IMPLEMENTATION OF SUPERPAVE MIX DESIGN AND ANALYSIS PROCEDURES FOR THE STATE OF NEVADA
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IMPLEMENTATION OF SUPERPAVE MIX DESIGN AND ANALYSIS PROCEDURES FOR THE STATE OF NEVADA

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EXECUTIVE SUMMARY

This research effort started in mid 1990's to evaluate the performance of Superpave mixtures under Nevada's conditions and to assess the possibility of implementing the Superpave mix design procedure. Field test sections were constructed to compare the performance of Superpave mixtures with the performance of Hveem under the same traffic and environmental conditions. Based on the field performance of several Superpave mixtures throughout the state of Nevada during the late 1990's, NDOT decided to modify the Superpave volumetric mix design method and construct two test sections side-by-side with the conventional NDOT Hveem mixtures on three projects. The modifications of the Superpave volumetric mix design included: a) eliminate the restricted zone requirement on aggregate gradation, b) include a minimum requirement on Hveem stability, c) verify potential performance in rutting with the APA, and d) include a minimum dry tensile strength of 65 psi and a retained tensile strength ratio of 70%.

Using the modified Superpave volumetric mix design, NDOT constructed three test sections: two on I-80 in the northern part of the state in 2001 and 2003 and one on I-15 in the southern part of the state in 2002. Each test section was built as part of a Hveem designed project which allowed for the direct comparison of the performance of mixtures designed with the modified Superpave and NDOT Hveem methods.

This report summarizes the laboratory evaluation of the mixtures from the two sections on each of the projects and the field performance of the sections. The laboratory evaluations assessed the resistance of the mixtures to the failure modes of rutting, thermal cracking, fatigue, and moisture damage. The field performance included the measurement of rutting data on the field sections.

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INTRODUCTION

The Superpave mix design process of HMA mixtures was developed as a result of the Strategic Highway Research Program (SHRP) effort on asphalt binders and mixtures between 1987 and 1992. The SHRP research recommended a new asphalt binder grading system and a new mixture design method. The combination of these two steps represents the basics for the Superpave HMA mixture design system. In other words a Superpave designed HMA mixture would have an asphalt binder selected based on the Superpave weather data and graded using the performance based binder grading system, aggregates that meet the Superpave criteria, and an optimum asphalt binder content selected based on the Superpave volumetric criteria.

The binder grading system is referred to as the PG grading system which stands for performance graded asphalt binders. The basic concept of the PG grading system is that asphalt binders should be graded based on their potential performance under the environmental and traffic conditions of the project. The potential performance of asphalt binders is evaluated in terms of their contributions to the HMA mixtures resistance to rutting, fatigue, and thermal cracking. Rheological properties are used to assess the contribution of the asphalt binders to the performance of HMA mixtures.

Using the measured rheological properties, the asphalt binder is graded based on the temperatures at which the properties limits are achieved. Figure 1 shows the PG grading chart for asphalt binders. The final grade is given in the form of PGXX-YY, where XX represents the highest seven-days average pavement temperature under which this binder can be used while the -YY represents the lowest single-day pavement temperature under which this binder can be used. For example a binder graded as PG64-28 represents a binder that can be used on a pavement where the anticipated highest seven-days average pavement temperature is 64°C and the lowest single-day pavement temperature is -28°C.

The Superpave volumetric mix design method is based on the use of the gyratory compactor coupled with a set of aggregate and mixture's volumetric criteria. The gyratory compactor is used to compact HMA mixtures at trial asphalt binder contents for specified number of gyrations (Table 1) (1). The mix volumetric criteria include limits on the air-voids (Va), voids in mineral aggregates (VMA), voids filled with asphalt (VFA), and filler to asphalt binder ratio. The volumetric criteria are established as a function of the number of gyrations as shown in Table 2 (2). The aggregate criteria include requirements on the fractured faces, sand equivalent, flat and elongated particles, and gradation as shown in Tables 3 and 4 (2). The aggregate properties are measured first and an acceptable aggregate blend and gradation is established. The optimum asphalt binder content is selected based on the mixture that meets all the volumetric criteria. The optimum binder content is expressed in terms of the total weight of the mix.

NDOT has been using the Hveem mix design method to design HMA mixtures for a long time. The Hveem method uses the kneading compactor and selects the optimum asphalt binder content based on: no flushing, 4% air-voids, and a minimum stability. NDOT has added the VMA requirement on the Hveem design method. The optimum binder content is expressed in terms of the dry weight of aggregates.

NDOT has developed a great historical record with excellent performing Hveem designed HMA mixtures throughout the entire state. It should be noted here that Nevada's environmental and traffic conditions are rather unique; pavement temperatures reaching both extremes coupled with severe winter freeze-thaw cycling in the northern part of the state. Also traffic volumes range from the extreme low in the rural areas to the extreme high in the urban areas. The combination of these extremes presented a real challenge, which NDOT combated with fundamental research and development efforts that brought the state highway system to an extremely high level of service.

NDOT's EARLY EXPERIENCE WITH SUPERPAVE MIXTURES

With good success with the current Hveem mix design method, NDOT is approaching the implementation of the Superpave mix design system with extreme caution. The following represents a brief summary of NDOT's early experience with Superpave mixtures.

- In 1996 a Superpave test section was constructed on SR 278 in Eureka County, Nevada under contract number 2751. The Superpave designed mixture was a ½" nominal maximum aggregate size with a PG64-28 binder at an optimum binder content of 6.3%. After three years of service, the section started showing some intermittent transverse cracking on isolated areas and after five years of service, the section showed extensive transverse, longitudinal, and block cracking throughout.

- In 1997 a Superpave test section was constructed on US 93 in White Pine County, Nevada under contract number 2827. The Superpave designed mixture was a 3/4" nominal maximum aggregate size with a PG64-34 binder at an optimum binder content of 5.6%. After four years of service, the section showed longitudinal and transverse cracking throughout.

- In 1998 two Superpave sections were constructed on I 80 in Churchill County, Nevada under contract number 2880: SP AC-20P and SP PG 64-22. The SP AC-20P mixture was a 3/4" nominal maximum aggregate size with an AC-20P binder at an optimum binder content of 5.8%. The SP PG64-22 mixture was a 3/4" nominal maximum aggregate size with a PG64-22 binder at an optimum binder content of 5.8%. After three years of service the SP AC-20P section experienced an average rut depth of 0.31" and the SP PG64-22 section experienced an average rut depth of 0.60" with severe flushing in the wheelpath.

The laboratory evaluations and field performance of these projects have been well documented in earlier reports and technical papers (3, 4, 5, 6, 7). Based on the early experiences with Superpave mixtures, NDOT decided to re-evaluate the Superpave volumetric mix design procedure with the following modifications:

- Eliminate the Restricted Zone requirement on aggregate gradation.
- Include a minimum requirement on Hveem stability.
- Verify potential performance at the mix design stage using the Asphalt Pavement Analyzer (APA).
- Include a minimum dry tensile strength of 65 psi on Hveem compacted samples at optimum.

- Include a minimum tensile strength ratio of 70% on Hveem compacted samples at optimum.

Between 2001 and 2003, NDOT implemented the above modifications on three test sections that are summarized in this report.

TEST SECTIONS WITH THE MODIFIED SUPERPAVE SYSTEM

Test Section on Contract 3064

The overall objective of this section was to compare the performance of a modified Superpave HMA mixture with a NDOT Hveem mixture. One Superpave test section was constructed as part of NDOT Hveem designed project on I-80 in Churchill County, east of Reno, Nevada on October 3, 2001. The entire project spans from milepost 2.20 to milepost 12.88 (2.232 to 12.832 CUM MP) in both the eastbound and westbound directions. The Superpave section is located between mileposts 5.81 and 6.78 (5.837 to 6.980 CUM MP) of the travel lane in the westbound direction.

The constructed layer consisted of milling the top 1.0” of the existing HMA mix (7.0”) and placing a 2.5” of new dense graded HMA mixture and a 3/4" open graded mixture. The supporting layers consist of 6.0” of the remaining old HMA and 10.0” aggregate base. The contractor for the project was Frehner Construction. Tables 5 and 6 summarize the mix design recommendations for the Superpave and Hveem sections, respectively. Figure 2 shows the gradations of the Superpave and Hveem sections. The gradation of the Superpave section violates the NDOT Type 2C gradation specifications but it satisfies the Superpave Control Points. Detailed materials properties, mix design information, and construction activities for this project are summarized in Reference 8.

The following traffic data apply to the location of the test sections:

One direction ADT:	3,520
Truck factor:	1.44
Percent trucks:	30%
Daily one direction ESALs:	1,521

20 years average growth rate:	2.1%
20 years design ESALs:	13,600,000

Test Section on Contract 3071

One Superpave test section was constructed as part of NDOT Hveem designed project on I-15 in Clark County, Nevada on October 23, 2002. The entire project spans from milepost 0.00 to milepost 16.34 (2.232 to 12.832 CUM MP) in both the northbound and southbound directions. The Superpave section is located between mileposts 2.00 and 3.00 (2.00 to 3.00 CUM MP) of the travel lane in the northbound direction.

The constructed layer consisted of milling the top 2.0" of the existing HMA mix (5 in.) and placing a 5.0" of new dense graded HMA mixture and a 3/4" open graded mixture. The supporting layers consist of 3.0" of the remaining old HMA and a 6.0" aggregate base. The contractor for the project was Las Vegas Paving Corporation. Tables 7 and 8 summarize the mix design recommendations for the Superpave and Hveem sections, respectively. Figure 3 shows the gradations of the Superpave and Hveem sections. The gradation of the Superpave section violates the NDOT Type 2C gradation specifications but it satisfies the Superpave Control Points. Detailed materials properties, mix design information, and construction activities for this project are summarized in Reference 8.

The following traffic data apply to the location of the test sections:

One direction ADT:	19,800
Truck factor:	1.293
Percent trucks:	18%
Daily one direction ESALs:	4,610
20 years average growth rate:	3.0%
20 years design ESALs:	45,200,000

Test Section on Contract 3140

One Superpave test section was constructed as part of NDOT Hveem designed project on I-80 in Elko County, Nevada on September 5, 2003. The entire project spans from milepost 310.00 milepost

330.00 (EL 32.00 to EL43.95 CUM MP) in both the eastbound and westbound directions. The Superpave section is located between mileposts 311.00 and 310.00 (373+03 to 320+23 CUM MP) of the travel lane in the west bound direction.

The constructed layer consisted of milling the top 1.0" of the existing HMA mix (5.0") and placing a 2.5" of new dense graded HMA mixture and a 3/4" open graded mixture. The supporting layers consist of 4.0" of the remaining old HMA and 6.0" aggregate base. The contractor for the project was Road & Highway Builders Construction Company. Tables 9 and 10 summarize the mix design recommendations for the Superpave and Hveem sections, respectively. Figure 4 shows the gradations of the Superpave and Hveem sections. The gradation of the Superpave section violates the NDOT Type 2C gradation specifications but it satisfies the Superpave Control Points. Detailed materials properties, mix design information, and construction activities for this project are summarized in Reference 8.

The following traffic data apply to the location of the test sections:

One direction ADT:	4000
Truck factor:	1.44
Percent trucks:	30%
Daily one direction ESALs:	635,700
20 years average growth rate:	2%
20 years design ESALs:	15,450,000

LABORATORY EVALUATION PROGRAM

Two types of materials were sampled during the construction of each section: virgin aggregates and binder and field mixtures. The virgin materials were used to produce lab mixed – lab compacted (LMLC) samples and the field mixtures were used to produce field mixed – lab compacted (FMLC) samples. In order to effectively compare the properties of lab mixtures with field mixtures, the LMLC mixtures were short-term aged following the Superpave procedure of 4 hours at 275°F while the FMLC mixtures were not subjected to aging. The Hveem and Superpave mixtures from each test section were tested in the laboratory to evaluate the following properties:

- Resilient modulus and tensile strength
- Resistance to moisture damage
- Resistance to permanent deformation
- Resistance to fatigue cracking
- Resistance to thermal cracking

Resilient Modulus and Tensile Strength

The resilient modulus and tensile strength properties were evaluated using the ASTM D4123 test method. The resilient modulus is measured by applying a repeated haversine vertical load (P) along the diametral direction of the specimen. The load duration is for 0.1 seconds and a rest period of 0.9 seconds. The corresponding horizontal deformations (Dt) are measured using two linear variable differential transducers (LVDTs) attached to the sample 180 degrees apart. The Mr is calculated using the following equation:

$$Mr = \frac{0.62\ P}{Dt} \tag{1}$$

The tensile strength is measured by applying an increasing compressive load at a rate of 2 in/min, along the diametral direction of the specimen until failure. The load at failure is referred to as P_{ult} and the TS is calculated as:

$$TS = \frac{2\ P_{ult}}{3.14DT} \tag{2}$$

Where, D is sample diameter and T is the thickness of the sample.

Resistance to Moisture Damage

The resistance of the HMA mixtures to moisture damage was evaluated following the AASHTO T-283 test method. The method measures the tensile strength of the HMA mixtures at the dry and moisture conditioned stages. The moisture conditioning process consists of one cycle of freezing and thawing of a compacted sample saturated to 75%. The air-voids of the samples are kept between 6.5 and 7.5%. In addition to the standard AASHTO T-283 process, this research evaluated the resilient modulus property at the unconditioned and conditioned stages.

