SHRP-A-390

Laboratory Aging of Asphalt-Aggregate Mixtures:

Field Validation

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Abstract

The hardening or stiffening associated with heating asphalt has been researched since the first use of asphalt in the United States around 1900, but little research has been accomplished on asphalt-aggregate mixtures. This hardening is referred to as aging and occurs in two stages: "short-term" aging which occurs during mixture mixing and placement, and "long-term" aging which occurs throughout the life of the pavement. A portion of the Strategic Highway Research Program (SHRP) has been dedicated to developing Accelerated Performance Tests (APTs) for aging of asphalt-aggregate mixtures. Two test procedures developed at Oregon State University utilize oven aging at 135°C and 85°C or 100°C (275° and 185° or 212°F) to simulate short- and long-term field aging. This report presents the results of the field validation of these two procedures. The short-term procedure of 4 hours at 135°C (275°F) prior to compaction is adequate for the majority of the field mixtures evaluated and conservative for some mixtures. Long-term oven aging for 2 days at 85°C (185°F) or 1 day at 100°C (212°F) after compaction and in addition to the short-term treatment appears representative of "young" mixtures (0 to 3 years old), in the field. Long-term oven aging for 4 to 8 days at 85°C (185°F) or 2 to 4 days at 100°C (212°F) appears representative of "older" (older than 3 years) mixtures in the field and conservative for some mixtures. Use of long-term oven aging at 85°C (185°F) is recommended, since 100°C (212°F) may damage specimens and result in unreliable data.

Continued analysis of the field sites used in this study and selection of additional sites is required to develop prediction models for all combinations of climatic region and asphalt grade. The continued study of the existing younger sites would require additional cores to be drilled, possibly 5, 10, and 15 years from now, to determine the field moduli at those times.

Executive Summary

A portion of the Strategic Highway Research Program (SHRP) has been dedicated to the study of asphalt-aggregate mixtures. The project designated SHRP A-003A with the University of California at Berkeley is titled "Performance-Related Testing and Measuring of Asphalt-Aggregate Interactions and Mixtures." As a subcontractor on this project, Oregon State University (OSU) is responsible for studying asphalt-aggregate mixture aging.

Accelerated Performance Testing (APT) procedures have been developed at OSU in an attempt to simulate field aging (both short- and long-term). If successful, these APTs will allow asphalt mix designers to incorporate evaluations of mixture aging into asphalt mixture designs. This report is a summary of the validation of three APTs developed at OSU —short-term oven aging (STOA) at 135°C and long-term oven aging (LTOA) at both 85°C and 100°C, to simulate short- and long-term aging. Companion reports describe the development of the laboratory aging procedures (Bell et al., 1992a) and an extensive laboratory testing program for a wide range of asphalt-aggregate combinations (Bell and Sosnovske, 1992).

The study described herein was accomplished in three stages: preliminary short-term validation, expanded validation, and supplementary validation. The first stage addressed only short-term aging and was aimed at identifying a common time period to short-term age the mixes to a state representing aging in the construction process. The second stage, referred to as expanded validation, gathered information on the validity of both short-term and long-term aging. Specimens were subjected to short-term (135°C (275°F)) and successive long-term (85°C (185°F) and 100°C (212°F)) oven aging procedures to simulate field aging. The third stage, referred to as supplementary validation, encompassed short-term (135°C (275°F)) and successive long-term (85°C (185°F) and 100°C (212°F)) oven-aging procedures for seven sites in the state of Washington. The sites range in age from 3 to 19 years, with five sites older than 9 years.

Following site selection and material gathering, cores from the field were trimmed and analyzed to determine their air void levels. Whenever possible, the asphalt content and aggregate gradation, as determined by extractions from prior studies, were retrieved for use in this study. **Laboratory specimens were prepared to the gradations, asphalt contents, and air void content as determined from field cores**. Laboratory specimens were subjected to varied aging treatments, and both field and laboratory mixtures were tested for resilient modulus. The results of these tests were compared to evaluate the effectiveness of the aging treatments, for simulating stiffening of the mixes in the field.

The following conclusions may be drawn from this study.

1) The triaxial resilient modulus results do not tend to follow the same general trend as the diametral modulus values, that of increased modulus with increased aging time. Also, the variation in triaxial modulus values was larger than the variation in the diametral moduli. This was true even though a large portion of the variation in testing was eliminated by having the same operator using the same equipment for each testing sequence.

2) The California and Georgia Asphalt-Aggregate Mixture Analysis Study (AAMAS) field moduli were much lower than expected, which may be due to the poor mix design identified in the AAMAS study (von Quintus et al., 1991). The wide variation in the Arizona SPS-6 (Special Pavement Study) field moduli and the small number of cores (three) make it difficult to distinguish whether the unaged or the STOA specimens best represent the field modulus after six months. Additional coring and testing of this site in the future may resolve this problem. Since the California AAMAS and the Arizona SPS-6 were the only long-term sites in a dry-freeze climatic zone, and the Georgia AAMAS was the only site in a wet–no freeze climate, no aging relationships based on climate can be identified at this time.

3) Discounting the three sites discussed (Arizona SPS-6, California AAMAS, and Georgia AAMAS), the remaining sites all have field moduli significantly higher than the unaged lab specimens. Two of these sites (California GPS-6 and Michigan SPS-6) are only a few months old and can be assumed to have moduli similar to the time when they were compacted. They both have field moduli averages very close to the STOA specimens. These data strengthen the conclusions of the preliminary study in which 4 hours of aging at 135°C, STOA, was decided to be representative of the aging due to the construction process.

4) A representation of the mixtures' hardening rates can be seen in the Tukey and least significant difference (LSD) plots in figures 4.1 through 4.14. The Michigan project, which used a low viscosity asphalt, had a modulus increase of more than 200% between the unaged and the 8-day LTOA specimens. The stiffer asphalt-aggregate combination of the Arizona SPS-5 project had a modulus increase of less than 50% over the same range. It was expected that heavier, stiffer mixtures would age more slowly, since there are fewer volatiles in the asphalts. While prediction of the aged modulus is not yet possible, comparison of aging rates for asphalt-aggregate combinations with similar asphalt properties can be made using the long-term oven-aging procedures. This is underway within another subtask of the SHRP study.

5) The results of the LTOA at 100°C (212°F) are similar to the LTOA at 85°C (185°F), but the higher temperature achieves similar hardening in less time. No degradation or deformation of the specimens was observed during the

100°C (212°F) aging procedure. However, there was more variability in the data, and the lower temperature is therefore preferred.

6) Five of the supplementary sites were older than 9 years and required at least the maximum amount of LTOA to statistically match the field aging, i.e., 8 days of LTOA at 85°C (185°F) or 4 days of LTOA at 100°C (212°F). Of these five sites, numbers 1006 and 1008 (ages 9 and 13 years) had field modulus values significantly higher than any of the aging treatments. Site 1801, age 18 years, was similar to the field at 8 days of 85°C (185°F) (LTOA) but was significantly lower than the field at 4 days of 100°C (212°F). Site 6049, age 19 years, had field values matching 4 days of LTOA at 100°C (212°F), while site 6048, age 14 years, encompassed all aging treatment due to a large spread of field core modulus values. These data indicate that LTOA of 4 days at 100°C (212°F) or 8 days at 85°C (185°F) is representative of all five of these older sites, while conservative for two of them.

7) Due to the large spread of field core modulus values for site 6048, a close correlation to laboratory aging treatments is not possible. Site 6048 was slightly cracked before coring, which could have resulted in the high variability in diametral modulus values between cores. For further study, cores from uncracked sections of the road would be needed.

8) It is apparent that the amount of traffic and the climatic region for a particular highway site play a role in the field modulus values of the cored specimens. The three supplementary sites over 9 years old with low relative traffic counts (1801, 1006, and 1008) had the highest average field moduli. Two of those sites (1006 and 1008) the youngest of those sites 9 years and older, had the highest yearly temperature deviations and also the highest field modulus values.

   The two sites over 9 years old with high traffic counts (6048 and 6049) had the lowest field modulus averages and the highest standard deviation between cores. Sites 6048 and 6049 also had two of the highest rainfall averages, indicating that the high moisture combined with the high traffic levels had some effect on the high variability as well as low modulus values among the cores.

9) It appears that climates with high temperature variations age (gain modulus) at a faster rate than wet climates with a low temperature variation. The three wet–no freeze sites have the three lowest average temperature deviations as well as the three highest yearly rainfall averages. The four dry-freeze sites have the four highest temperature deviations as well as the four lowest rainfall averages (see table 5.4).

   The three sites over 9 years old in the wet–no freeze zone have two of the three lowest modulus averages. The two dry-freeze sites (1008 and 1006) have the two highest modulus values.

A comparison between sites 1006 and 1801 strengthens this conclusion. Site 1006, containing Pave Bond Special (PBS), has an aging rate only half that of site 1801. Table 5.3 shows that after 8 days of aging at 85°C (185°F) both lab sites have very similar modulus values. Site 1006 had an unaged modulus almost twice that of site 1801 and thus was able to match 1801's modulus even though it had only half the aging ratio. Therefore, if field conditions (traffic and weather) were similar, site 1006 should have achieved modulus values similar to site 1801 for the same time in the field. But after 9 years, site 1006 shows a higher modulus than the 18-year-old site 1801. (This lab data tends to show that the PBS in the 1006 field samples is not the cause of the high modulus gain in only 9 years.)

10) The PBS contained in lab cores 1006 and 1008 tends to reduce the aging rate, while at the same time increasing the initial unaged modulus. Table 5.3 shows that sites 1006 and 1008 have the two lowest aging ratios. The sites also have two of the highest unaged modulus values. (Site 1006 has by far the highest unaged modulus, 325 ksi.) Even though the two sites have low aging ratios, the combination of their high initial moduli and their extreme temperature fluctuations between seasons result in high field moduli after relatively low aging time in the field.

11) Although 9- and 18-year-old sites, such as 1006 and 1801, achieve similar hardening in the field, this study does not conclude what a field pavement's maximum modulus is, when it reaches its maximum, or what happens after it reaches its maximum. Only theories can be discussed.

    For instance, site 1801 may have reached 850 ksi during its first 9 years, then started to deteriorate due to the high rainfall. The asphalt modulus may then have remained about the same, even though the asphalt continued to age. Or this site may have had a modulus of only 600 ksi after 9 years, and then slowly gained modulus until 18 years, when it was cored.

    Site 1006, while it now has an 852-ksi modulus, may continue to gain modulus in the field until a certain point and then also decline in modulus to the mid 800s in its later years. Or this site may continue to gain modulus its whole field life.

The following recommendations may be made from the results of this study.

1) To further analyze the effectiveness of the short-term aging period of 4 hours, additional sites should be selected. Of the agencies contacted when searching for retained materials, few indicated the use of diametral resilient modulus for testing newly laid pavements. Since this method is common practice in Oregon, additional Oregon sites are being considered.

2) Increasing the number of sites and the total number of specimens prepared will facilitate the use of regression analysis to determine prediction models. The

sites selected should have in-service lives ranging from 1 to 20 or more years to encompass all long-term aging in the field. A reduction in the 95% confidence intervals shown on the Tukey honest significant difference (HSD), and LSD plots in this study could lead to correlation of the laboratory procedures and the age of the field cores. This could lead to prediction models where a known treatment is used to predict the stiffness of field pavements (e.g., for an AC-10 in the dry-freeze region, STOA and 4-day LTOA are very similar to 6 years in service).

3) This study addressed validation of STOA for 4 hours at 135°C (275°F) and the LTOA at 85°C (185°F) and 100°C (212°F). One additional test for long-term aging has been developed at OSU and deserves additional validation study. This is the low-pressure oxidation test (LPO) at varied temperatures. The test involves passing oxygen through a specimen at elevated temperatures of 60°C or 85°C (140° or 185°F). The pressures involved with this procedure are not high enough to pose safety problems similar to those of high-pressure oxidation studied in the past. Additional specimens were prepared with the intent of using them in a validation effort for low-pressure oxidation, but due to time limitations, the test was not completed.

4) To obtain a more accurate model to simulate field aging, more parameters are needed to determine a multiple linear regression relationship. Possible inputs could be traffic, high and low average field temperatures, average rainfall, field age, and lab aging time to match the field modulus. Field modulus could be the dependent variable, and the other variables could be independent or explanatory variables. With this data, several regression models could be tried until the best regression fit is obtained. It may be the case that not all of the independent variables are used, but having them available would ensure the best fit.

The following are preliminary guidelines for implementing the results from this study.

Although only five sites older than 9 years old were studied, and all were in Washington, they included dry-freeze and wet no-freeze zones which cover a good portion of the United States (see figure 2.2.). The dry no-freeze portion of the U.S., and wet-freeze zones did not contain any sites over 5 years old. Since not enough young and old sites were available from each climatic zone, only a few definite recommendations can be made at this time.

1) 0–2 years, all zones: STOA

Based on the Oregon preliminary study data and the two expanded sites, California GPS-6 and Michigan SPS-6, it appears that 4 hours of lab oven aging at 135°C (275°F) is a good (although conservative for some sites) estimate of the aging taking place during field mixing and up to 2 years after. Minnesota SPS-5 was over 1 year old and had a field modulus similar to STOA.

Two 2-year-old sites, California AAMAS and Georgia AAMAS, had poor field cores that did not allow a good comparison. The only undamaged site 1–2 years old with a field modulus matching the unaged lab specimens was Arizona SPS-6. Arizona SPS-5, in a more extreme environment than Arizona SPS-6, had a field modulus closer to the LTOA specimens aged for 2 days at 85°C (185°F).

This recommendation takes into account three climactic zones and is a conservative estimate. As mentioned earlier, to get a true indication of what happens in each zone, a more thorough study is needed.

2) Over 9 years for the dry-freeze zone: 8 days of LTOA at 85°C (185°F)
Over 18 years for the wet no-freeze zone: 8 days of LTOA at 85°C (185°F)

Long-term oven aging at 85°C (185°F) for 8 days appears to represent (conservatively) the sites 9 years or older in the dry-freeze zone, and 18 years or older in the wet no-freeze zone. It is not clear what the modulus is for the wet no-freeze sites between 9 and 18 years, therefore no general conclusion can be made for all of these 9-year or older sites. Again, further research in each of these zones is needed.

For the following field aging periods, only an estimate can be made by combining all of the climactic zones. This is only for discussion purposes, and not recommended.

3) 2–6 years: LTOA of 2 days at 85°C (185°F)

Four sites were studied in this time range: Wisconsin AAMAS (3 years old), Washington 6056 (5 years old), Washington 1002 (3 years old), and the France LCPC site (5 years old). The Wisconsin field modulus was similar to LTOA of 2 and 4 days at 85°C (185°F), as was the Washington site 6056. The France site field modulus was similar to LTOA of 8 days at 85°C (185°F), and the Washington site 1002 had a field modulus matching the STOA specimens. Field cores from the Washington site 1002 were overlain after only 3 years in the field and were considered to be in poor condition (a 61 pavement rating).

A conservative estimate of field aging for this period is LTOA of 2 days at 85°C (185°F).

4) 6–9 years: Unknown

No field sites were available from this time period. A hypothesis would be that LTOA of 4 days at 85°C (185°F) would be similar to this amount of field aging.

1

Introduction[1]

1.1 Problem Statement

Although asphalt has been used as a paving material in Europe since the mid 1800s, and in the United States since the late 1800s, there has been very little study of the aging phenomenon found in asphalt-aggregate mixtures (Bell, 1989). Most of the research has focused on the hardening or aging of asphalt alone. It has long been known that asphalt subjected to heat will cool to a harder condition than the original asphalt. Asphalt exposed to the environment also becomes harder with time.

This hardening of asphalt has been referred to as age hardening, embrittlement, or more simply, aging. It is represented by a stiffening of the asphalt, a higher viscosity, and a more brittle condition. The asphalt is also more susceptible to cracking and deterioration due to wear and moisture. When used as a component in asphalt paving, asphalt undergoes hardening primarily due to two factors: loss of volatiles and oxidation of the asphalt.

The main loss of volatiles occurs in asphalt-aggregate mixtures between the time of mixing and final placement, when the mixture is at elevated temperatures. This is referred to as short-term aging. The longer, never-ending process of oxidation occurs partially throughout the short-term aging time frame, but much more extensively over time, while the mixture is in service and exposed to the environment. This is referred to as long-term aging.

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[1]Note on Units:

Numerical units within the text of this report, with the exception of diametral and trixial resilient modulus, are reported in Standard International Units. (SI) The diametral and triaxial modulus values, listed in the text, figures, and appendixes, are given in ksi (kips per square inch, i.e., 1000 pounds per square inch).

The conversion to SI units is: 1 ksi = 6.89 MPa
= 6,890,000 Pa.

While a stiffening or embrittlement of the asphalt binder in asphalt-aggregate mixtures will lead to increased fatigue and temperature cracking, it can sometimes be beneficial, such as in mixtures prone to deformation. Determining the aging potential and incorporating an evaluation of this in the design process would also be beneficial.

A portion of the Strategic Highway Research Program (SHRP) has been dedicated to the study of asphalt-aggregate mixtures. The project designated SHRP A-003A with the University of California at Berkeley is titled "Performance-Related Testing and Measuring of Asphalt-Aggregate Interactions and Mixtures." As a subcontractor on this project, Oregon State University (OSU) is responsible for studying asphalt-aggregate mixture aging.

Accelerated Performance Testing (APT) procedures have been developed at OSU in an attempt to simulate field aging (both short- and long-term). If successful, these APTs will allow asphalt mix designers to incorporate evaluations of mixture aging into asphalt mixture designs. This report is a summary of the validation of three APTs developed at OSU—short-term oven aging (STOA) at 135°C (275°F) and long-term oven aging (LTOA) at 85°C (185°F) and 100°C (212°F), to simulate short- and long-term aging. The following section reviews the background to the development of these test procedures.

1.2 Background

A thorough literature review by Bell (1989) revealed extensive testing for the effects of aging on asphalt. However, limited research has been accomplished that highlights the effects of aging on asphalt-aggregate mixtures. Asphalt is a key ingredient in these mixtures and acts as a binder or "glue." Changes in the binder aging properties due to the asphalt-aggregate interaction influence the performance of the mixture.

1.2.1 Causes of Aging

The first documented studies of asphalt aging were by A. W. Dow (1903), who related heating of asphalt to a reduction in the weight and penetration of asphalt recovered from mixtures. More extensive research began in the 1930s, again centered around asphalt hardening only. By 1961, Traxler had concluded the causes of asphalt aging were

1) oxidation,
2) volatilization,
3) time (led to structuring),
4) polymerization induced by actinic light, and
5) condensation polymerization (by heat).

Traxler expanded this list to 15 in 1963. The effects of light were divided into aging by direct light and by reflected light. Microbiological deterioration was also considered a contributor to the hardening of asphalt.

Of the 15 causes listed by Traxler, four were believed to be the major contributors to hardening; in 1984 Petersen reduced these to three primary causes of aging in asphalt:

1) loss of oily components by volatility or adsorption,
2) changes in composition by reaction with atmospheric oxygen, and
3) molecular structuring that produces thixotropic effects (steric hardening).

These three are still considered the primary contributors to asphalt hardening.

Although most researchers agree that steric hardening or structuring of asphalt contributes to asphalt aging, no tests have been developed to quantify its precise role (Bell, 1989).

1.2.2 Asphalt Aging Methods

The thin film oven test (TFOT) was introduced in 1940 to differentiate and evaluate asphalts by their viscosities after a 5-hour treatment at 163°C (325°F). The initial test used a 3000-micron (.13 in.) thick sample 140 mm (5.5 in.) diameter (Lewis and Welborn, 1940). This test was adopted by the Association of American State Highway and Transportation Officials (AASHTO) in 1959 and by the American Standards and Testing Methods (ATSM) in 1969. Variations of this test have been suggested by various researchers and include changing the sample size and duration of treatment (Griffin et al. 1955, Hveem et al. 1963, Welborn 1979). Most researchers conclude the effectiveness of the TFOT is limited to simulating of short-term aging.

An alternative to the TFOT was developed for the California Department of Highways in 1955. It utilized a rotating jar to spread the asphalt in thinner films (1250 microns (.05 in.)). This was termed the rolling thin film oven test (RTFOT) and was finally adopted by ASTM in 1970. This has been designated ASTM D 2872.

Additional tests have been developed since the RTFOT, such as a modified version which tilts the oven back 1.06° (Kemp and Predoehl 1981), and others that vary the duration, temperature, and sample size for the test (Edler, 1985). Although many tests claim to simulate field aging of asphalt, some are too severe. The best correlations with field aging are limited to simulated short-term aging by the TFOT and RTFOT (Petersen, 1989).

Petersen (1989) incorporated some previous modifications to the RTFOT to develop the thin film accelerated aging test (TFAAT). A 4-gram asphalt sample is aged for 72 hours at 113°C (235°F). The level of aging in the TFAAT was comparable to the level of aging in the field for the asphalts test, but the rate of aging in the TFAAT did not decrease with time as in the field.

Oxidation vessels have been used in an attempt to accelerate oxidation of asphalt and to represent long-term aging in a process similar to the use of heat to accelerate the loss of volatiles. The most notable research with this method has been by D.Y. Lee (1973) for the Iowa State Highway Commission. Lee developed a two-stage test procedure for asphalt that utilized a TFOT to simulate short-term aging of the asphalt prior to using a pressure oxidation vessel to simulate long-term oxidation aging of the mixture. The result was a hyperbolic model to relate field aging and laboratory aging as measured by penetration and viscosity. Lee concluded that 46 hours of mixture oxidation aging in the pressure vessel, in addition to the asphalt aging prior to mixing, was equivalent to 60 months of field aging under Iowa conditions. Portions of the SHRP study are developing pressure oxidation procedures for aging neat asphalt and aggregate-asphalt mixtures.

1.2.3 Asphalt-Aggregate Aging Methods

Tests on asphalt-aggregate mixtures have utilized extended heating, oxidation, and light exposure methods with only limited success to date. A major conclusion from these tests was that permeability is a better indicator of aging susceptibility than air voids in oxidation tests (Goode and Lufsey, 1966). Permeability indicates the connectivity of the air voids and of the ability of air to pass through the mixture.

A study by Edler et al. (1985) concluded that lime has a considerable effect on retarding the aging of asphalt-aggregate mixtures.

1.3 Study Approach

The study described herein was accomplished in three stages: preliminary short-term validation, expanded validation, and supplementary validation. The first stage addressed only short-term aging and was aimed at identifying a common time period to short-term age the mixtures to a state representing aging in the construction process. The second stage, referred to as expanded validation, gathered information on the validity of both short-term and long-term aging. Specimens were subjected to short-term (135°C (275°F)) and successive long-term (85°C (185°F) and 100°C (212°F)) oven-aging procedures to simulate field aging. The third stage, referred to as supplementary validation, encompassed short-term (135°C (275°F)) and successive long-term (85°C (185°F) and 100°C (212°F)) oven-aging procedures for seven sites in the state of Washington. These sites range in age from 3 to 19 years, with five sites older than 9 years.

The approach of the expanded validation study is shown in the flow chart of figure 1.1. Following site selection and material gathering, cores from the field were trimmed and analyzed to determine their air void levels. Whenever possible, the asphalt content and aggregate gradation as determined by extractions from prior studies were retrieved for use in this study. **Laboratory specimens were prepared to the field gradations and asphalt contents and the target air voids, as determined from the field cores.** Laboratory specimens were subjected to varied aging treatments, and both field and laboratory mixtures were tested for resilient modulus. The results of these tests were compared to evaluate the effectiveness of the aging treatments for simulating stiffening of the mixtures in the field.

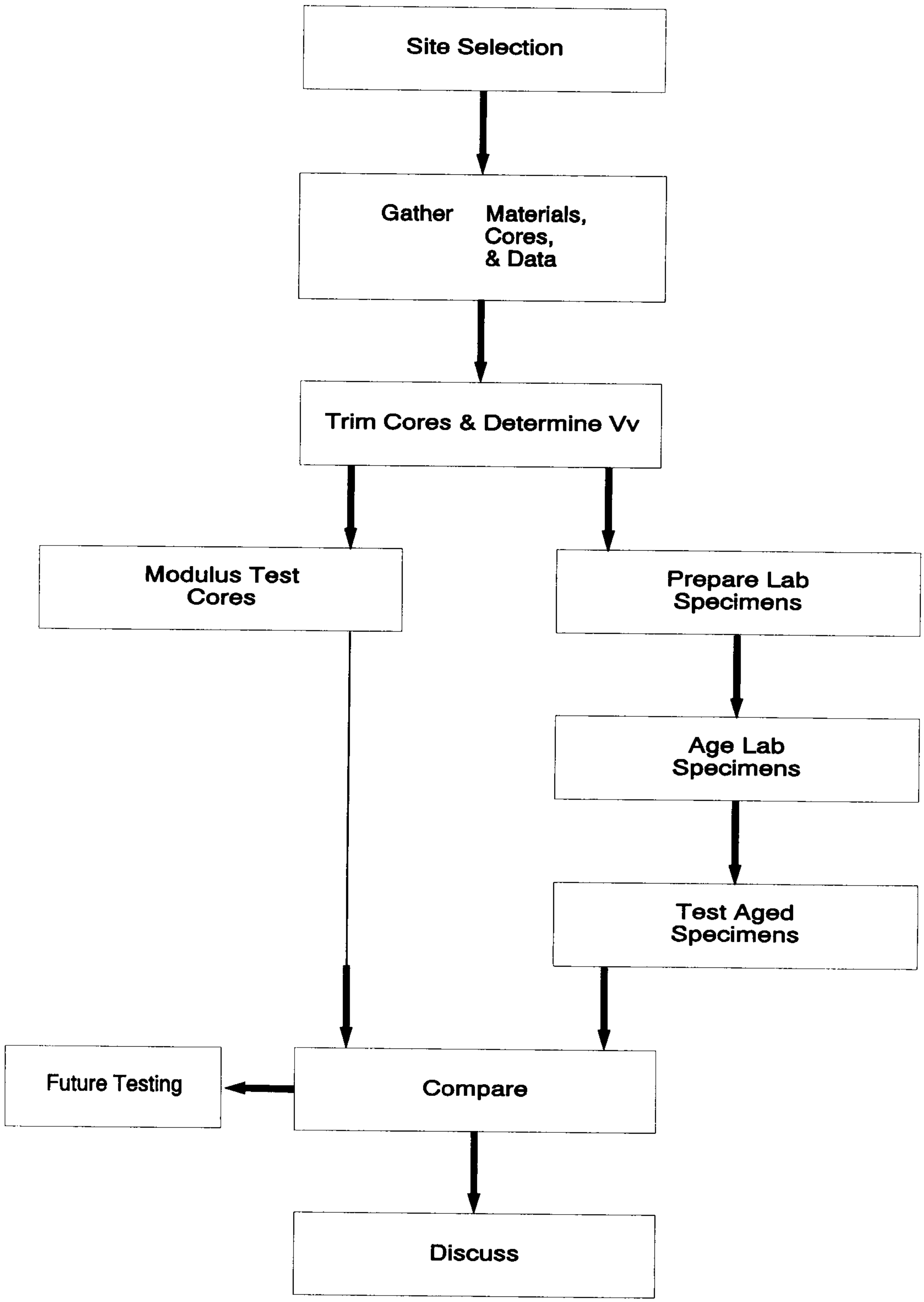

Figure 1.1 Study Approach-Expanded Validation Study

This report covers both short- and long-term validation, including site selection, evaluation of field data and/or cores; preparation, treatment, and testing of laboratory specimens; and comparison of field and laboratory data.

2

Experiment Design

2.1 Site Selection

2.1.1 Selection Criteria

Evaluating the change in properties of mixtures subjected to the laboratory aging procedures required a knowledge of existing pavement mixtures and their properties. **The primary consideration in selecting field sites for use in this evaluation was the availability of original materials.** Retained materials were sought in order to eliminate variation in asphalt and aggregate properties between materials used during placement and those available today. Questionnaires were sent to over 35 state material laboratories, as well as to organizations such as The Asphalt Institute and Western Research Institute, requesting information on the availability of retained materials.

The best source of retained materials was the SHRP Materials Reference Laboratory (MRL), which maintains an inventory of materials from the National Cooperative Highway Research Program's (NCHRP) Asphalt-Aggregate Mixture Analysis Study (AAMAS) and the SHRP Special Pavement Studies (SPS) projects. Several projects from both of these studies were selected for use in the expanded validation effort. These sites are referred to simply by their AAMAS or SPS identifier throughout this report. The only drawback of the AAMAS and SPS projects was their age: most of the projects were constructed after 1987, less than three years ago. Some materials were obtained from state agencies. Figures 2.1 and 2.2 show the general locations of the project sites selected for both the preliminary and expanded studies. Figure 2.3 shows the locations of the supplementary sites.

The climatic region in which a pavement was located was also an important factor in the selection process for the expanded study. The goal was to have at least two sites from each climatic region (dry–no freeze, wet–no freeze, dry-freeze, and wet-freeze) and a backup site in case one fell through. By adding the seven Washington supplementary sites, the goal was achieved.

