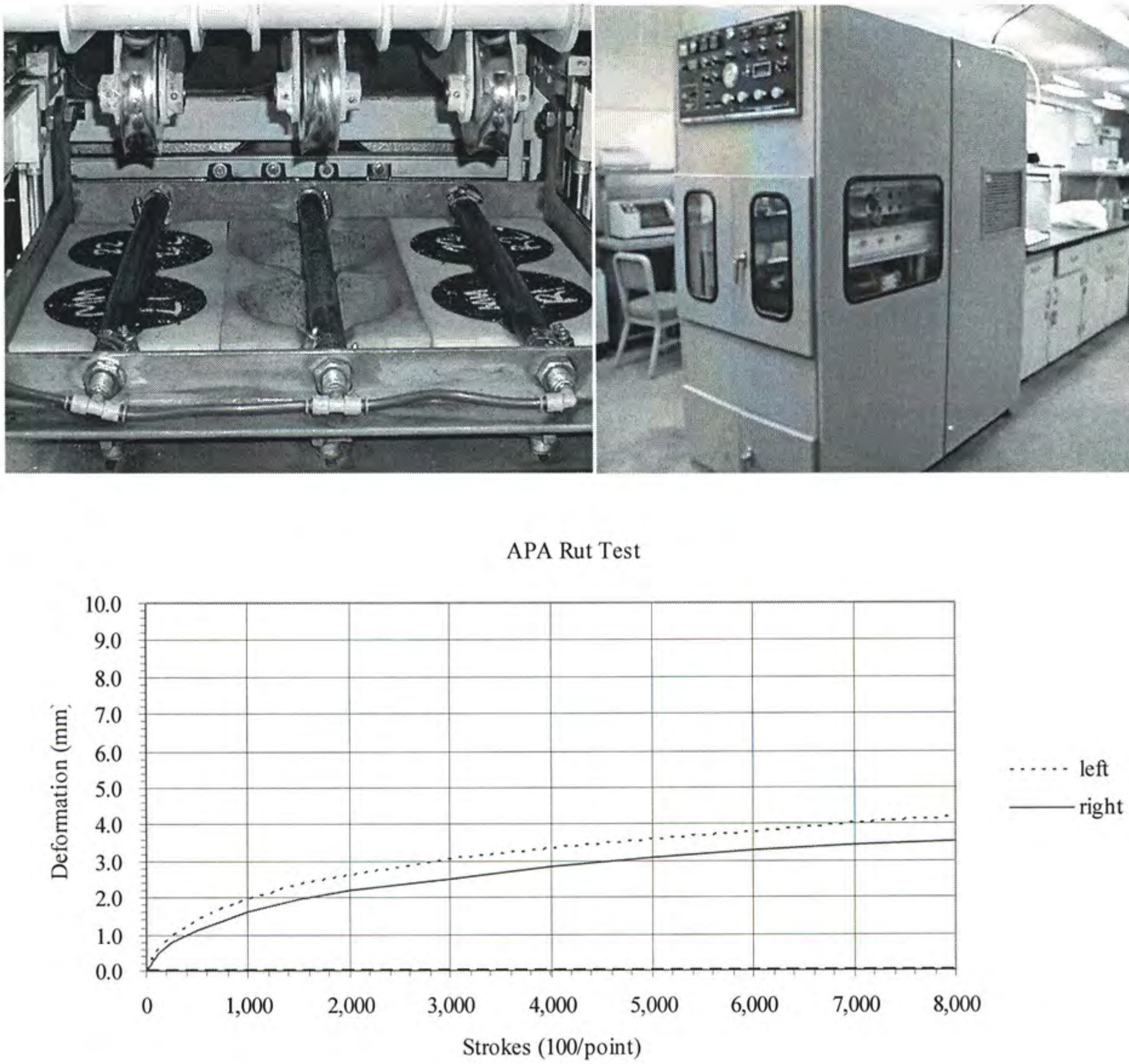


Figure 10 Schematics of the Asphalt Pavement Analyzer.