Resistance to Permanent Deformation

The resistance of the mixtures to permanent deformation has been evaluated through the three different laboratory tests presented below.

Asphalt Pavement Analyzer (APA): The APA test is standardized under AASHTO TP63-03, where a loaded concave steel wheel travels along a pressurized rubber hose that rests on top of the HMA sample. Four six-inch diameter cylindrical samples were compacted for each mix using the Superpave Gyratory Compactor to a height of 3.0”. The 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 maintained at 140°F for four hours before being tested in the dry condition at 140°F for a total of 8,000 cycles. A data acquisition program records rut depths at 2 points within each sample and their average is reported.

Repeated Shear Constant Height (RSCH): The RSCH test is run on a 6” diameter by 2” height specimen. The specimen is compacted using the Superpave Gyratory compactor or a field core. The RSCH test measures the resistance of the HMA mixtures to rutting under elevated temperature and reduced air voids (2-4%). During the test, the sample is maintained at a constant height (vertical pressure is varied as needed) while a repetitive haversine shear stress is applied. The magnitude of the shear stress is 10 psi with duration of 0.1 second and a rest period of 0.6 seconds. The permanent shear strain developed in the specimen is measured as a function of the number of load cycles. The test is ran for a total of 5,000 cycles and the magnitude of the permanent shear strain at the end of the test period provides an indication of the mixture’s resistance to rutting. The temperature of the RSCH test is selected based on the location of the project.

Repeated Load Triaxial (RLT) Test: The RLT test measures the axial permanent deformation in the

HMA mixture as it is subjected to triaxial stress conditions. The test specimen is a 4”x6” cylindrical sample that is cored from the center of a 6”x7” gyratory compacted sample. The triaxial condition is achieved by applying a static radial confining pressure of 30 psi using compressed air and a repeated deviator vertical stress of 45 psi. The repeated deviator stress is applied for 0.1 sec followed by a 0.5 sec rest period. The test is conducted for a total of 12,000 cycles with continuous measurements of the vertical strains along the middle 4.0” of the sample as a function of load cycles.

Resistance to Fatigue Cracking

The resistance of the HMA mixtures to fatigue cracking was evaluated using the flexural beam fatigue test “AASHTO T321-03.” 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. The test specimen is a 2”x2.5”x15” beam compacted using the Hveem kneading compactor.

In this research, the constant strain test was conducted at different strain levels using a repeated sinusoidal load at a frequency of 10 Hz, and a test temperature of 72°F. The initial flexural stiffness is 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:

$$N_f = k_1 \left(\frac{1}{\varepsilon_t} \right)^{k_2} \tag{3}$$

Where N_f is the fatigue life (number of load repetitions to fatigue failure), ε_t is the applied tensile strain, k_1 and k_2 are experimentally determined coefficients.

Resistance to Thermal Cracking

The Thermal Stress Restrained Specimen Test (TSRST) (AASHTO TP10-93) measures the resistance of HMA mixtures to thermal cracking. The test specimen is a 2"x2"x10" in beam compacted using the Hveem kneading compactor. An electro-hydraulic system is used to maintain the specimen at a constant height. As the HMA is cooled down at a rate of 10°C/hr and is forced to maintain a constant height, tensile stresses are generated throughout the length of the sample. These thermally induced stresses increase as the temperature of the specimen decreases until the specimen fractures. At the break point, the stress reaches its maximum value, which is referred to as the fracture stress, with the corresponding temperature is referred to as the fracture temperature.

ANALYSIS OF THE LABORATORY DATA

The main objective of this analysis is to compare the performance of the Superpave and Hveem mixtures within each of the three contracts. Since each contract was produced with different asphalt binder and aggregate source, the comparison among the contracts will only be done on a limited basis where such analysis is needed to support the findings.

Resilient Modulus and Tensile strength

The resilient modulus (Mr) of the HMA mixture represents the overall strength quality of the mix and the tensile strength (TS) represents the ability of the mix to resist tensile stresses. The Mr property of the HMA mix is used in the mechanistic analysis of pavement structures under traffic loads. In general a Mr property higher than 1,000 ksi indicates a high potential for the mix to become brittle with age and a mixture having Mr below 200 ksi may become soft in a warm climate.

Table 11 summarizes the Mr and TS properties of the various mixtures. The data show that the mixtures from sections on Contracts 3064 and 3071 exhibit good Mr and TS properties while the mixtures from sections on Contract 3140 produce significantly lower Mr and TS properties. Based on this data, the sections on Contract 3140 may experience some early distresses.

Figures 5, 6, and 7 compare the Mr and TS properties of the FMLC and LMLC mixtures and between the Superpave and Hveem mixtures. The ranges on top of the data columns represent the expected variability in the measured property based on two standard deviations of the data. The amount of overlap between the ranges can be used to compare the various mixtures. A significant overlap indicates a similarity between the mixtures while no overlap indicates a difference. For example, in Figure 5 there is no overlap in the ranges of the Mr properties of the FMLC and LMLC Hveem mixtures which indicates that these two mixtures have significantly different Mr properties. On the other hand, there is a significant overlap in the ranges of the TS properties of the FMLC and LMLC Hveem mixtures which indicates that these mixtures have similar TS properties. Looking at the comparisons summarized in Figures 5, 6, and 7 the following conclusions can be made:

- The FMLC samples from the Hveem section on Contract 3064 that were used in testing for Mr behave differently than the rest of the mixtures. It seems that these samples may have been overheated during the preparation for Mr testing which led to their significant difference from the LMLC samples and their extremely high Mr property. Therefore, these samples will be excluded from any further analysis.

- On all three contracts and for both the Superpave and Hveem mixtures, the Mr and TS properties measured on the FMLC and LMLC samples were statistically similar. This indicates that the short-term oven aging of the LMLC mixtures that were evaluated in this research effectively simulate the aging process that occurred in the hot plant.

- On all three contracts, the Mr and TS properties of the Superpave and Hveem mixtures are statistically similar. Typically the Mr and TS properties influence the rutting and fatigue resistance, respectively. This observation indicates that the Superpave and Hveem sections should have similar performance.

- The similarity in the Mr and TS properties of the FMLC and LMLC samples leads to the conclusion that LMLC mixtures prepared during the mix design process and subjected to short-term aging can be effectively used to assess the potential strength of field produced mixtures.

Moisture Sensitivity

Table 12 summarizes the moisture sensitivity data for the various sections. Both the Mr and TS retained ratios are calculated. The moisture sensitivity data showed that all sections exhibit relatively high retained strength ratios. Eventhough the sections on Contract 3140 exhibit high retained ratios, they are also showing low strength properties which draws a concern relative to their long-term performance.

It should be noted that all mixtures are treated with lime. In summary, the lime treatment of the mixtures seems to effectively increase their retained strength ratios, but the mixtures on Contract 3140 may still suffer from moisture damage due to their low original properties.

Resistance to Permanent Deformation

The resistance of HMA to permanent deformation is typically measured in the laboratory in terms of the accumulated permanent strain that the mix experience under repeated loadings. This research used the APA, RSCH, and RLT to measure the accumulated permanent strains in the HMA mixtures. As described earlier, each test uses a different approach to assess the resistance of the mix to permanent deformation. The main objective of using all three tests is to assess how consistent the tests are and how the APA compares to the more complex tests. Table 13 summarizes the permanent deformation characteristics of the various mixtures. Prior to looking at the data in Table 13, the following criteria should be stated:

- A commonly used failure criterion for the APA is a maximum of 0.30” (8 mm) after 8,000 cycles.
- Research conducted during the Strategic Highway Research Program (SHRP) recommended a failure criterion for the RSCH of a maximum of 5% permanent shear strain after 5,000 cycles.
- A recommended failure criterion for the RTLT is a maximum of 3% permanent axial strain after 12,000 cycles.

The data in Table 13 show that all three testing methods consistently indicated that the Superpave and Hveem sections within each of the three contracts have similar resistance to permanent deformation except in the case of the RLT on contract 3140. Both the test sections on contract 3140 did not survive the full 12,000 cycles of the RLT. The Superpave mixtures reached the 3% permanent strain shortly after 8400 cycles and the Hveem mixtures reached the 3% permanent strain shortly after 5300 cycles. In general, the Superpave and Hveem sections on contracts 3064 and 3071 have significantly higher resistance to permanent deformation (almost double) than the Superpave and Hveem sections on contract 3140. Applying the above criteria on the data in Table 13 indicates that the Superpave and Hveem sections on contracts 3064 and 3071 are expected to perform well in rutting while the Superpave and Hveem sections on contract 3140 may experience some rutting failures. It should be noted that contracts 3064 and 3140 have very close 20-years design traffic while the 20-years design traffic of contract 3071 is three times higher. Again, looking at the data in Table 13 in conjunction of the design traffic information for each of the sections leads to the following conclusion: the sections on contracts 3064 and 3071 should not experience any rutting problems while the sections on contract 3140 may experience some early rutting problems.

The fact that the three testing methods led to the same observations on all three contracts indicates that the inclusion of the APA in the modified Superpave mix design method recommended by NDOT is an appropriate step. Since the APA provided similar information concerning the resistance of mixture to permanent deformation, there is no need to conduct the more complicated tests of RSCH and RLT during the mix design process. However, since the sections on contract 3140 failed aggressively in the RLT test while they experienced 4.5 mm rutting in the APA, it is recommended that NDOT re-evaluate the applicability of the APA criterion of 8.0 mm for high volume roads. Again, since the short-term aged LMLC mixtures behaved very similar to the FMLC mixtures in all three tests, they can be effectively used to assess mixtures during the mix design stage.

Resistance to Fatigue Cracking

The resistance of HMA mixtures to fatigue cracking is measured in terms of the fatigue life of each individual mixture defined as the number of load cycles a mixture can withstand under a given level of bending strain. As the strain level increases, the number of load cycles to failure decreases. The most comprehensive fatigue testing technique for HMA mixtures is the flexural beam fatigue test as described earlier. In this research, 5-6 HMA beams were tested from each mix at various strain levels to establish a significant relationship between the strain level and the number of cycles to failure. Regression analysis of the data was used to determine the K_1 and K_2 coefficients of the fatigue model for each mix as described in Equation 3. Table 14 summarizes the fatigue models for the various mixtures. The R^2 value in Table 14 represents the fit between the measured data and the regression model.

All mixtures were subjected to long-term oven aging for 5 days at 185°F and tested at 72°F. The LMLC samples were subjected to short-term aging prior to the long-term aging while the FMLC samples were subjected to long-term aging only. It should be noted that the fatigue cracking of HMA mixtures becomes critical after the mix has been aged in the field and becomes brittle at which time it will not be able to resist the strains generated by traffic loads. Therefore, the fatigue samples are subjected to long-term aging to simulate their in service conditions.

Figures 8-13 summarize the fatigue data and the corresponding curves for the various mixtures. Statistical analyses were conducted to assess the differences among the fatigue resistance of the various mixtures. The results of the statistical analyses are summarized on the right-hand side of each figure. For example, Figure 8 compares the fatigue resistance of the FMLC Superpave and Hveem mixtures from contract 3064, the statistical analysis showed that the Superpave and Hveem mixtures have similar fatigue behavior at all three bending strain levels of 800, 500, and 350 microns as indicated by the label “NS” on the right hand box. By examining the fatigue data and curves in Figures 8-13 along with the results of the statistical analyses, it can be concluded that on all three contracts, the Superpave and Hveem mixtures exhibit similar fatigue resistance except for the FMLC samples on Contract 3071 (Figure 10). The fatigue data shown in Figure 10 indicate that the Superpave section on Contract 3071 exhibits significantly higher fatigue resistance than the Hveem section when subjected to bending strains of 500 and 350 microns.

Another statistical analysis was conducted to compare the fatigue resistance of the FMLC and LMLC samples from each test section. This analysis concluded that the FMLC and LMLC samples have similar fatigue resistance except for the Hveem section on Contract 3071 where the LMLC samples showed significantly higher fatigue resistance than the FMLC samples. It should be noted that the disagreement between the fatigue resistance of the FMLC and LMLC samples from the Hveem section on Contract 3071 contributed to the significant difference between the Superpave and Hveem mixtures noted in Figure 10. In other words, if the FMLC samples from the Hveem section on Contract 3071 would have performed similar to their LMLC counterparts, then there will be no significant difference between the two sections. Several factors could lead to the difference between the FMLC and LMLC samples, among them is the long-term aging of the FMLC samples. Future monitoring of these two sections will provide data to substantiate these observations.

The analysis of the fatigue data also shows that the Superpave and Hveem sections on Contract 3140 have significantly higher fatigue resistance than the sections on the other two contracts. For example, at the strain level of 500 microns, the laboratory fatigue lives of the Superpave sections on Contracts 3064 and 3071 are 70,000 and 40,000 cycles, respectively, while the laboratory fatigue life of the Superpave section on Contract 3140 would be over 400,000 cycles. This coincides very well with the performance of the mixtures from Contract 3140 in Mr, TS, and resistance to permanent deformation. It can concluded that the mixtures on Contract 3140 are relatively soft with lower resistance to rutting and higher resistance to fatigue cracking as compared to the mixtures on contracts 3064 and 3071.