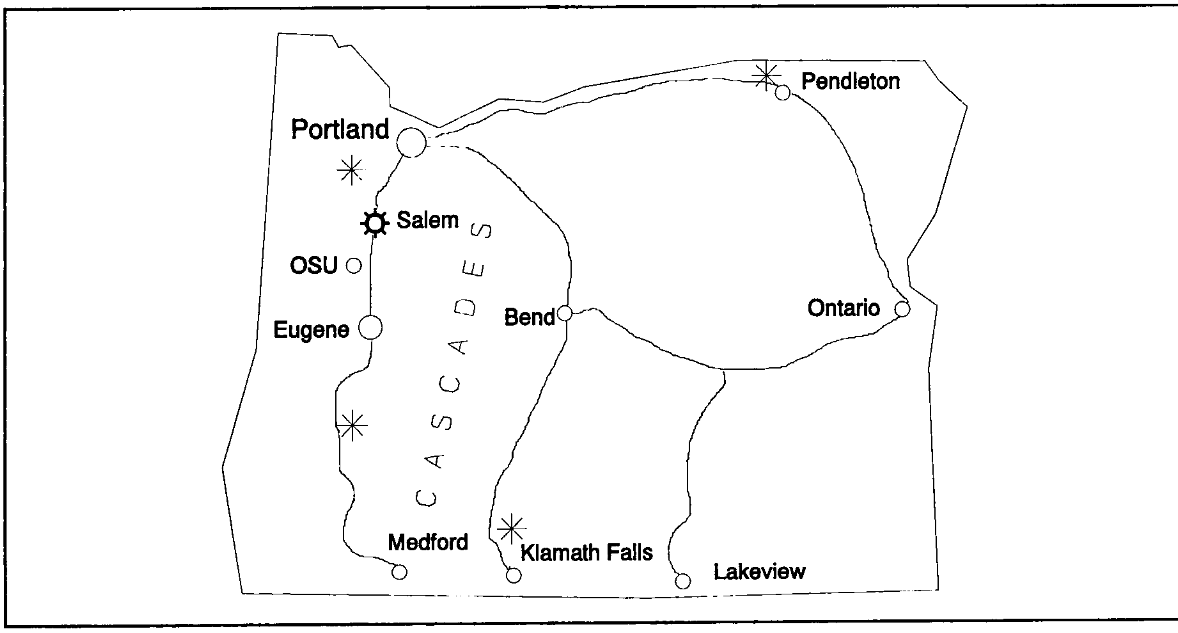

Figure 2.1 Preliminary Study Sites

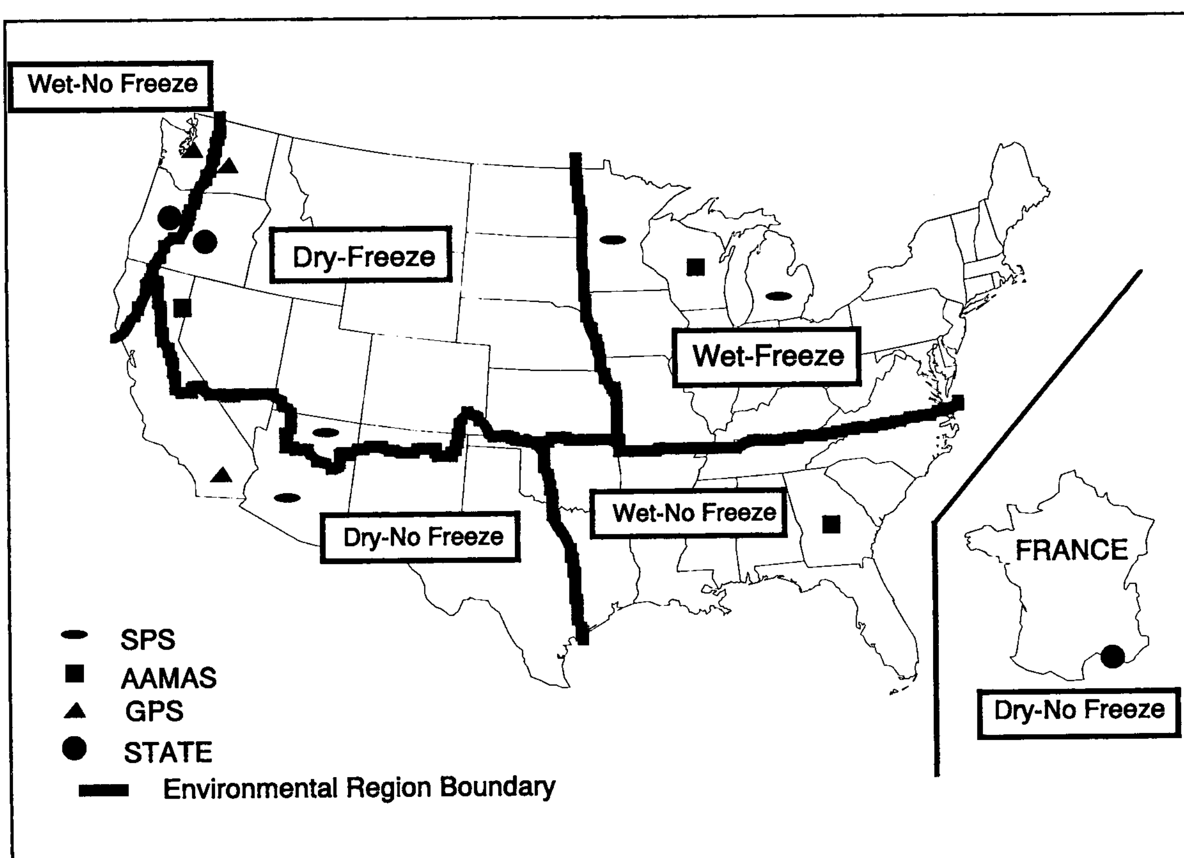

Figure 2.2 Expanded Validation Study Sites

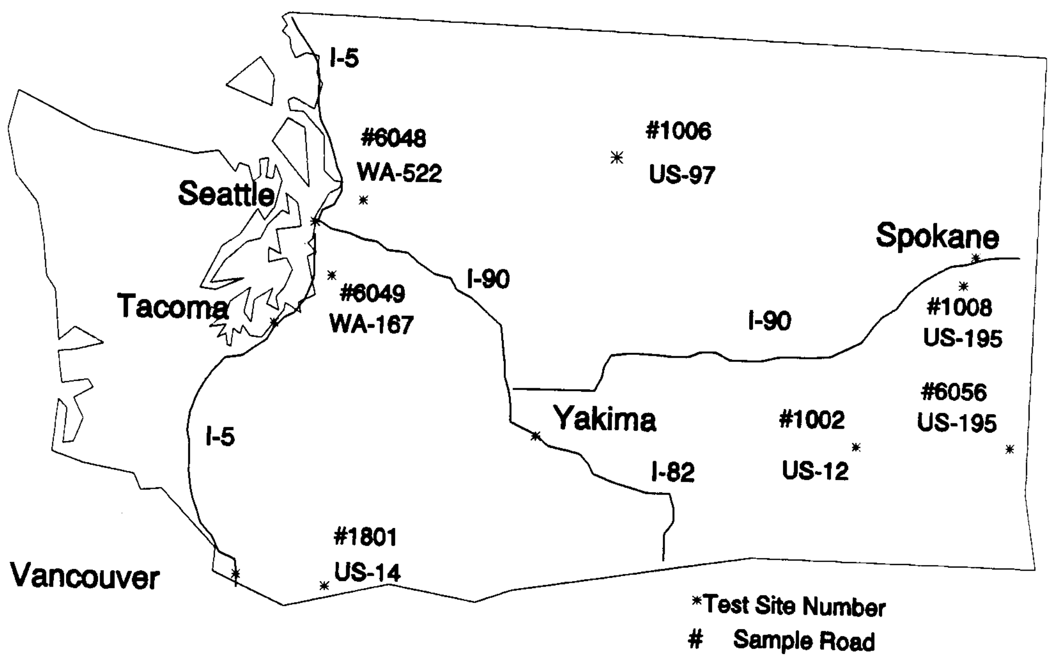

Figure 2.3 Supplementary Validation Study Sites

The laboratory specimens were to be prepared in the same mix proportions as those placed in the field, so adequate information about mix designs and material sources was required. The MRL maintains a database of mixture information about each project for which it has materials. This provided vital access to the job mix formula and any extraction data from prior studies. Information for state projects came from the respective state materials laboratories.

Other considerations for site selection included traffic level, pavement design, and the willingness of the local agency to allow coring. In one instance, the local agency refused to allow any cores be taken from the roadway. Since the primary purpose of this effort was to compare laboratory and field properties, this precluded that particular site from being used, although retained original materials were readily available.

An attempt was made to include sites offering a variety of asphalt grades. The grade of asphalt used in the original design is based largely on the climate. Selecting projects from all the climatic regions also resulted in varied asphalt grades, as will be shown below. Due to the limited number of sites with available retained materials, no special consideration was given to aggregate types.

2.1.2 Preliminary Validation Study Sites

The first phase of this validation effort was a preliminary study of the short-term oven aging (STOA) procedure that had been developed. Specimens prepared in the laboratory were placed in a forced draft oven for varied time periods at 135°C (275°F) prior to compaction. The time was varied to determine an aging time representative of short-term aging in the field. The sites selected for evaluating this procedure were selected from Oregon Department of Transportation (DOT) projects. Two were located in western Oregon (wet-no freeze) and two in eastern Oregon (dry-freeze). These are listed by project title in table 2.1, along with their designation for this study, asphalt content, and grade. The description of these sites follows.

1) <u>Stag Hollow-Wapato Road</u>: Located in northwest Oregon along the Yamhill-Newberg Highway, this "C" mix required 6.2 percent asphalt (McCall AC-15) by total mixture weight.

2) <u>Butter Creek-Old Oregon Trail</u>: An eastern Oregon project near Pendleton in Umatilla County, this "B" mix used 5.9 percent by total weight of a Koch AC-15.

3) <u>Rock Creek-Anlauf</u>: A modified "B" mix on the Umpqua Highway near Roseburg. It had 5.3 percent by total weight of a McCall AC-20. This site also had a 0.5 percent Pave Bond Special (PBS) admixture.

Table 2.1 Preliminary Validation Projects

Site	Project #	Asphalt	% AC*	Admix
Stag Hollow–Wapato	913	AC-15	6.2	None
Butter Creek–Old Oregon Trail	816	AC-15	5.9	None
Rock Creek–Anlauf	852	AC-20	5.3	PBS
Lobert	874	AC-15	5.8	Lime

* By weight of total mix.

4) Lobert: The final site was along the Dalles-to-California Highway in south central Oregon. This "B" mix had 5.8 percent by total weight Witco AC-15 asphalt and a 1 percent lime treatment of the aggregate.

2.1.3 Expanded Validation Study Sites

Additional sites were selected to accomplish the expanded validation. Information on the effectiveness of the short-term and long-term procedures was obtained from testing these sites. To adequately represent each climatic region, these sites were selected from across the United States, with an additional one in France. Environmental zones are listed in table 2.2. These sites were:

1) Arizona SPS-5: The Arizona SPS-5 project was an asphalt overlay of an existing asphalt pavement on Interstate 8 near Casa Grande in southern Arizona. This mix was also specified as an Arizona DOT 20-mm (.75-in.) modified mix, but rather than lime it had 2 percent Type II portland cement by weight of aggregate as an admixture. The cement was from the Arizona Portland Cement Company, and the AC-40 asphalt was from Chevron Oil's Richmond, California, refinery. The aggregates were from a local pit and were classified as coarse aggregates, washed sand, and crushed fines. This site is considered to be in a dry–no freeze climate.

2) Arizona SPS-6: The Arizona SPS-6 site is an asphalt overlay on portland cement concrete (PCC) located in northern Arizona on the Flagstaff–Walnut Canyon Highway. This site is considered to be in a dry-freeze climate. The asphalt was an AC-20 from Sahuaro Asphalt and Petroleum, and the aggregate was a combination of basalt, cinder, and sands. There was also a mineral admixture of 1.5 percent Type N hydrated lime from Chemstar Lime. The mix was designated by Arizona DOT as a 20-mm (.75-in.) modified mix.

3) California AAMAS: The California AAMAS site is located on U.S. 395 near Doyle, in northeastern California and was produced using both a batch and an Aztec drum plant. Although the same type "A" job mix formula was

Table 2.2 Environmental Zones—Expanded Study

Site*	Route Number	Construction Date	Environmental Zone
AZ5	Interstate 8 near Casa Grande, AZ	1990	Dry-no freeze
AZ6	Interstate 40, 10 miles east of Flagstaff, AZ	August 1990	Dry-freeze
CAB	U.S. 395 near Doyle, CA	1989	Dry-freeze
CAD	U.S. 395 near Doyle, CA	1989	Dry-freeze
CAG	Interstate 8 near El Centro, CA	1991	Dry-no freeze
GAA	U.S. 76 approximately 3 miles west of Hiawassee, GA	1989	Wet-no freeze
MI6	Interstate 75, Saginaw County, MI	October 1990	Wet-freeze
MN5	No Data	1990	Wet-freeze
WIA	No Data	1989	Wet-freeze
France	Autoroute A08	April 1986	Dry-no freeze

*See table A11 for designations for each site.

specified, extractions showed there was a difference in the asphalt content and aggregate gradations of the mixtures produced by each method and as such, they were treated as two sites in this effort. The drum site is referred to as "CAD" and the batch site as "CAB." The asphalt was an AR-4000 from Shell Oil, and the "sensitive" mix was crushed gravel with both crushed and natural fines. The climate of these sites is dry-freeze.

4) California GPS-6 - This is a SHRP general pavement study (GPS) site near El Centro in southern California, on Interstate 8. It consists of a 89-mm (3.5 in.) overlay placed on asphalt concrete (AC) in two lifts. The location is in a dry–no freeze zone. The asphalt type is unknown at this time.

5) France LCPC, 3 sections: The final location for long-term validation was actually considered three separate projects for this effort. A portion of Autoroute A08 in southern France was paved in April 1986 for a study by the Laboratoire Central des Ponts et Chaussées (LCPC). Several test sections were placed using the same aggregate and mix design for each, but the asphalt supplier was varied. The asphalts were all 40-50 Pen. The aggregate was a combination of basalt gravels, basalt sand, and silica sand. The sections selected for this effort have been designated A, B, and C. Cores from these sections were taken in November 1990; the site is in a dry–no freeze zone.

6) Georgia AAMAS: The second AAMAS site selected was in Georgia and represented the wet–no freeze climate. The type "B" mixture used at this site

was considered susceptible to moisture damage and deformation. This mixture was not used on high volume roads. It was placed as an overlay along Highway 129. The aggregate was entirely crushed granite with a high mica content. Due to the moisture damage susceptibility, hydrated lime from Longview was added at 1 percent by aggregate weight. The asphalt was an Amoco Oil AC-20.

7) Michigan SPS-6: One site from the wet-freeze climatic region was the Michigan SPS-6 site. It is located along Interstate 75 and is an asphalt overlay on PCC. The asphalt was an AC-10 from Amoco, and the aggregate was comprised of 14-mm (.6-in.) chips, crushed fines, and a mineral filler. The mineral filler was 0.7 percent by aggregate weight of flyash from the Lansing Board Power & Light.

8) Minnesota SPS-5: This is a SHRP SPS, located in a wet-freeze zone. It consists of a 127-mm (5-in.) overlay on asphalt concrete. This is a late addition to this study, and the asphalt type is unknown at this time.

9) Wisconsin AAMAS: Another wet-freeze site was an AAMAS project in Wisconsin. This project utilized a recycled mix design. Since this particular mix design had developed rutting in the past, it was not placed on a high-volume road. The mixture contained 45 percent recycled asphalt pavement (RAP), and the new aggregate was crushed gravel. The new asphalt was a 200-300 Pen (similar in viscosity to an AC-5) asphalt supplied by Koch Asphalt Company.

The aggregate gradations for each site are shown in Appendix A, along with additional details about the aggregate, asphalt, and mixture properties, pavement conditions, and climatic data obtained from the field sites. A summary of the mixture components for the expanded validation sites is given in table 2.3.

2.1.4 Supplementary Validation Study Sites

Seven older sites from Washington State were used in the supplementary study to further validate the short- and long-term aging procedures. These sites ranged in age from 3 to 19 years, with four sites older than 13 years. Four of the sites were in the "dry-freeze" portion of the state and three were located on the "wet–no freeze" western side (table 2.4).

A cooperative study of asphalt aging at Pennsylvania State University (PSU) is still in progress using these same seven sites. The exact materials and gradations used at Oregon State University (OSU) were sent to PSU, as well as extra cans of asphalt obtained from the Washington Department of Transportation.

A discussion of these seven sites follows.

Table 2.3 Mix Design Components—Expanded Study

Site	Asphalt Type	Asphalt Source	Aggregate Type	Admixtures
AZ5	AC-40	Chevron USA, Richmond, CA	Course aggregate, washed sand, crushed fines	Type II PCC
AZ6	AC-20	Sahuaro/ Edgington	Basalt, cinder, sands	Lime
CAB	AR-4000	Shell Oil	Crushed gravel	None
CAD	AR-4000	Shell Oil	Crushed gravel	None
CAG	Not available	Not available	Not available	None
GAA	AC-20	Amoco Oil Co.	Crushed granite with high mica content	Hydrated lime
MI6K	AC-10	Amoco Oil Co.	.6-in. chips, crushed fines	Flyash
MN5	Not available	Not available	Not available	None
WIA	AC-5	Koch Asphalt Co.	Crushed gravel	Recycle
France "A"	40/50 Pen	Elf	Basalt	None
France "B"	40/50 Pen	Shell	Basalt	None
France "C"	40/50 Pen	Total	Basalt	None

1) Washington 1801: (18 years old) This wet–no freeze site was placed in 1973 as a 102-mm (4-in.) surface course over a 102-mm (4-in.) bituminous bound base. The site receives 2.4 (94.5 in.) of rainfall yearly on average. The asphalt was an 85/100 grade with no admixtures, produced by Shell Oil.

2) Washington 6048: (14 years old) This site is also located in a wet–no freeze zone and has only a 15.5°C (60°F) average yearly temperature deviation. It was resurfaced in 1977 with a 46-mm (1.8-in.) asphalt layer, after the original 107-mm (4.3-in.) surface was placed in 1965. The asphalt used was an AR-4000 from U.S. Oil refining. The road section rating in 1992 was the second lowest of all of the Washington sites, 63, due to flushing and longitudinal cracking. A second overlay was placed in 1992, after the coring for this project had taken place.

3) Washington 6049: (19 years old) This wet–no freeze site was resurfaced in 1972 after the original 107-mm (4.3-in.) surface was placed in 1966. The asphalt grade used was an 85/100 from Sound Refining in Tacoma,

Table 2.4 **Field Site Locations—Supplementary Study**

Site	Route Number	Vicinity	Environmental Zone
1801	SR 14	10 miles east of Vancouver, WA	Wet–no freeze
6048	SR 522	10 miles north of Seattle, WA	Wet–no freeze
6049	SR 167	Near Puyallup, WA	Wet–no freeze
1002	SR 12	North of Walla Walla, WA West of Clarkston, WA	Dry-freeze
1006	US 97	Near Brewster in north central WA	Dry-freeze
1008	US 195	10 miles south of Spokane, WA	Dry-freeze
6056	US 195	20 miles north of Clarkston in southeastern WA	Dry-freeze

Washington. This site had the highest pavement rating of all of the Washington sites, 79, in 1992, even though it had been subjected to 10,683,000 ESALs (equivalent single axle loads) since 1972. A visit to the site confirmed that it was in good condition.

4) Washington 1002: (3 years old) This dry-freeze site was originally reconstructed in 1984 and surfaced with 107-mm (4.3-in.) of asphalt. It was resurfaced in 1987 with a 13-mm (.5-in.) surface treatment, porous friction course. The pavement rating before the surface treatment was 66 in 1986, indicating that the cores used in this study were in poor condition. For this study, the top surface course was removed and only the 107-mm (4.3-in.) layer was considered. An AR-4000 asphalt from Cenex refining in Laurel, Montana, was used for this project.

5) Washington 1006: (9 years old) The original 76.2-mm (3-in.) surface was placed in 1983 as part of a reconstruction project. This site also used an AR-4000 asphalt from Laurel, Montana. The AR-4000 contained 0.5 percent of Pave Bond Special (PBS). The mix design confirmed that PBS was also used on the road. This site is located in the dry-freeze zone of the United States and had the highest average yearly temperature deviation of all of the Washington sites, 30°C (86°F), and the lowest yearly rainfall average of 0.4 meters (15.8 in.).

6) Washington 1008: (13 years old) A 91-mm (3.6 in.) surface was placed in 1979 as new construction. The asphalt used was an AR-4000 from Billings, Montana, and contained 0.5 percent PBS. This road was in very poor condition at the time of coring and had a 49 pavement rating. It had longitudinal cracking, raveling, patching, and alligator cracking, as well as 8-mm (0.3-in.) ruts. The site is in a dry-freeze zone.

7) Washington 6056: (5 years old) The original surface of 91 mm (3.6 in.) was placed in 1970 and followed with a 46-mm (1.8-in.) resurfacing in 1986. The asphalt used was an AR-4000 from Conoco Oil of Billings, Montana. Only the 46-mm (1.8-in.) resurfacing was considered in this study, as the original 1970 materials were not available. The section had a pavement rating of 76 in 1992, and a field visit confirmed that the dry-freeze site was in good condition.

Note: See Appendix D for a summary of the mix design and compaction data relating to these seven sites.

2.2 Tests for Laboratory Specimens

2.2.1 Volumetric Properties

The specimens prepared in the lab were measured for physical characteristics such as bulk-specific gravity (G_{MB}) and thickness. The bulk-specific gravity was calculated by weighing the specimen dry, coated in Parafilm, and, finally, coated in Parafilm while submerged. The bulk-specific gravity was calculated as:

$$G_{MB} = \frac{Wt_A}{(Wt_C - Wt_W) - \left(\frac{Wt_C - Wt_A}{0.9}\right)} \qquad \text{(Eq. 2.1)}$$

where Wt_A = weight of dry sample in air,
Wt_C = weight of sample coated with Parafilm, and
Wt_W = weight of coated sample in water.

Two mixtures, one with STOA and one without STOA, were prepared for each site and used to determine the theoretical maximum specific gravity, also referred to as the Rice specific gravity (G_{MM}). The bulk-specific gravity and the Rice specific gravity were used to calculate the percent air voids (V_V) in each specimen:

$$V_V = \left(1 - \frac{G_{MB}}{G_{MM}}\right) \cdot 100 \qquad \text{(Eq. 2.2)}$$

The thickness (height) of each cylinder was measured three times about the specimen and the average was recorded. This measurement is required in the computation of the diametral resilient modulus.

2.2.2 *Modulus Testing*

Following compaction and extrusion, each specimen was conditioned for at least 4 hours in an environmental cabinet to stabilize its temperature to 25°C (77°F) and then was subjected to diametral resilient modulus (M_R) testing in accordance with ASTM D 4123. A static load of 44.5 N (10 lb) was applied to restrain the sample in the test apparatus. A pulse load was applied for 0.1 seconds and then the specimen was allowed to relax for 0.9 seconds. The pulse load was increased until a constant-strain condition of 100 μstrain was maintained. Each sample was tested, rotated 90°, and retested. If the values were not within 10 percent of the mean, the sample was rotated another 90° and retested. The average diametral M_R value for the two tests within 10 percent of each other was used as the diametral M_R of the sample. The diametral M_R is calculated by the equation:

$$\text{Diametral } M_R = 0.6183 \frac{P}{(d \cdot t)} \qquad \text{(Eq. 2.3)}$$

where M_R = resilient modulus (psi),
P = load (lb),
d = deformation (in.), and
t = thickness (in.).

An automated data acquisition system developed for previous testing (AbWahab, Ph.D. Thesis, 1992) was used in this study. In addition to monitoring the linear voltage displacement transducer (LVDT) and load cell outputs, the computer program displays the outputs graphically and calculates an approximate M_R value in real time. The data from three pulses is saved to hard disk and can be retrieved for subsequent calculation of M_R and hardcopy output.

Each of the long-term aging specimens was also tested to determine the resilient modulus in a triaxial configuration at a constant-strain condition of 100 μstrain and a static load of 134 N (30 lb). The length over which the triaxial strains were recorded was 51 mm (2.0 in.). A computer program similar to that used for diametral testing was used for the triaxial testing.

2.3 Tests for Field Cores

2.3.1 *Coring*

For the expanded study, the controlling agency for each site was asked to take cores from the wheelpaths and from the area between the wheelpaths during the summer of 1990. Some agencies took the cores themselves, while others allowed the SHRP regional offices to arrange for coring. The request was for 102-mm (4-in.) diameter, dry cored samples whenever possible. Some of the agencies were able to provide this quality of core while others could only produce 152-mm (6-in.) diameter and/or wet cored samples. Shorter cores [less than 102-mm (4-in.)] with 152-mm (6-in.) diameters were recored at OSU with a 102-mm (4-in.) dry core machine. Samples taller than 102 mm (4 in.) in height (Georgia AAMAS) could not be recored with the dry-cut type core bit and were recored to 102 mm (4 in.) in diameter with a wet core machine. Water introduced during this process was allowed to evaporate at room temperature for 7 days before proceeding. The supplementary study cores were cored by Washington DOT in the summer of 1991. All of the pavement layers considered were the top surfaces, with the exception of site 1002, which had a surface treatment in 1987 (table E4).

2.3.2 Evaluation

The first step after receiving of the cores was to determine the representative lift of the cores. Data provided by the local agencies and SHRP regional offices allowed determining which portion of the core was representative of the project. In one case, Georgia AAMAS, the project of interest had already been resurfaced with a 51-mm (2-in.) overlay. In all others, the topmost section of the core was from the project of interest.

In the California drum (CAD) samples, a line of excess asphalt was noted between the second and third lifts from the surface. This portion of the core also had fine grained soil in the voids. It is assumed traffic was allowed on the section prior to placement of the top lifts, and the excess asphalt and soil was a result of the tack coat and traffic. This phenomenon was not observed in the California batch (CAB) samples.

2.3.3 Trimming

Once the desired portion of the cores was determined, the samples were trimmed to 64 mm (2.5 in.) or, if possible, 102 mm (4 in.) in height. The heights were selected to correspond with earlier work done under the SHRP A-003A contract at OSU, allowing for diametral resilient modulus testing on all samples and triaxial resilient modulus testing on the 102-mm (4 in.) tall samples. Samples less than 38 mm (1.5 in.) in height were not tested, since the geometry of the sample decreased its stability in the load frame.

Whenever possible, the top 6 mm (.25 in.) or so of the sample was removed when consolidation and clogging of the voids was noted. Some samples had been cut prior to receipt (Michigan SPS-6) and were too short to allow further trimming of the surface effect. Others were too short as placed (France) to allow further trimming without sacrificing safety (while cutting) and quality (in the diametral testing phase). All cutting at OSU was done using a carbon dioxide (CO_2) cooled dry-cut diamond-blade saw, to avoid introducing additional moisture to the samples. Table D7 lists the actual layer thicknesses obtained for the supplementary sites, versus the construction design.

2.3.4 Volumetric Properties

The trimmed samples were allowed to dry at room temperature at least 4 days prior to completing bulk-specific gravity and air void determinations. The Rice or theoretical maximum specific gravity (G_{MM}) of the mixture was determined from the laboratory mixtures produced at OSU according to aggregate gradations and asphalt contents representative of the cores. These were compared to the design G_{MM} values supplied by the local agencies and were within 0.02. The target air void level for the laboratory-produced specimens was the mean air void level of the field cores for each site. The mean V_V values for the laboratory specimens were not significantly different from the field V_V values for all but one case (Arizona SPS-6). In other SHRP efforts at OSU, it has been observed that the diametral M_R decreases with an increase in the percent air voids of asphalt mixtures. This rate of decrease varies with each asphalt-aggregate combination, and the mean is about 100 kPa (0.015 ksi) decrease per 1 percent air voids increase (Bell and Sosnovske, 1992).

2.3.5 Testing

Prior to modulus testing, all cores were stored in a humidity-controlled room at 10°C (50°F) and a low (less than 50 percent) relative humidity. This was to reduce the intrusion of moisture from the air into the sample.

Each core was conditioned in an environmental cabinet and tested for diametral M_R as described above for the laboratory specimens. Samples which were 102 mm (4 in.) or greater in height were also subjected to triaxial resilient modulus testing. The results of these tests for the expanded and supplementary sites are shown in Appendix B and Appendix E.

2.3.6 Future Testing

Further testing by indirect tensile strength (split tension test) was planned for selected samples from each site. However, due to time constraints, this was not possible.

To evaluate changes in asphalt properties and make comparisons between laboratory-aged specimens and field samples, recovered asphalt tests were also planned. Again, these tests have not been done due to time constraints. However, specimens have been stored for possible future testing.

2.4 Test Program

2.4.1 Specimen Preparation

The original aggregate from each site was sieved in accordance with protocols for aggregate processing developed by the SHRP coordinators. The aggregate was shaken for 5 minutes in batches of approximately 4.5 kg (10 lb) and separated on 37.5-mm (1.5-in.), 20-mm (.8-in.), 14-mm (.5-in.), and 10-mm (.4-in.) screens and on U.S. sieves 5 mm (No. 4) and 600 µm (No. 30). Each fraction was then treated as a separate source bin. Any aggregate passing one or both of the sieves was subjected to wet sieve analysis. This resulted in the accurate gradation of the fine fractions for each of these bins.

The aggregate was recombined using a least sum of squared errors method to produce gradations that match those determined by extractions from the projects or, if extraction data were not available, gradations that closely matched the job mix formula. For the preliminary short-term aging validation, quantities to produce 102-mm (4-in.) diameter by 64-mm (2.5-in.) high specimens were used; material to produce 102-mm (4-in.) diameter by 102-mm (4-in.) high cylinders was used in preparing the expanded validation specimens.

Any required dry admixtures were weighed and added to the aggregate while dry, prior to heating. When lime was the admixture, the combined aggregate and lime was stirred until a uniform color was noted and then lightly sprayed with tap water. Stirring continued, and water was added until the aggregate was damp but not excessively wet. When portland cement or flyash was the admixture, it was added dry and mixed well.

The original aggregate was available for all seven supplementary sites. The same procedure used for sample preparation at the expanded sites was followed for five of the study sites. For two sites it was necessary to crush the aggregates with a laboratory crusher to achieve the desired gradation. These two sites, 1002 and 6056, had several modifications. After lab crushing, many elongated particles were present. These were removed by the Oregon State Highway Department (OSHD) test method 229-86.

Once all aggregate sizes were obtained for the two crushed sites, a batched sample was subjected to a wet sieve analysis. Adjustments were made to the gradation and more washes done until the batch gradation closely matched the field gradation. The whole sample was wet sieved due to the high fines content after crushing.

2.4.2 Mixing

The asphalt content used in preparing the laboratory specimens was representative of extraction data—or of the job mix formula if extraction data was not available. As stated above, the asphalts retained from the original projects were used, eliminating any variation effects from the source.

The original asphalts for the supplementary sites were available but in short supply. Since the original asphalt supply was minimal, several asphalts of viscosity similar to the originals were selected from the extra supply of MRL asphalts at OSU. These were used to fabricate trial mixes, to determine compactive efforts needed to produce laboratory mixture specimens that match the field voids. Due to the difficulty in obtaining field voids for most sites, the asphalt content was raised 0.2 percent to 0.3 percent (table D2; also see table D1 for mix design designations).

Specimen preparation followed protocols developed by the SHRP A-003A study team and is based upon ASTM 1561-81a for the preparation of Hveem specimens. The aggregate was heated to the mixing temperature corresponding to a viscosity of 170 centistokes for the asphalt. The asphalt was heated no more than 2 hours and was stirred often to avoid localized overheating. Mixing was done for 4 minutes in a Cox mechanical mixer, and the loose mixture was spread into a metal baking pan.

2.4.3 Preliminary Short-Term Aging

Five specimens were prepared for each of the preliminary short-term validation projects. These specimens were spread into a baking pan with a surface area of about 690 cm^2 (107 in^2). For each site, one specimen was cured for 15 hours at 60° (140°F) as per the current ODOT practice and another was used to make a determination of the Rice specific gravity. The third sample was placed in a forced draft oven immediately after mixing and compacted when the mixture reached the compaction temperature corresponding to a viscosity of 665 centistokes for the asphalt. The remaining specimens were placed in a forced draft oven at 135°C (275°F) for 4 and 8 hours. The STOA procedure requires stirring the mixtures every hour with a spoon or spatula. Using a spatula seemed the easiest and allowed thorough upending of the mixture, similar to flipping pancakes. The mixtures were removed from the oven for less than 1 minute when being stirred. To reduce the effects of varying temperature and air flow within the oven, the relative placement of the mixtures within the oven was changed after each stirring. Compaction was with a California kneading compactor, in accordance with ASTM D 1561-81a with an effort to produce specimens at the target air voids level corresponding to each site. One modification was to use a compaction temperature corresponding to 665 centistokes for the asphalt rather than 110°C (230°F) as recommended in the ASTM approach. Compaction temperatures based on this viscosity varied considerably with asphalt grade; this modification was deemed essential to produce consistent compaction densities and asphalt film thicknesses.

For the two projects requiring admixtures, additional specimens were prepared without the admixtures to analyze the effect of the admixtures on the aging procedure. In addition to those described above, one specimen from both projects was prepared with the admixtures and conditioned in the 135°C (275°F) oven for a 12-hour period.