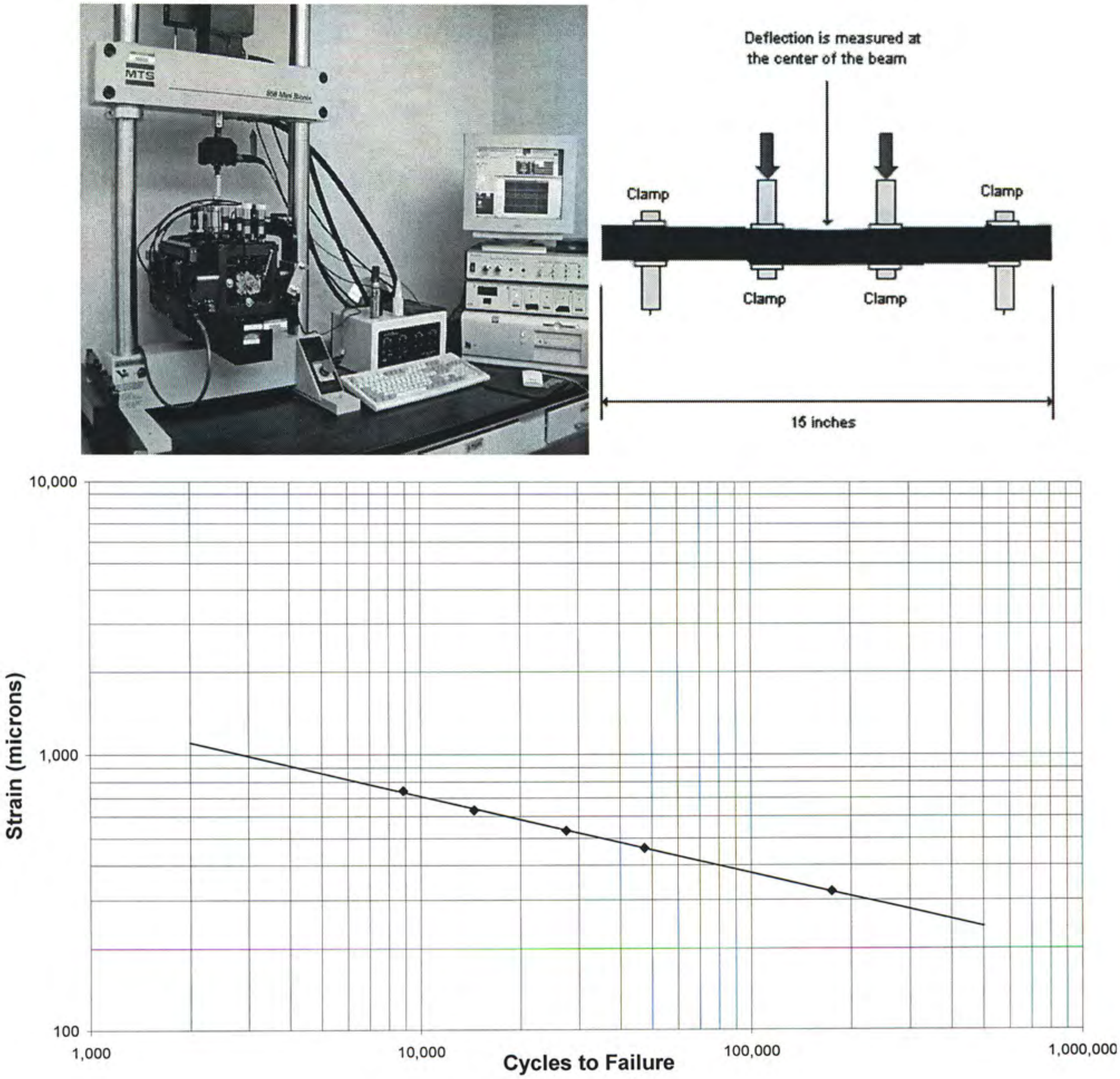


Figure 11 Schematics of the Flexural Beam Fatigue.