Resistance to Thermal Cracking

Thermal cracking of HMA pavements manifests itself in the form of transverse cracks that run straight across the pavement at 90 degrees to the direction of travel. Once the thermal cracking occurs, the cracks keep on widening and become a major inlet of moisture into the pavement structure. As the thermal cracks become wider than ¼” their maintenance become very problematic and they contribute significantly to reflective cracking of the HMA overlay.

Table 15 summarizes the TSRST fracture temperatures of the various mixtures. The fracture temperatures data indicate that the Superpave and Hveem mixtures on each project have similar resistance to thermal cracking. The fracture temperatures measured on the FMLC and LMLC mixtures are similar except in the case of the Superpave mix on contract 3140 which showed a warmer fracture temperature for the FMLC mix. Again, since it is one out six cases that the FMLC and LMLC mixtures exhibit different results, it may have been due to samples conditioning.

In summary, the TSRST data is consistent with the fundamental concept that the thermal cracking resistance of HMA mixtures is mainly controlled by the grade of the asphalt binder. In addition the TSRST fracture temperatures measured in this research are colder than the expected low temperatures of the binders. Therefore, it is safe to say that neither the Superpave nor the Hveem mix designs significantly impact the resistance of HMA mixtures to thermal cracking which is mainly controlled by the grade of the binder.

FIELD PERFORMANCE

The field performance of the test sections on all three projects have been monitored in terms of measuring the rut depth as a function pavement age. Figures 14, 15, and 16 summarize the rut depth of the Superpave and Hveem sections on the three field projects. Since contract 3064 was constructed first, it has the longest performance while contract 3140 was constructed last and has the shortest history and contract 3071 is in between the two projects. The field measurements showed that all of the rut depth on all sections showed an initial increase immediately after construction but stabilizes below 4.0 mm which is relatively low. At this point the low rut depth on the various sections can be considered as traffic densification and not rut formation. Therefore, the up-to-date rut depth data does not indicate any differences in the field performance of the Superpave and Hveem sections on the various projects.

SUMMARY AND RECOMMENDATIONS

This report summarizes the laboratory evaluation and early field performance of Superpave and Hveem sections on three field projects. The laboratory evaluation includes the resistance of mixtures to moisture sensitivity, permanent deformation, fatigue cracking, and thermal cracking. The early field performance includes the monitoring of the rutting performance of the test sections. The analysis of the laboratory evaluation data and the assessment of the field performance data, led to the following conclusions and recommendations.

- The Superpave mix design system as modified by NDOT led to the design and construction of field sections that have performed similar to the Hveem sections based on the laboratory evaluation and the short-term field performance of the sections.

- The laboratory evaluation indicated that the Superpave and Hveem mixtures have similar behavior in resisting to fatigue and thermal cracking. The long-term field performance of the test sections should be monitored to validate the findings of the laboratory evaluation of the mixtures in terms of their resistance to fatigue and thermal cracking.

- The laboratory evaluation indicated that the lab mixed-lab compacted mixtures that are short-term aged exhibit similar properties to the field mixed-lab compacted mixtures. This supports the use of the LMLC mixtures to assess the potential properties of the mixtures produced during the construction of field projects.

- The APA was as effective as the RSCH and RLT tests to assess the resistance of the mixtures to permanent deformation. It is recommended that NDOT continues to use the APA to assess the resistance of mixtures to permanent deformation at the mix design stage. However, it is also recommended that the 8.0 mm be re-evaluated for implementation on high volume roads. The permanent deformation data generated in this research indicate that a more conservative criterion may be warranted for high volume roads.

- NDOT has built an extensive long-term data base of successful experience with Type 2C gradations. This research effort shows that the use of the Superpave mix design process as modified by NDOT leads to mixtures that will perform similar to the Hveem designed mixtures. Based on these observations, it is highly recommended that if NDOT considers the implementation of the modified Superpave mix design system should keep the current gradation specifications in place.

- It is recommended that NDOT construct two full projects during the 2006 construction season designed with the modified Superpave mix design. The objective of this effort is to build experience with Superpave designed mixtures across the HMA industry in the state of Nevada, including: NDOT personnel, contractors personnel, and the engineering consultants.

REFERENCES

1. "PP28: Practice for Superpave Volumetric Design of Hot-Mix Asphalt (HMA)," AASHTO Specifications, 2002.

2. "MP2: Specifications for Superpave Volumetric Mix Design," AASHTO Specifications, 2002.

3. "Design and Construction of NDOT Test Sections on Interstate 80," NDOT Report No: RDT03-038, December 2003.

4. "Evaluation of Rutting Resistance of Superpave and Hveem Mixtures Volume I – Introduction and Background," NDOT Report No: RDT03-039, June 2000.

5. "Evaluation of Rutting Resistance of Superpave and Hveem Mixtures Volume II – Impact of Aggregate Gradations," NDOT Report No: RDT03-040, June 2000.

6. "Evaluation of Rutting Resistance of Superpave and Hveem Mixtures Volume III – Impact of Gyratory Compaction," NDOT Report No: RDT03-041, July 2000.

7. "Performance of Superpave and Hveem Sections in Nevada – Volume IV," NDOT Report No: RDT03-036, July 2003.

8. "Design and Construction of NDOT 2001-2003 Superpave Test Sections," NDOT Report No: RDT04-047, August 2004.

Table 1. Superpave Design gyratory compaction efforts.

Design ESALs (million)	**Compaction Paramters**		
	$N_{initial}$	**N_{design}**	**N_{max}**
< 0.3	6	50	75
0.3 to < 3	7	75	115
3 to < 30	8	100	160
≥ 30	9	125	205

Table 2. Superpave volumetric mixture design requirements.

Design ESALs (million)	**Required Density (% of theoretical maximum specific gravity)**			**Voids in Mineral Aggregate, VMA percent, minimum**					**Voids Filled with Asphalt, VFA, %, Minimum**	**Dust-to-Binder Ratio**
	$N_{initial}$	**N_{design}**	**N_{max}**	**Nominal maximum aggregate size, mm**						
				37.5	**25.0**	**19.0**	**12.5**	**9.5**		
<0.3	≤ 91.5	96.0	≤ 98.0	11.0	12.0	13.0	14.0	15.0	70 - 80	0.6 - 1.2
0.3 to < 3	≤ 90.5								65 - 78	
3 to < 10	≤ 89.0								65-75	
10 to < 30										
≥ 30										

Table 3. Superpave aggregate consensus property requirements.

Design ESALs (million)	Fractured Faces, CA, %, min.		Uncompacted voids, FA, %, min.		Sand Equivalent %, min.	Flat & Elong., %, min.
	≤ 100 mm	> 100 mm	≤ 100 mm	> 100 mm		
< 0.3	55/-	-/-	-	-	40	-
0.3 to 3	75/-	50/-	40	40	40	10
3 to < 10	85/80[2]	60/-	45	40	45	
10 to < 30	95/90	80/75	45	40	45	
≥ 30	100/100	100/100	45	45	50	

(2) 85/80 denotes that 85 percent of the coarse aggregate has one fractured face and 80 percent has two or more fractured faces.

Table 4. Superpave aggregate gradation control points.

Sieve Size (mm)	Nominal maximum aggregate size - control point (percent passing)									
	37.5 mm		25.0 mm		19.0 mm		12.5 mm		9.5 mm	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
50.0	100									
37.5	90	100	100							
25.0		90	90	100	100					
19.0					90	100	100			
12.5							90	100	100	
9.5									90	100
4.75										90
2.36	15	41	19	45	23	49	28	58	32	67
0.075	0	6	1	7	2	8	2	10	2	10

Table 5. Mix design for the Superpave section on Contract 3064.

Mix Property	**Value**	**Criteria**
Binder Grade	AC-20P	
Optimum Binder Content %	4.25 twm, 4.44 dwa	
Air-voids @ N_{design} = 100, %	4.0	4.0
VMA, %	13.4	13.0 % min.
VFA, %	71.0	65 - 75 %
Dust Proportion, $P_{0.075}/P_{be}$	1.42	0.8-1.6
%Gmm @ Nini = 8	87.0	< 89%
% Gmm @ Nmax = 160	97.2	< 98%
Film Thickness, microns	8.07	
Hveem Stability on 4" samples	53	37 min.
Dry Tensile Strength on 4" Hveem samples, psi	70	65 min.
Wet Tensile Strength on 4" Hveem samples, psi	54	
Tensile Strength Ratio, %	77	70 min.
APA Rut Depth after 8,000 cycles @ 60°C, mm	2.8	8mm, max.

Table 6. Mix design for the Hveem section on 3064.

Mix Property	**Value**	**NDOT Specifications**
Binder Grade	AC-20P	
Optimum Binder Content	4.75 % dwa	
Air-voids, %	5.1 %	4 - 7 %
Stability	39	37 min.
VMA, %	15.8 %	12 - 22 %
Sand Equivalent, %	47	
+#4 Water Absorption	1.1 %	4 % max.
SS Soundness Coarse, %	5	12 % max.
SS Soundness Fines, %	5	15 % max.
L.A. Abrasion, %	19	37 % max.
Fractured Faces	100 %	80% min.
Original Tensile Strength, psi	76 psi	65 psi min.
% Retained Strength	81 %	70 % min.

Table 7. Mix design for the Superpave section on 3071.

Mix Property	Value	Criteria
Binder Grade	PG76-22NV	
Optimum Binder Content %	4.00 twm, 4.20 dwa	
Air-voids @ N_{design} = 125, %	4.0	4.0
VMA, %	13.6	13.0 % min.
VFA, %	71.5	65 - 75 %
Dust Proportion, $P_{0.075}/P_{be}$	1.30	0.8-1.6
%Gmm @ Nini = 9	88.7	< 89%
% Gmm @ Nmax = 205	96.6	< 98%
Film Thickness, microns	8.37	
Hveem Stability on 4” samples	40	37 min.
Dry Tensile Strength on 4" Hveem samples, psi	122	65 min.
Wet Tensile Strength on 4" Hveem samples, psi	109	
Tensile Strength Ratio, %	89	70 min.
APA Rut Depth after 8,000 cycles @60°C, mm	1.8	8 mm, max.

Table 8. Mix design for the Hveem section on 3071.

Mix Property	Value	NDOT Specifications
Binder Grade	PG76-22NV	
Optimum Binder Content	4.30 % dwa	
Air-voids, %	5.5%	4 - 7 %
Stability	49	37 min.
VMA, %	13.8 %	12 - 22 %
Sand Equivalent, %	62	
+#4 Water Absorption	0.8 %	4 % max.
SS Soundness Coarse, %	1	12 % max.
SS Soundness Fines, %	3	15 % max.
L.A. Abrasion, %	23	37 % max.
Fractured Faces	100 %	80% min.
Original Tensile Strength, psi	120 psi	65 psi min.
% Retained Strength	85 %	70 % min.

Table 9. Mix design for the Superpave section on 3140.

Mix Property	Value	Criteria
Binder Grade	AC-20P	
Optimum Binder Content %	5.4 twm, 5.7 dwa	
Air-voids @ N_{design} = 100, %	4.0	4.0
VMA, %	14.5	13.0 % min.
VFA, %	71.0	65 - 75 %
Dust Proportion, $P_{0.075}/P_{be}$	0.80	0.8-1.6
%Gmm @ Nini = 8	87.0	< 89%
% Gmm @ Nmax = 160	97.2	< 98%
Film Thickness, microns	12.82	
Hveem Stability on 4" samples	40	37 min.
Dry Tensile Strength on 4" Hveem samples, psi	74	65 min.
Wet Tensile Strength on 4" Hveem samples, psi	62	
Tensile Strength Ratio, %	84	70 min.
APA Rut Depth after 8,000 cycles @ 60°C, mm	1.3	8mm, max.

Table 10. Mix design for the Hveem section on 3140.

Mix Property	Value	NDOT Specifications
Binder Garde	AC-20P	
Optimum Binder Content	6.0 % dwa	
Air-voids, %	4.9 %	4 - 7 %
Stability	41	37 min.
VMA, %	17.6 %	12 - 22 %
Sand Equivalent, %	71	
+#4 Water Absorption	1.4 %	5 % max.
SS Soundness Coarse, %	5	12 % max.
SS Soundness Fines, %	6	15 % max.
L.A. Abrasion, %	25.3	37 % max.
Fractured Faces	100 %	80% min.
Original Tensile Strength, psi	76.6 psi	65 psi min.
% Retained Strength	83 %	70 % min.

Table 11. Resilient modulus and tensile strength properties of the various mixtures.

Contract	**Section**	**Mix**	**Air-Voids (%)**	**Dry Mr @ 77°F (ksi)**		**Dry TS @ 77°F (psi)**	
				Average	**STD**	**Average**	**STD**
3064	Hveem	FMLC	7.6	697	50	128	19
		LMLC	7.3	230	35	99	18
	Superpave	FMLC	7.0	480	29	108	14
		LMLC	7.7	350	31	99	10
3071	Hveem	FMLC	7.1	492	48	104	7
		LMLC	7.7	393	44	102	14
	Superpave	FMLC	7.5	557	55	107	5
		LMLC	6.1	559	55	124	10
3140	Hveem	FMLC	7.6	193	18	69	4
		LMLC	7.5	202	16	76	9
	Superpave	FMLC	6.9	229	36	82	3
		LMLC	7.5	154	25	85	5

Table 12. Moisture sensitivity properties of the various mixtures.