After compaction, the specimens were placed in a 60° (140°F) forced draft oven for 1.5 to 2 hours and then subjected to a 53.4-kN (12,000-lb) static "leveling" load. Following leveling, the specimens were allowed to cool to room temperature for at least 12 hours before extrusion from the compaction molds. The specimens were marked for identification, and physical measurements of height and bulk-specific gravity were made.

The specimens were then tested for resilient modulus in a diametral configuration as described previously. Diametral resilient modulus data from field samples were obtained from ODOT for each project. The values from ODOT were compared with those determined by the laboratory testing of the conditioned specimens. The comparisons are discussed in the section on short-term aging results.

2.4.4 Expanded Study—Mixing and STOA

The treatment and evaluation sequence for the expanded study of the short- and long-term aging test procedures is longer and involves multiple treatments and testing of the laboratory specimens. This process is shown graphically in Figure 2.4 and is explained below. Six samples to be used for future testing are shown in Figure 2.4. Three of these were used for the long-term aging at 100°C (212°F) for 1, 2, and 4 days.

For each long-term validation site, 14 mixtures were prepared as above and spread into a pan with a surface area of approximately 935 cm^2 (145 $in.^2$), equating to a depth of about 13 mm (.5 in.). The samples were larger than for the preliminary study in order to fabricate 102-mm (4-in.) tall specimens. Specimens had to be at least 102-mm (4-in.) tall to correspond with earlier work done at OSU under the A-003A study. They were then allowed to cool to room temperature (20°C (68°F)) for 2 hours after mixing. Four mixtures were treated as controls and were not subjected to any aging procedures after being spread into the pans. The remaining loose mixtures were placed in a 135°C (275°F) forced draft oven for a four-hour short-term aging (STOA) procedure, to simulate the aging occurring in the field between mixing and final compaction. The mixtures were stirred hourly as described above for STOA. After the 4 hours of STOA, the mixtures were allowed to cool at room temperature for at least 12 hours.

The cooling period following mixing was not consistent with previous sample preparation under the SHRP A-003A contract. The cooling period was initiated to simulate the possible requirements of smaller agencies with limited oven capacity who may use this test. They may be required to delay STOA after mixing (i.e., allowing the samples to cool), until oven space becomes available. All specimens for this study were prepared in this manner. Two mixtures (one control and one with STOA) were used for determining the maximum theoretical specific gravity.

2.4.5 Supplementary Study—Mixing and STOA

Several changes from the expanded study occurred in this phase. For sites where two cans of asphalt were available, nine samples were made, two control specimens and seven STOA specimens, with one STOA specimen being a Rice gravity sample. The two controls were brought to compaction temperature and compacted immediately after mixing. The STOA specimens were placed in a 135°C (275°F) oven immediately after mixing, then brought to compaction temperature and compacted immediately after 4 hours of aging. This differs from the cooling period used after mixing and aging in the expanded study.

For sites where only one can of asphalt was available, five to seven specimens were made—two controls and five STOA specimens—with one STOA specimen being a Rice gravity sample.

To obtain the required three specimens for LTOA at 85°C (185°F), several control specimens were tested for resilient modulus and then used as STOA specimens. They were heated slightly, broken up thoroughly, aged at 135°C (275°F) for 4 hours, stirred every hour, and compacted. This was done for a total of four specimens (see modulus summaries in Appendix E, which note the cores that were recompacted).

The resulting resilient modulus values for the controls aged into STOA specimens were comparable with the STOA resilient modulus values for the specimens prepared according to the protocol for each site.

2.4.6 Expanded Study—Compaction

In preparation for compaction, 12 mixtures were heated in a forced draft oven to a temperature corresponding to an asphalt viscosity of 665 centistokes and then compacted as above. The target air void levels for the laboratory specimens were the mean air voids from the field samples for each site. Every attempt was made to achieve the target void level without degrading the aggregate.

The compacted specimens were placed in a 60° (140°F) oven for 1.5 to 2 hours and were then leveled, cooled, and extracted as described above. The specimens were then marked for identification.

2.4.7 Supplementary Study—Compaction

In an effort to decrease the voids for the WDOT sites, the fines were increased from 0.5 percent to 2.0 percent for all but site 1801 (tables D6 and D7). Compaction temperatures were raised 5°C to 7°C (41°F to 45°F) for all sites, again to try to decrease the voids (table D4). Even with these increases, sites 6049, 1002, and 6056 had lab voids from 3 to 5 percent higher than the field voids (table D5).

2.4.8 Expanded and Supplementary Study—Oven Aging

The specimens that had been subjected to STOA prior to compaction were divided into three groups of three, based on their air voids level. A random specimen was selected from each of the three groups in an attempt to get a distribution of void levels about the mean. These three specimens were tested for resilient modulus in the same manner as the control specimens and then subjected to LTOA at 85°C (185°F) in a forced draft oven for 2 days.

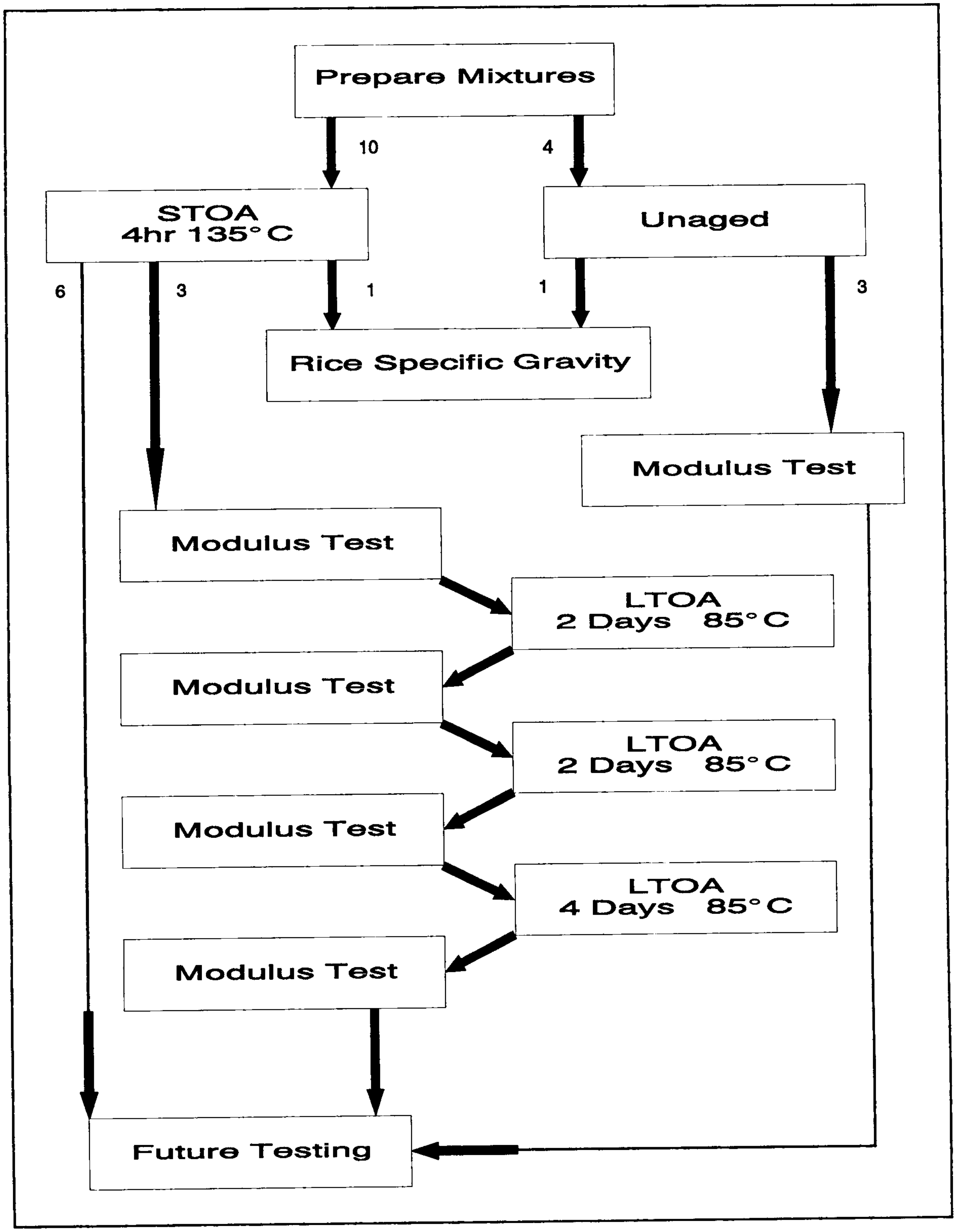

Figure 2.4 **Expanded Study—Laboratory Aging Process (85°C (185°F))**

The specimens subjected to the LTOA procedure were inverted, and their relative positions within the oven were changed every 24 hours. Inversion of the specimens every 24 hours balanced the aging from top to bottom and reduced deformation near their bottoms. The rotation within the oven reduced the effects of varying temperature and air flow within the oven. Handling of the specimens was kept to a minimum while they were at 85°C (185°F) to avoid possible specimen degradation. After a cumulative 4 and 8 days in the 85°C (185°F) oven, some specimens suffered a loss of aggregate (chipping) along the edges due to handling and the increased brittleness of the asphalt. The same procedure was followed for the 100°C (212°F) specimens, but with aging for 1, 2, and 4 days.

2.4.9 Expanded Study—Testing

After the first two days of LTOA at 85°C (185°F), the specimens were removed from the oven and allowed to cool to room temperature for at least 24 hours but not more than 30 hours. They were then placed in the environmental chamber for 6 to 8 hours and tested for resilient modulus in both diametral and triaxial configurations as before. The entire process of heating, cooling, and testing was repeated for another 2 days and 4 days after that. This yielded modulus values for the LTOA specimens at 0, 2, 4, and 8 days of LTOA following the 4-hour STOA treatment. The results of these modulus tests are shown in Appendix C.

A change was initiated for the 100°C (212°F) cooling procedure. A side study was done to determine the change in diametral resilient modulus values versus days of cooling after aging in the oven (see figures 2.5a and 2.5b). All ten expanded validation sites were used, with one specimen from each site. Samples were aged in the oven for 1 day at 100°C (212°F) and then allowed to sit (at room temperature, 25°C (77°F)) for 1, 2, and 3 days, and tested for diametral resilient modulus after each day. They were then aged for 2 days and 4 days, and the process repeated.

The trend was for modulus values to increase for up to 2 days after aging, and then to remain at a relatively constant level. A 2-day cooling period after aging was therefore used for all 100°C (212°F) aging samples before testing, and also for the 85°C (185°F) and 100°C (212°F) Minnesota SPS-5 and California GPS-6 sites.

The control (unaged) specimens were placed in an environmental cabinet to stabilize their temperature at 25°C (77°F) before being subjected to diametral resilient modulus tests at a constant strain of 100 μstrain. The specimens were returned to the environmental cabinet and tested later for triaxial resilient modulus, also at a constant strain of 100 μstrain. The constant strain conditions were selected to correspond to testing done earlier for the aging portion of the A-003 contact.

To eliminate the possibility of variation between different people conducting the resilient modulus testing, all testing of the laboratory specimens for each 85°C (185°F) and 100°C (212°F) aging procedure was done by one person; i.e., one person conducted all 85°C (185°F) testing and another conducted all 100°C (212°F) testing.

2.4.10 Supplementary Study—Testing

The same procedure used for the expanded study was followed for the 85°C (185°F) aging of the Washington specimens; i.e., the LTOA was conducted for 0, 2, 4, and 8 days. For 100°C (212°F) aging, LTOA was conducted for 2 and 4 days.

All samples aged in the supplementary study were tested 44-52 hours after each oven aging treatment (i.e., about 2 days afterwards), the same as in the 100°C (212°F) expanded procedure.

2.4.11 Future Testing

As stated earlier, testing of indirect tensile strength and various tests on recovered asphalt was not performed. Dynamic mechanical analysis was also eliminated. These tests should be conducted in the future.

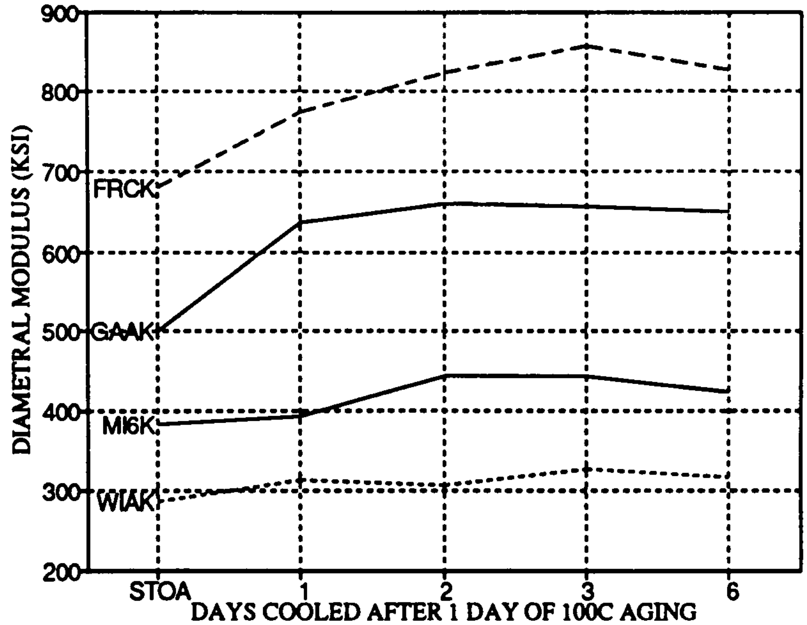

Figure 2.5a Diametral Modulus after 1, 2, 3, and 6 Days of Resting (After 1 Day of 100°C (212°F) Aging)

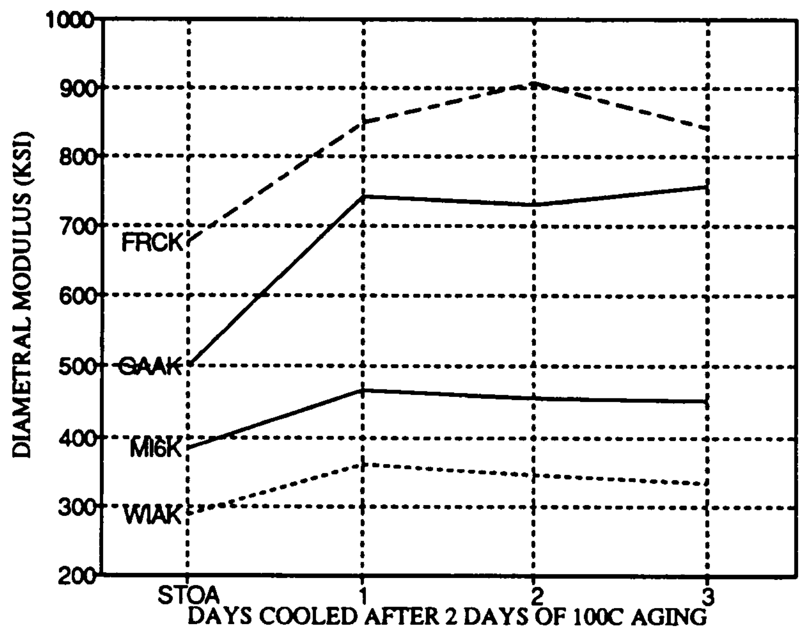

Figure 2.5b Diametral Modulus after 1, 2, and 3 Days of Resting (After 2 Days of 100°C (212°F) Aging)

3

Test Results—Preliminary Study

3.1 Lab Results

Table 3.1 shows the diametral resilient modulus values for the preliminary short-term validation specimens. The specimens identified as "regular" were subjected to a 15-hour cure period at 60°C (140°F) in accordance with the kneading compactor specimens preparation procedure used by the Oregon Department of Transportation (ODOT). None of the aged specimens, including the 0-hour short-term oven aging (STOA), were subjected to a 15-hour curing period. Each resilient modulus value shown represents a single specimen.

In chapter 4, specimens from the expanded validation sites, which are referred to as STOA, were subjected to 4 hours at 135°C (275°F) prior to compaction. Field data were not obtained immediately after placement, and an exact comparison of the laboratory and field moduli is not possible. However, since several of the expanded study projects are relatively new (less than 6 months), it is expected the observed field values are close to the actual values after placement.

3.2 Field Results

Table 3.1 also shows modulus values obtained by ODOT for the projects selected for short-term validation. The ODOT lab value is the modulus value obtained during the design of the mixture. Mixtures at three asphalt contents were prepared and subjected to the 15-hour cure at 60°C (140°F) prior to compaction. The resilient modulus values shown in table 3.1 are interpolated from the three specimens to the asphalt content specified in the contract for placement.

The ODOT field values are the moduli of specimens prepared from samples of the mixtures obtained during construction. ODOT takes a sample of a mixture from the paving machine in the field, returns it to the laboratory, and reheats it to 93°C (200°F) to soften and quarter it. The quartered mixture is cured for 15 hours at 60°C (140°F). It is then heated to 110°C (230°F) and compacted and tested for resilient diametral modulus in a manner similar to the

Table 3.1 Diametral Modulus after Short-Term Aging: Preliminary Sites*

Treatment		Site Number** 913	816	852	874
Regular (15-hr cure)		—	—	335	264
0 hr STOA no admixture	No 15-hr cure	251	196	—	—
4-hr STOA "	"	499	348	570	341
8-hr STOA "	"	1028	509	773	813
12-hr STOA "	"	—	—	896	—
0-hr STOA with admixture	"	—	—	455	220
4-hr STOA "	"	—	—	590	311
8-hr STOA "	"	—	—	650	754
12-hr STOA "	"	—	—	740	847
ODOT Lab (15-hr cure)		227	153	270	222
ODOT Field		598	403	800	796

* All values in ksi.
** See table 2.1 for identification of sites.

laboratory prepared specimens. This value represents the modulus of a mixture that has undergone short-term aging in the field.

3.3 Discussion

The specimen prepared at Oregon State University (OSU) and cured to ODOT procedures (60°C (140°F) for 15 hours) was a control to check the variability between the mixing, compacting, and testing procedures used at OSU and those at the ODOT materials lab. The modulus values shown in table 3.1 for the control specimens (Regular) were close to the values obtained by ODOT during the mix design (ODOT Lab). This indicated that the OSU mixture preparation and testing methods were comparable to those of ODOT and that additional modulus values obtained at OSU could be reliably compared to those from ODOT.

Another interesting and unexpected pattern was noted. For sites 913, 816, and 874, the specimens that were compacted shortly after mixing, with no curing or STOA (0-hour STOA), had modulus values close to those of the 15-hour cured specimens. This indicated that for many mixes the cure period used by ODOT does not have a significant effect on resilient modulus. At site 852, the unaged (0-hr STOA) specimen had a modulus about 40 percent higher than the regular cure specimens.

The modulus values obtained from each specimen are plotted against the hours of treatment and compared to the field modulus value obtained from ODOT. This is shown in figures 3.1 through 3.4. Each data point represents a single laboratory specimen.

The mixtures with and without admixtures are plotted together to show the possible effect of the admixture on STOA. Addition of the lime admixture (project 874) retarded aging as would be expected (Edler et al. 1985). The addition of Pave Bond Special (PBS) (project 852) had a more pronounced retardation effect on the modulus change induced by the short-term oven aging. Both lime and PBS are added to reduce stripping of the asphalt from the aggregate in wet conditions; therefore they improve the adhesion between asphalt and aggregate. Bell and Sosnovske (1992) postulate that there may be a relationship between adhesion and aging mitigation.

The effects of reheating the field mixture to 93°C (200°F) to soften the mixture at the ODOT lab are considered negligible. Although it is generally accepted that aging due to a loss of volatiles occurs at elevated temperatures, this reheat cycle is neither hot enough nor long enough to result in significant additional stiffening. This process of reheating the field mixture is the most practical method to accomplish this type of evaluation; taking a California kneading compactor to several job sites to prepare specimens while the mixture is still hot would be impractical, if not impossible.

The plots in figures 3.1 through 3.4 show that the range of STOA times to age the laboratory specimens to produce a resilient modulus equal to those in the field is from 4.5 hours to over 12 hours. The STOA procedure of 4 hours at 135°C (275°F) appears conservative on the whole. The limited number of projects and specimens prepared in this study prevents an adequate statistical analysis or development of accurate models, but the 4-hour period does make a realistic contribution to the aging observed for the sites in this portion of the study (aging of site 874 was expected to take longer due to the lime admixture). Using a 6- or 8-hour period at 135°C (275°F) may be too severe for some mixtures and places additional constraints (overtime labor costs) on the agency preparing the specimens. Also, a 4-hour period was recommended previously by von Quintus et al. (1991).

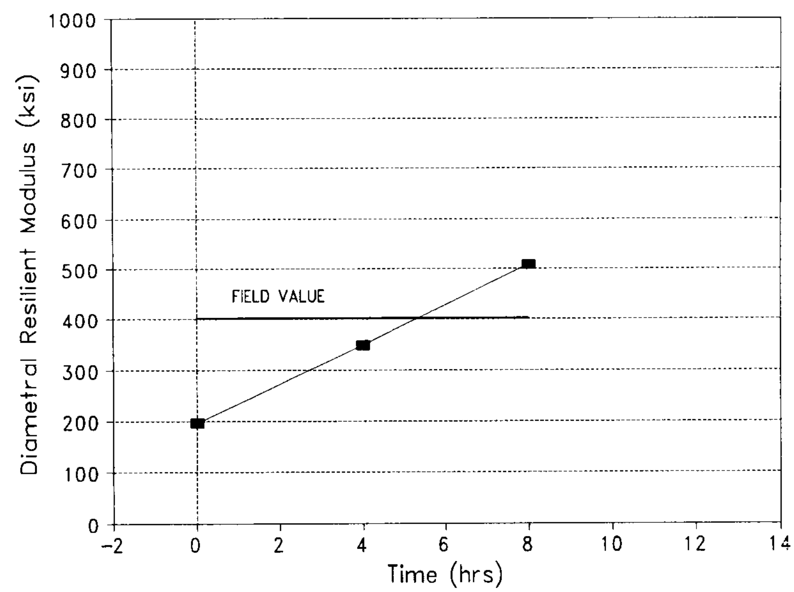

Figure 3.1 Short-Term Aging at 135°C (275°F)—ODOT Project 816

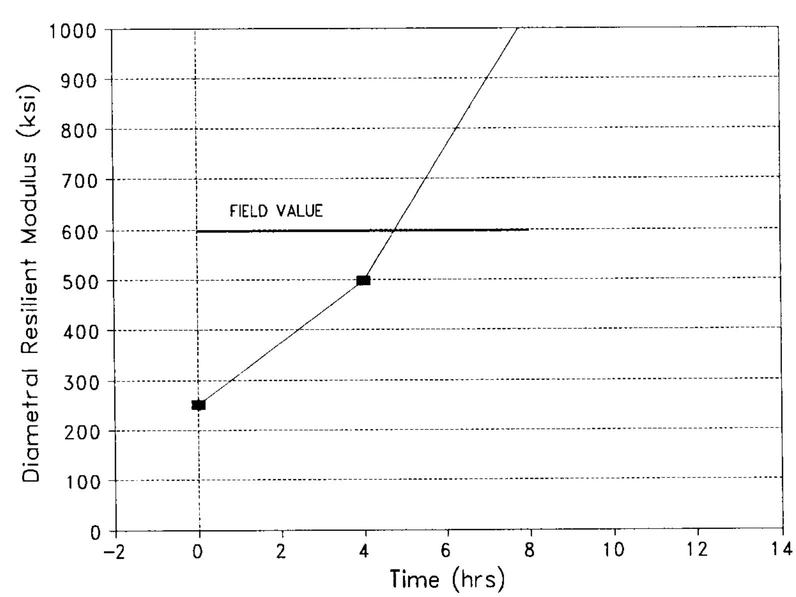

Figure 3.2 Short-Term Aging at 135°C (275°F)—ODOT Project 913

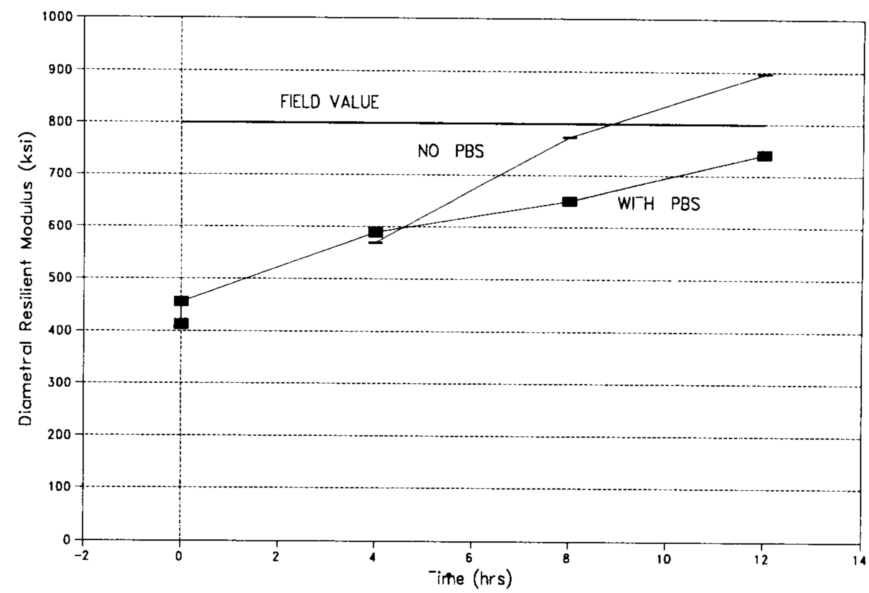

Figure 3.3 Short-Term Aging at 135°C (275°F)—ODOT Project 852

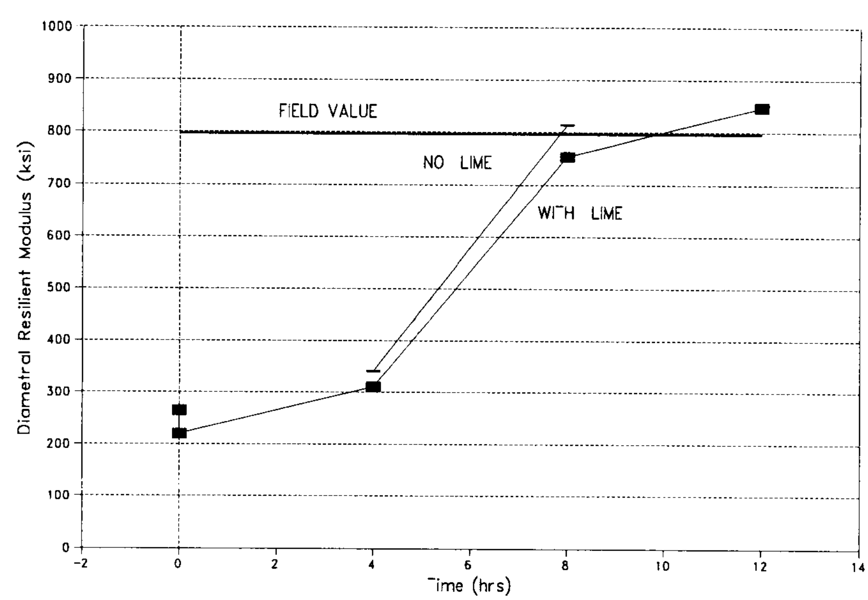

Figure 3.4 Short-term Aging at 135°C (275°F)—ODOT Project 874

4

Test Results—Expanded Study[1]

4.1 Lab Results

The resilient modulus values for the laboratory-prepared specimens in the diametral and triaxial configurations are summarized in the tables of Appendix C. Plots of the resilient modulus values versus air voids and aging treatment are shown in figures 4.1 through 4.12 at the end of this chapter. Since the sections in France utilized the same asphalt grade (but different suppliers) and were subjected to the same traffic and environmental conditions, additional plots were made combining the data from those sites. The same is true of the California Asphalt-Aggregate Mixture Analysis Study (AAMAS) sites. Both California sites contained the same asphalt, AR-4000. The mix for both sites was crushed gravel with both crushed and natural fines.

For the figure 4 series, a, b, and c from each site are Tukey and least significant difference (LSD) statistical comparisons for the lab-aged samples. They show which lab aging treatment has a mean modulus closest to the field modulus. Figures a and b compare the Tukey and the LSD analysis (see table 4.1) and show that the LSD analysis usually narrowed the confidence intervals. Figures b and c compare the 85°C (185°F) aging procedure for each site with the 100°C (212°F) aging procedure. Figures b and c show that the lab diametral modulus for samples aged 8 days at 85°C (185°F) was usually fairly close to the diametral modulus for samples aged 4 days at 100°C (212°F).

Figures d through g for each site are graphic displays of the diametral and triaxial modulus values for each site plotted against the voids contents. Figures d and e are 85°C (185°F) plots and f and g are 100°C (212°F) plots. These plots for each site show how much the triaxial modulus values vary in both the lab and in the field, compared to the diametral modulus. They also show how the voids from the lab samples varied from the field voids.

[1]Note on units: The diametral and triaxial resilient modulus values in the following figures are given in kips/square inch (ksi). The conversion from ksi to megapascals is: 1 ksi = 6.89 MPa.

Table 4.1 **Aging Treatment Means "Not Significantly Different" from Field Means**

Site	Age	Tukey (85°C)	LSD (85°C)	LSD (100°C)
AZ5K	6 months	STOA LTOA All	STOA LTOA All	LTOA1, 2, 4
AZ6K	Few months	Unaged STOA	Unaged STOA	Unaged STOA
CAL6	Few months		STOA	STOA
GAAK	2 years	None	None	None
MI6K	6 months	STOA LTOA2, 4	STOA	STOA LTOA1, 2
MIN5	1-1/2 years		Unaged STOA, LTOA2	Unaged STOA, LTOA1
WIAK	Over 3 years	LTOA2, 4	LTOA2, 4	LTOA2
California Combined	Over 2 years	Unaged	Unaged	Unaged
France Combined	5 years	LTOA8	LTOA8	None

Key: None = All of the aging treatments are significantly different from the field mean.
Mean = Average of diametral resilient modulus tests.

4.2 Field Results

Not all the cores received could be tested thoroughly. In many cases, disbonded or thin lifts made it impossible to complete diametral and triaxial testing on every core from a particular site. Some problems in the trimming and recording process resulted in some of the cores being inaccurately tested. Nonparallel faces produced outlier results during triaxial testing and recored samples that were not cored perpendicular to the road surface. This resulted in samples that appeared trapezoidal from the side and produced varied modulus values when tested diametrally. The results of the field core modulus values are summarized in the tables of Appendix B.

4.3 Discussion

The statistical comparison of the samples by the treatment they received was performed, and Tukey HSD (honest significant difference) and LSD intervals were determined. "Honest" means that the analysis protects against false claims that there are significant differences by constructing confidence intervals large enough to account for the expected difference between the biggest and smallest averages. The analyses were performed using the STATGRAPHICS computer program, with hand calculations used to verify the results. LSD was chosen because it is a common method used when planned comparisons are made between various treatments and the "control" field cores. The Tukey is more commonly used when there are no plans prior to the study to compare certain means. Using Tukey, all means are compared against all others. However, this is sometimes conservative and can cause true differences to go undetected. In order to capture any similar means from a large group, the Tukey confidence intervals have a larger spread (i.e., more conservative) than the LSD intervals. The LSD's tighter intervals allow true differences to be detected, especially in the case of planned comparisons.