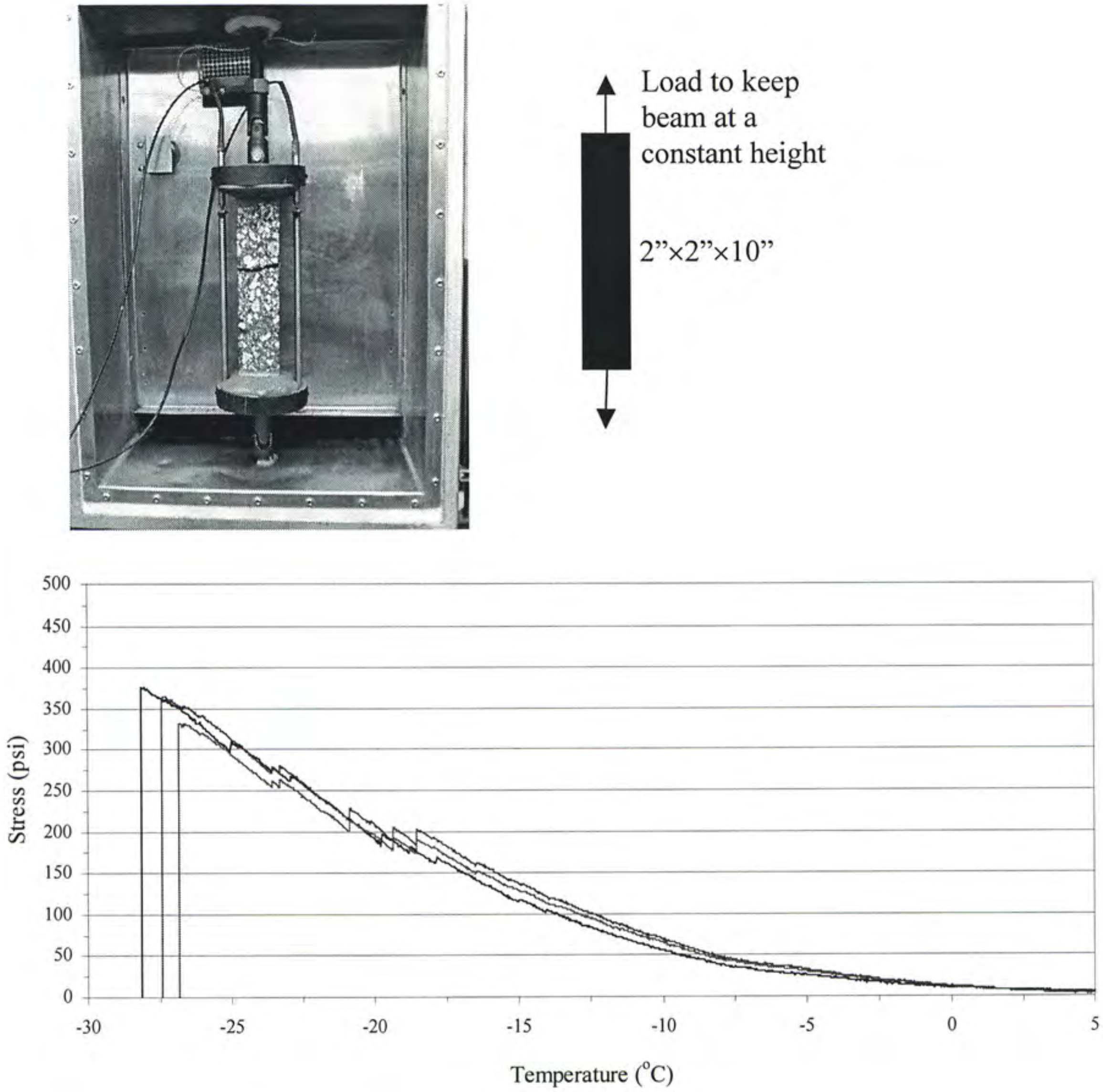


Figure 12 Schematics of the TSRST.

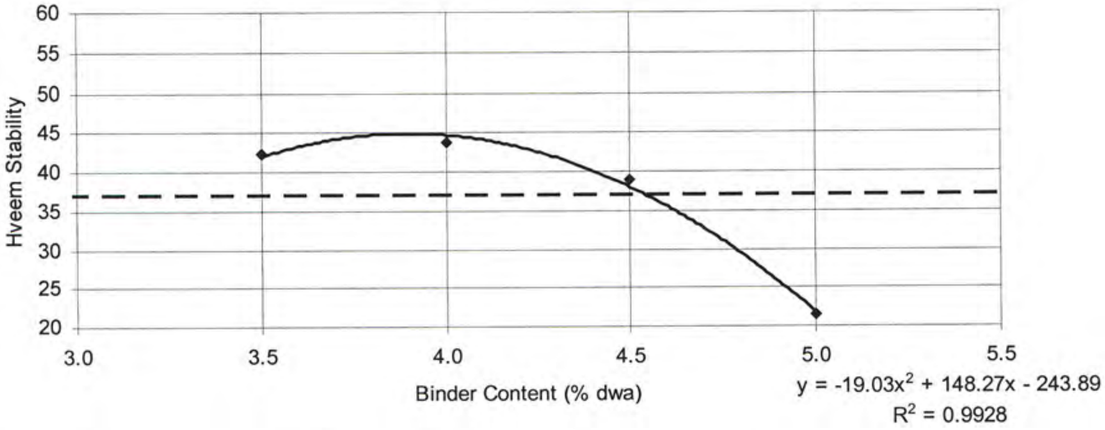


Figure 13 Hveem Stability for the Lockwood Aggregate Source.

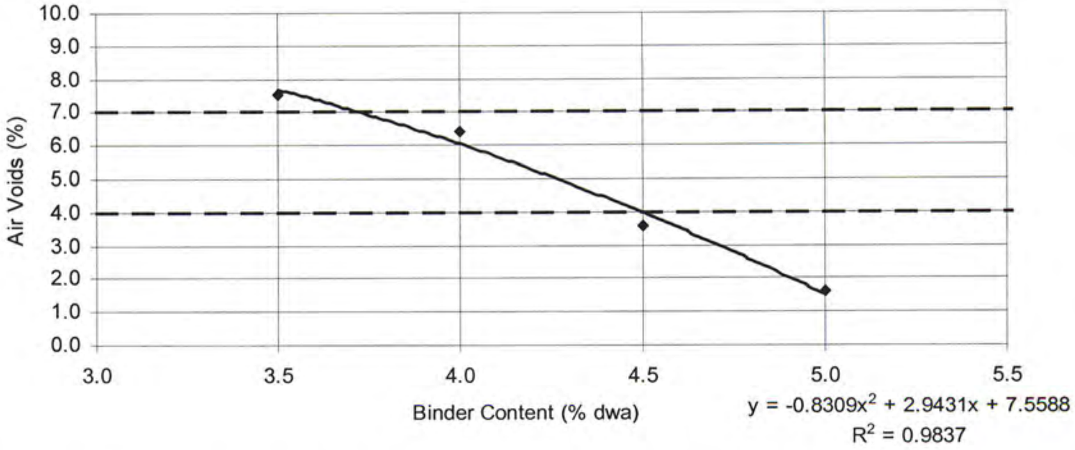


Figure 14 Percent Air-Voids for the Lockwood Aggregate Source.

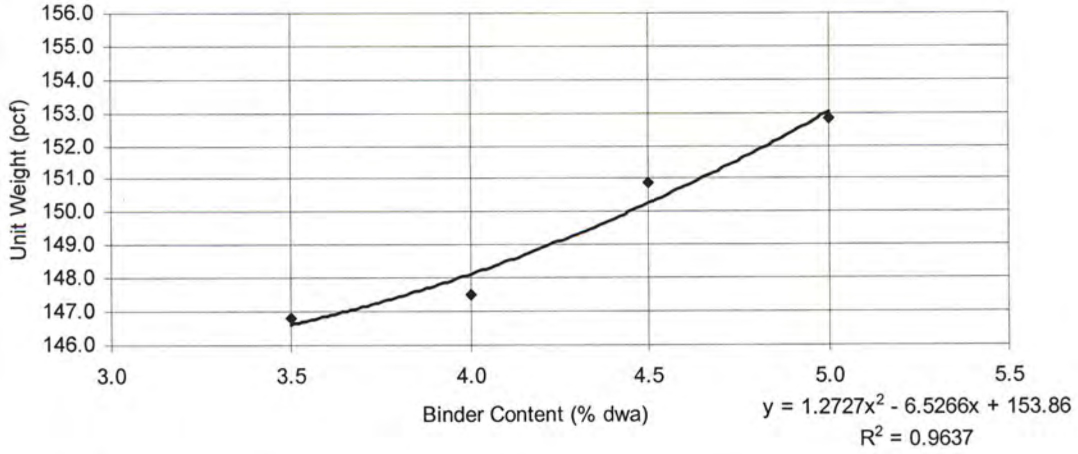


Figure 15 Unit Weight for the Lockwood Aggregate Source.