Contract	**Section**	**Mix**	**Mr @ 77°F (ksi)**			**TS @ 77°F (psi)**		
			Dry	**Wet**	**Ratio***	**Dry**	**Wet**	**Ratio**
3064	Hveem	FMLC	697	590	85	128	134	100
		LMLC	230	315	100	99	93	94
	Superpave	FMLC	480	535	100	108	134	100
		LMLC	350	425	100	99	118	100
3071	Hveem	FMLC	492	540	100	104	102	98
		LMLC	393	480	100	102	93	91
	Superpave	FMLC	557	505	91	107	101	94
		LMLC	559	530	95	124	103	83
3140	Hveem	FMLC	193	287	100	69	68	99
		LMLC	202	225	100	76	71	93
	Superpave	FMLC	229	201	88	82	83	100
		LMLC	154	208	100	85	78	92

* If ratio is higher than 100% then 100 is entered.

Table 13. Rutting resistance of the various mixtures.

Contract	**Section**	**Mix**	**APA @ 140°F (8,000 cycles)**		**RSCH at 148°F (5,000 cycles)**		**RLT @ 104°F (12,000 cycles)**	
			Air-voids (%)	**Rut depth (in)/(mm)**	**Air-voids (%)**	**Perm. shear Strain (%)**	**Air-voids (%)**	**Perm. Comp. Strain (%)**
3064	Hveem	FMLC	7.7	0.09/2.23	7.9	1.7	6.6	1.0
		LMLC	7.0	0.09/2.00	6.9	1.1	7.6	0.7
	Superpave	FMLC	6.5	0.08/2.17	7.1	1.6	6.3	0.4
		LMLC	6.2	0.07/1.64	7.0	1.0	7.2	1.5
3071	Hveem	FMLC	7.7	0.10/2.50	7.5	0.8	7.6	0.2
		LMLC	7.6	0.11/2.85	6.8	0.6	7.0	0.2
	Superpave	FMLC	7.4	0.05/1.20	7.8	0.7	7.7	0.2
		LMLC	7.4	0.09/2.27	6.7	0.5	6.5	0.3
3140	Hveem	FMLC	7.3	0.18/4.58	7.7	2.5		3(5333)*
		LMLC	6.9	0.18/4.52	7.3	2.0		3(5528)
	Superpave	FMLC	7.0	0.18/4.63	7.1	2.4		3(8431)
		LMLC	7.1	0.14/3.48	6.8	1.7		3(8495)

* 3% permanent compressive strain under 5333 cycles.

Table 14. Fatigue characteristics of the various mixtures.

Contract	**Section**	**Mix**	**Air-voids (%)**	**Strain Range (microns)**	K_1	K_2	R^2 (%)
3064	Hveem	FMLC	7.7	340 – 800	9.06E-11	4.50	96
		LMLC	7.0	260 – 1255	6.35E-06	3.02	97
	Superpave	FMLC	6.6	350 – 910	6.77E-14	5.45	94
		LMLC	6.6	320 – 790	8.12E-13	5.09	98
3071	Hveem	FMLC	7.6	285 – 780	2.02E-06	3.05	99
		LMLC	6.5	330 – 895	1.43E-07	3.56	98
	Superpave	FMLC	6.8	320 – 900	2.02E-07	3.49	99
		LMLC	6.3	300 – 815	7.58E-09	3.90	99
3140	Hveem	FMLC	7.7	480 – 1380	1.39E-04	2.87	98
		LMLC	7.3	410 – 1235	1.49E-05	3.18	99
	Superpave	FMLC	6.4	680 – 1400	4.72E-07	3.69	96
		LMLC	6.5	715 – 1295	1.50E-06	3.54	90

All mixtures were long-term oven aged for 5 days at 185°F and tested at 72°F.

Table 15. Thermal characteristics of the various mixtures.

Contract	**Section**	**Mix**	**Air-voids (%)**	**Fracture Temperature (°C)**	**Binder Grade**
3064	Hveem	FMLC	7.7	-27.6	AC20P
		LMLC	7.0	-27.2	
	Superpave	FMLC	7.7	-28.7	
		LMLC	7.4	-28.2	
3071	Hveem	FMLC	7.5	-32.7	PG76-22NV
		LMLC	7.7	-29.3	
	Superpave	FMLC	7.7	-28.2	
		LMLC	7.3	-29.6	
3140	Hveem	FMLC	7.4	-30.9	AC20P
		LMLC	6.9	-29.5	
	Superpave	FMLC	6.9	-25.9	
		LMLC	7.5	-29.1	

All mixtures were long-term oven aged for 5 days at 185°F.

PERFORMANCE GRADE		PG 46			PG 52							PG 58					PG 64					
		34	40	46	10	16	22	28	34	40	46	16	22	28	34	40	10	16	22	28	34	40
Avg 7-day Max. Pav. Temp., C		<46			<52							<58					<64					
Min. Pav. Design Temp, C		>-34	>-40	>-46	>-10	>-16	>-22	>-28	>-34	>-40	>-46	>-16	>-22	>-28	>-34	>-40	>-10	>-16	>-22	>-28	>-34	>-40
ORIGINAL BINDER																						
Flash Point, T48, Min. °C		230																				
Viscosity, T316, Max. 3 Pa.s, Test Temp., °C		135																				
Dynamic Shear, T315, G*/sinδ, Min. 1.00 kPa, Test Temp. @ 10 rad/s, °C		46			52							58					64					
ROLLING THIN FILM OVEN RESIDUE (T240)																						
Mass Loss, max., Percent		1.00																				
Dynamic Shear, T315, G*/sinδ, Min. 2.20 kPa, Test Temp. @ 10 rad/s, °C		46			52							58					64					
PRESSURE AGING VESSEL RESIDUE (PP1)																						
PAV Aging Temp, °C		90			90							100					100					
Dynamic Shear, T315, G*sinδ, Max. 5000 kPa, Test Temp. @ 10 rad/s, °C		10	7	4	25	22	19	16	13	10	7	25	22	19	16	13	31	28	25	22	19	16
Physical Hardening		Report																				
M320	Creep Stiffness, T313: S, Max. 300 Mpa, m-value, Min. 0.300, Test Temp. @ 60 s, °C	-24	-30	-36	0	-6	-12	-18	-24	-30	-36	-6	-12	-18	-24	-30	0	-6	-12	-18	-24	-30
	Direct Tension, T314, failure Strain, Min. 1.0%, Test Temp @ 1.0 mm/min, °C	-24	-30	-36	0	-6	-12	-18	-24	-30	-36	-6	-12	-18	-24	-30	0	-6	-12	-18	-24	-30
MP1a	Critical Low Cracking Temp, PP42: Determine critical cracking temp as described in PP42, Test Temp, °C	-24	-30	-36	0	-6	-12	-18	-24	-30	-36	-6	-12	-18	-24	-30	0	-6	-12	-18	-24	-30

Figure 1. Superpave Performance Grade Asphalt Binder Specification M320 & MP1a.

PERFORMANCE GRADE		PG 70						PG 76					PG 82				
		10	16	22	28	34	40	10	16	22	28	34	10	16	22	28	34
Avg 7-day Max. Pav. Temp., C		<70						<76					<82				
Min. Pav. Design Temp, C		>-10	>-16	>-22	>-28	>-34	>-40	>-10	>-16	>-22	>-28	>-34	>-10	>-16	>-22	>-28	>-34
ORIGINAL BINDER																	
Flash Point, T48, Min. °C		230															
Viscosity, T316, Max. 3 Pa.s, Test Temp., °C		135															
Dynamic Shear, T315, G*/sinδ, Min. 1.00 kPa, Test Temp. @ 10 rad/s, °C		70						76					82				
ROLLING THIN FILM OVEN RESIDUE (T240)																	
Mass Loss, max., Percent		1.00															
Dynamic Shear, T315, G*/sinδ, Min. 2.20 kPa, Test Temp. @ 10 rad/s, °C		70						76					82				
PRESSURE AGING VESSEL RESIDUE (PP1)																	
PAV Aging Temp,°C		100(110)						100(110)					100(110)				
Dynamic Shear, T315, G*sinδ, Max. 5000 kPa, Test Temp. @ 10 rad/s, °C		34	31	28	25	22	19	37	34	31	28	25	40	37	34	31	28
Physical Hardening																	
M320	Creep Stiffness, T313: S, Max. 300 Mpa, m-value, Min. 0.300, Test Temp. @ 60 s, °C	0	-6	-12	-18	-24	-30	0	-6	-12	-18	-24	0	-6	-12	-18	-24
	Direct Tension, T314, failure Strain, Min. 1.0%, Test Temp @ 1.0 mm/min, °C	0	-6	-12	-18	-24	-30	0	-6	-12	-18	-24	0	-6	-12	-18	-24
MP1a	Critical Low Cracking Temp, PP42: Determine critical cracking temp as described in PP42, Test Temp, °C	0	-6	-12	-18	-24	-30	0	-6	-12	-18	-24	0	-6	-12	-18	-24

Figure 1. Superpave Performance Grade Asphalt Binder Specification M320 & MP1a (Cont.)

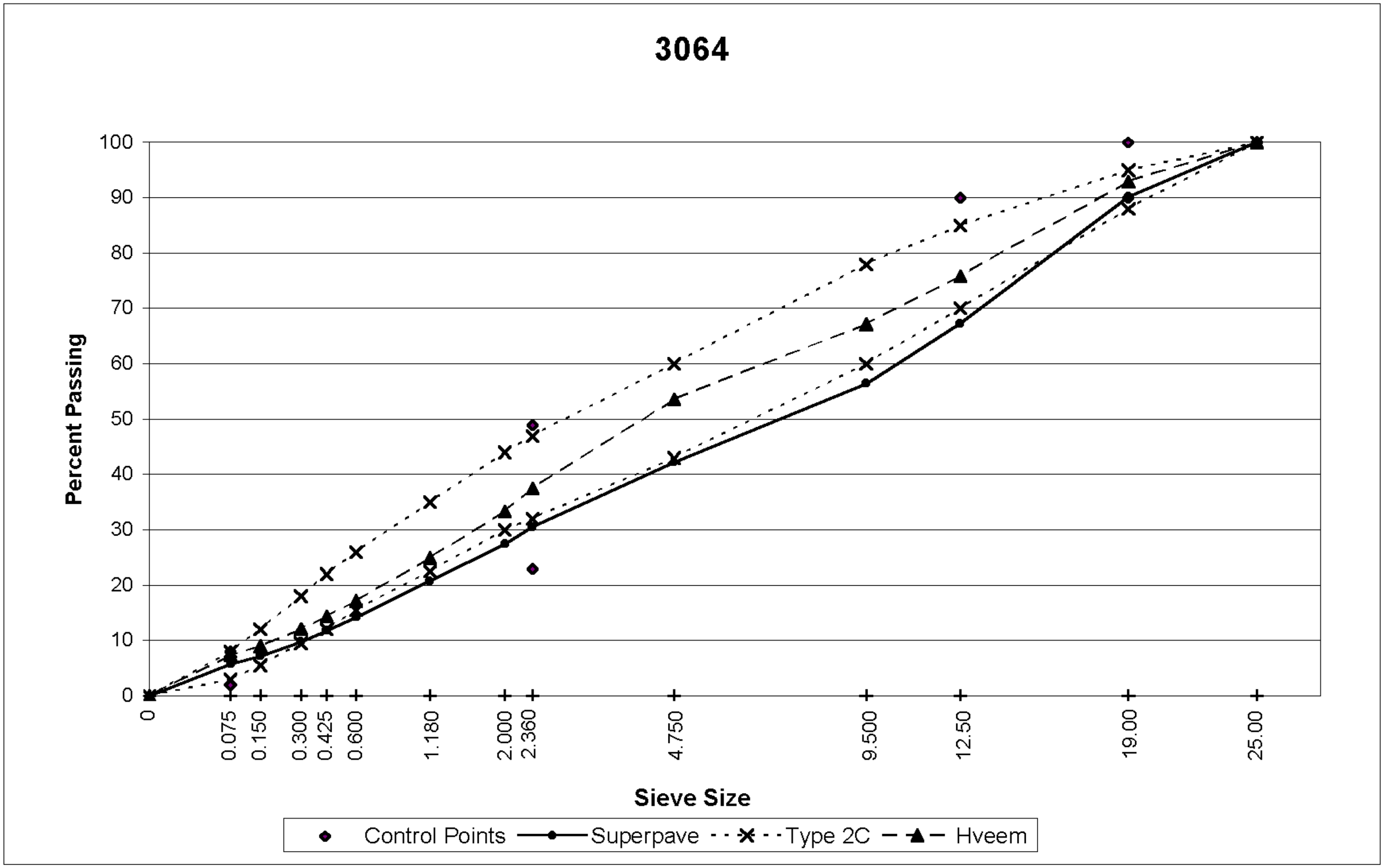


Figure 2. Aggregate gradation curves for the Superpave and Hveem sections on 3064.