For all of the sites studied, an F-test was used as an initial screening device to ensure that some of the means were different from the others. The F-test is useful for considering the hypothesis that all group means are equal. If there are significant differences, then the analysis continues, using methods such as Tukey and LSD for multiple comparisons.

In order to use these multiple comparison procedures, all data sets are required to be independent of each other. For this study, the short-term oven-aging (STOA) specimens were also long-term oven aged (LTOA), i.e., the same specimens were used for four sets of data. Thus, each group of three specimens was tested four times, both diametrally and triaxially. This was done after the initial STOA, and then after each aging period. To provide independence for this study, other factors within the sample preparation (mixing and compacting temperature variability) and the modulus testing (modulus variability depending on the side of the core tested) are assumed to cause more variability in modulus results than testing the same samples several times after aging treatments.

Table 4.1 shows a comparison of the Tukey and LSD analyses at 85°C (185°F). The LSD narrowed the "not significantly different" means at the Michigan site. The remaining sites were the same, although the LSD did narrow the gaps. A treatment mean was considered to be not significantly different from the field modulus mean if its LSD interval for the mean contained any of the field interval. This was based on a 5 percent significance level. This is the same as rejecting any p-values less than or equal to 0.05, and accepting values greater than 0.05 as being "not significantly different" from the mean (see table 4.2).

Table 4.2 Interpretation of a p-value

2-Sided p-value	Evidence of a Difference? (For null hypothesis : u1-u2 = 0)	Comments
> 0.1	No	No evidence that u1 is different from u2
0.05	Suggestive	Suggestive but inconclusive
< 0.01	Convincing	Convincing evidence that u1 is not equal to u2

The 100°C (212°F) LSD aging is compared with the 85°C (185°F) LSD in table 4.1. The total treatment for 85°C (185°F) aging closely resembles the 100°C (212°F) treatment. Once again, the combined data from the California AAMAS sites and from the France sites are also displayed. The data for each site are discussed below.

Note: The following discussions are based on LSD analyses unless otherwise noted.

4.3.1 Arizona SPS-5

For the Arizona SPS-5 (special pavement study) data, the mean field modulus values are not statistically different from any of the aged (STOA or STOA + LTOA) group means at 85°C (185°F), or aged (STOA + LOTA) at 100°C (212°F). The variation in each of the treatment groups was larger for these specimens than for any other site. As can be seen from the plot of modulus versus voids in figure 4.1e and figure 4.1g, the specimens subjected to the STOA and LTOA were higher in air voids than were the field cores and had a larger spread of air voids, resulting in a larger spread of modulus values.

4.3.2 Arizona SPS-6

For the Arizona SPS-6 site, the mean field modulus value was not statistically different from the unaged or STOA specimens. This site is located in a dry-freeze climate and was in place only a few months before coring took place. It should be monitored, and additional cores should be tested in the future. The air void levels in the laboratory specimens were consistently higher than in the field cores. Even if there is a decrease in resilient modulus with increased air voids, as has been seen in other efforts at Oregon State University (OSU), the field values will still be close to the unaged values. Typical changes in modulus of around 15 ksi per percent air voids have been observed (Bell and Sosnovske, 1992).

4.3.3 California AAMAS

All of the field data for the California AAMAS sites were similar to the modulus values of the unaged specimens prepared in the lab. Although this site had been in place for over 2 years, and the void levels of the unaged lab specimens were very close to the air void levels of the field cores, the resilient moduli are lower than expected from a normally cured laboratory specimen. The most reasonable explanation for the lower-than-expected field modulus values is the known "sensitivity" of the mixture.

A review of the AAMAS report (von Quintus et. al., 1991) indicated that the mixture used for the California site in the AAMAS study was selected because of its propensity to fail under heavy loading conditions in the field. A portion of the AAMAS study evaluated the ability of laboratory design methods to distinguish a good mixture from an inferior one during design, prior to contract award and placement. The mixture used for the California AAMAS site, and subsequently used in this study, was selected for use in the AAMAS study based on its known poor performance characteristics. As stated earlier, it was selected for inclusion in this effort because of the availability of retained materials.

The design asphalt content was 5.3 percent. Brittleness is expressed if the asphalt content is lower than that, and a plastic behavior susceptible to distortion is expected if the asphalt content is higher. With these constraints, the mix is deemed "sensitive." The bulk sampled asphalt contents determined in the AAMAS study were 4.76 and 5.95 percent for the drum and batch plants, respectively.

4.3.4 California GPS-6

The lab-fabricated specimens' voids content closely matched that of the field specimens. Both 100°C and 85°C (212°F and 185°F) aging resulted in the STOA treatment being statistically similar to the field aging of a few months. This is consistent with the preliminary short-term aging projects, which indicated that aging occurs during construction due to the heating at the batch or drum plants. Only a few months old, this site would not have undergone any significant long-term aging at the time of coring.

4.3.5 France LCPC

Since only two cores were obtained from each of the French sections (one wheelpath, one shoulder), the 95 percent confidence intervals about the means are much larger for these sites. Combining all three sites (figure 4.12) shows that the field modulus values are not significantly different from those of the laboratory specimens aged with 8 days of LTOA at 85°C (185°F) after the initial STOA. For 100°C (212°F) aging, none of the aging treatments matched the field modulus. These sections had been in place for 5 years when the cores were taken.

The cores received were about 152 mm (6 in.) in diameter and about 51 mm (2 in.) in height. They were recored dry, but no trimming of the top or bottom surfaces was performed. Although the rough top and bottom condition could account for some of the variation in the field air voids, it does not explain all of the variation, nor does the lane location, since the wheelpath cores were not consistently lower than the shoulder cores. Additional cores have been requested to try to account for more of this variation. No triaxial data were available from the field site because of the 51-mm (2-in.) core height.

It should also be noted that the French mixtures were the most difficult to compact to the target air voids, and the result can be seen as a wide range of laboratory void levels within each site. The basalt aggregate could not withstand high compactive efforts without severe degradation. The compaction temperature was elevated 2°C with only a slight reduction in air voids. The range of air voids in the six field cores was from 2.5 to 10.1 percent. It is doubtful that the very low air voids observed in one of the field cores could be achieved with a kneading compactor without degradation of the basalt aggregate or high compaction temperatures.

4.3.6 Georgia AAMAS

As with the California AAMAS pavements, the mixture used in Georgia was known to be inferior and susceptible to moisture damage and permanent deformation. Although the pavement was only about 3 years old, it had already failed in the field and had been overlain with another asphalt layer. The sealing effect of the overlay probably severely limited any additional pavement oxidation after the overlay was placed. The age of the original pavement at the time of overlay was unavailable. The field modulus values were significantly lower than all of the aging treatments, including unaged.

Also, the cores received at OSU were nearly 203-mm (8-in.) tall and 152 mm (6 in.) in diameter, which meant they had to be recored. These were the only samples recored using the wet core machine at OSU. Samples from other sites were wet cored in the field, and no correlation between expected modulus and actual modulus was noted.

4.3.7 Michigan SPS-6

The Michigan SPS-6 site had been in place about 6 months before it was cored. The field diametral resilient modulus values are comparable to those of the STOA laboratory specimens. Statistically, the field modulus is not different from the STOA specimens or the specimens with STOA and 2- and 4-day LTOA at 85°C (185°F) (based on the Tukey Comparison). Since there is a significant difference between the unaged and field values, it can be concluded that preparing laboratory specimens without any aging treatment is not representative of the modulus seen in the field just 6 months after construction. The LSD comparison at 85°C (185°F) narrowed the "not significantly" different gap to the STOA specimens, as noted earlier.

Like the cores from France, these cores were too thin to allow trimming of the top 6 mm (.25 in.) but it is not believed to have affected the modulus values. Unlike the French cores, the variation in the air voids was relatively low, and the range in air voids for the laboratory specimens used in the LTOA analysis spanned the range of voids in the field cores.

4.3.8 Minnesota SPS-5

Voids obtained from the laboratory specimens closely matched the field core voids. The treatments resembling the field cores were the unaged, STOA, and LTOA2 (long-term oven aged for 2 days) at 85°C (185°F), and LTOA1 (long-term oven aged for 1 day) at 100°C (212°F) (both based on LSD comparisons). The spread of diametral modulus averages ranged from only 171 ksi for the unaged samples to 370 ksi for the LTOA4 samples at 100°C (212°F); the field values were 224 ksi. This could account for the three treatments being close to the field mean. Based solely on averages, the 198 ksi STOA mean most closely resembles the field average of 224 ksi.

4.3.9 Wisconsin AAMAS

Since this mixture contained 45 percent recycled asphalt pavement (RAP), it posed the most problems. The RAP and virgin aggregate were combined prior to heating and were heated together to the mix temperature for only 2 hours. Although the aggregate had stabilized at the mix temperature of 137°C (279°F), the asphalt in the RAP had not softened enough even to mark the pans. No information could be obtained about the asphalt properties of the RAP. In all other ways, this was treated like the other mixtures.

The air voids obtained in the laboratory were lower than those in the field cores, although a very light compactive effort was used. This may be attributed to the asphalt in the RAP. Like the California AAMAS mixture, this mix was expected to be "sensitive" in the field (von Quintus et al., 1991).

The moduli of the field cores are not significantly different from the 2- and 4-day LTOA at 85°C (185°F) specimens and the 2-day LTOA at 100°C (212°F) specimens. They are significantly different from the unaged and STOA specimens. This was expected, since the pavement was placed more than 3 years before the cores were taken.