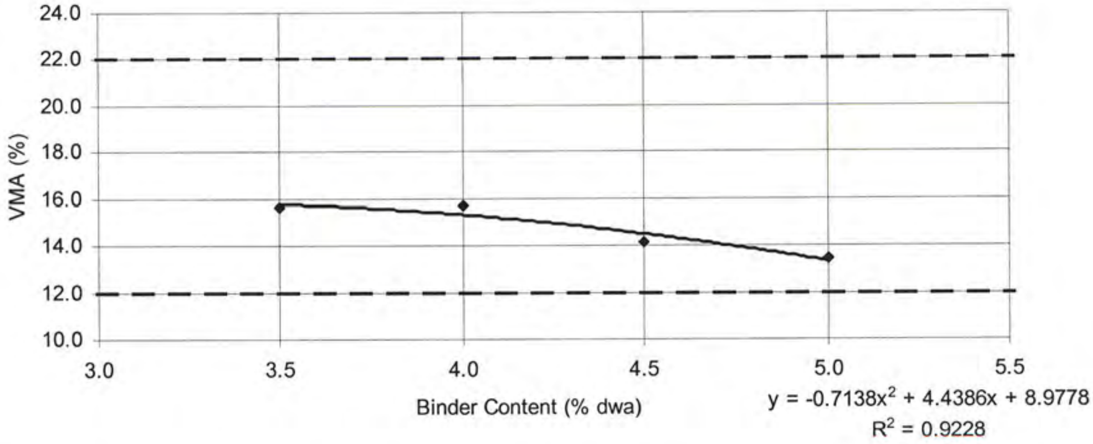


Figure 16 Percent VMA for the Lockwood Aggregate Source.

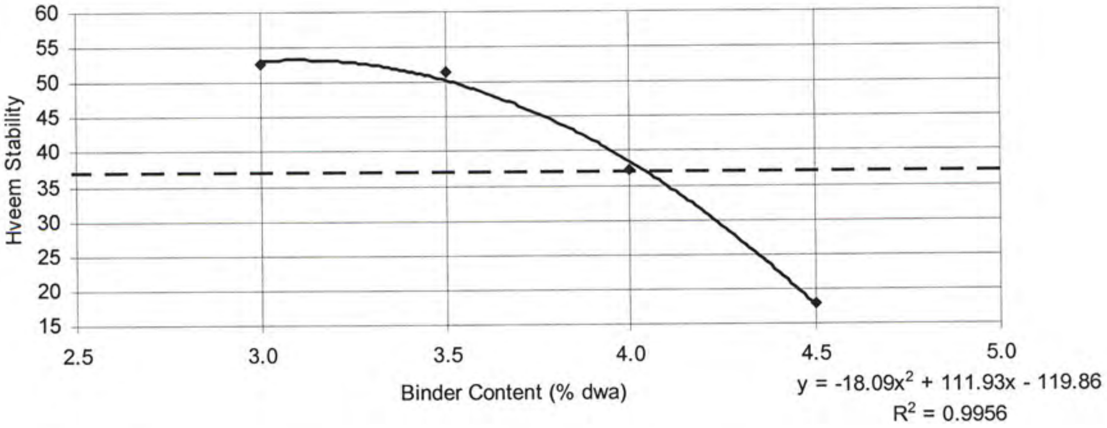


Figure 17 Hveem Stability for the Sloan Aggregate Source.

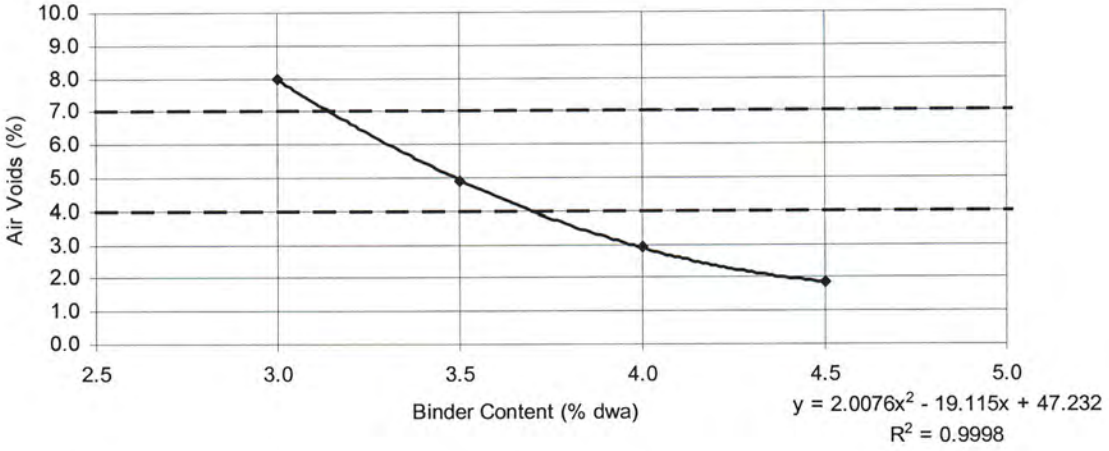


Figure 18 Percent Air-Voids for the Sloan Aggregate Source.