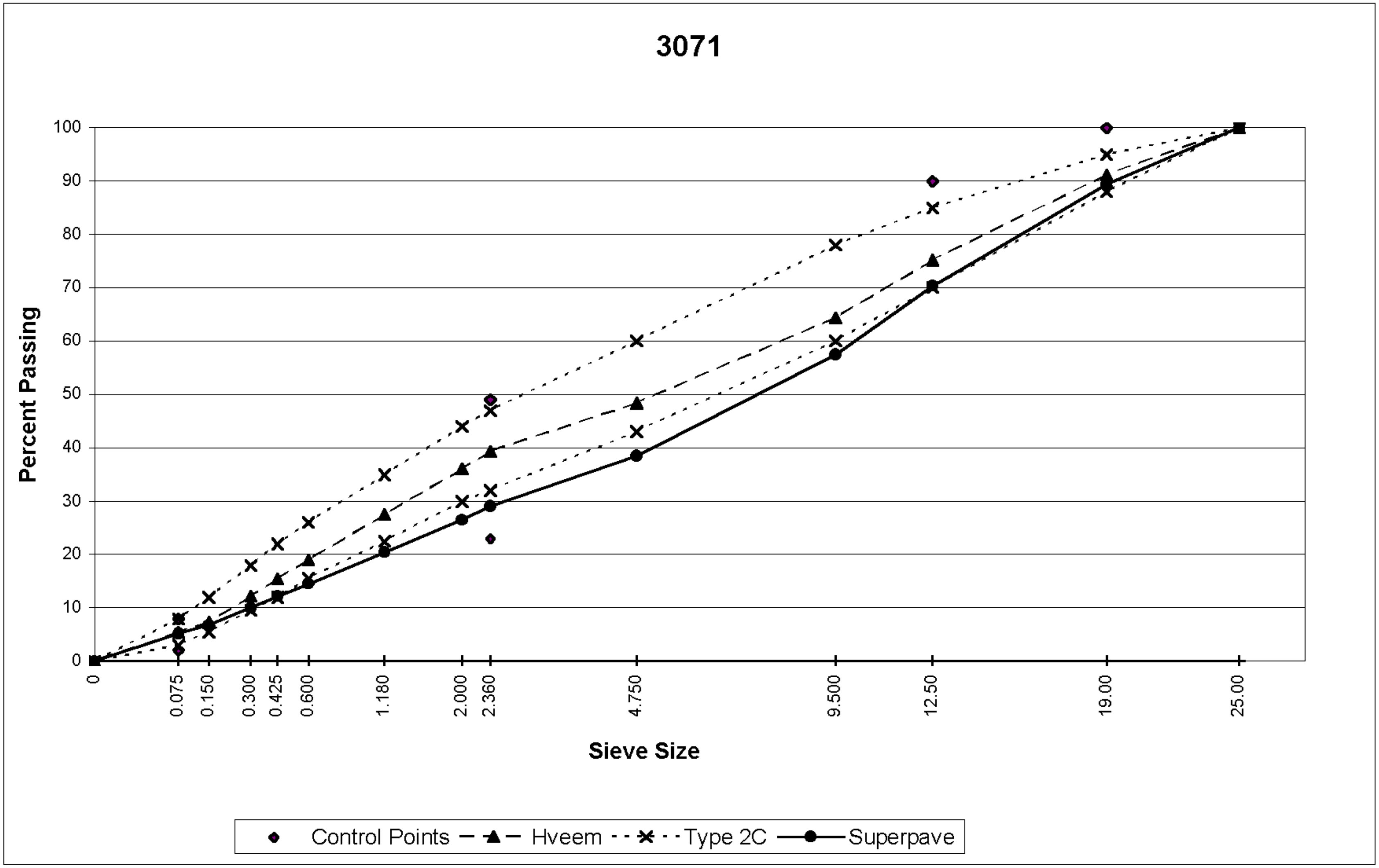


Figure 3. Aggregate gradation curves for the Superpave and Hveem sections on 3071.

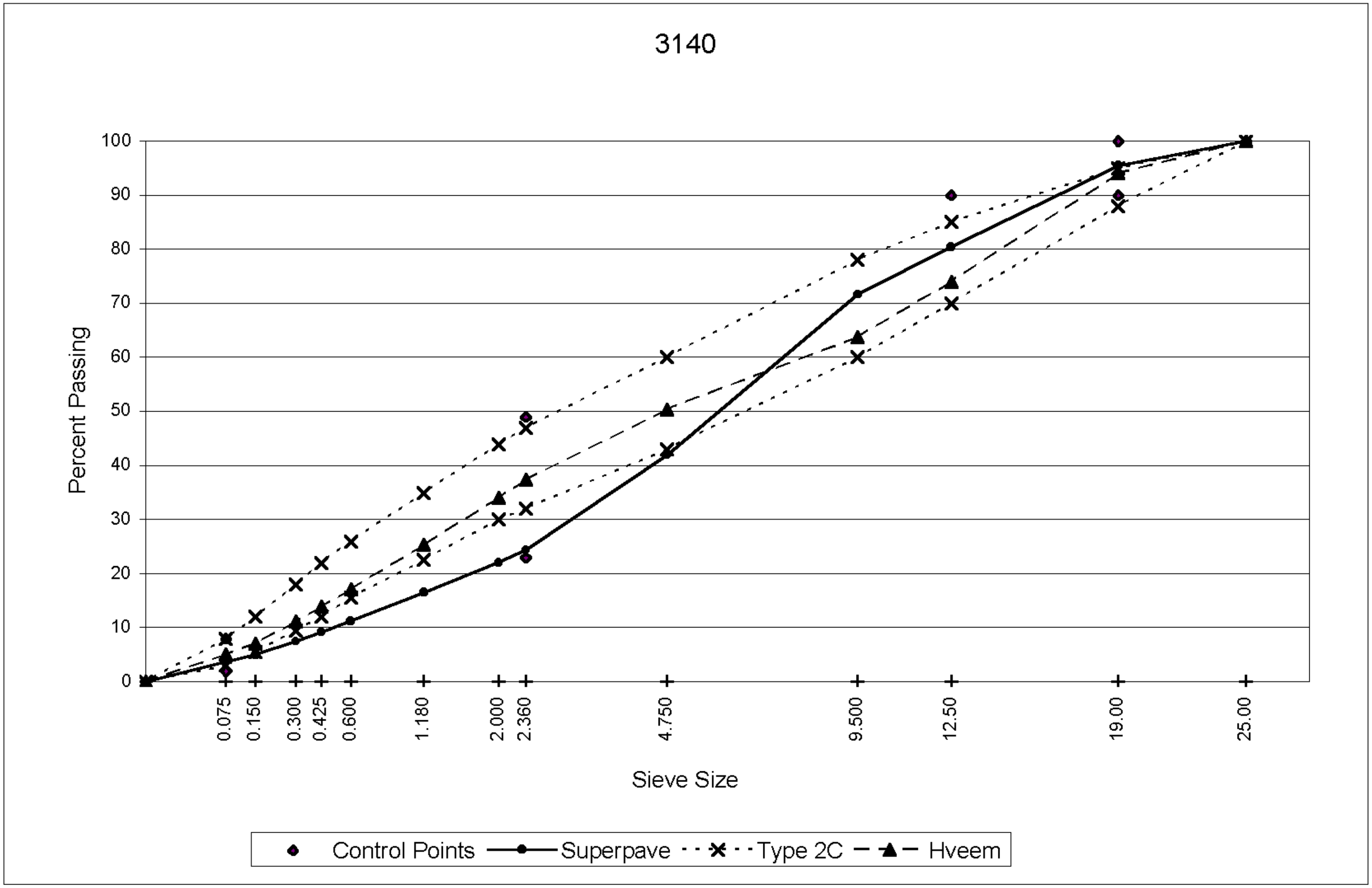
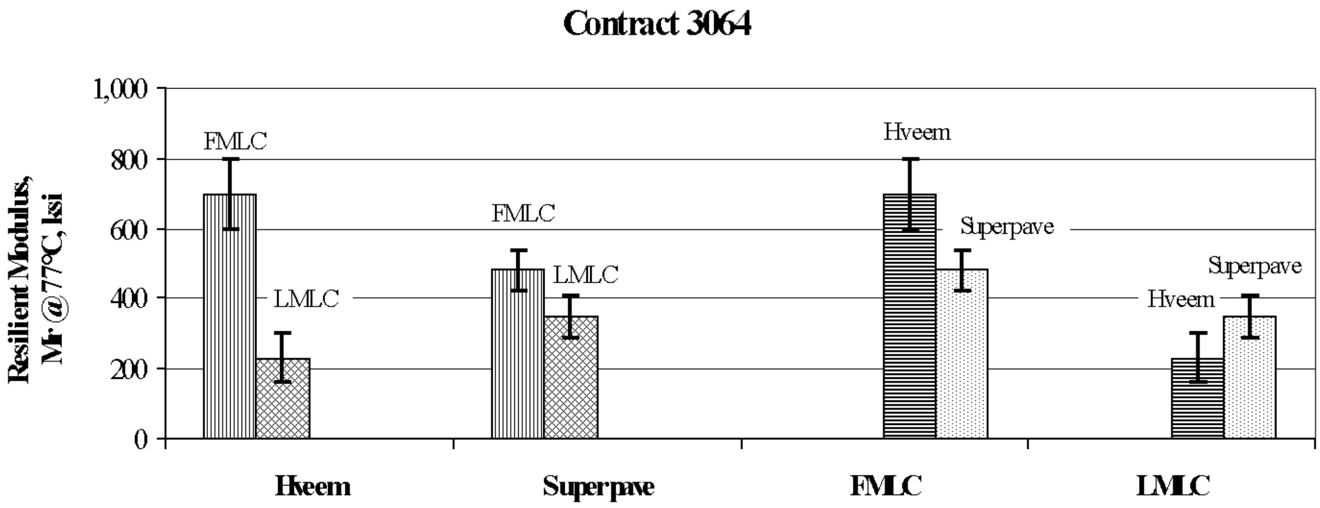


Figure 4. Aggregate gradation curves for the Superpave and Hveem sections on 3140.



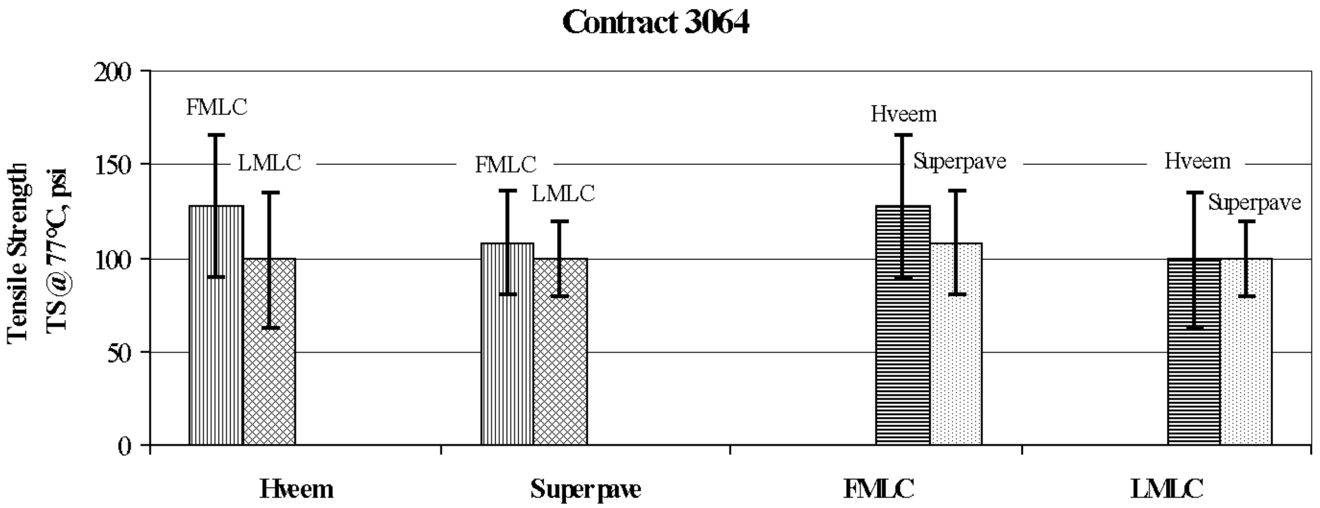
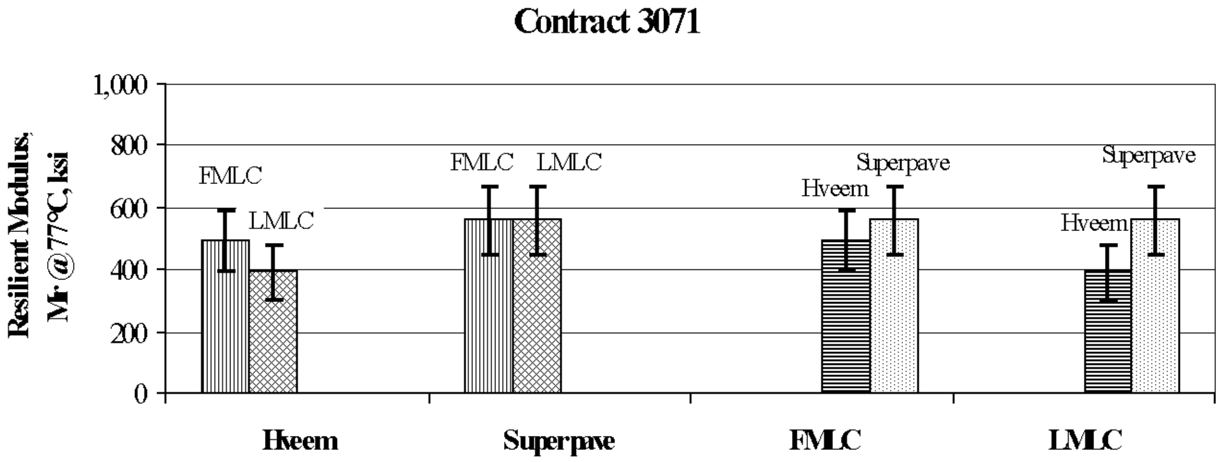


Figure 5. Resilient modulus and tensile strength properties of the various mixtures on Contract 3064.