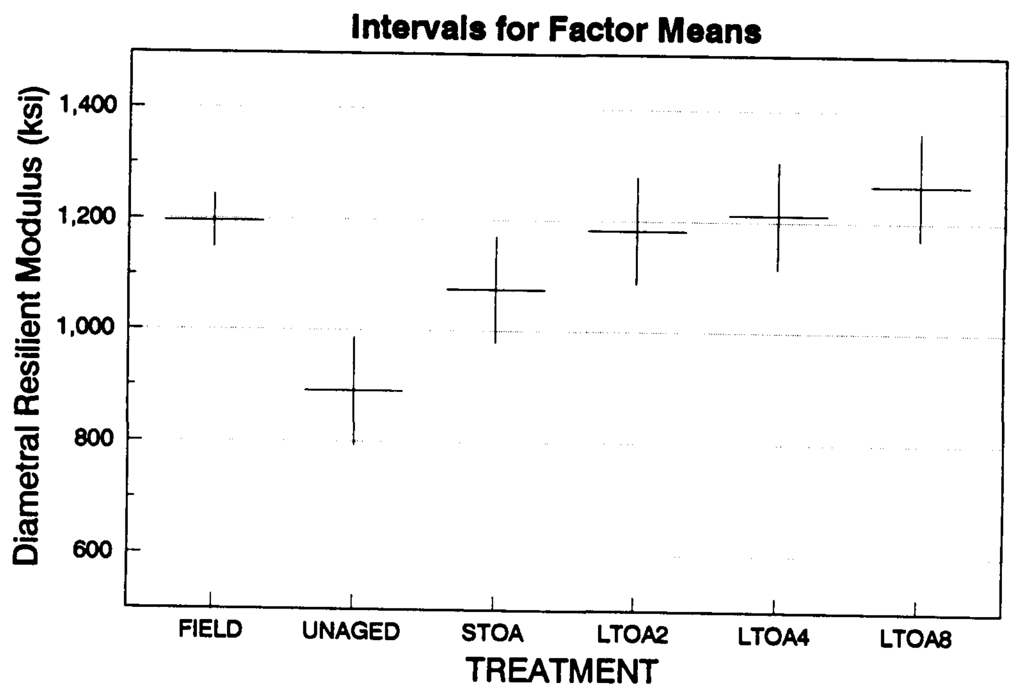

Figure 4.1a Arizona SPS-5 Tukey Comparison, 85°C (185°F) Aging

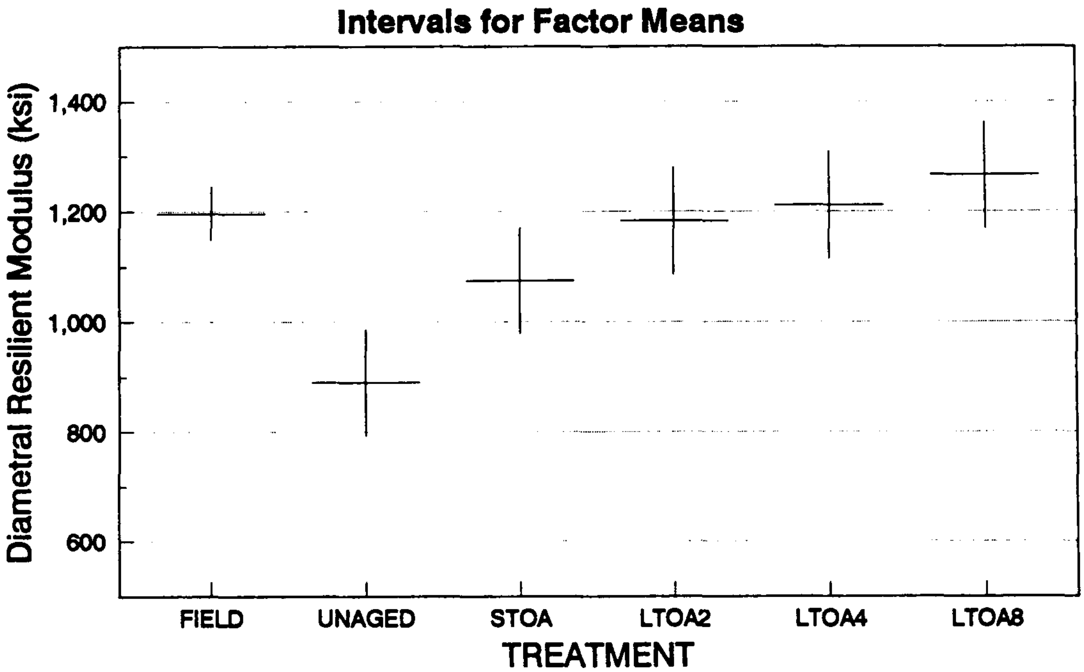

Figure 4.1b Arizona SPS-5 LSD Comparison, 85°C (185°F) Aging

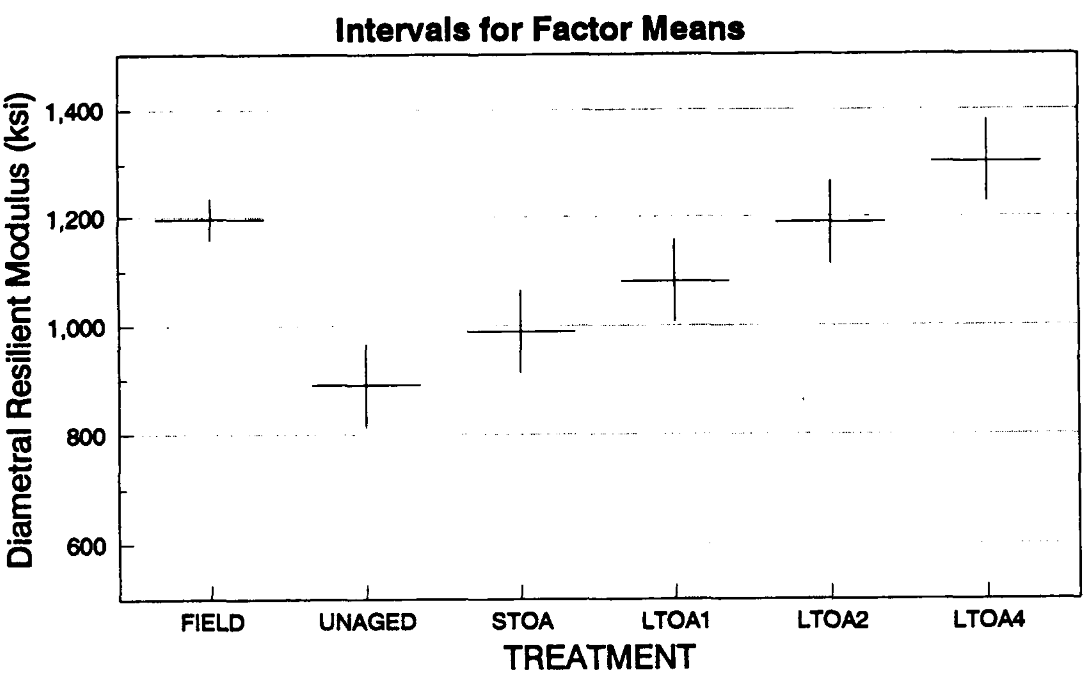

Figure 4.1c Arizona SPS-5 LSD Comparison, 100°C (212°F) Aging

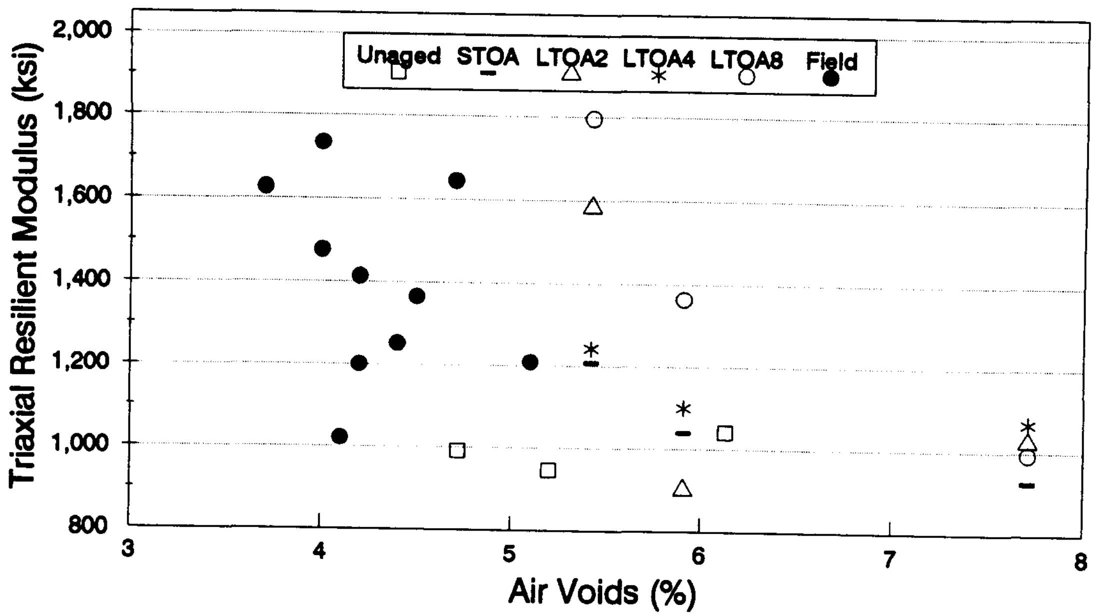

Figure 4.1d Arizona SPS-5 Triaxial Resilient Modulus, 85°C (185°F) Aging

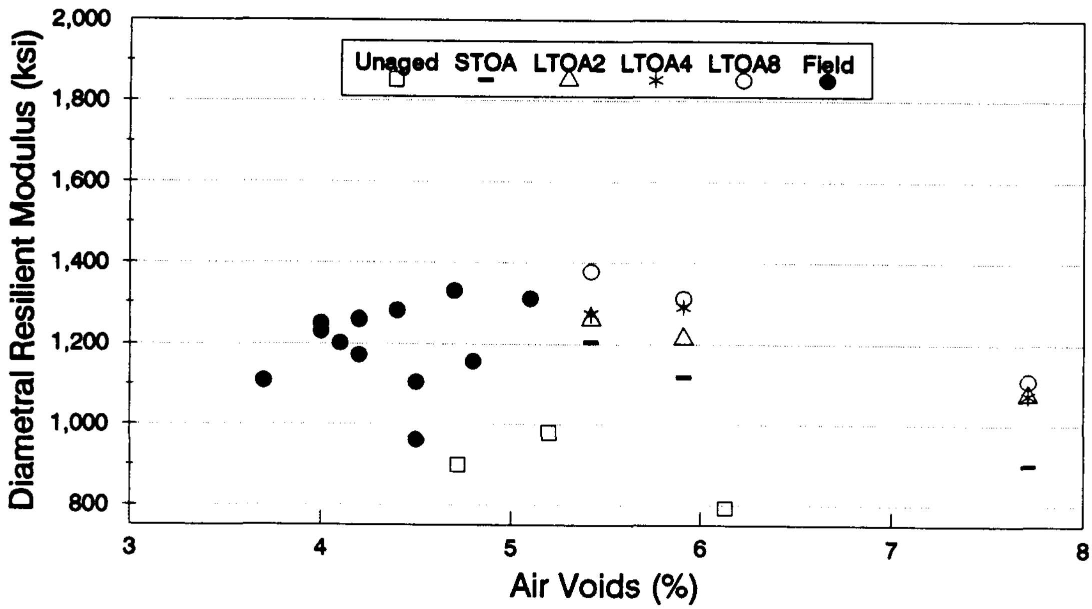

Figure 4.1e Arizona SPS-5 Diametral Resilient Modulus, 85°C (185°F) Aging

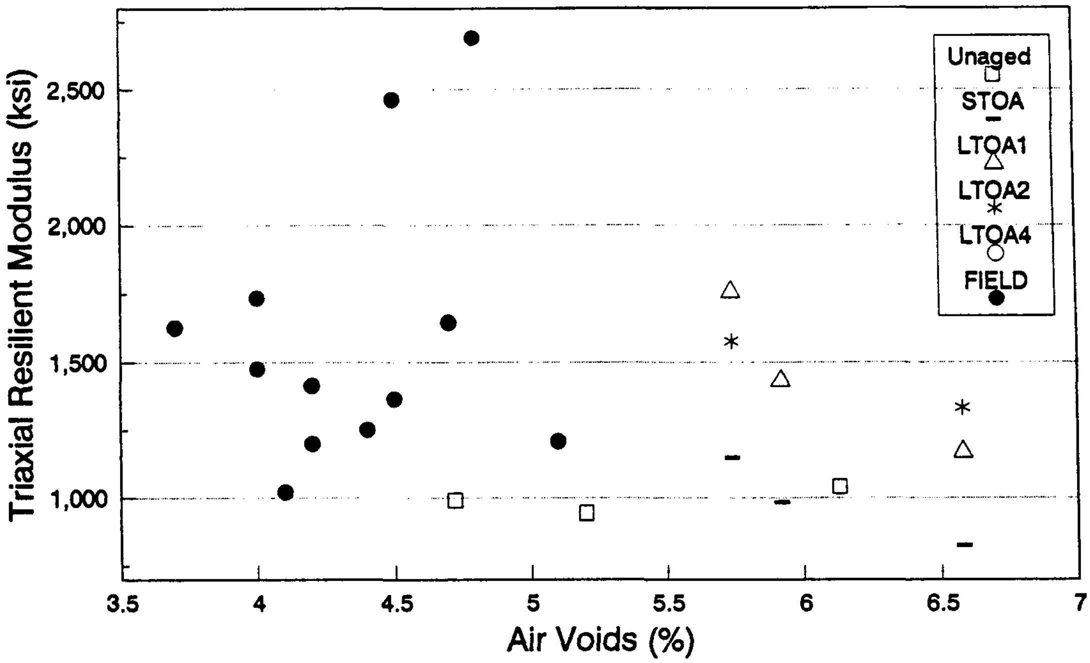

Figure 4.1f **Arizona SPS-5 Triaxial Resilient Modulus, 100°C (212°F) Aging**

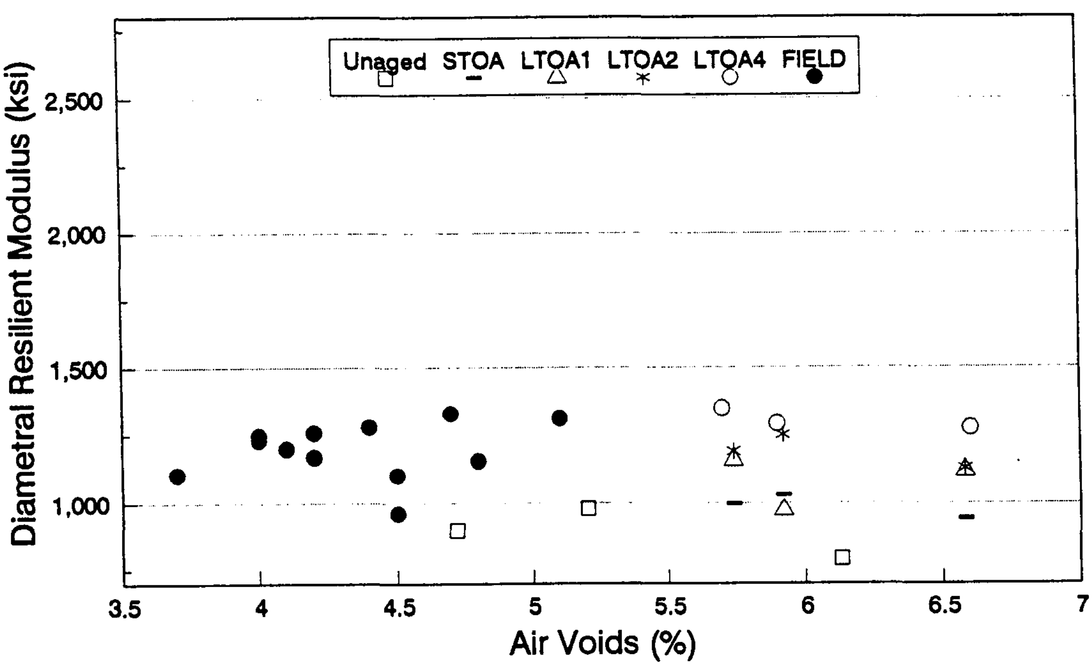

Figure 4.1g **Arizona SPS-5 Diametral Resilient Modulus, 100°C (212°F) Aging**

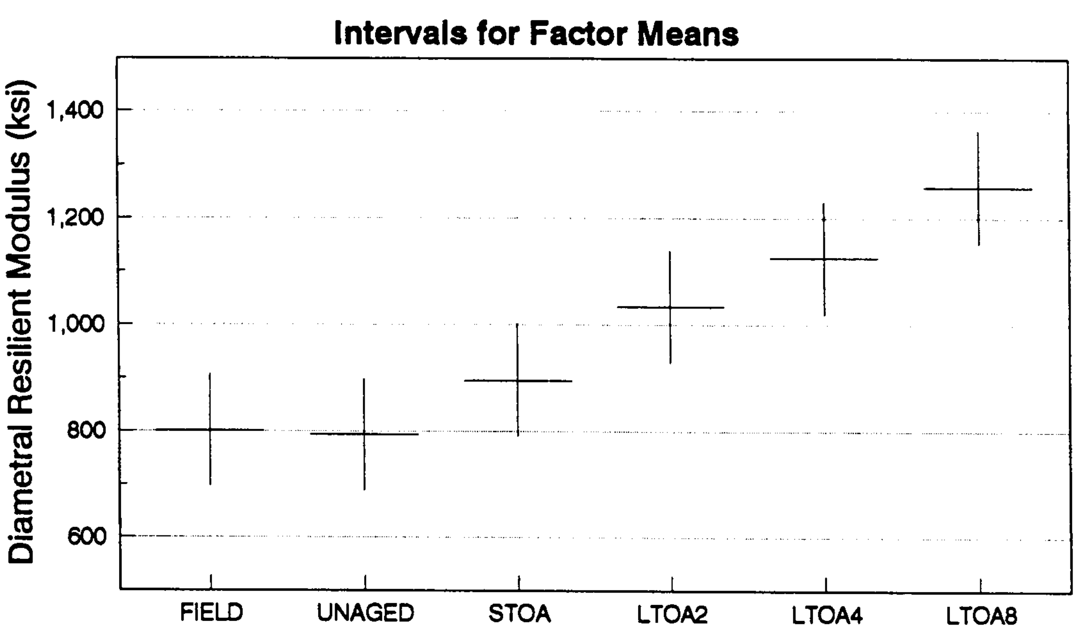

Figure 4.2a Arizona SPS-6 Tukey Comparison, 85°C (185°F) Aging

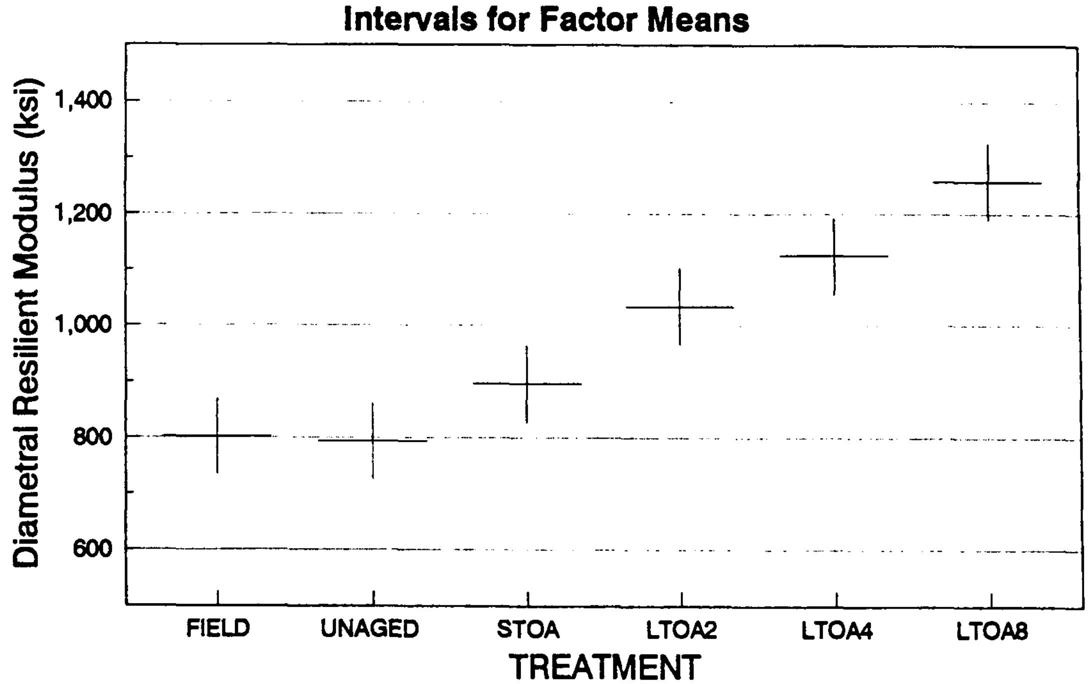

Figure 4.2b Arizona SPS-6 LSD Comparison, 85°C (185°F) Aging

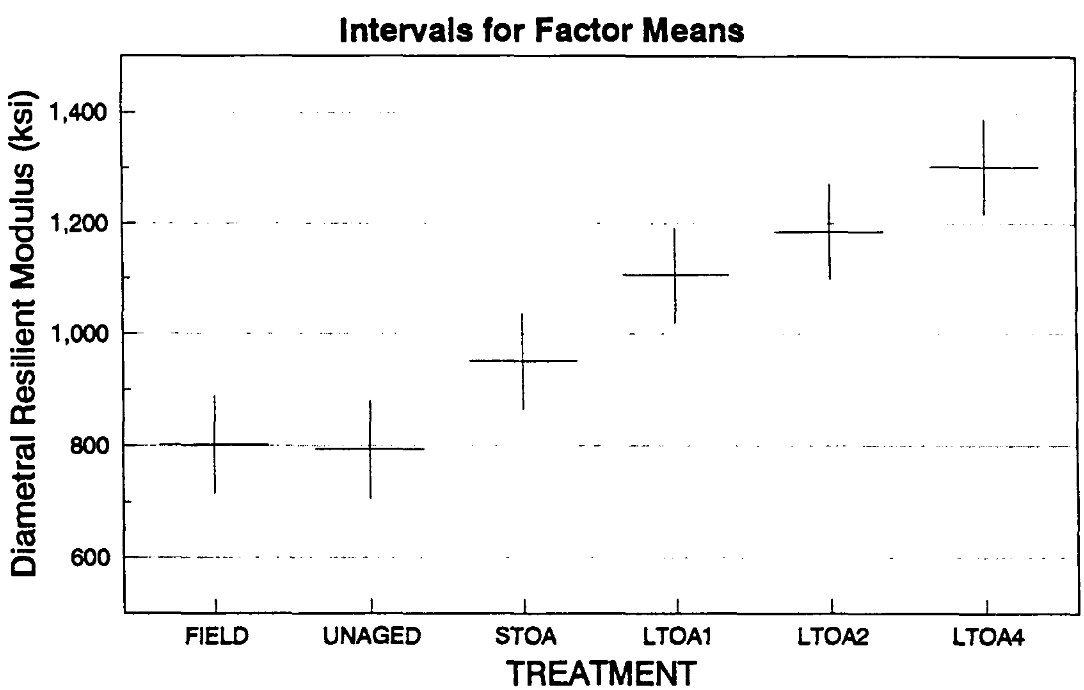

Figure 4.2c Arizona SPS-6 LSD Comparison, 100°C (212°F) Aging

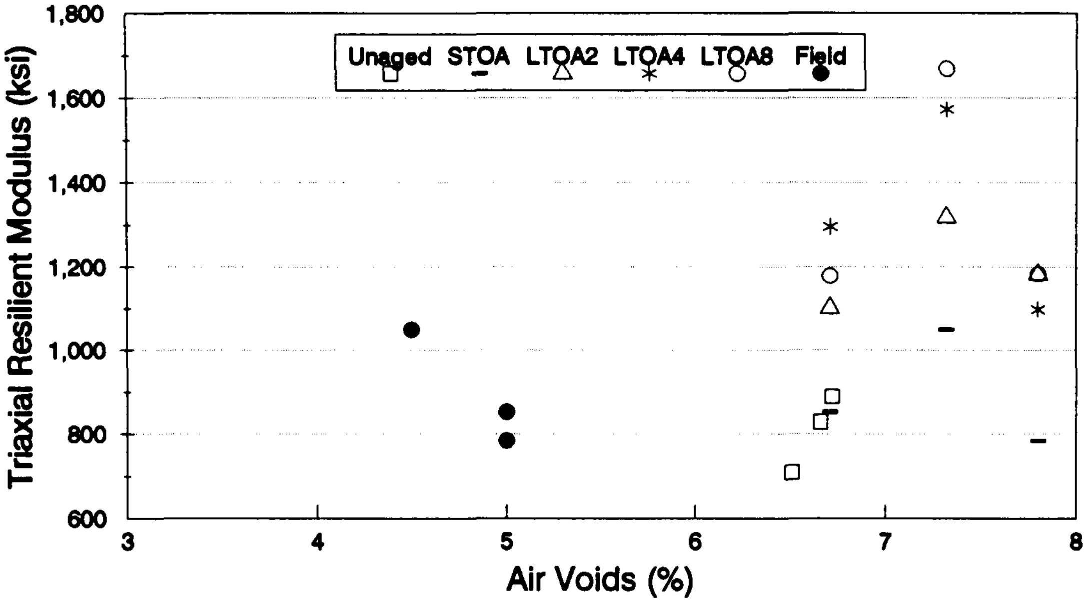

Figure 4.2d Arizona SPS-6 Triaxial Resilient Modulus, 85°C (185°F) Aging

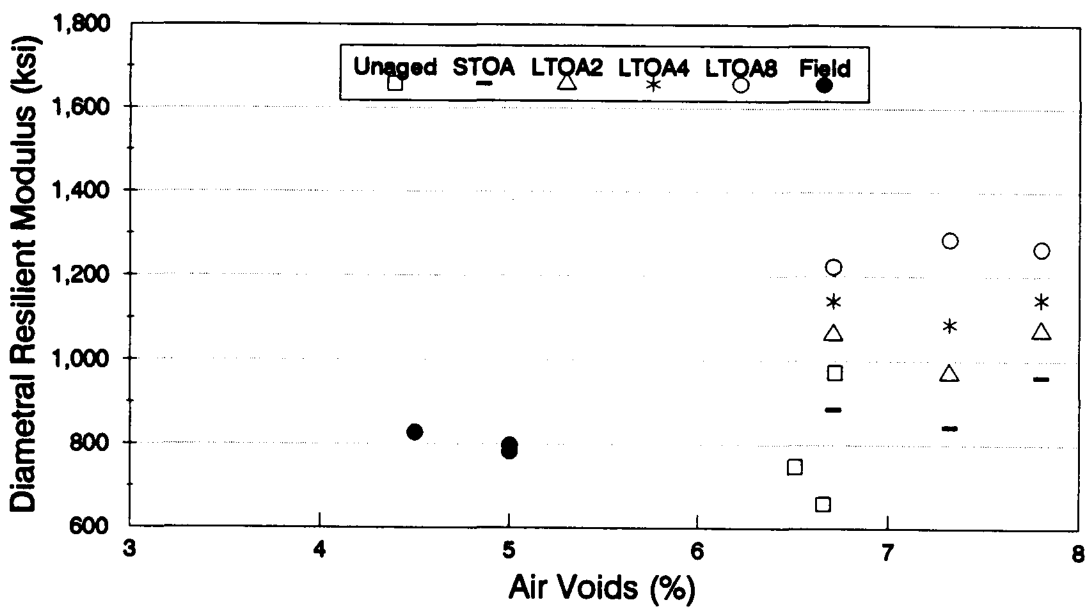

Figure 4.2e Arizona SPS-6 Diametral Resilient Modulus, 85°C (185°F) Aging

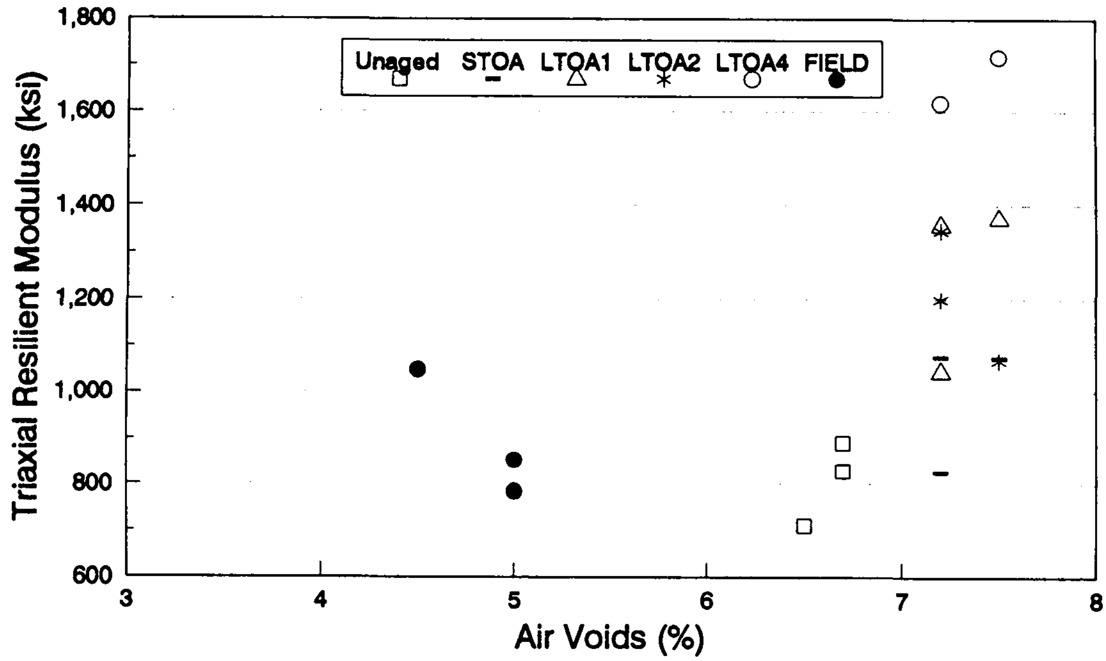

Figure 4.2f Arizona SPS-6 Triaxial Resilient Modulus, 100°C (212°F) Aging

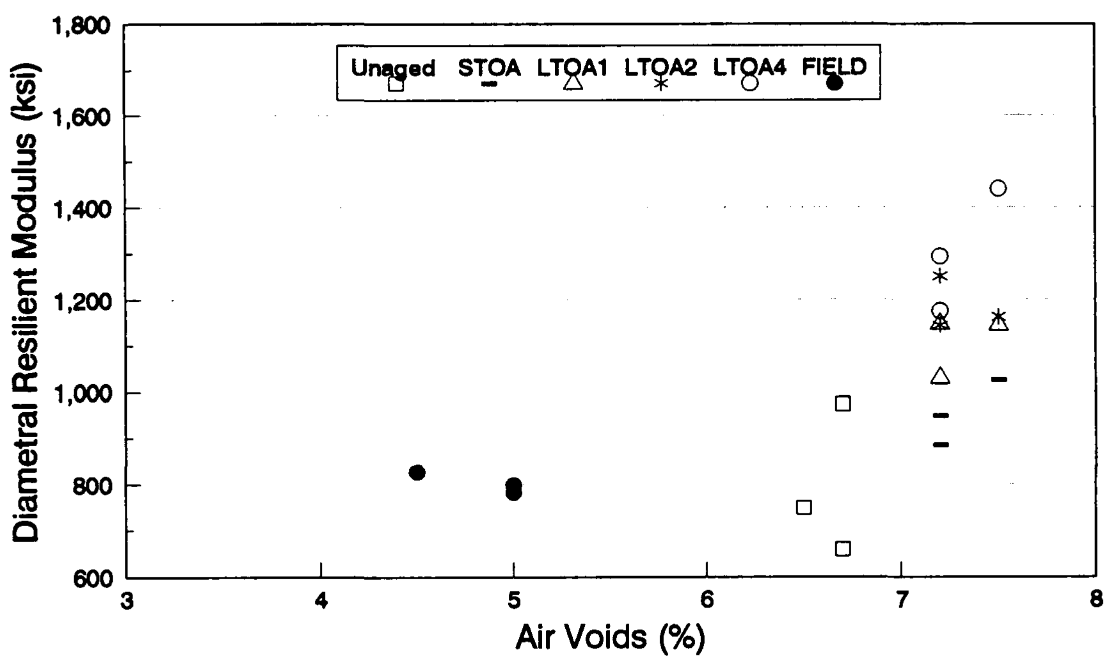

Figure 4.2g Arizona SPS-6 Diametral Resilient Modulus, 100°C (212°F) Aging

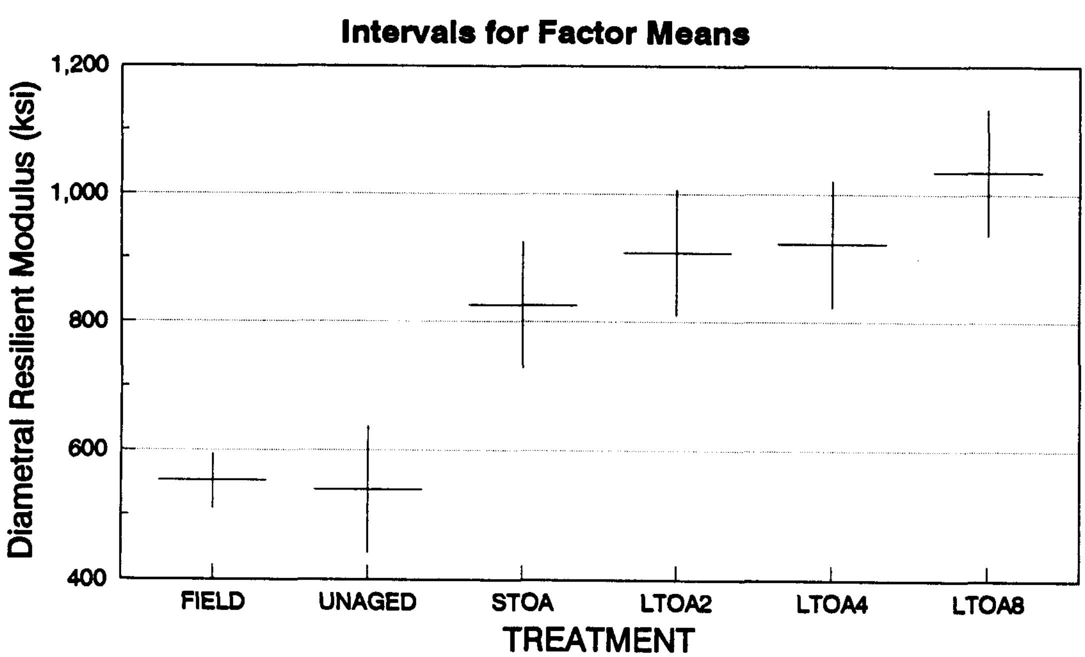

Figure 4.3a California AAMAS "Batch" Tukey Comparison, 85°C (185°F) Aging

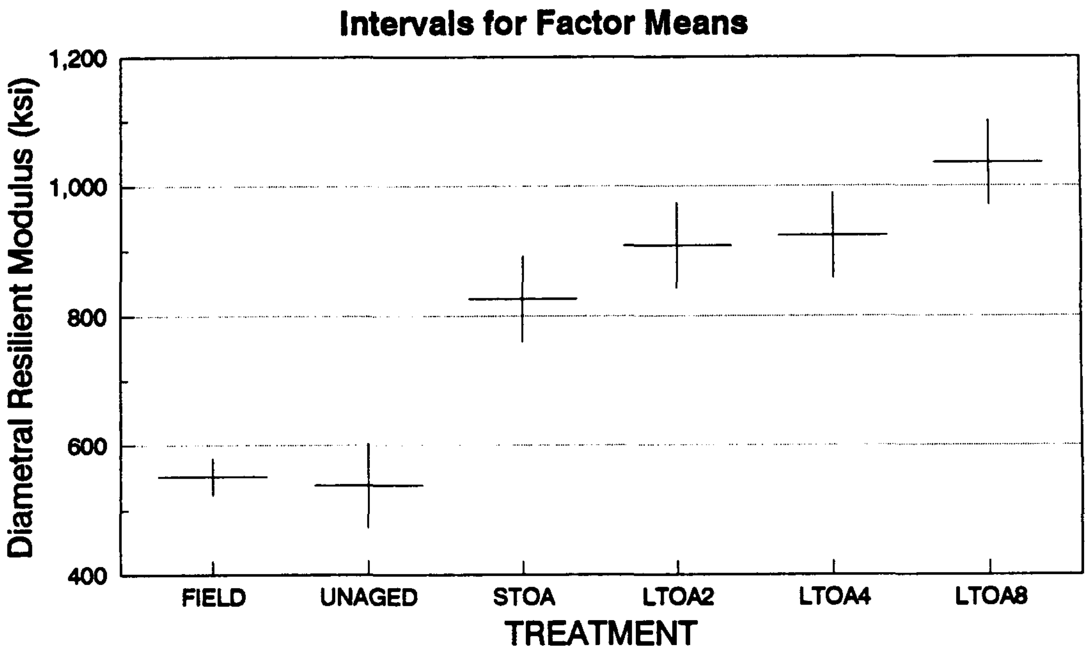

Figure 4.3b California AAMAS "Batch" LSD Comparison, 85°C (185°F) Aging

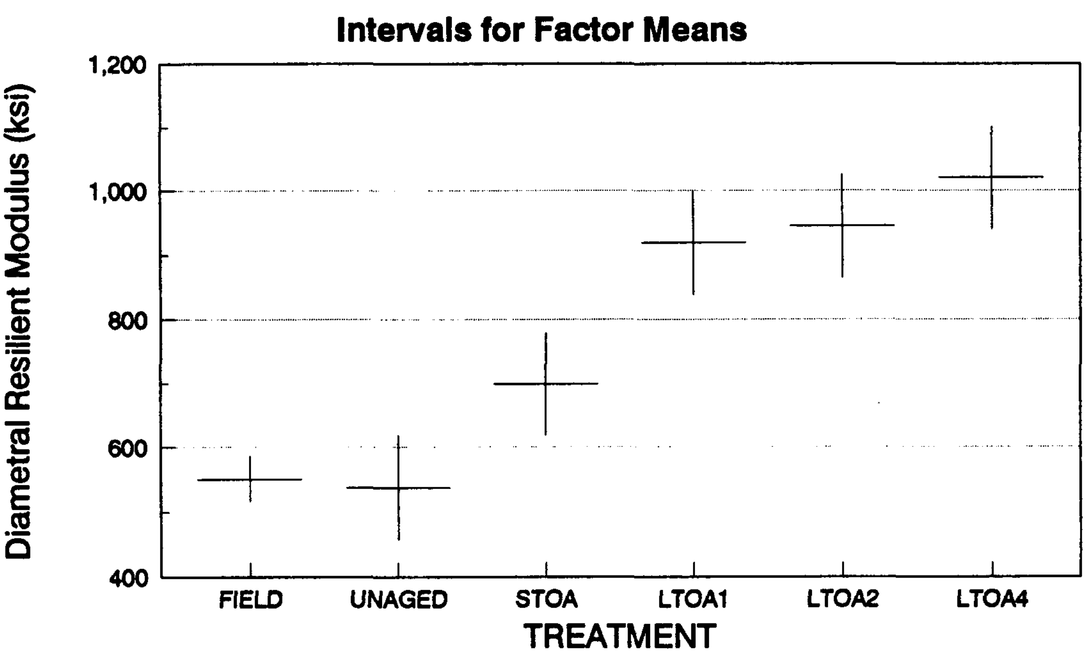

Figure 4.3c California AAMAS "Batch" LSD Comparison, 100°C (212°F) Aging

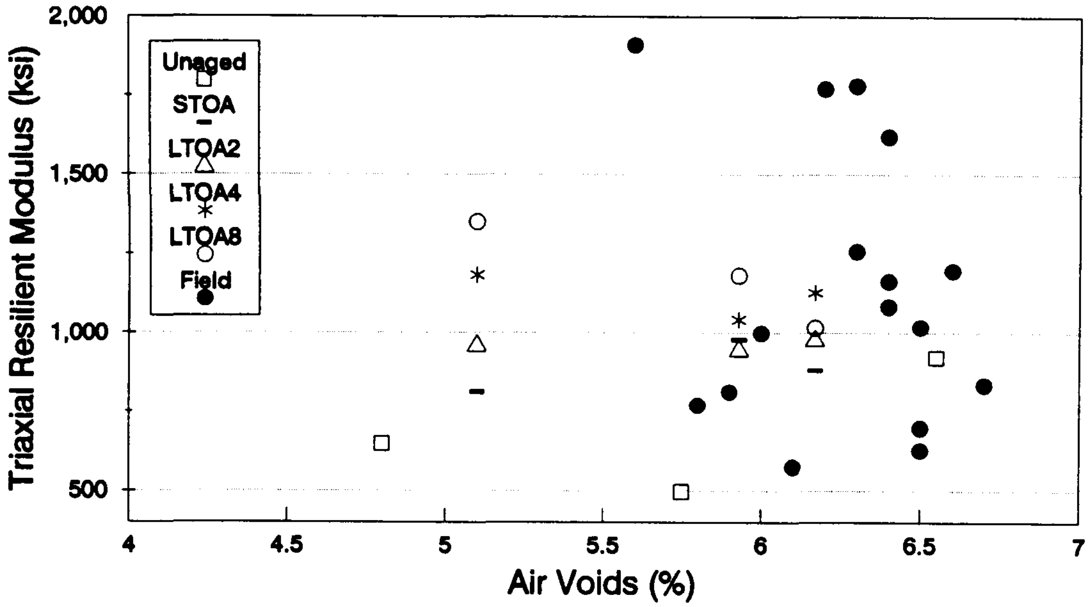

Figure 4.3d California AAMAS "Batch" Triaxial Resilient Modulus, 85°C (185°F) Aging

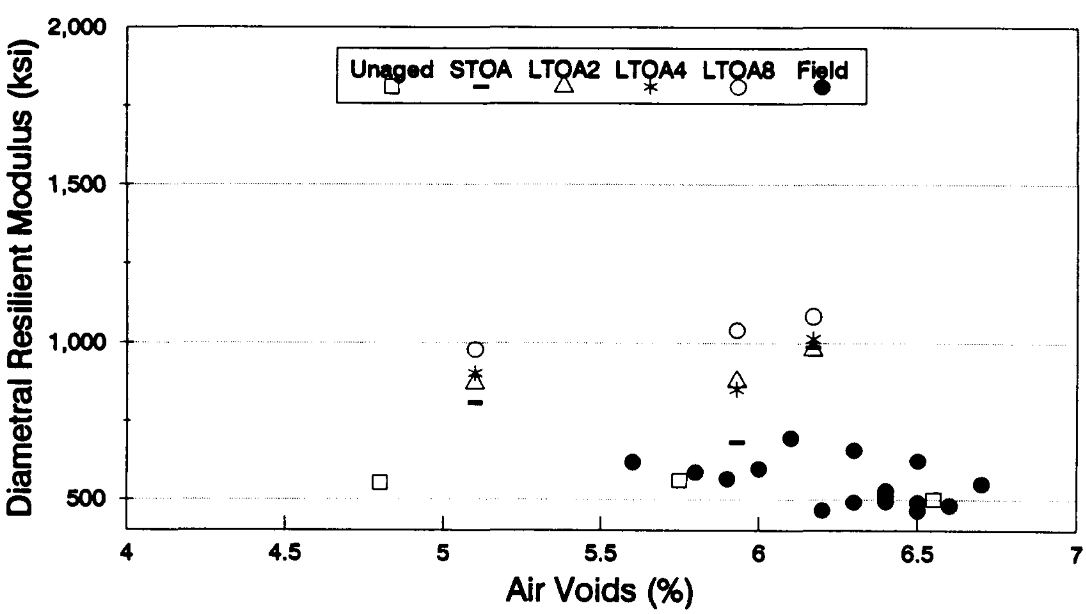

Figure 4.3e California AAMAS "Batch" Diametral Resilient Modulus, 85°C (185°F) Aging

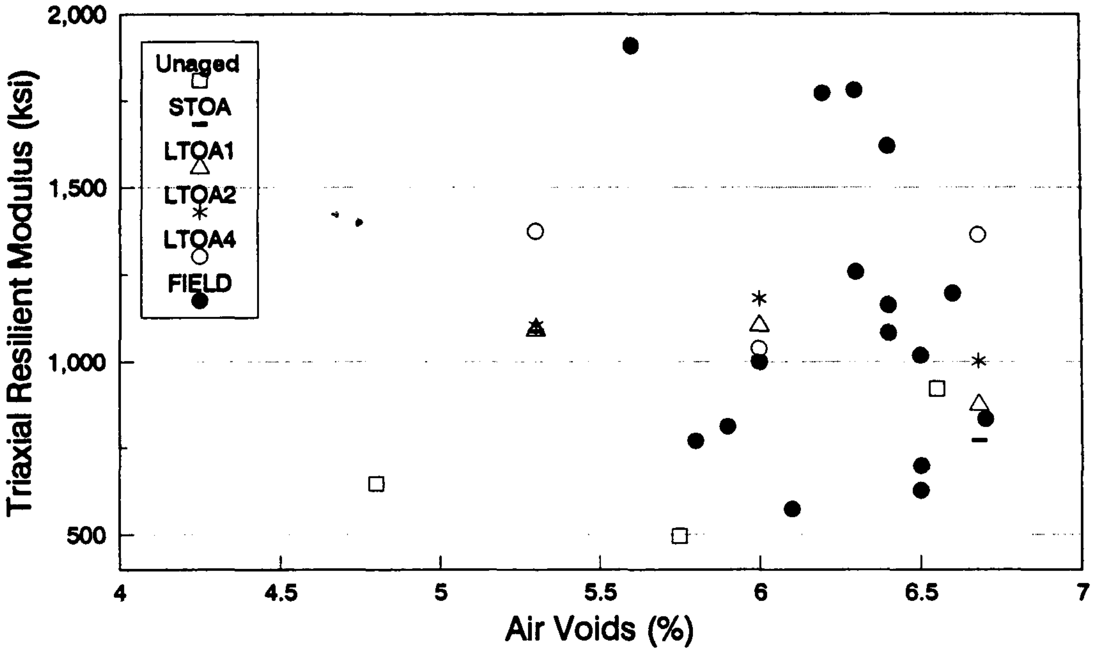

Figure 4.3f **California AAMAS "Batch" Triaxial Resilient Modulus, 100°C (212°F) Aging**

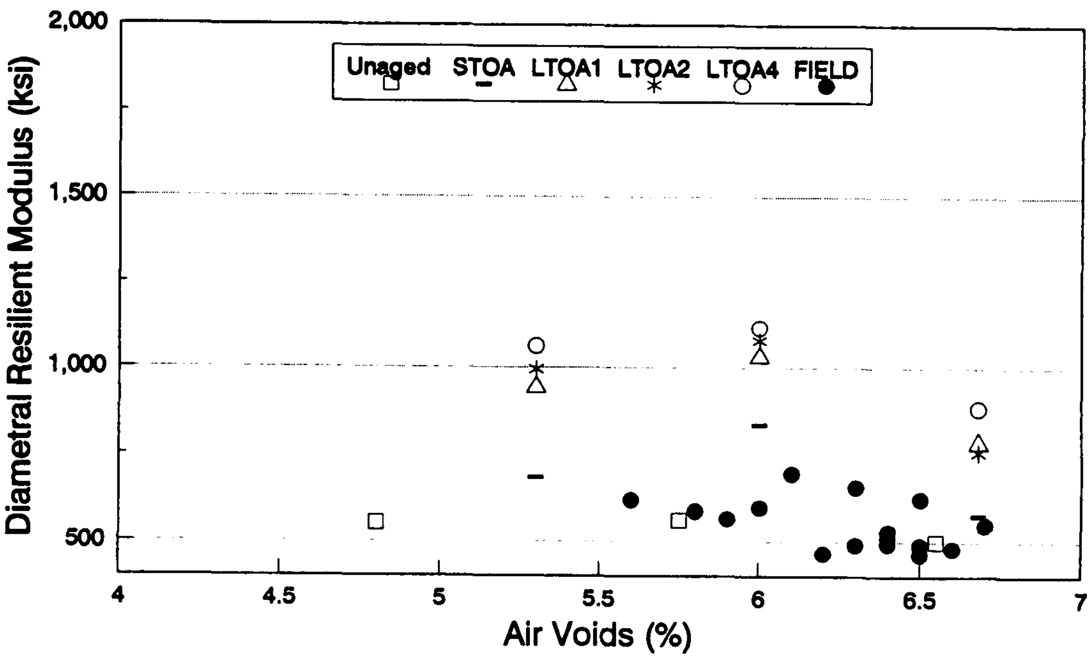

Figure 4.3g **California AAMAS "Batch" Diametral Resilient Modulus, 100°C (212°F) Aging**