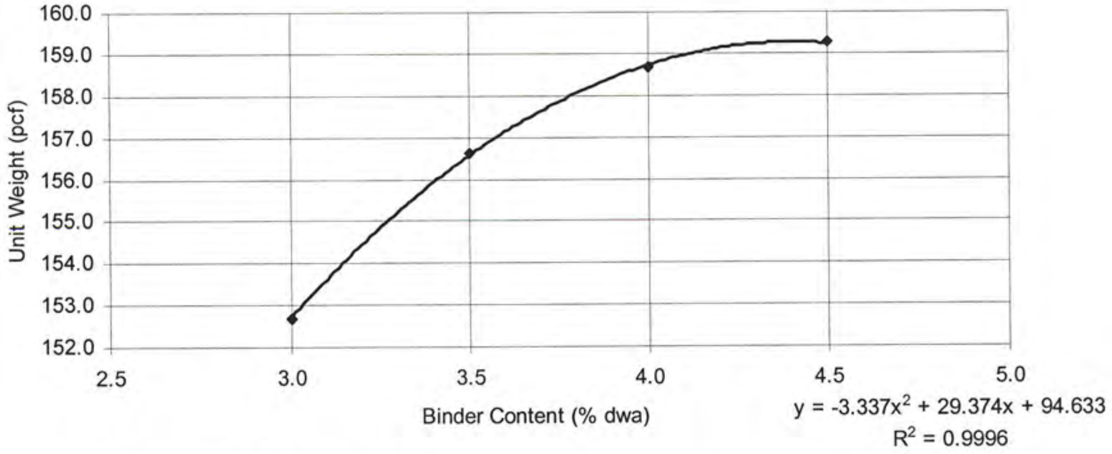


Figure 19 Unit Weight for the Sloan Aggregate Source.

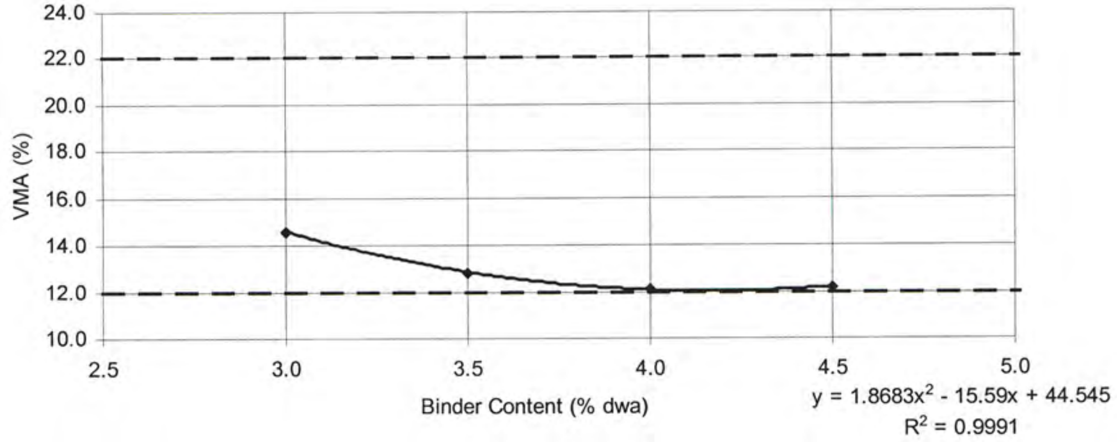


Figure 20 Percent VMA for the Sloan Aggregate Source.

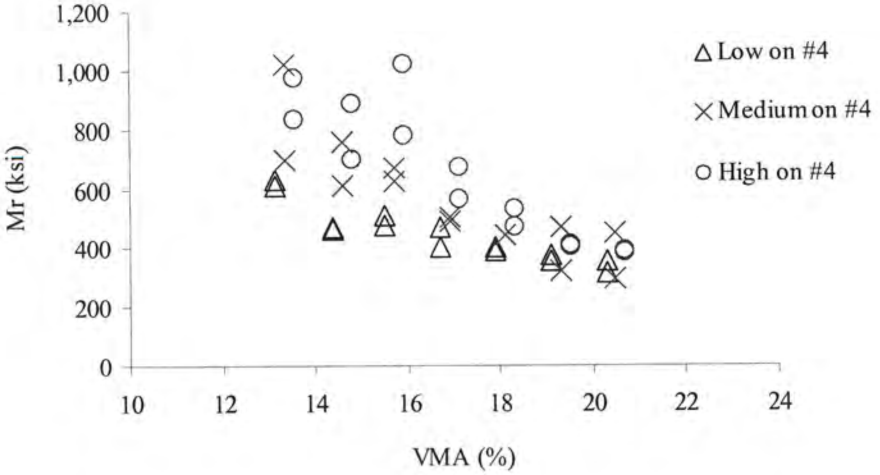


Figure 21 Resilient Modulus Vs. Percent VMA for the Lockwood Aggregate Source.