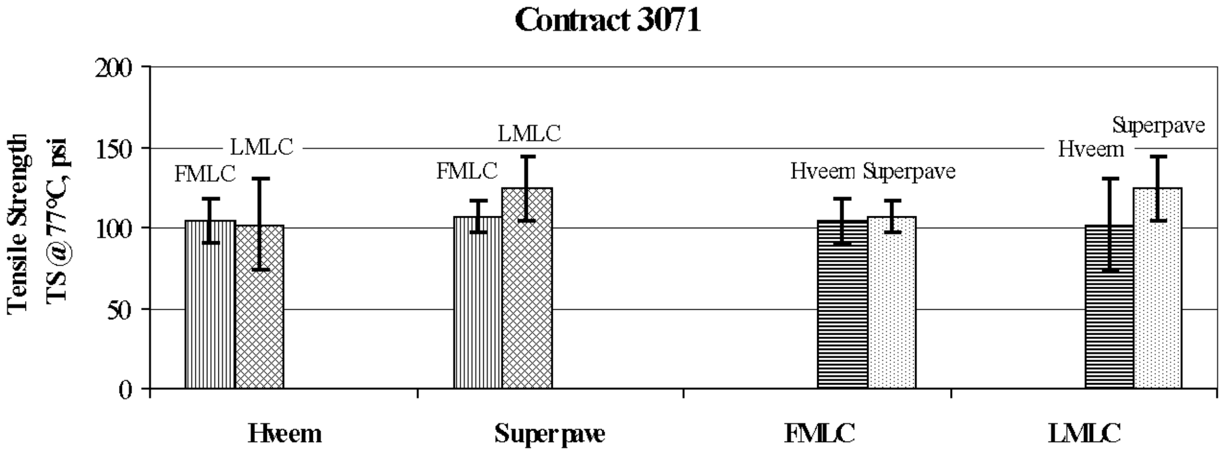
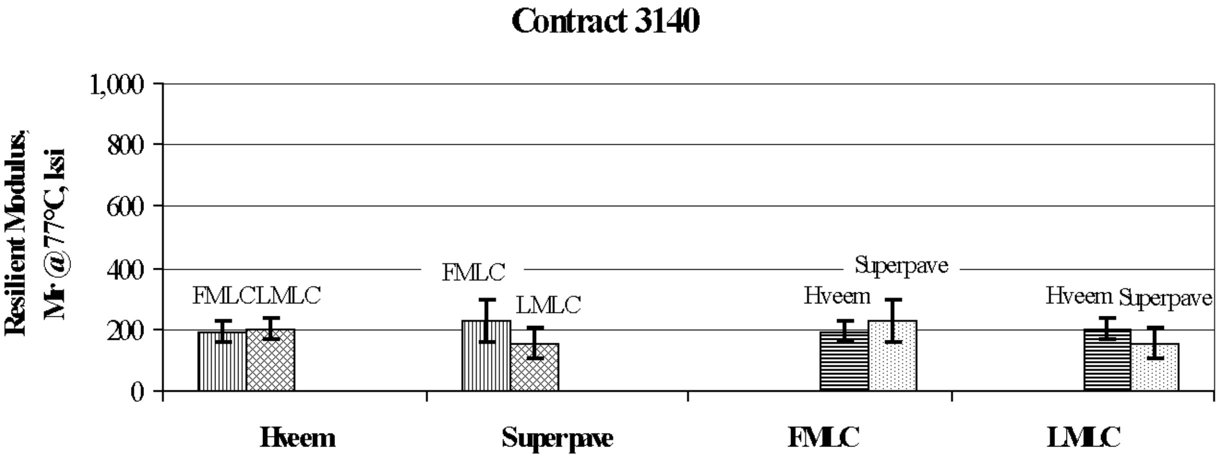


Figure 6. Resilient modulus and tensile strength properties of the various mixtures on Contract 3071.



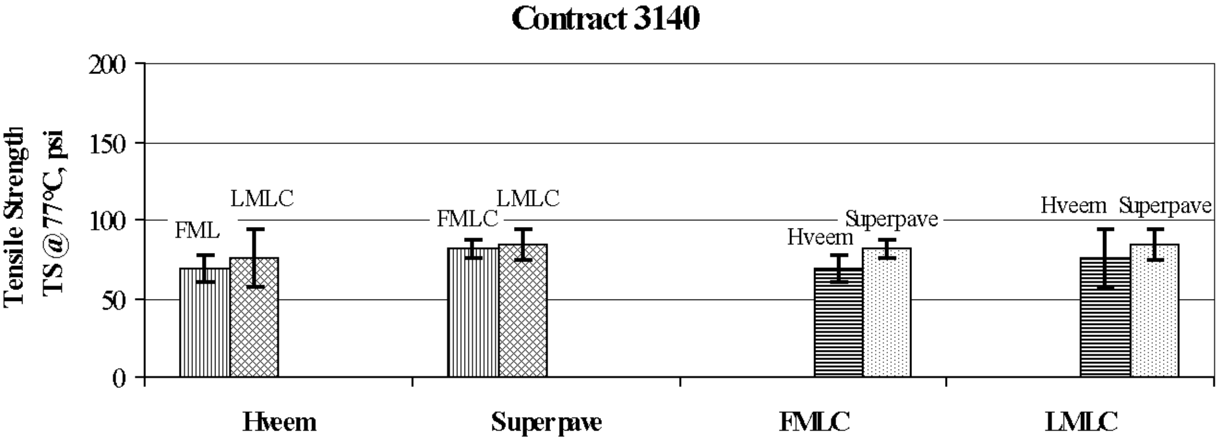
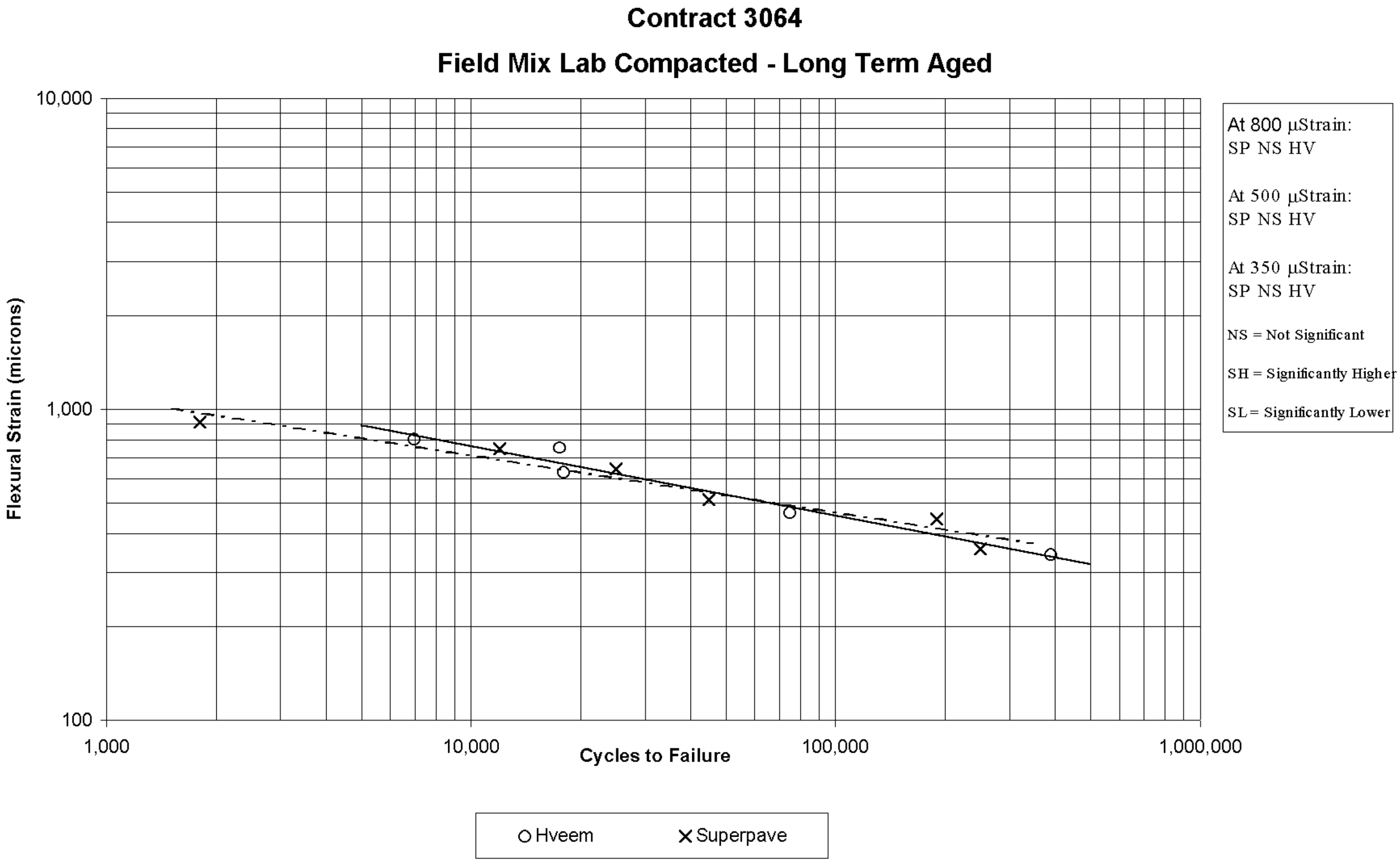


Figure 7. Resilient modulus and tensile strength properties of the various mixtures on Contract 3140.



At 800 µStrain:
SP NS HV

At 500 µStrain:
SP NS HV

At 350 µStrain:
SP NS HV

NS = Not Significant

SH = Significantly Higher

SL = Significantly Lower

Figure 8. Fatigue curves of the FMLC mixtures from the Superpave and Hveem sections on Contract 3064.

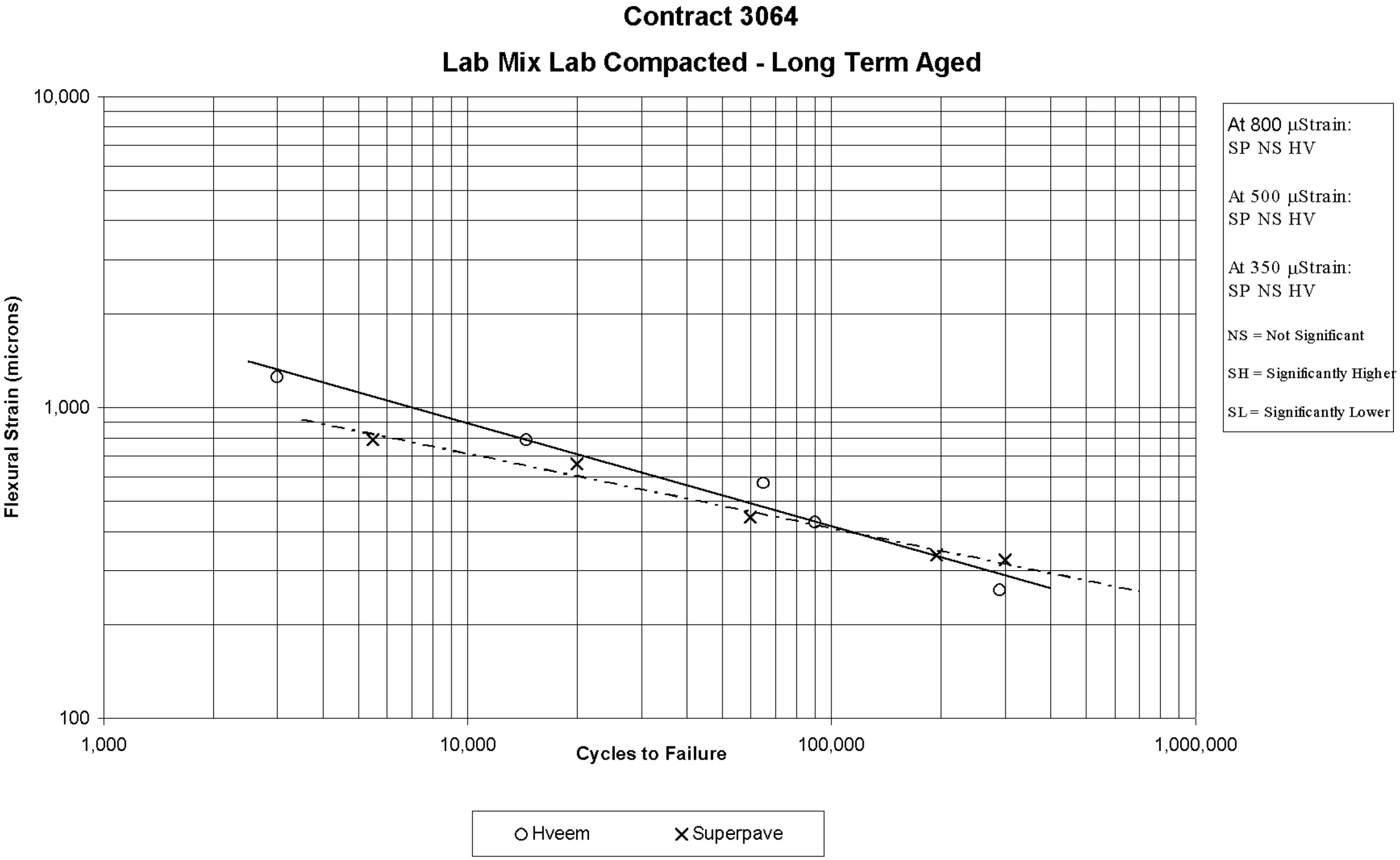


Figure 9. Fatigue curves of the LMLC mixtures from the Superpave and Hveem sections on Contract 3064.