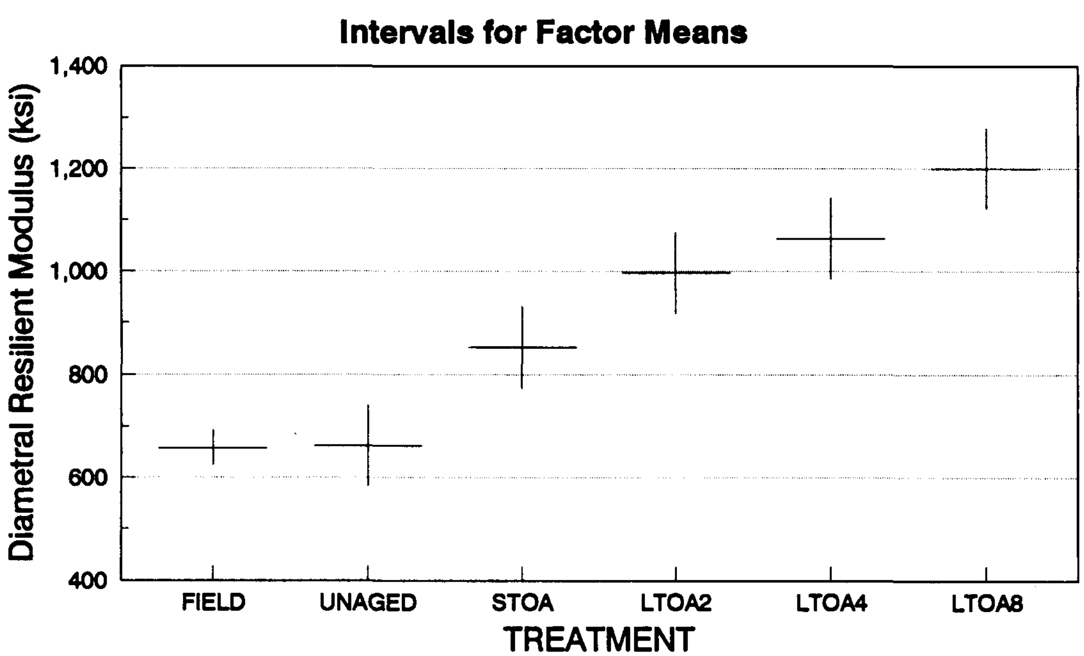

Figure 4.4a California AAMAS "Drum" Tukey Comparison, 85°C (185°F) Aging

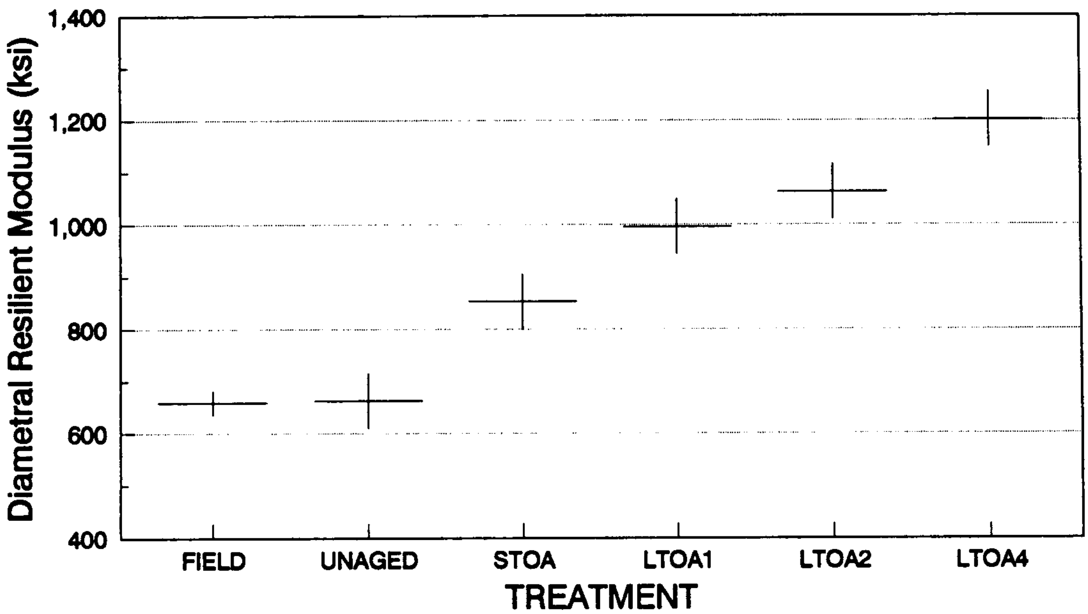

Figure 4.4b California AAMAS "Drum" LSD Comparison, 85°C (185°F) Aging

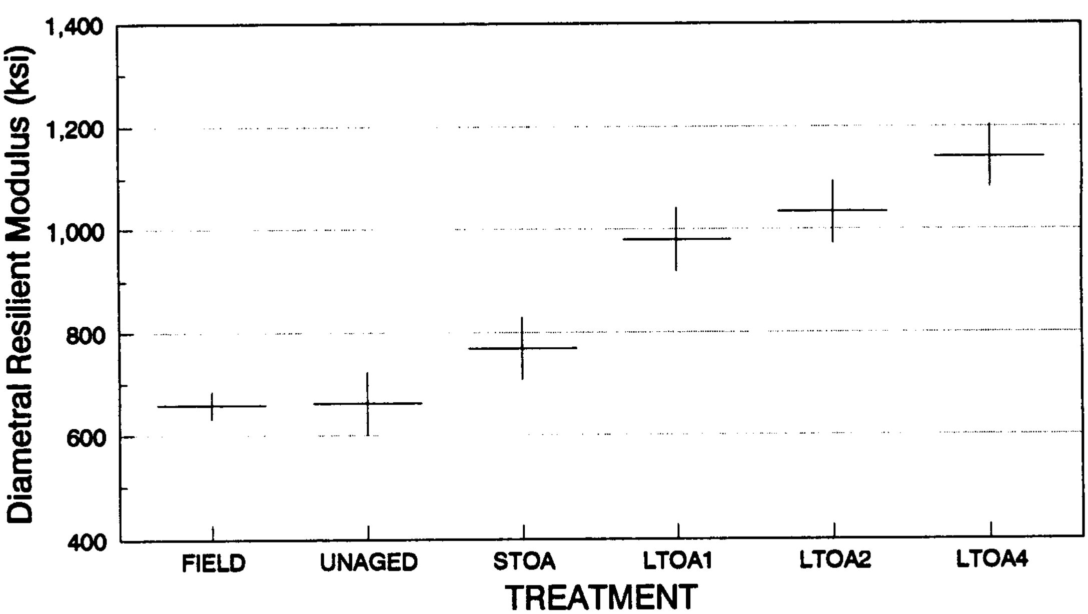

Figure 4.4c California AAMAS "Drum" LSD Comparison, 100°C (212°F) (212° F) Aging

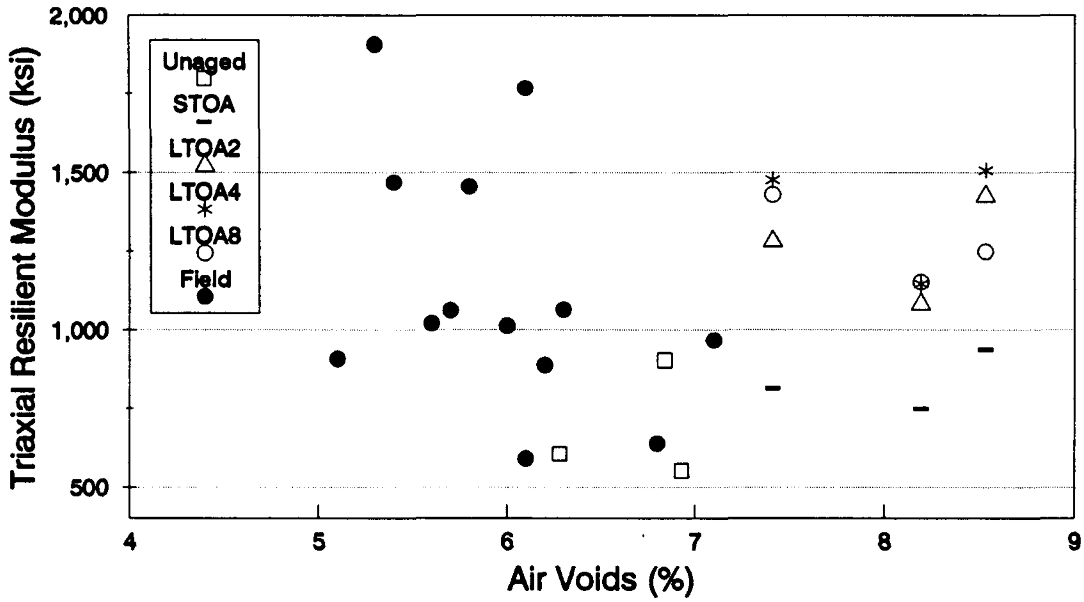

Figure 4.4d California AAMAS "Drum" Triaxial Resilient Modulus, 85°C (185°F) Aging

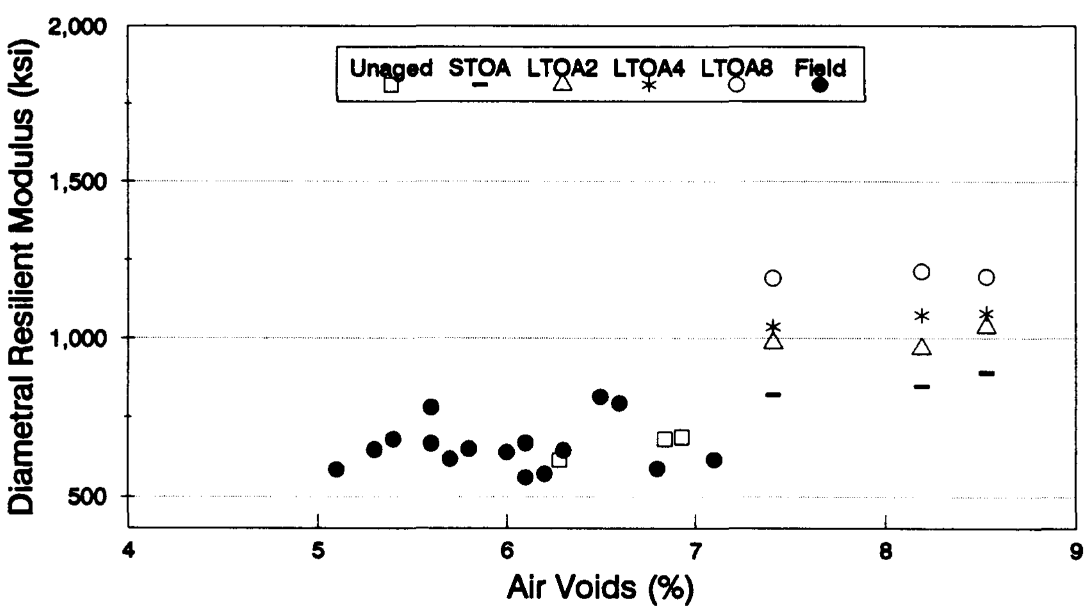

Figure 4.4e California AAMAS "Drum" Diametral Resilient Modulus, 85°C (185°F) Aging

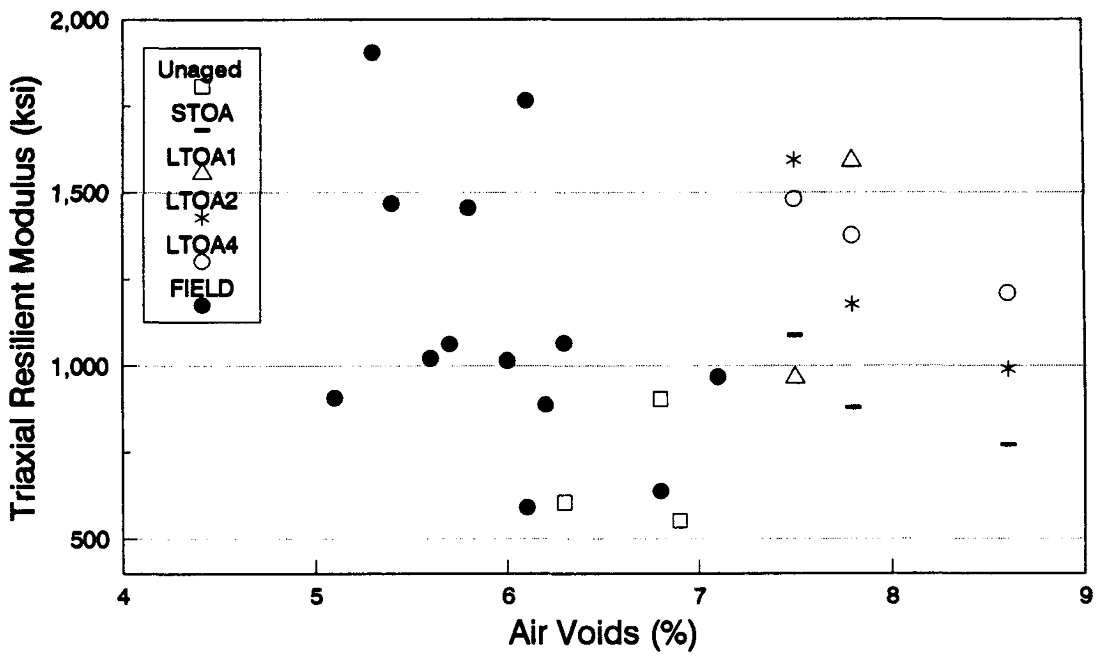

Figure 4.4f California AAMAS "Drum" Triaxial Resilient Modulus, 100°C (212°F) Aging

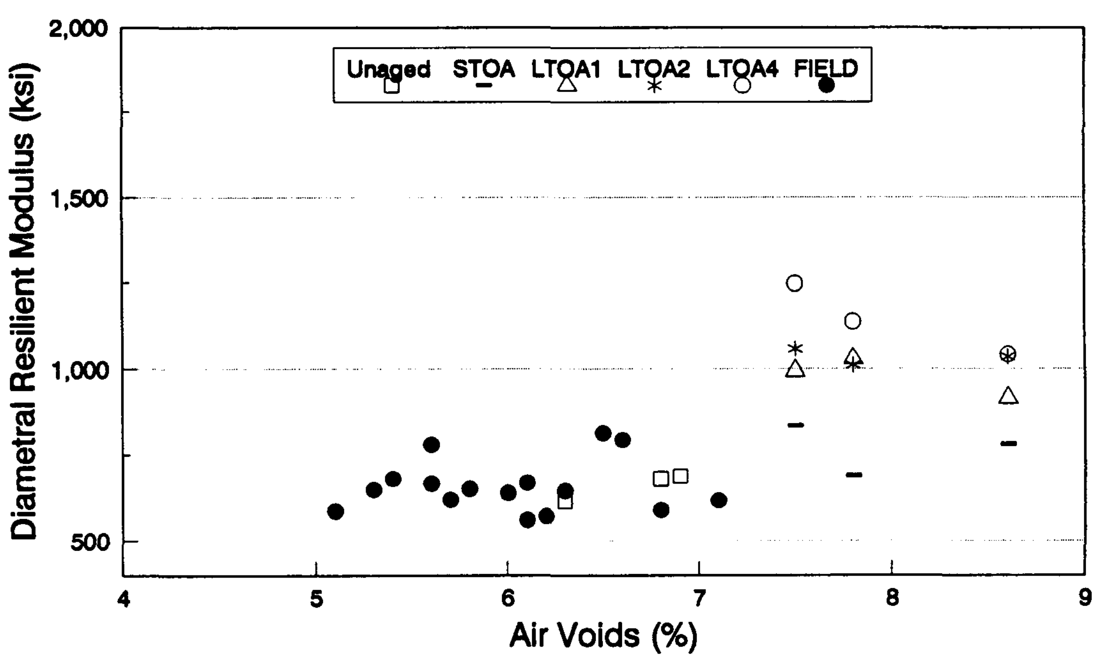

Figure 4.4g California AAMAS "Drum" Diametral Resilient Modulus, 100°C (212°F) Aging