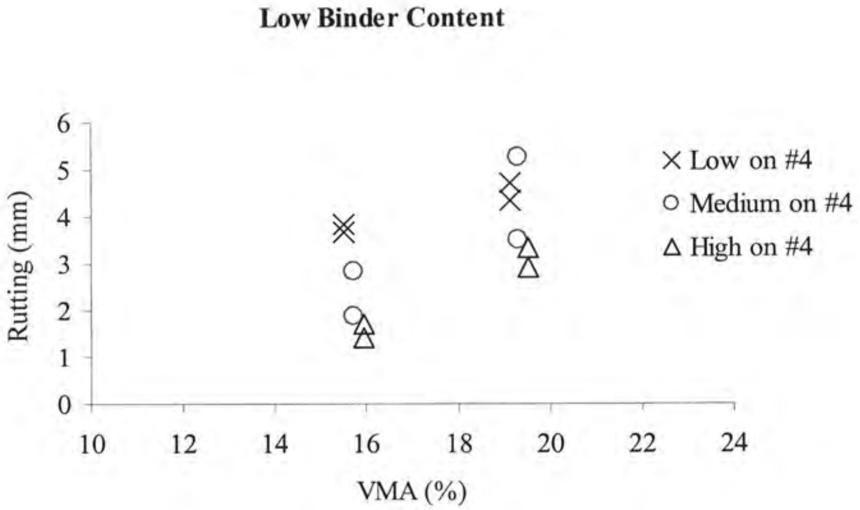


Figure 22 Rutting Vs. Percent VMA for the Lockwood Aggregate Source at Low %AC

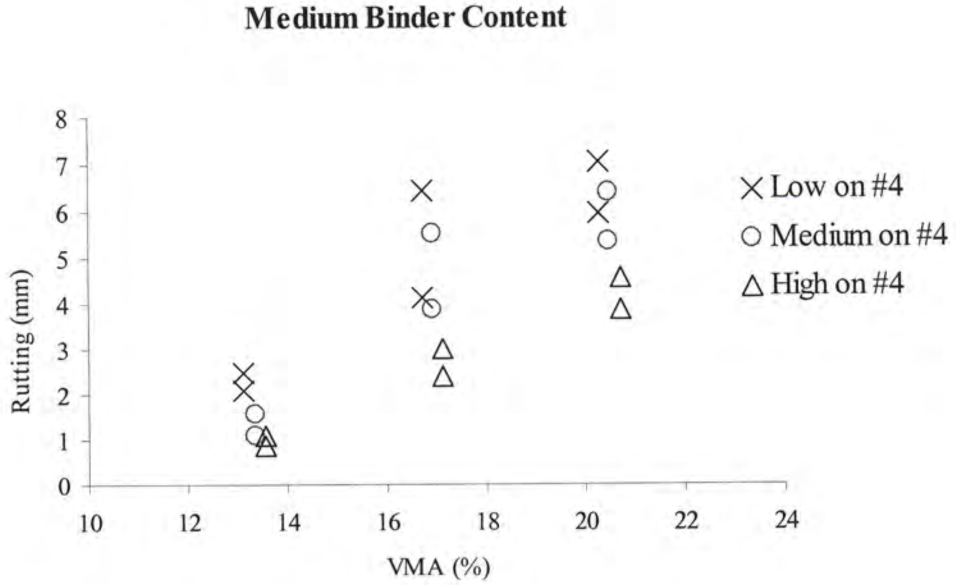


Figure 23 Rutting Vs. VMA for the Lockwood Aggregate Source at Medium %AC

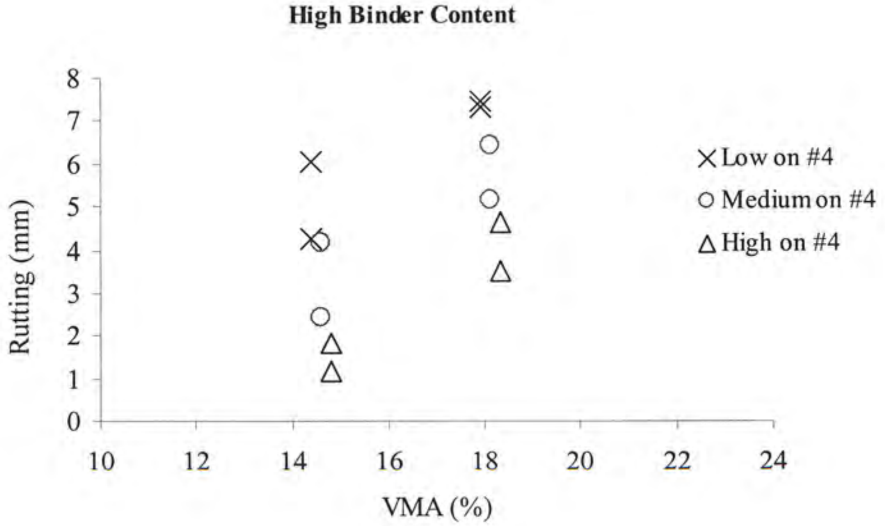


Figure 24 Rutting Vs. Percent VMA for the Lockwood Aggregate Source at High %AC