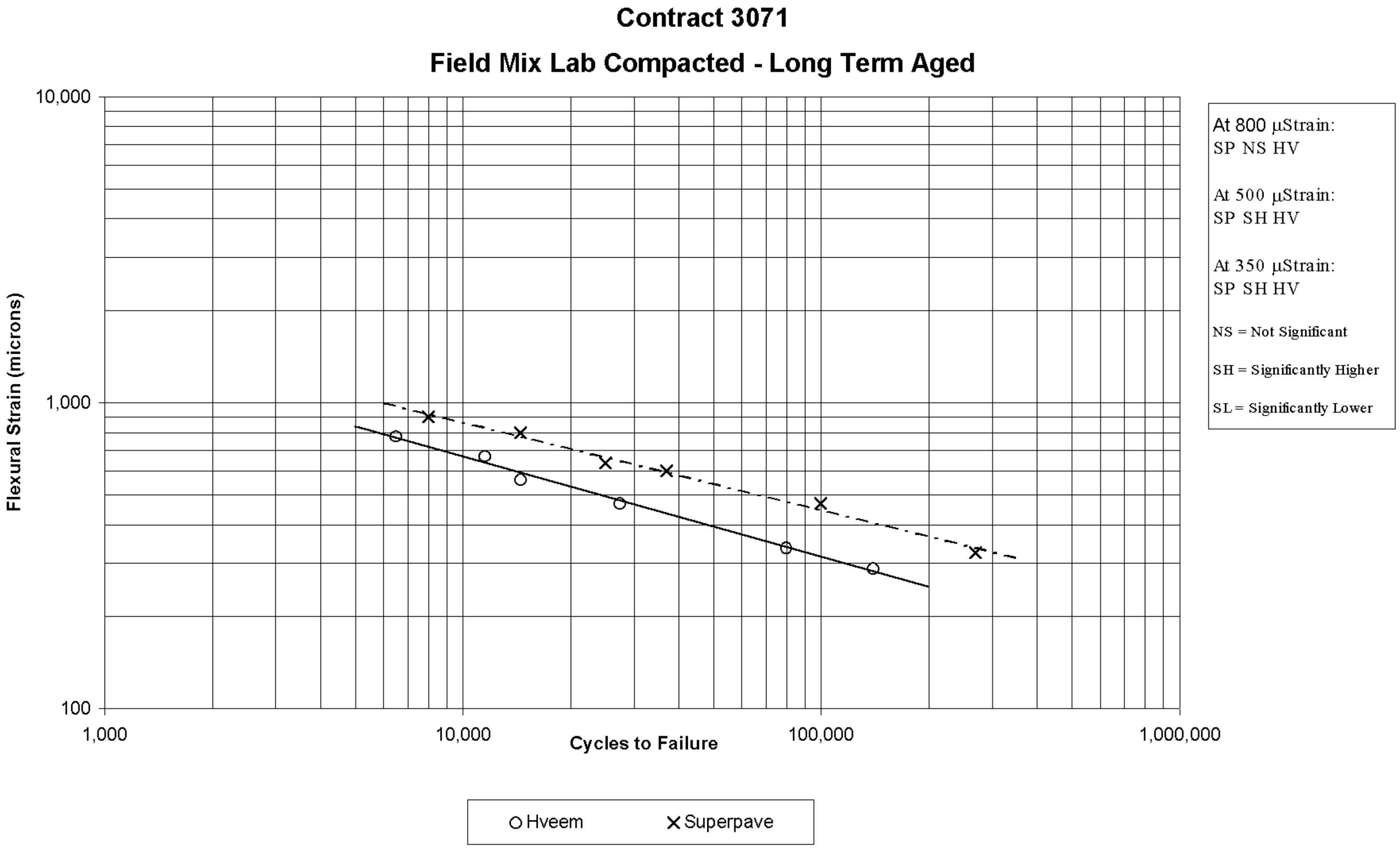


Figure 10. Fatigue curves of the FMLC mixtures from the Superpave and Hveem sections on Contract 3071.

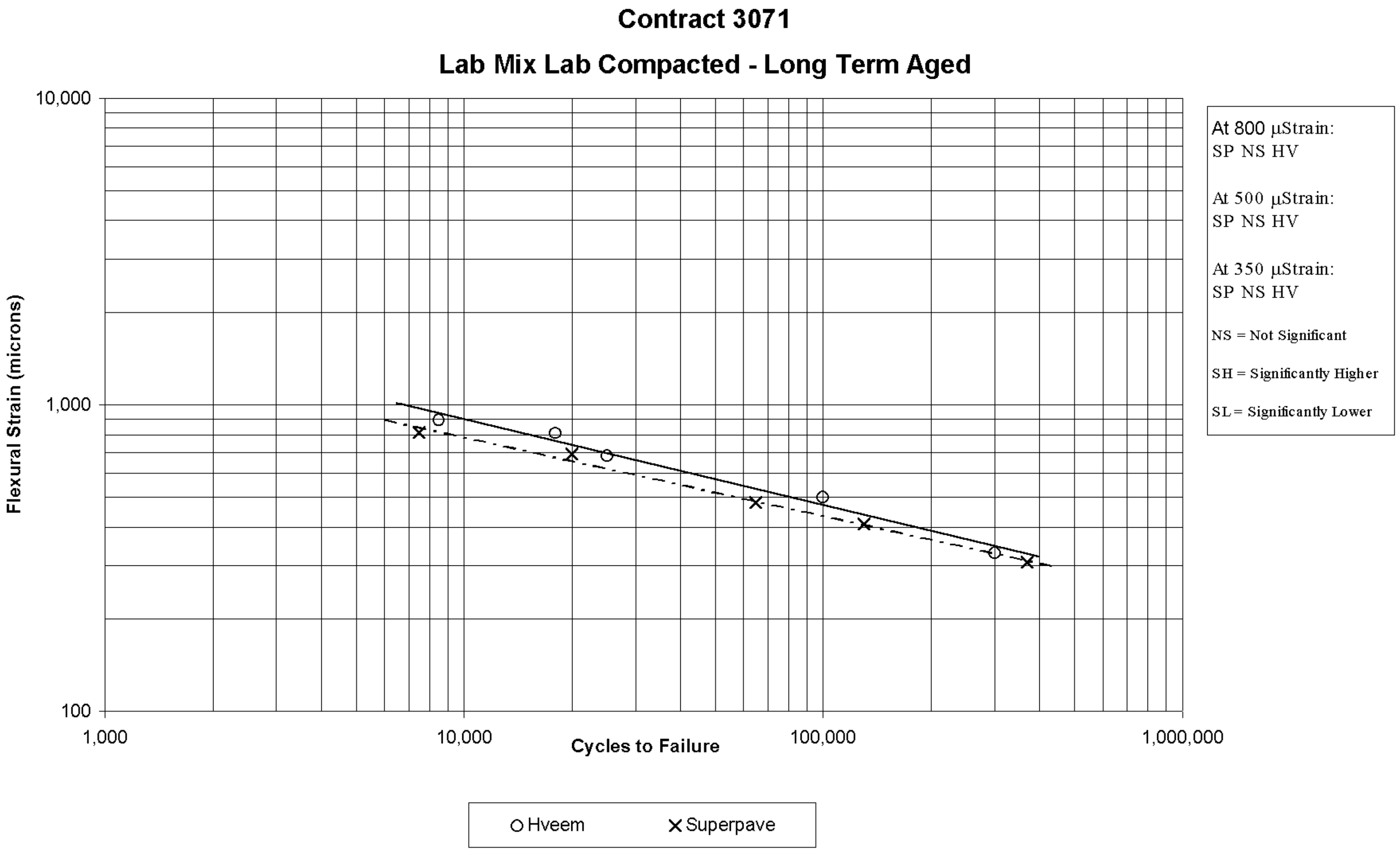


Figure 11. Fatigue curves of the LMLC mixtures from the Superpave and Hveem sections on Contract 3071.

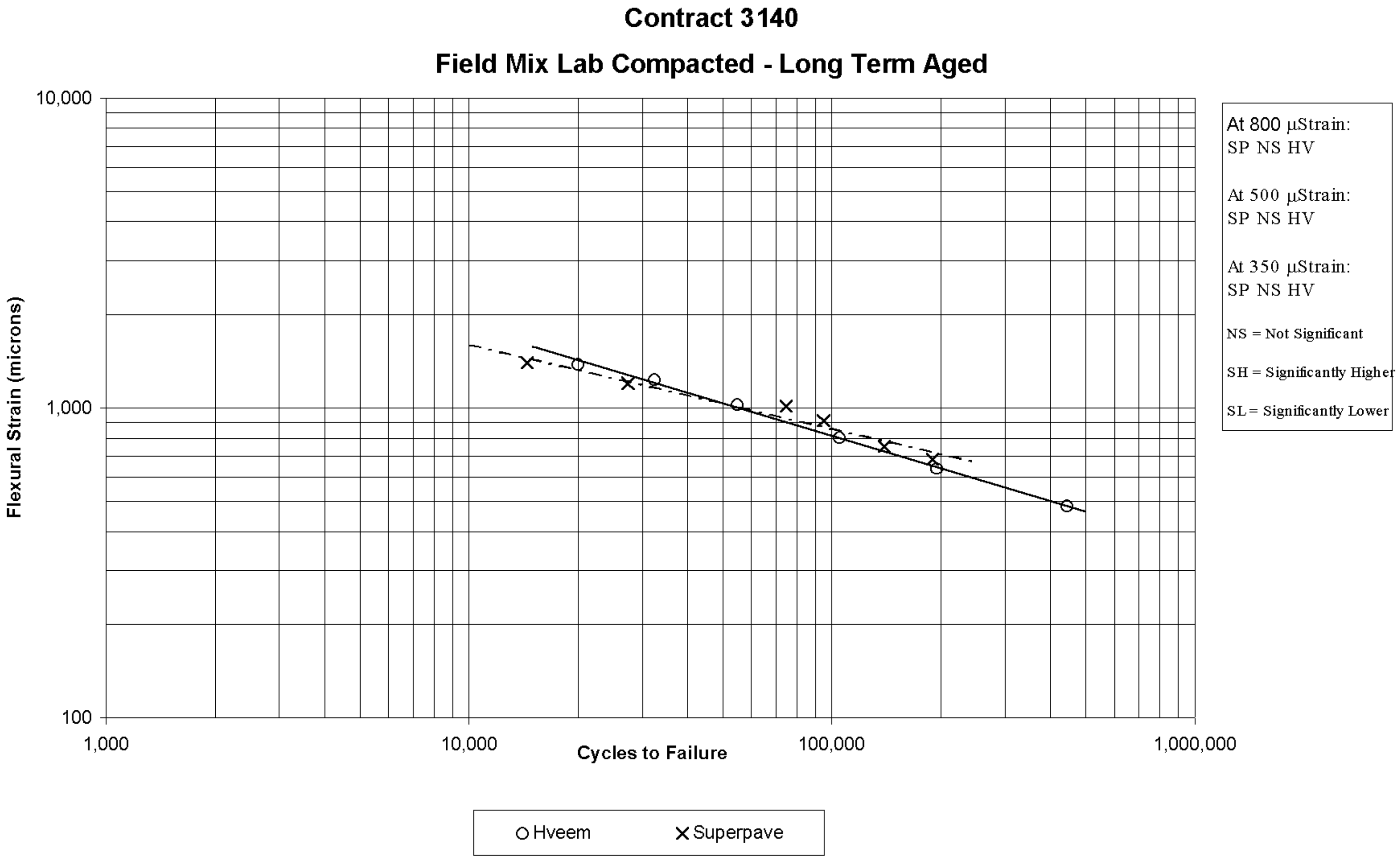
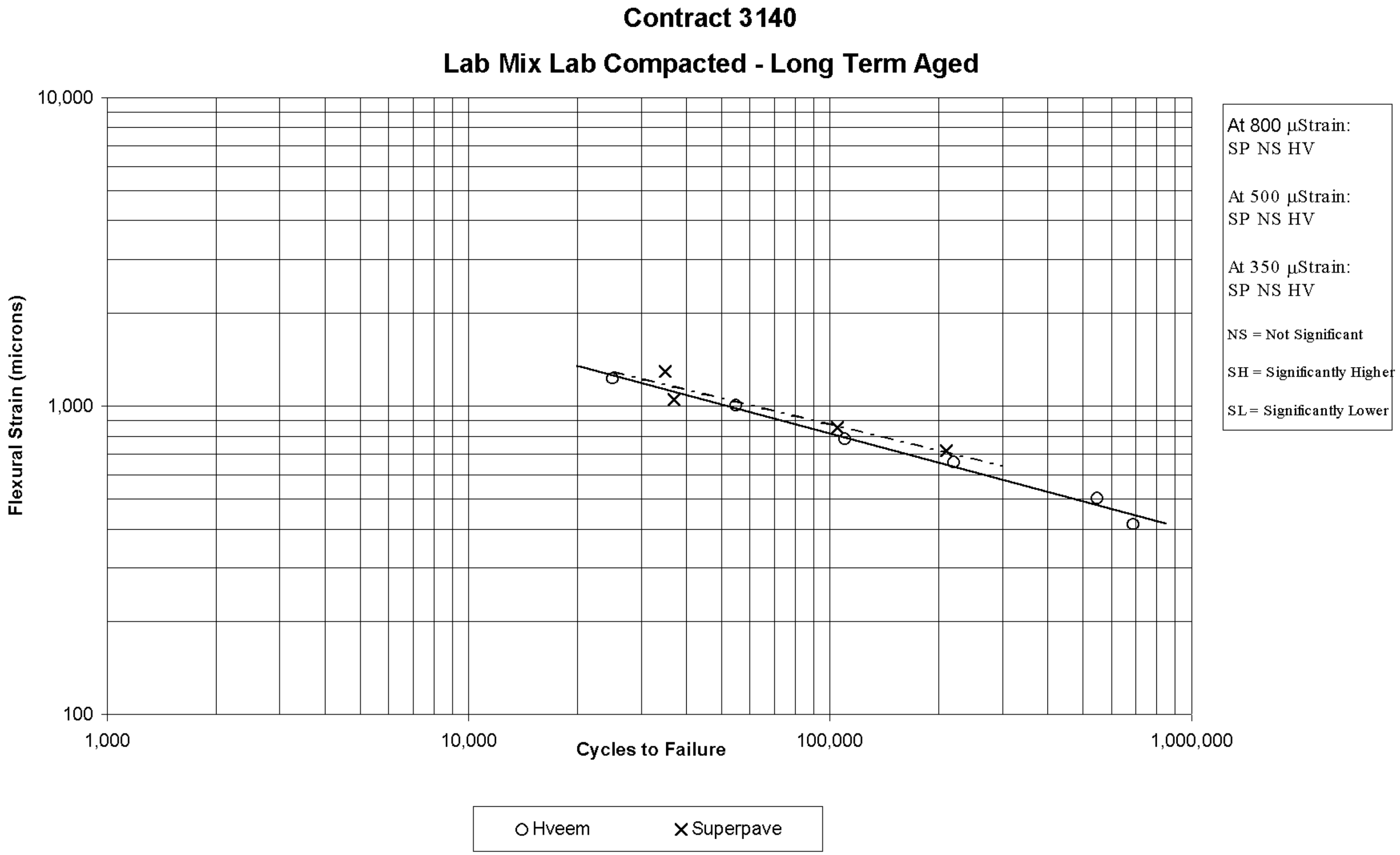