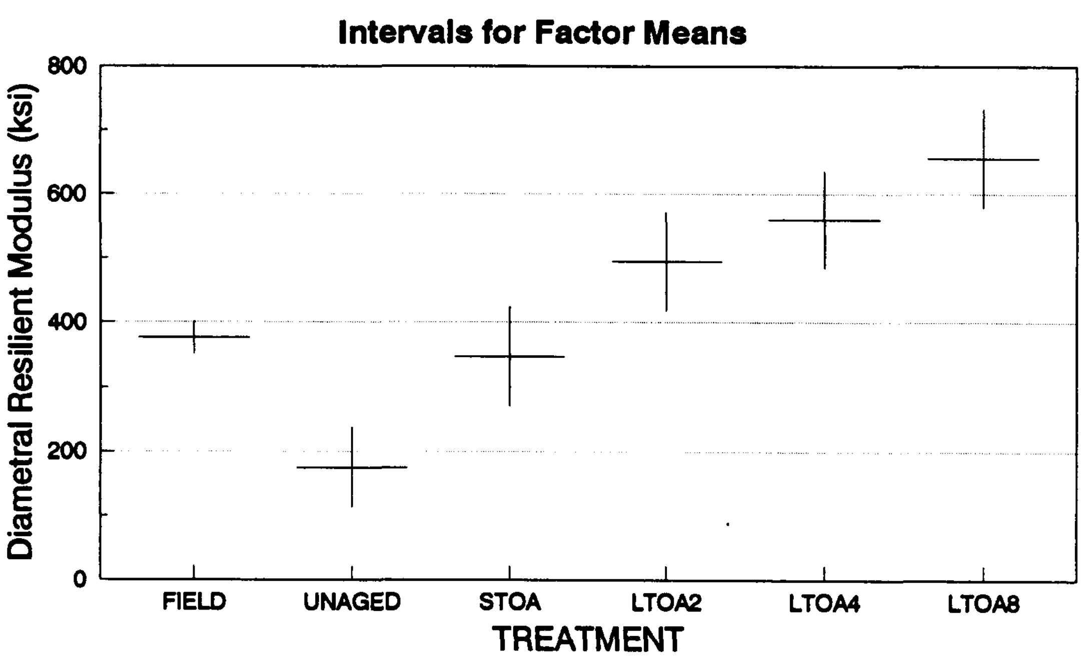

Figure 4.5a California GPS-6 Tukey Comparison, 85°C (185°F) Aging

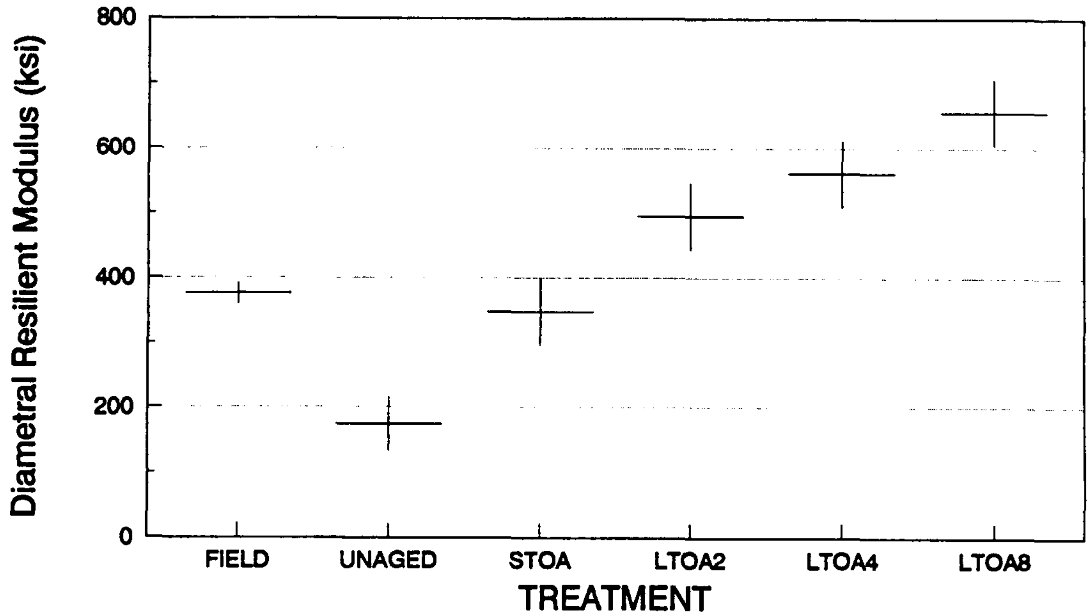

Figure 4.5b California GPS-6 LSD Comparison, 85°C (185°F) Aging

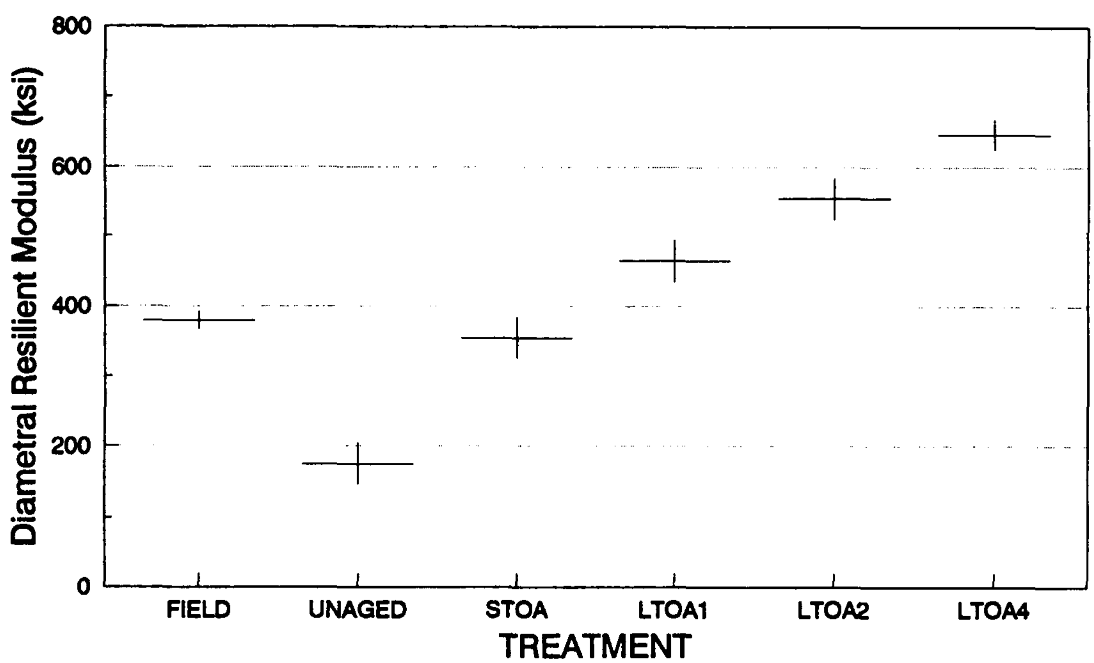

Figure 4.5c California GPS-6 LSD Comparison, 100°C (212°F) Aging

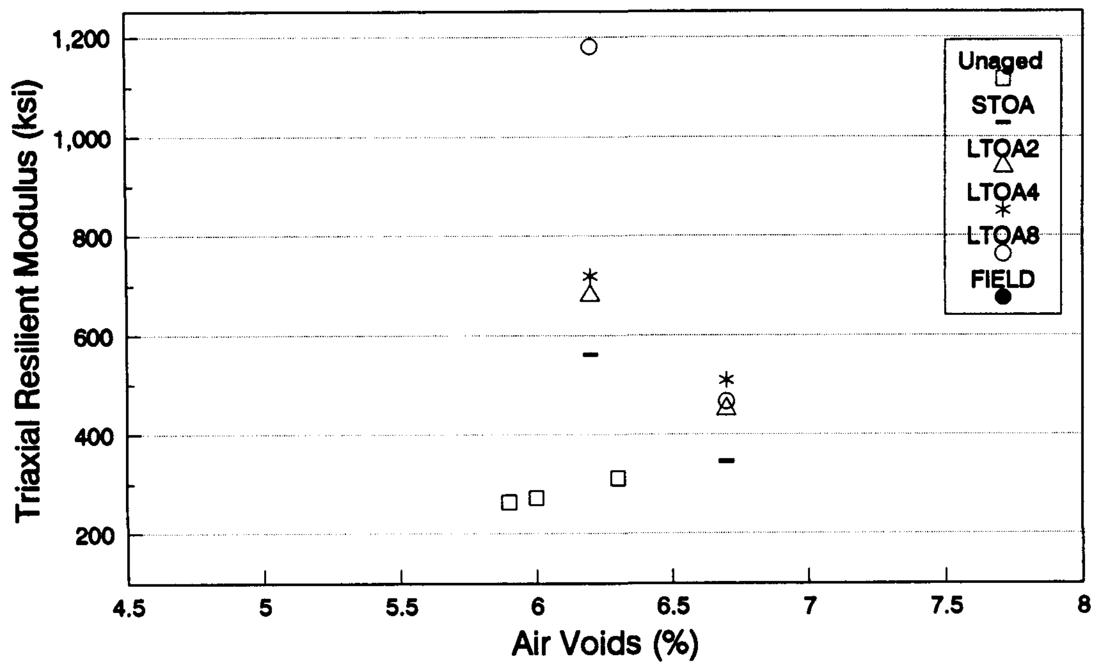

Figure 4.5d California GPS-6 Triaxial Resilient Modulus, 85°C (185°F) Aging

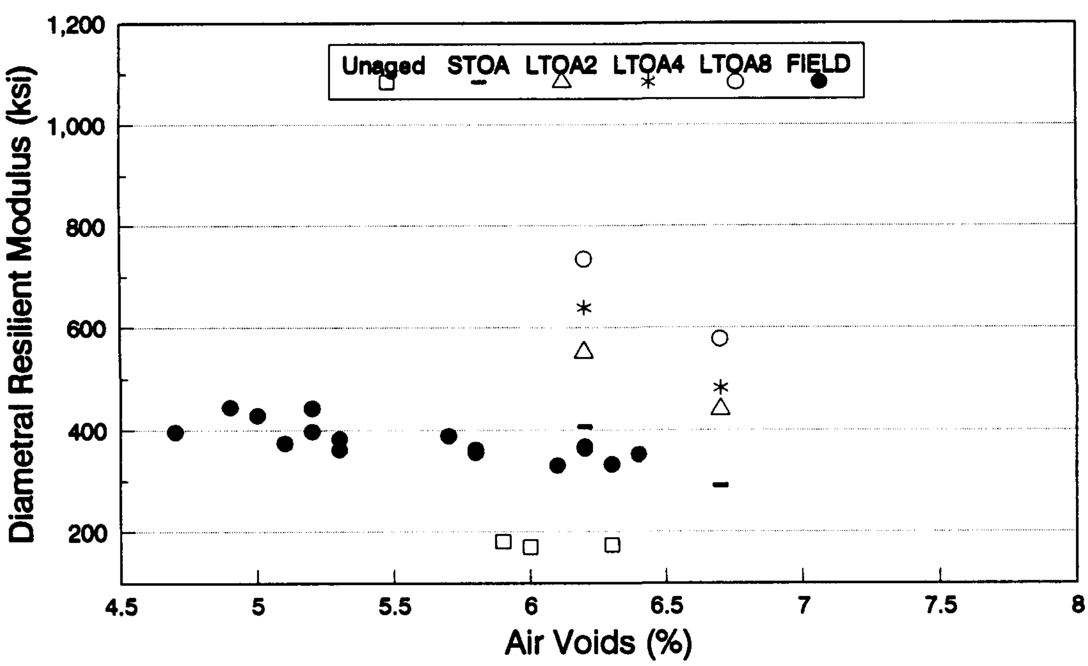

Figure 4.5e California GPS-6 Diametral Resilient Modulus, 85°C (185°F) Aging

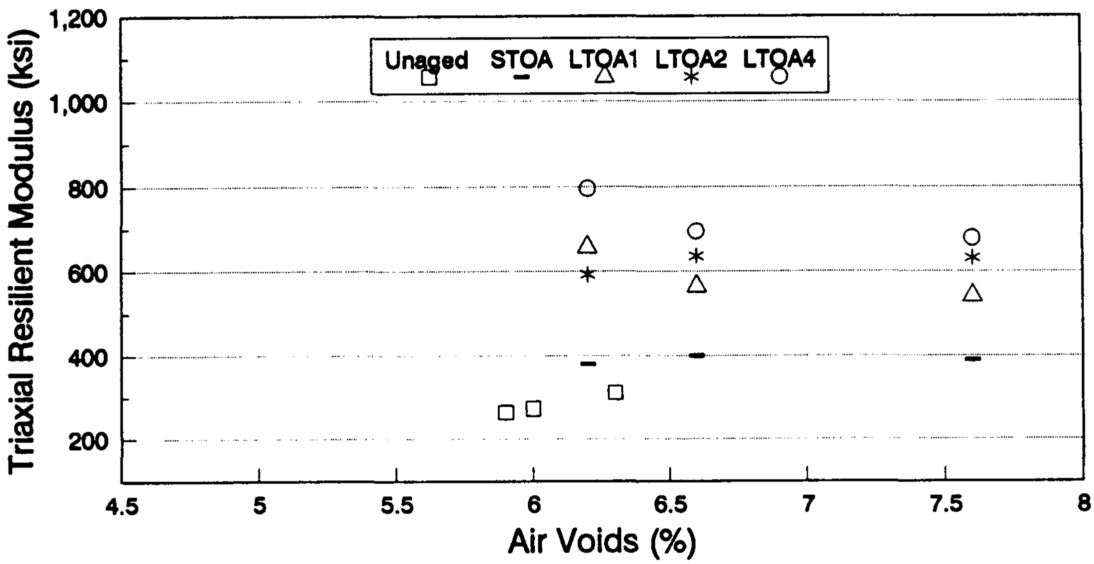

Figure 4.5f California GPS-6 Triaxial Resilient Modulus, 100°C (212°F) Aging

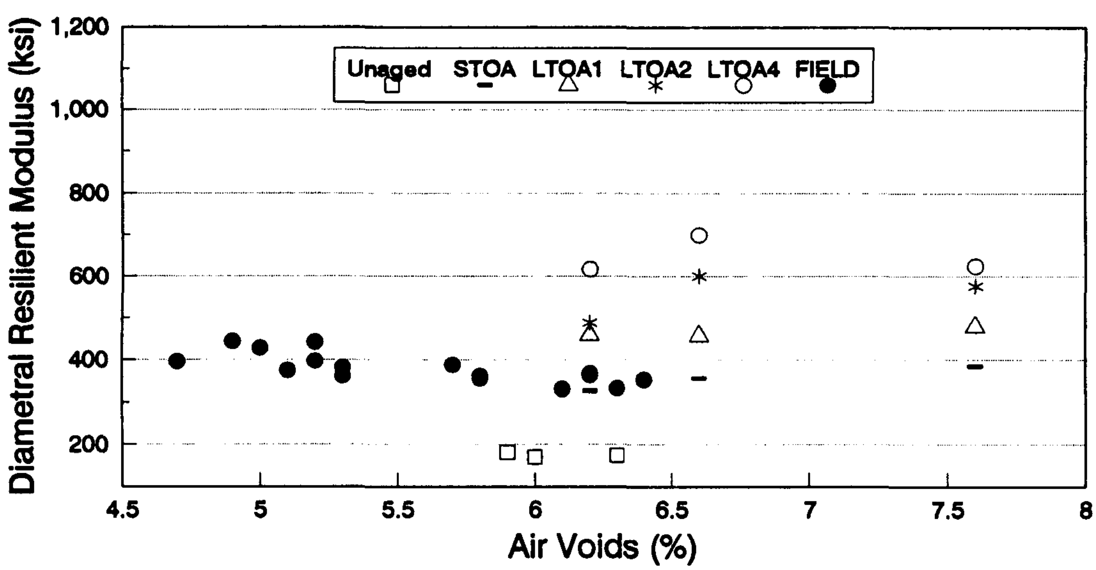

Figure 4.5g California GPS-6 Diametral Resilient Modulus, 100°C (212°F) Aging

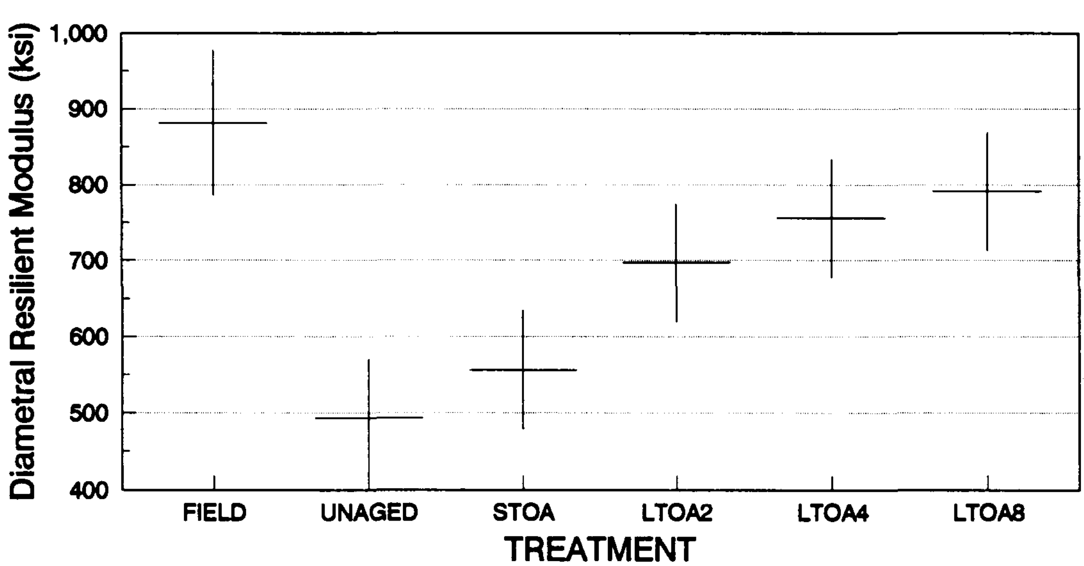

Figure 4.6a France A Section Tukey Comparison, 85°C (185°F) Aging

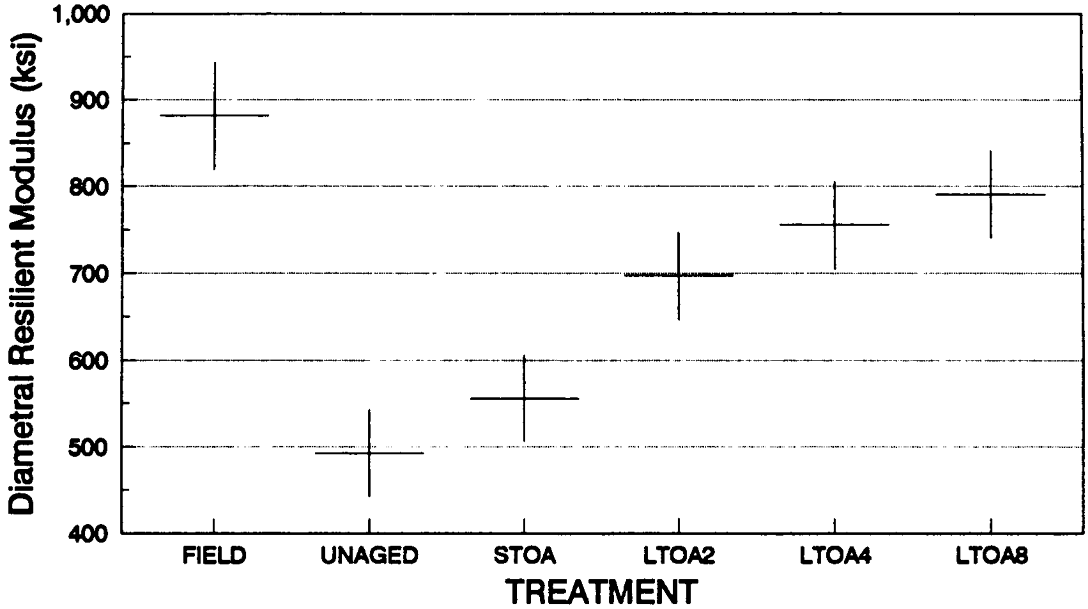

Figure 4.6b France A Section LSD Comparison, 85°C (185°F) Aging

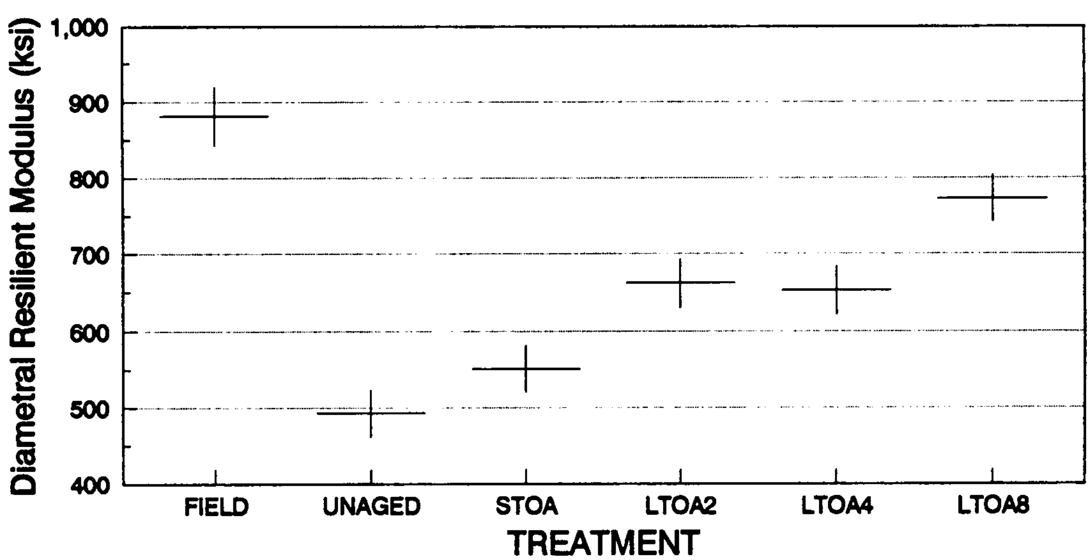

Figure 4.6c France A Section LSD Comparison, 100°C (212°F) Aging

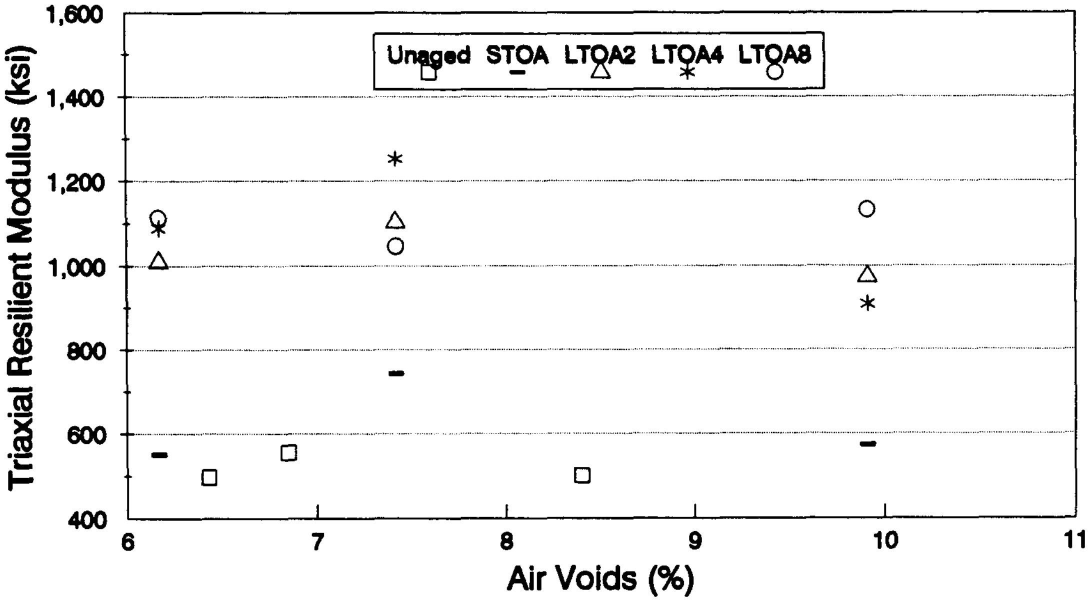

Figure 4.6d France A Section Triaxial Resilient Modulus, 85°C (185°F) Aging

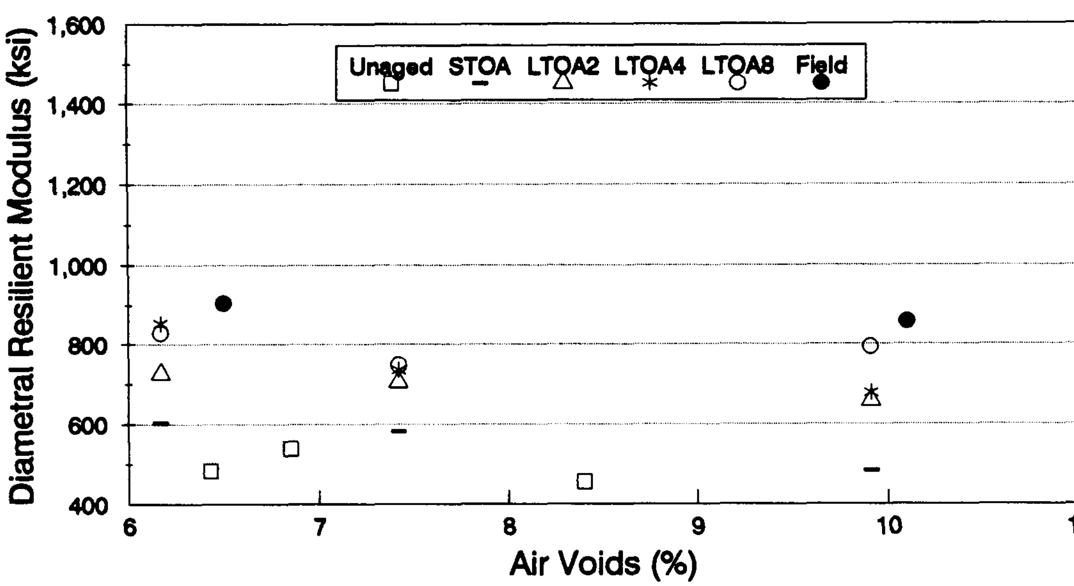

Figure 4.6e France A Section Diametral Resilient Modulus, 85°C (185°F) Aging

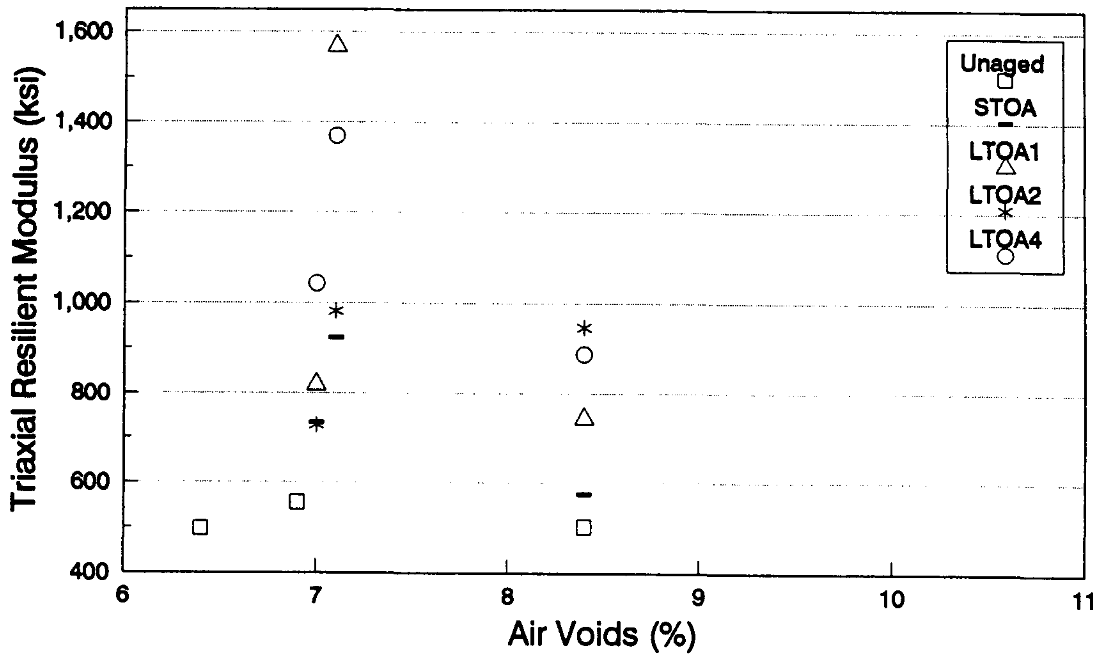

Figure 4.6f France A Section Triaxial Resilient Modulus, 100°C (212°F) Aging

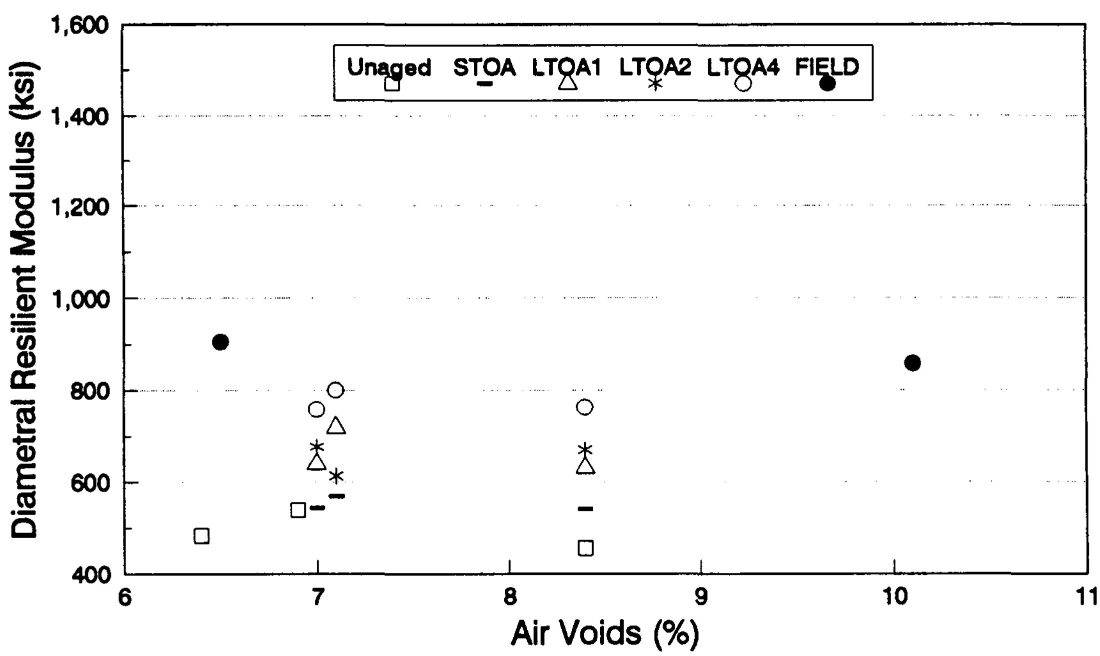

Figure 4.6g France A Section Diametral Resilient Modulus, 100°C (212°F) Aging

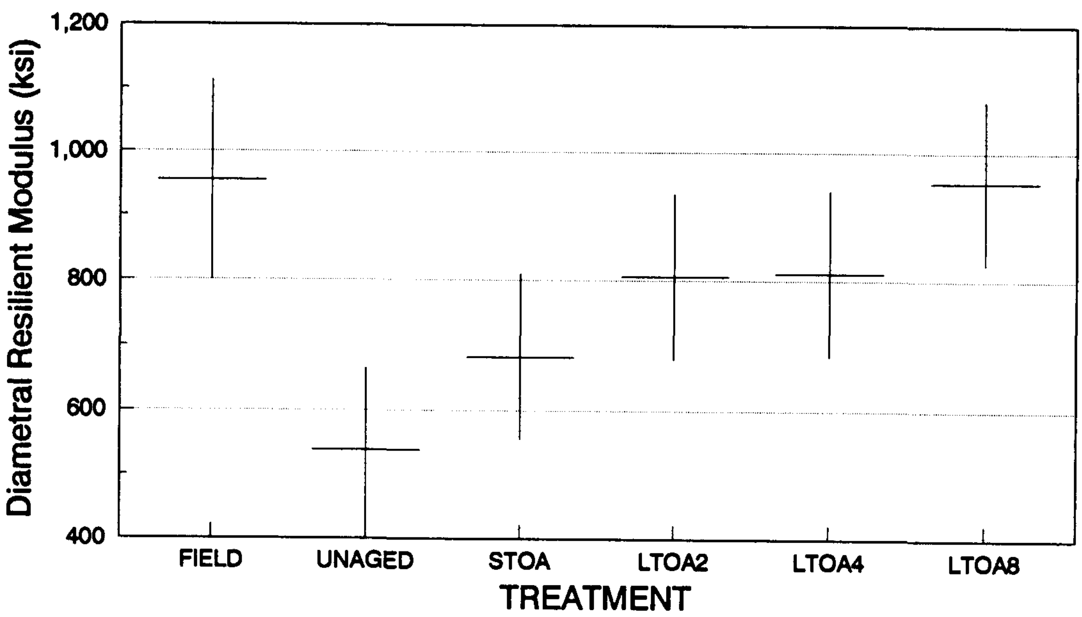

Figure 4.7a France B Section Tukey Comparison, 85°C (185°F) Aging

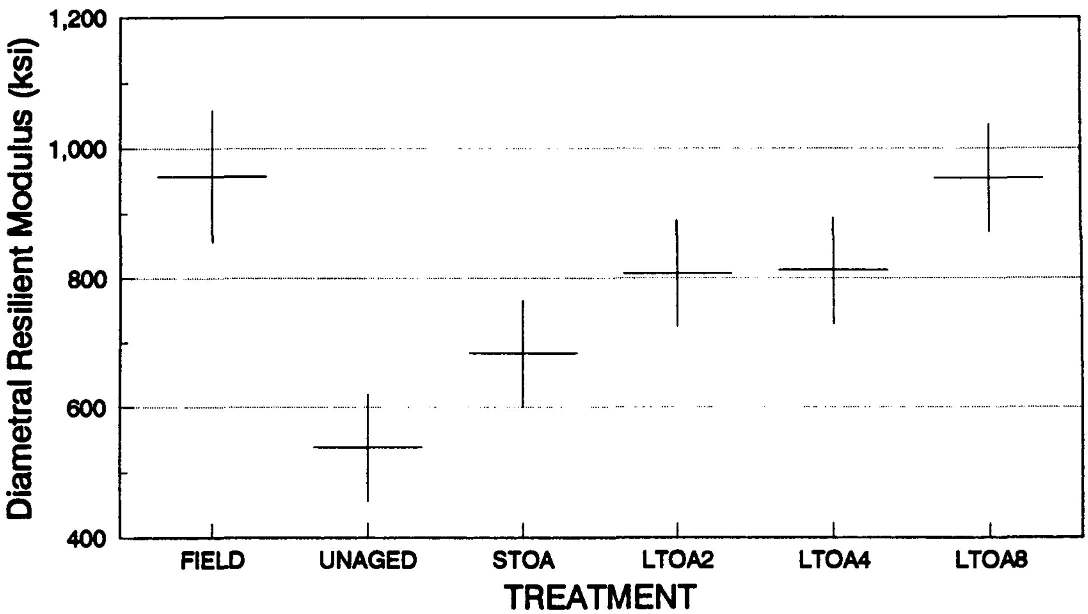

Figure 4.7b France B Section LSD Comparison, 85°C (185°F) Aging

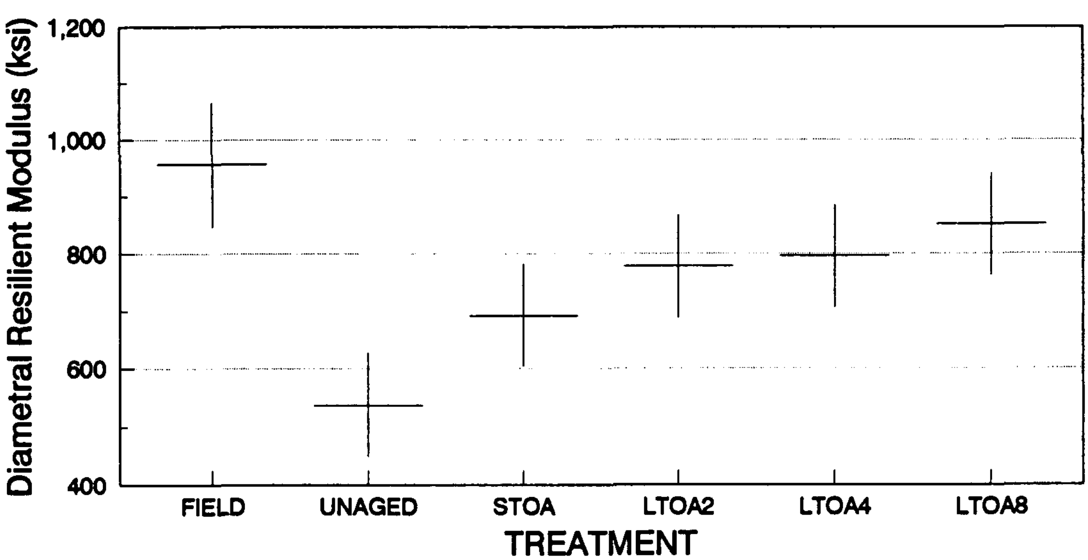

Figure 4.7c France B Section LSD Comparison, 100°C (212°F) Aging

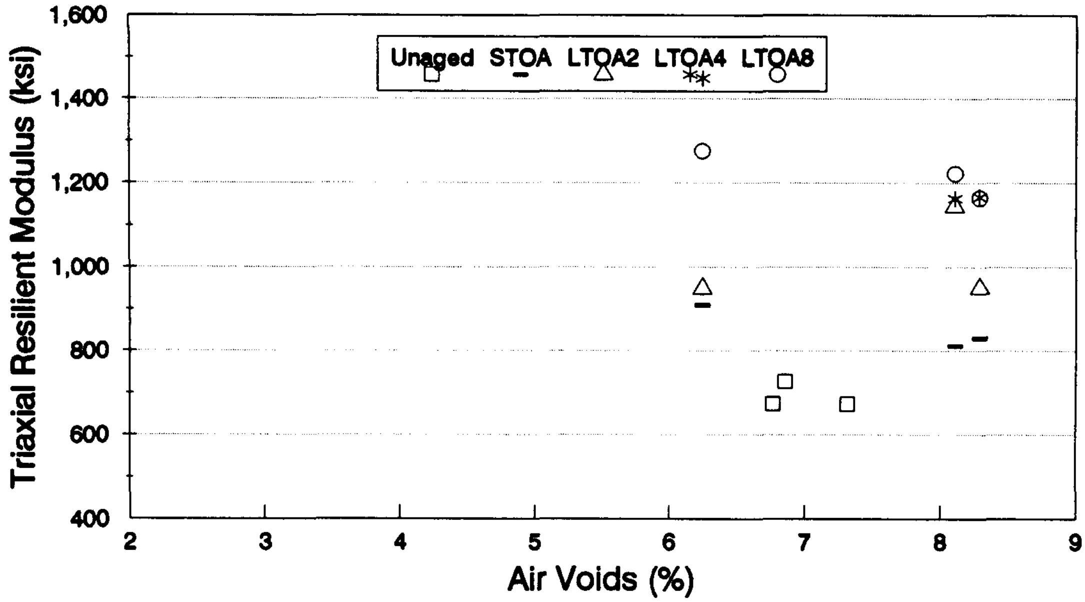

Figure 4.7d France B Section Triaxial Resilient Modulus, 85°C (185°F) Aging