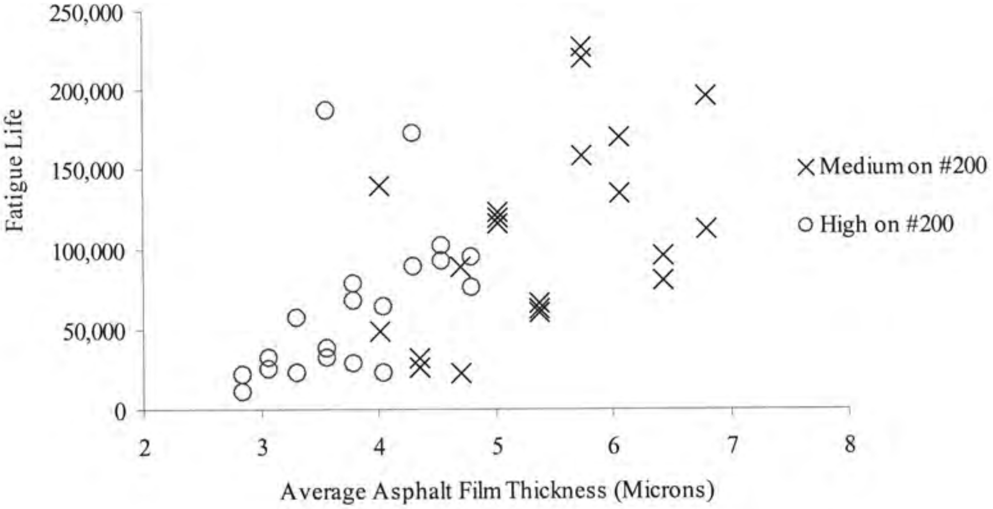


Figure 25 Fatigue Life Vs. Film Thickness for the Lockwood Aggregate Source.

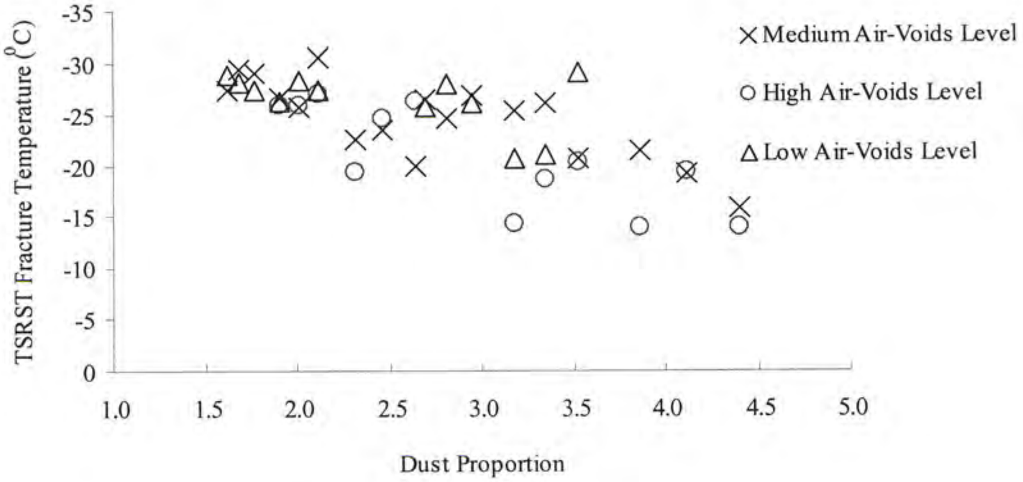


Figure 26 Fracture Temp Vs. Dust Proportion for the Lockwood Aggregate Source.

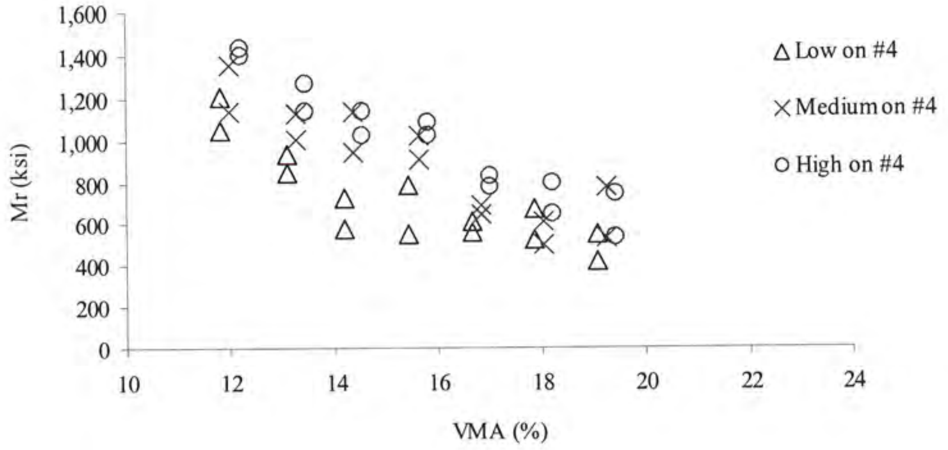


Figure 27 Resilient Modulus Vs. Percent VMA for the Sloan Aggregate Source.