Figure 12. Fatigue curves of the FMLC mixtures from the Superpave and Hveem sections on Contract 3140.


Contract 3140

Lab Mix Lab Compacted - Long Term Aged

Figure 13. Fatigue curves of the LMLC mixtures from the Superpave and Hveem sections on Contract 3140.

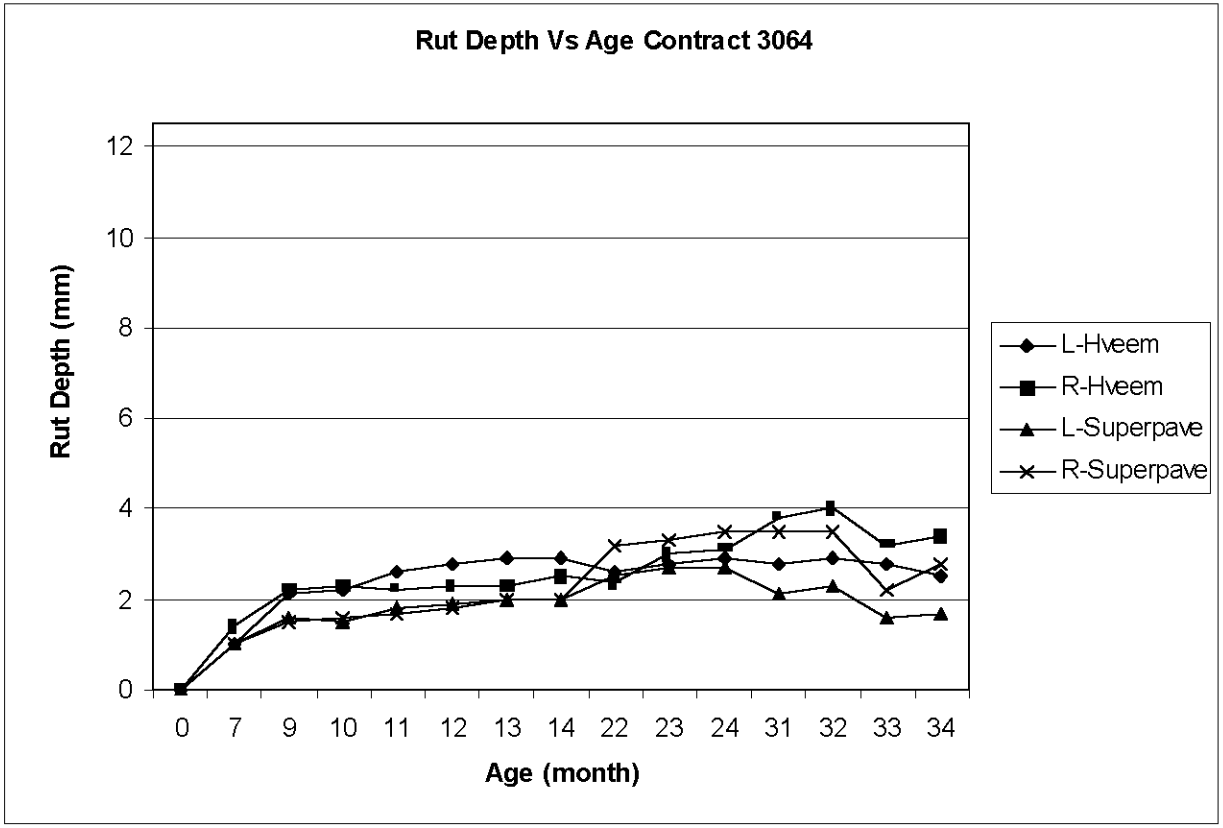


Figure 14. Rut depth as a function of pavement age for the Superpave and Hveem sections on contract 3064.

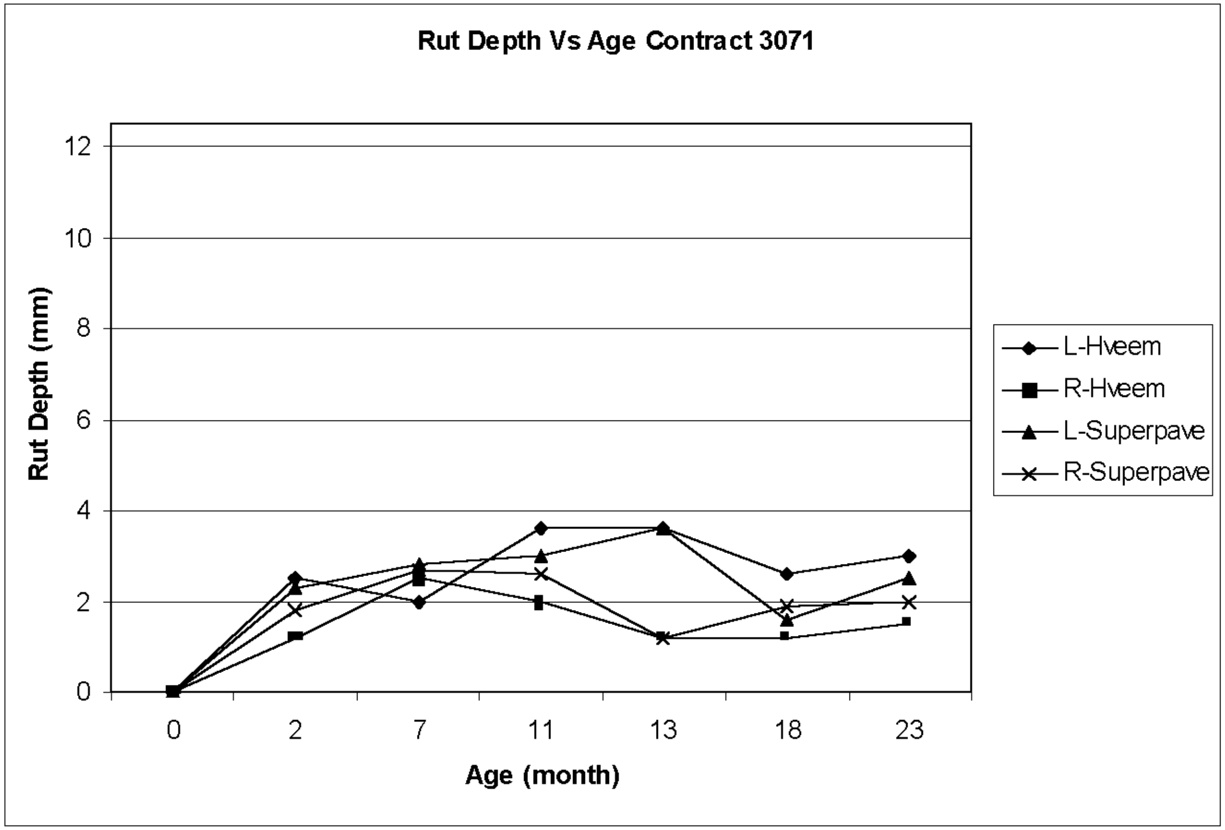


Figure 15. Rut depth as a function of pavement age for the Superpave and Hveem sections on contract 3071.

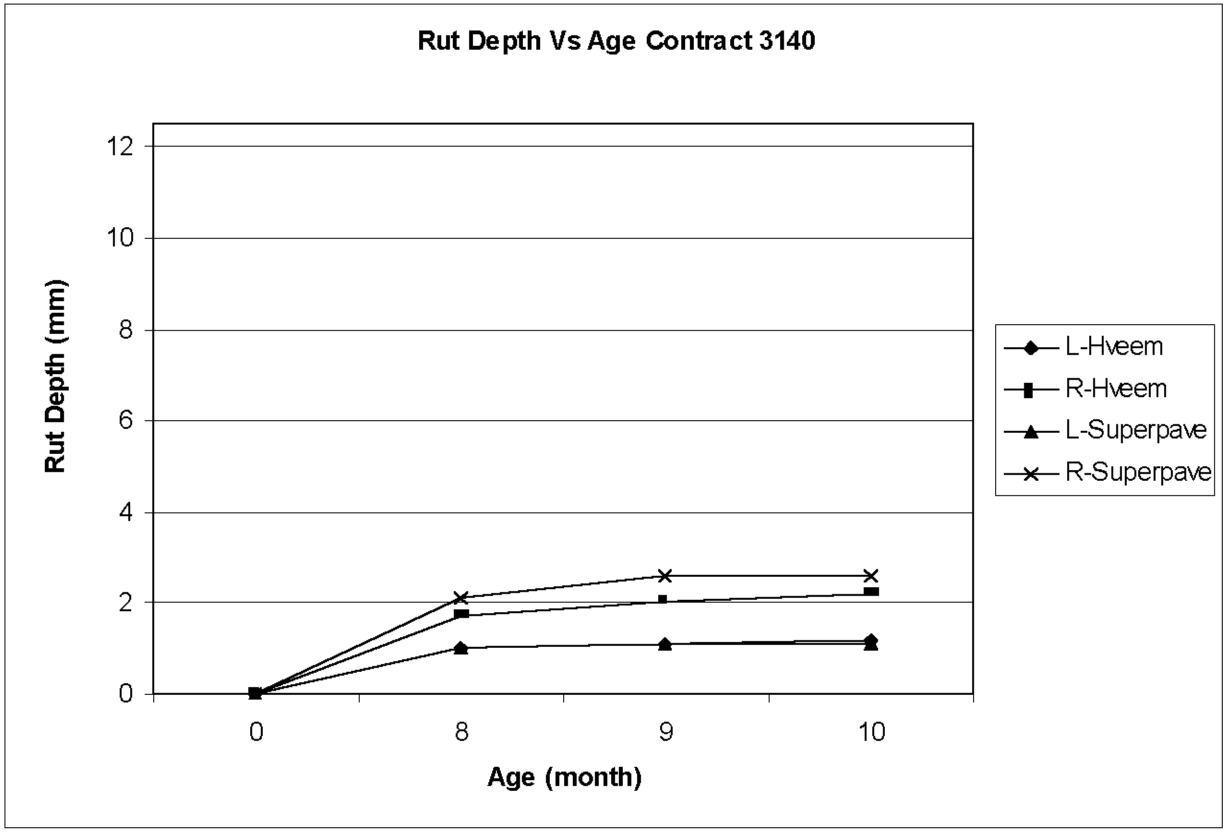


Figure 16. Rut depth as a function of pavement age for the Superpave and Hveem sections on contract 3140.