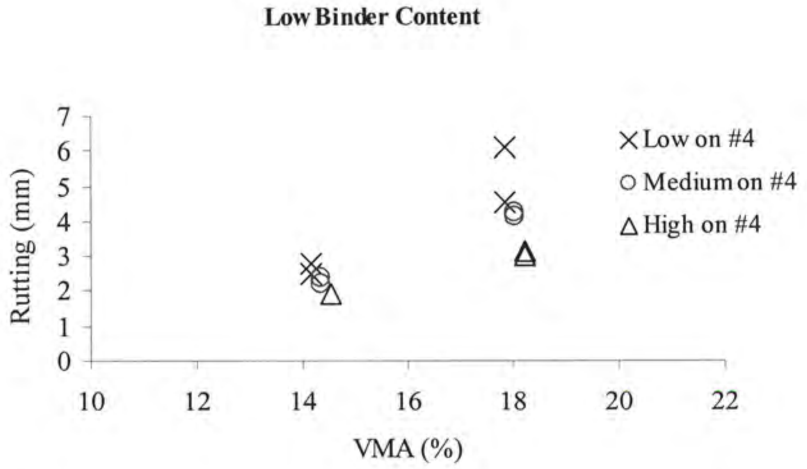


Figure 28 Rutting Vs. Percent VMA for the Sloan Aggregate Source at Low %AC

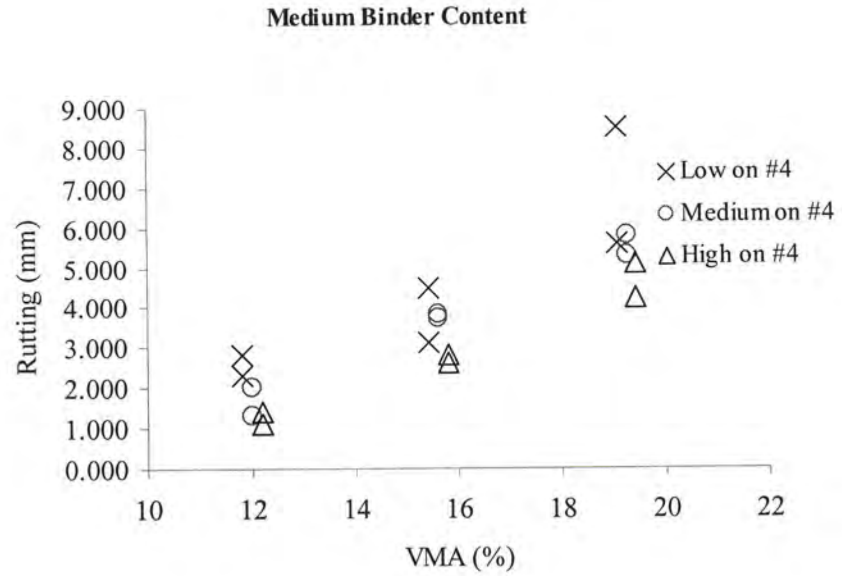


Figure 29 Rutting Vs. Percent VMA for the Sloan Aggregate Source at Medium %AC

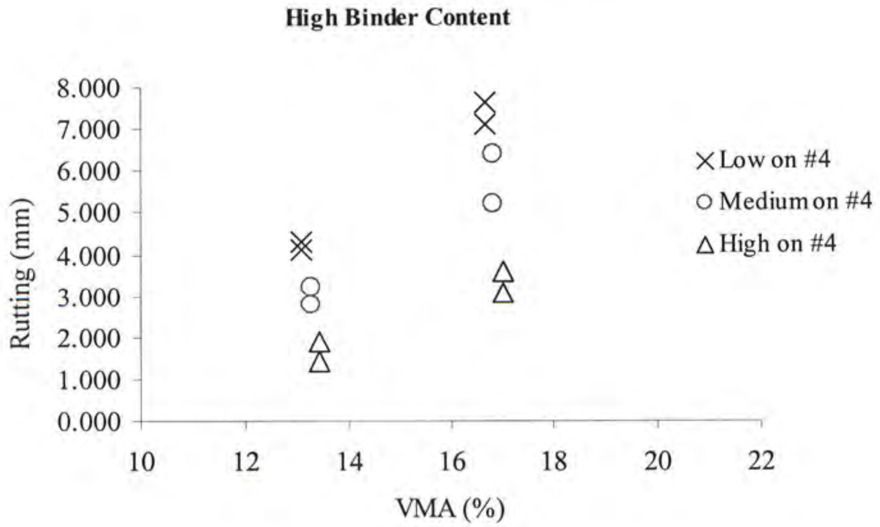


Figure 30 Rutting Vs. Percent VMA for the Sloan Aggregate Source at High %AC

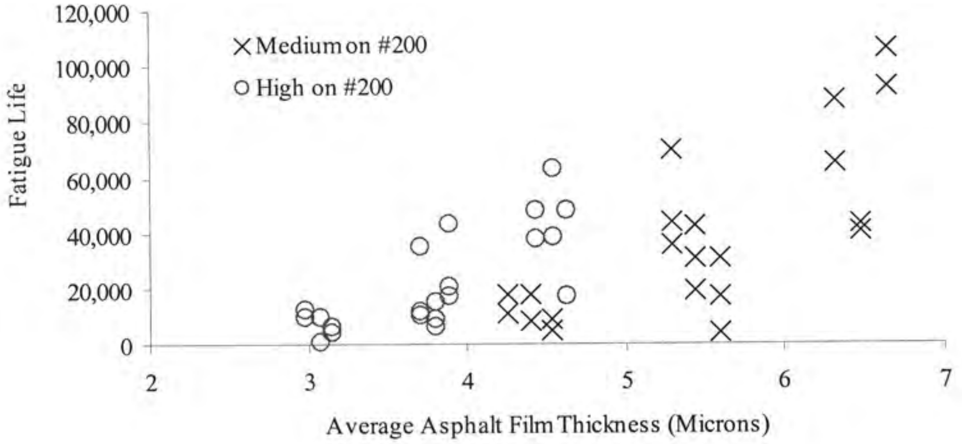


Figure 31 Fatigue Life Vs. Film Thickness for the Sloan Aggregate Source.

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