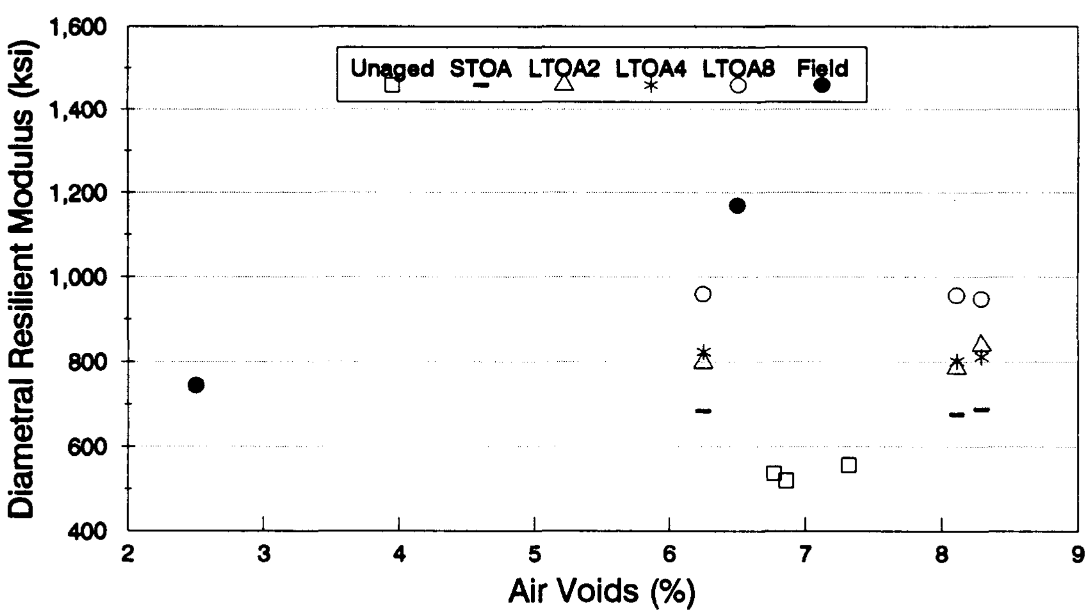

Figure 4.7e France B Section Diametral Resilient Modulus, 85°C (185°F) Aging

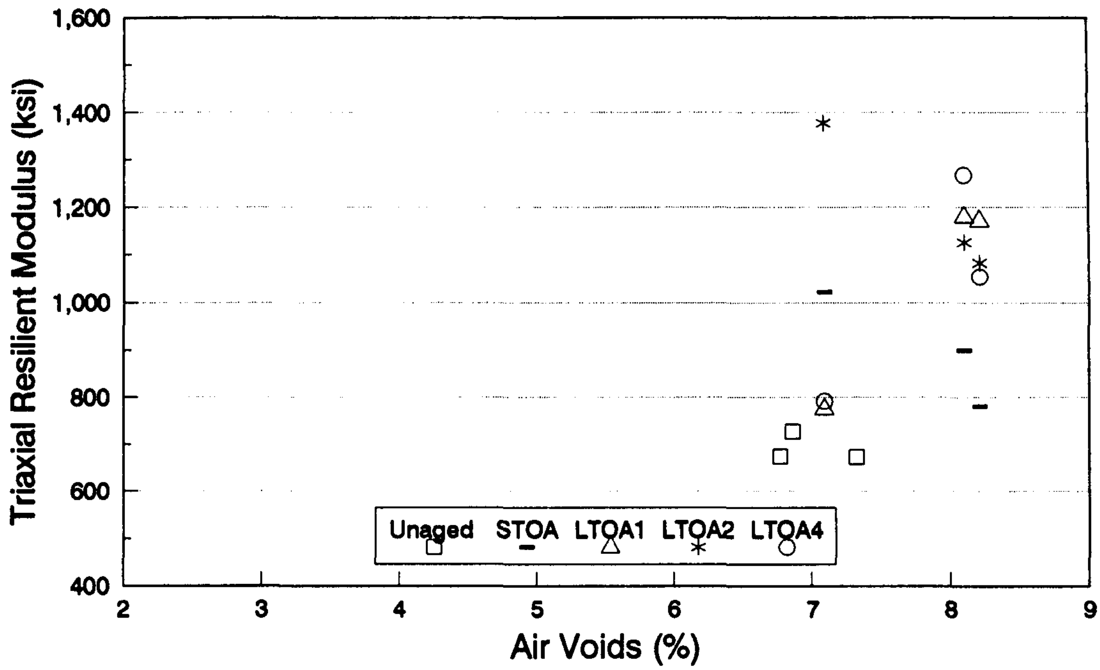

Figure 4.7f France B Section Triaxial Resilient Modulus, 100°C (212°F) Aging

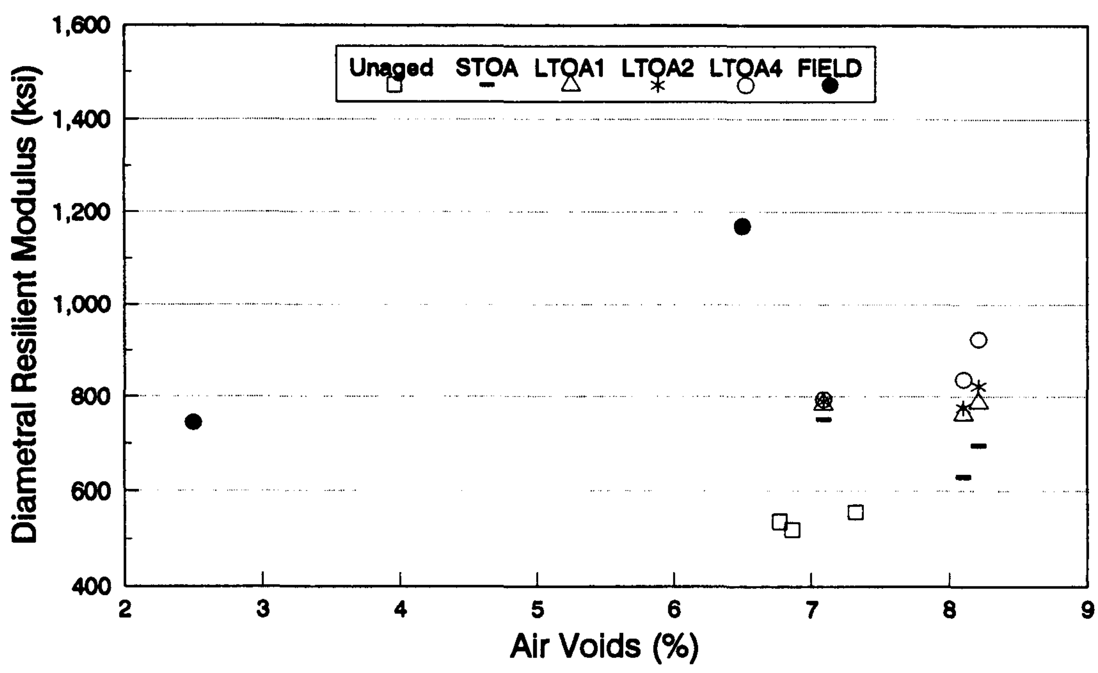

Figure 4.7g France B Section Diametral Resilient Modulus, 100°C (212°F) Aging

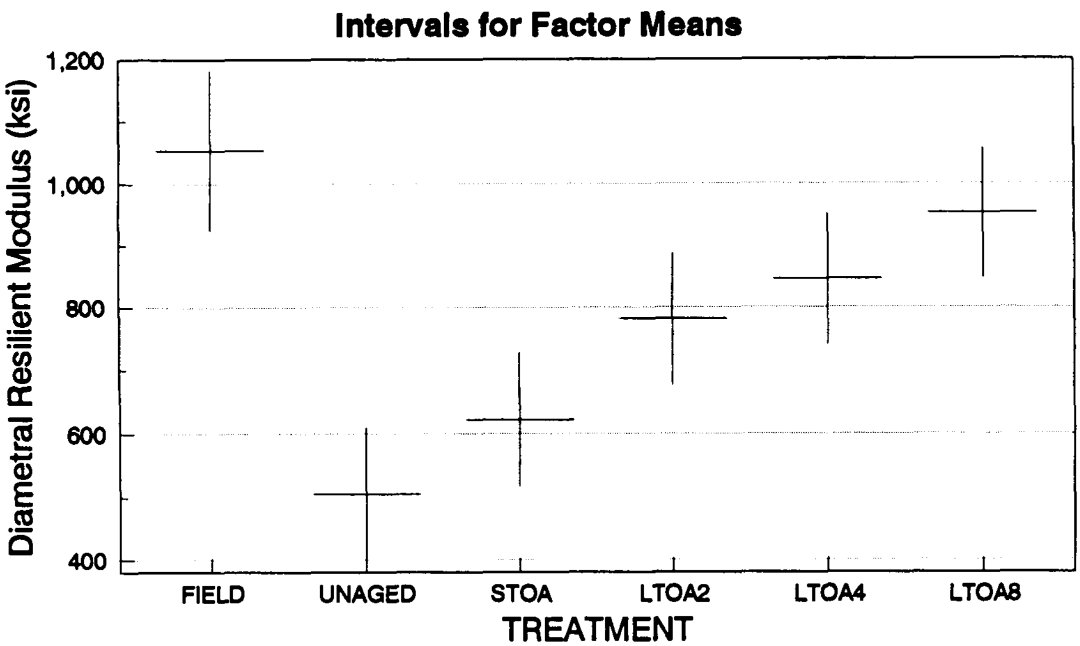

Figure 4.8a France C Section Tukey Comparison, 85°C (185°F) Aging

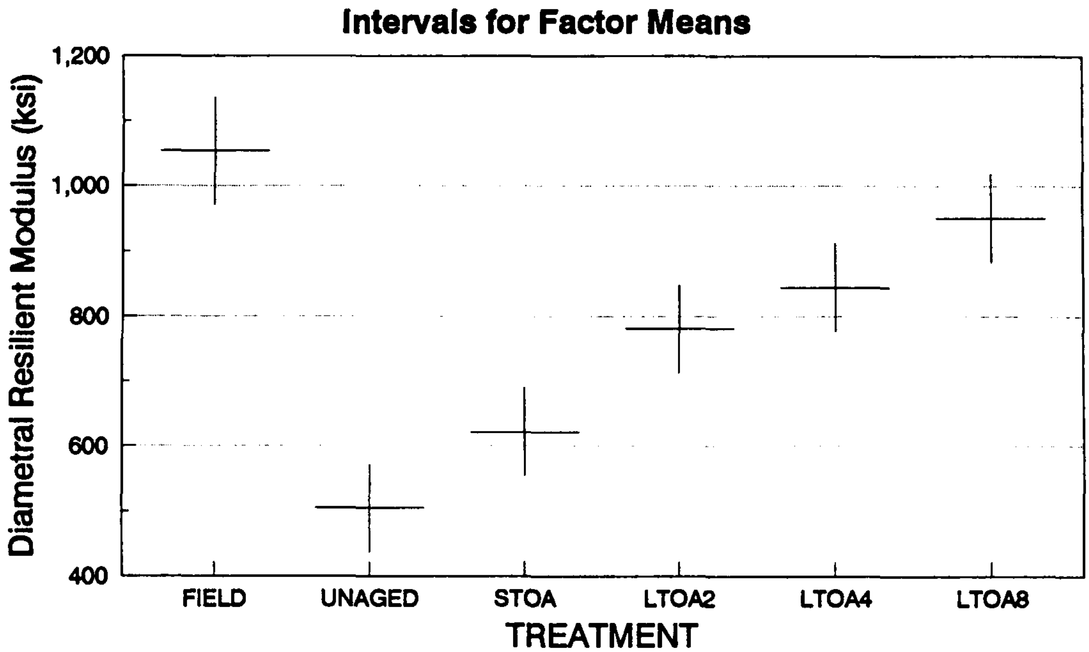

Figure 4.8b **France C Section LSD Comparison, 85°C (185°F) Aging**

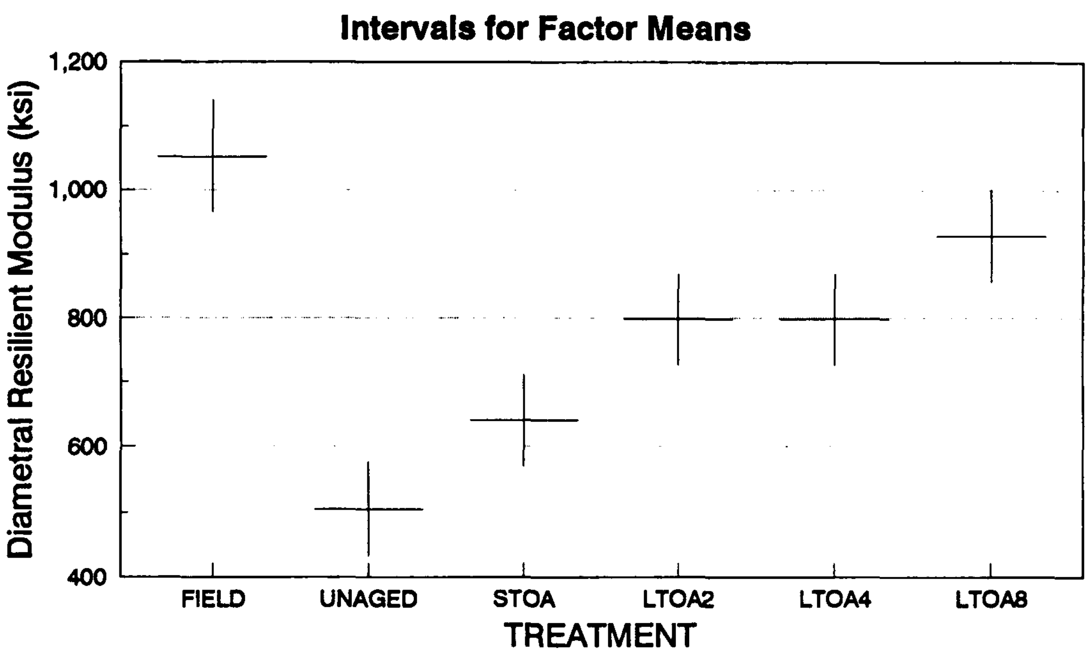

Figure 4.8c **France C Section LSD Comparison, 100°C (212°F) Aging**

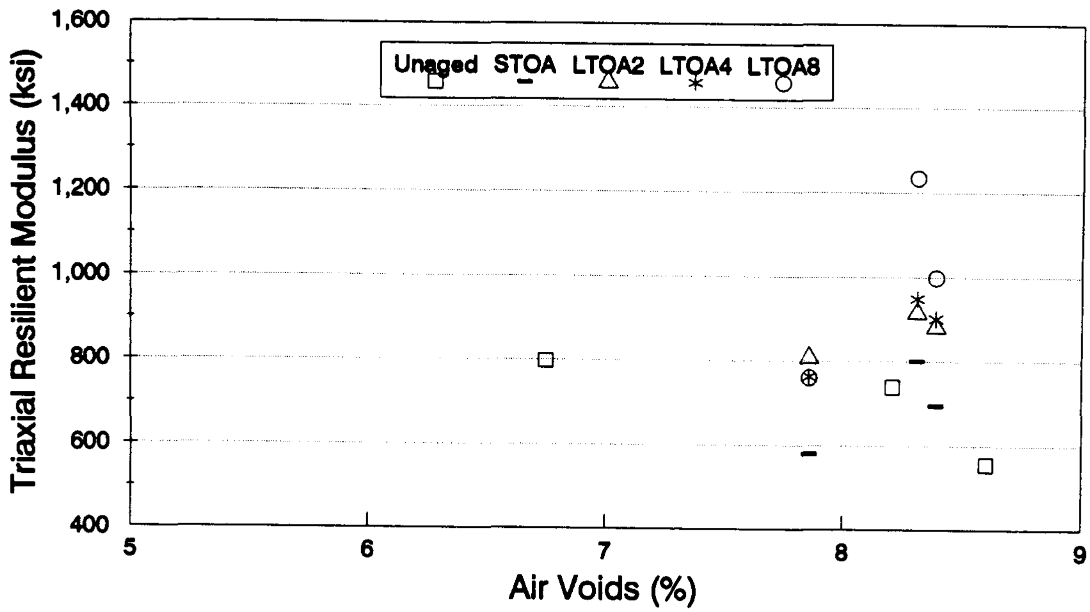

Figure 4.8d France C Section Triaxial Resilient Modulus, 85°C (185°F) Aging

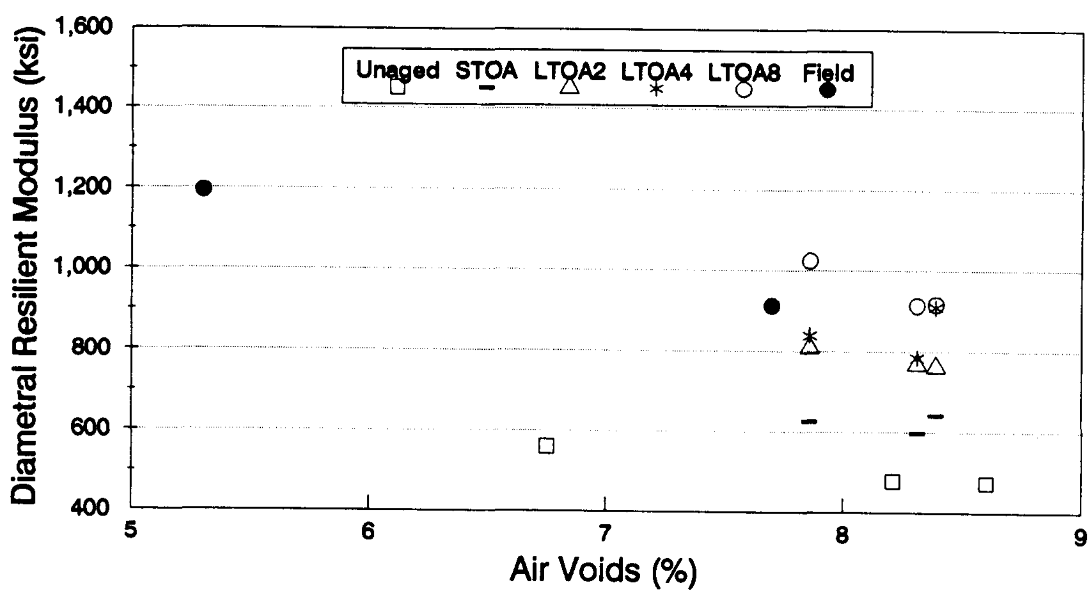

Figure 4.8e France C Section Diametral Resilient Modulus, 85°C (185°F) Aging

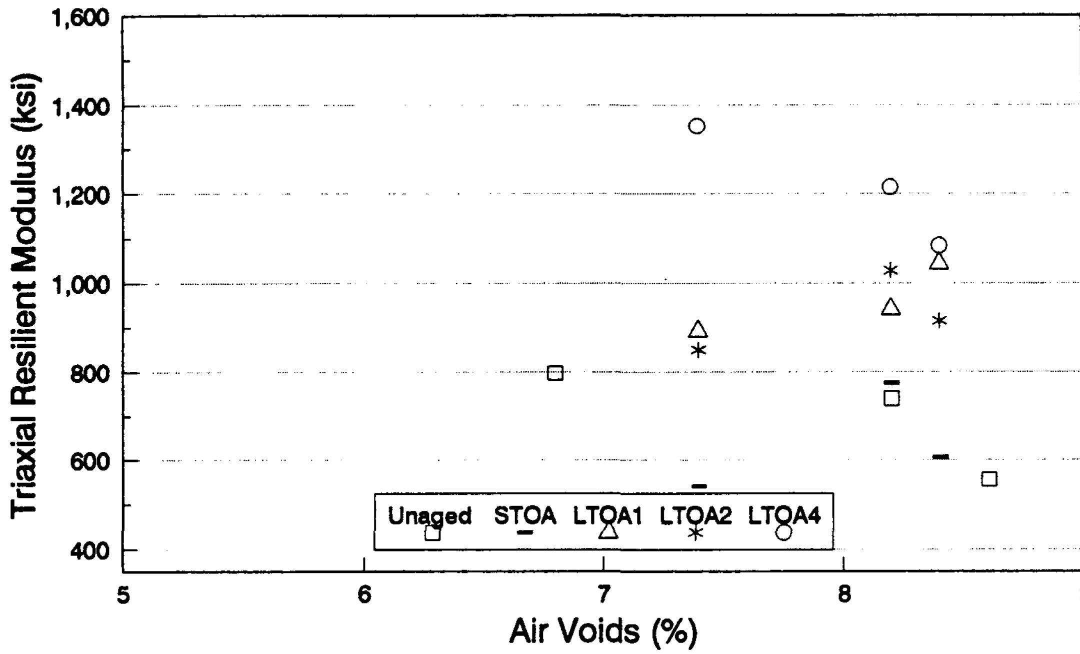

Figure 4.8f France C Section Triaxial Resilient Modulus, 100°C (212°F) Aging

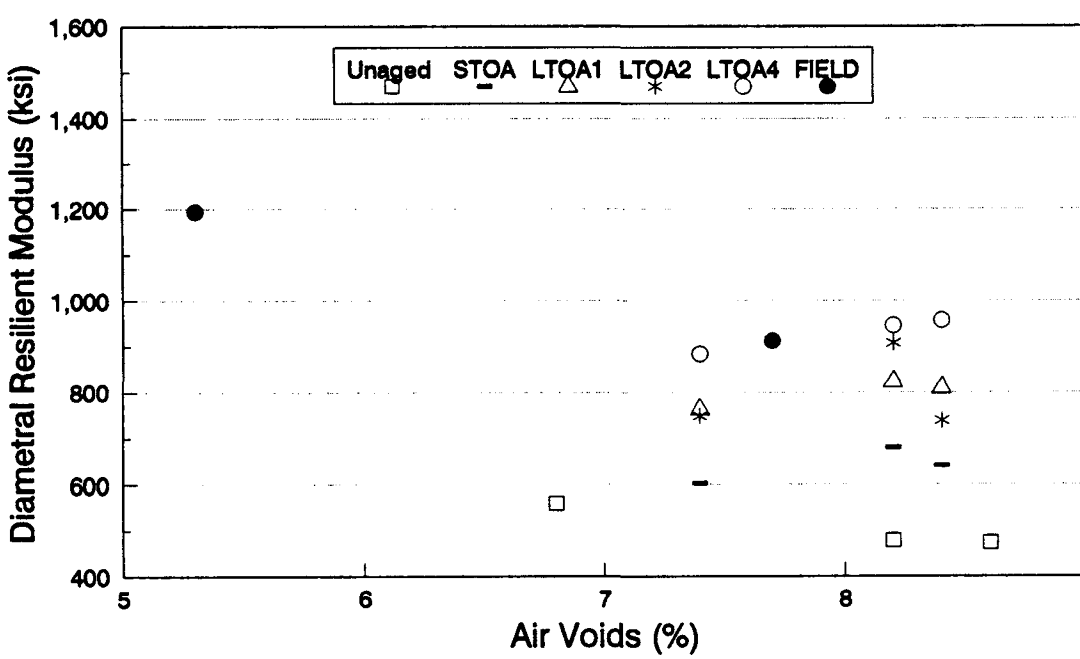

Figure 4.8g France C Section Diametral Resilient Modulus, 100°C (212°F) Aging

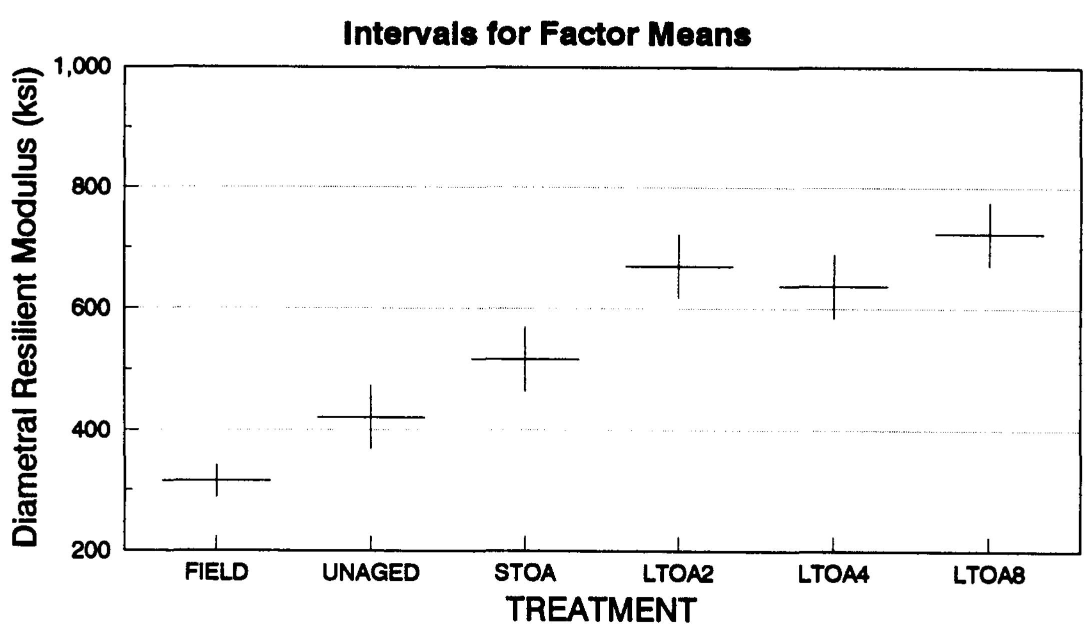

Figure 4.9a Georgia AAMAS Tukey Comparison, 85°C (185°F) Aging

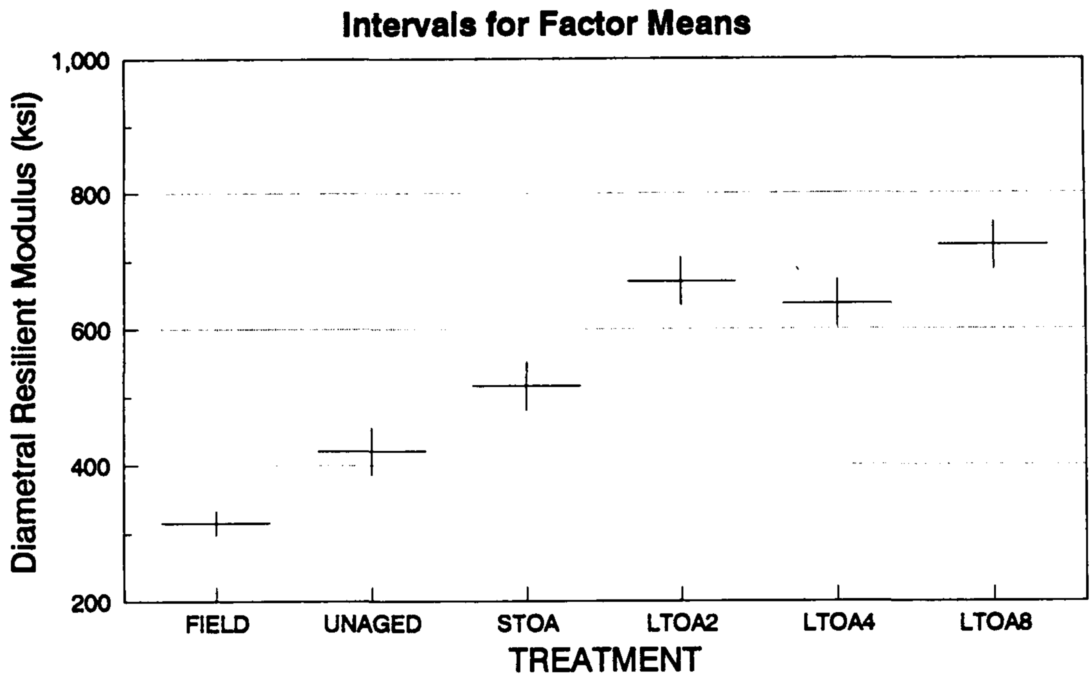

Figure 4.9b Georgia AAMAS LSD Comparison, 85°C (185°F) Aging

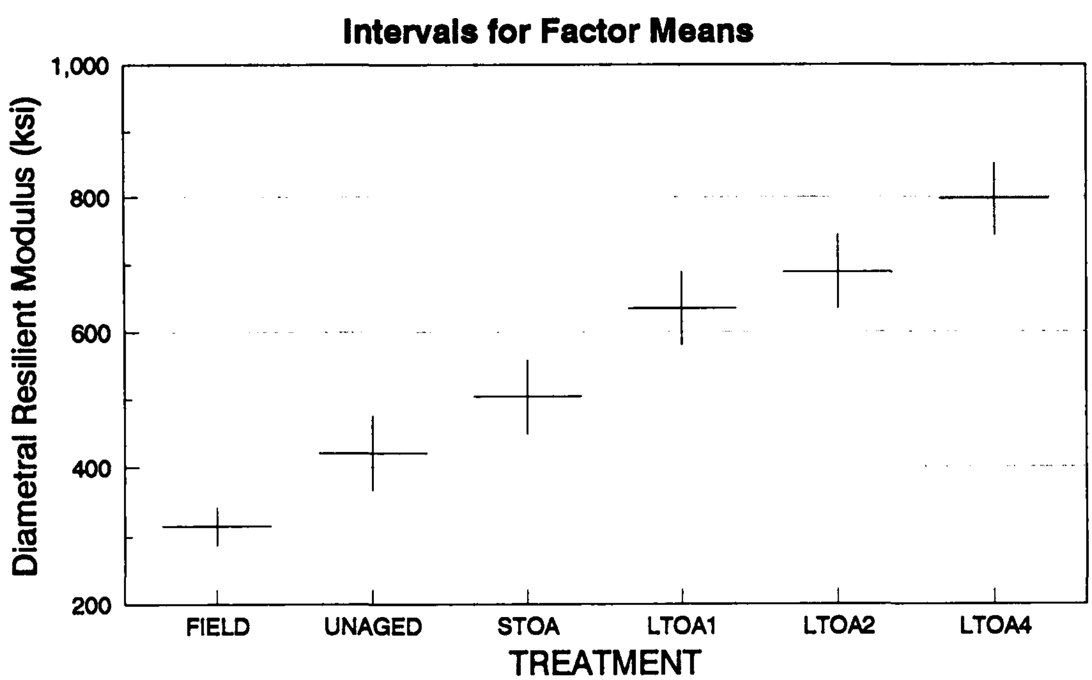

Figure 4.9c Georgia AAMAS LSD Comparison, 100°C (212°F) Aging

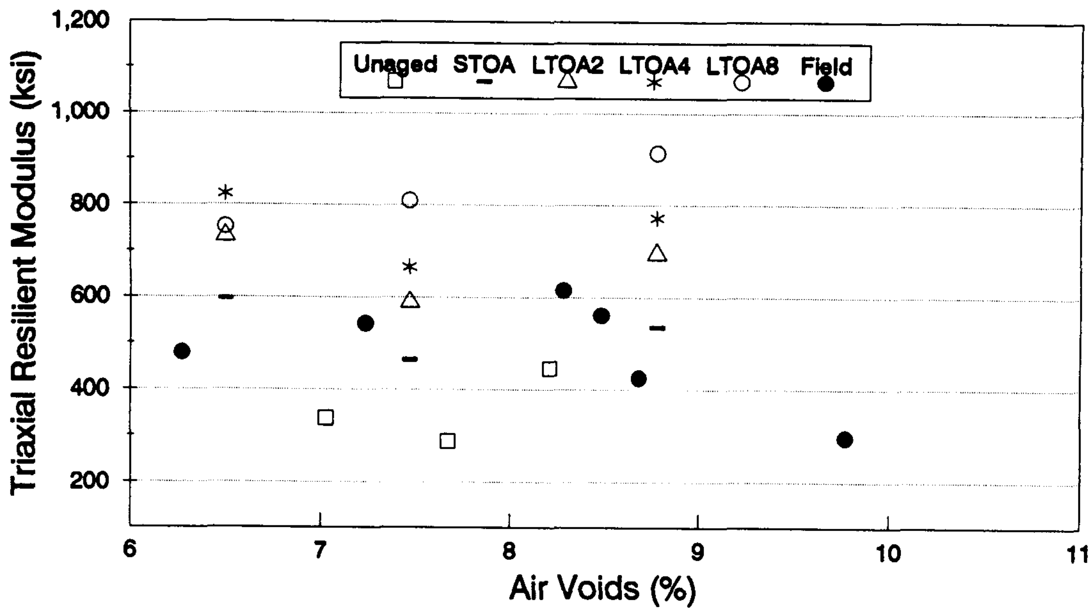

Figure 4.9d Georgia AAMAS Triaxial Resilient Modulus, 85°C (185°F) Aging

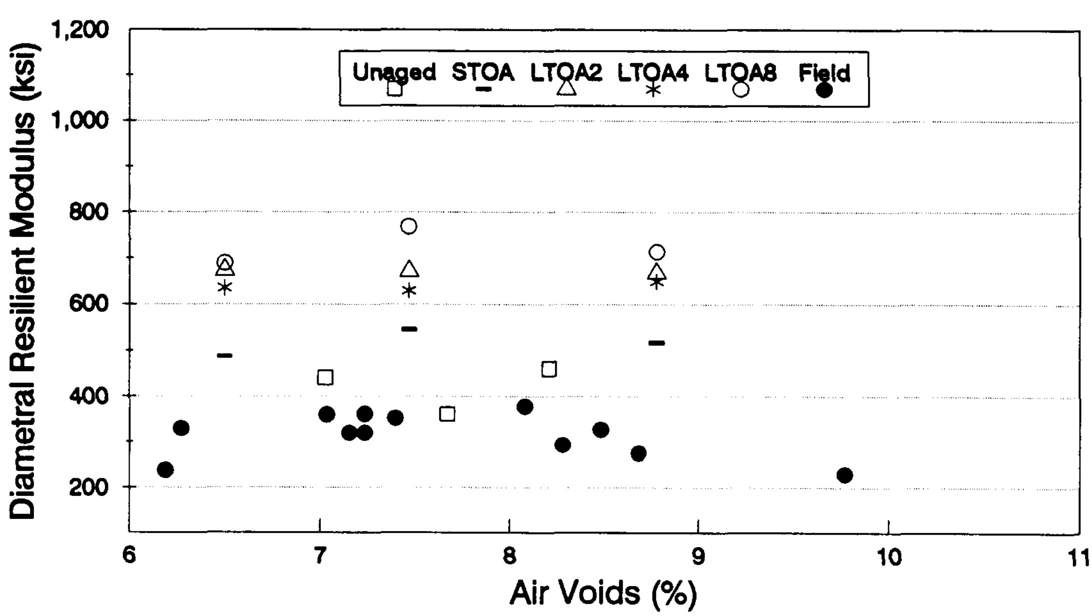

Figure 4.9e Georgia AAMAS Diametral Resilient Modulus, 85°C (185°F) Aging

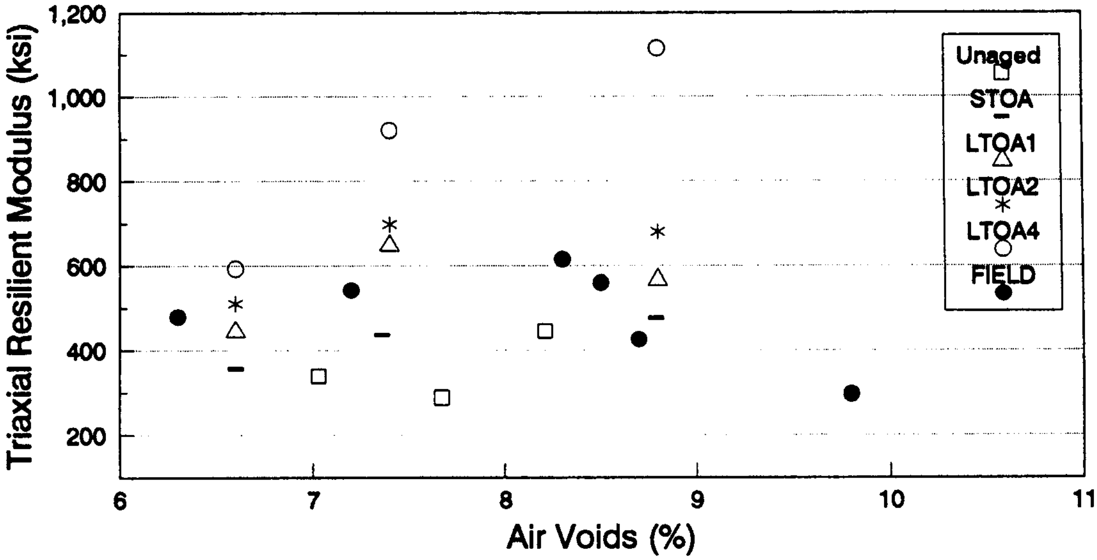

Figure 4.9f Georgia AAMAS Triaxial Resilient Modulus, 100°C (212°F) Aging

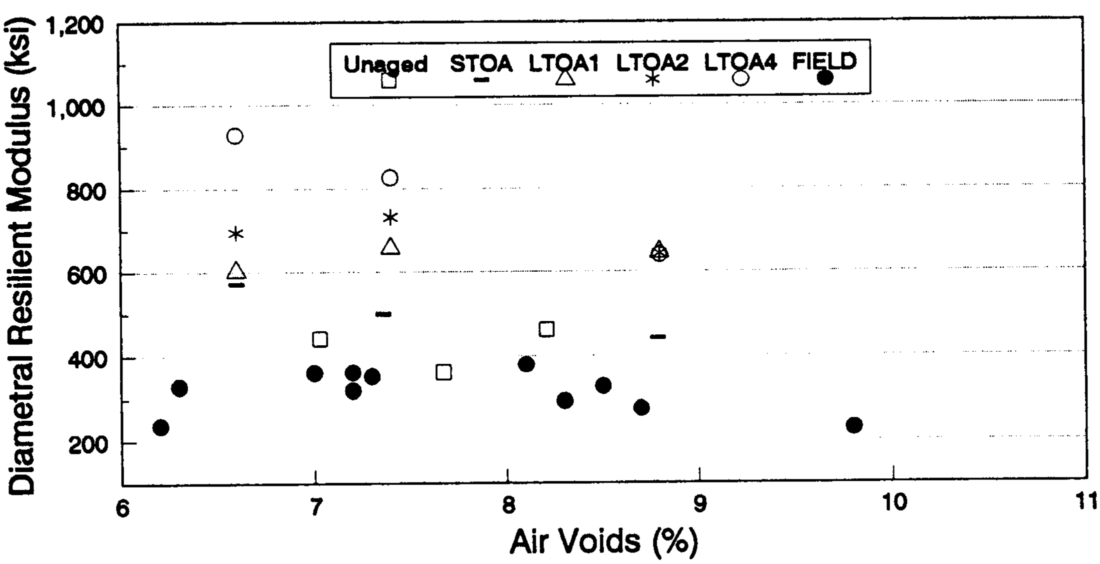

Figure 4.9g Georgia AAMAS Diametral Resilient Modulus, 100°C (212°F) Aging

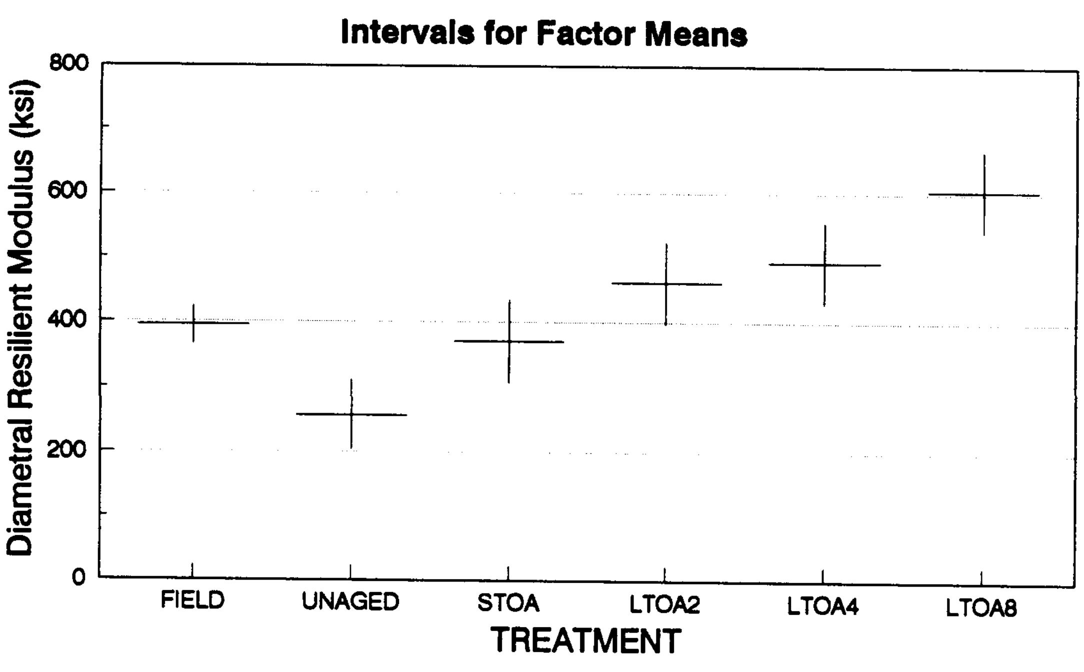

Figure 4.10a Michigan SPS-6 Tukey Comparison, 85°C (185°F) Aging

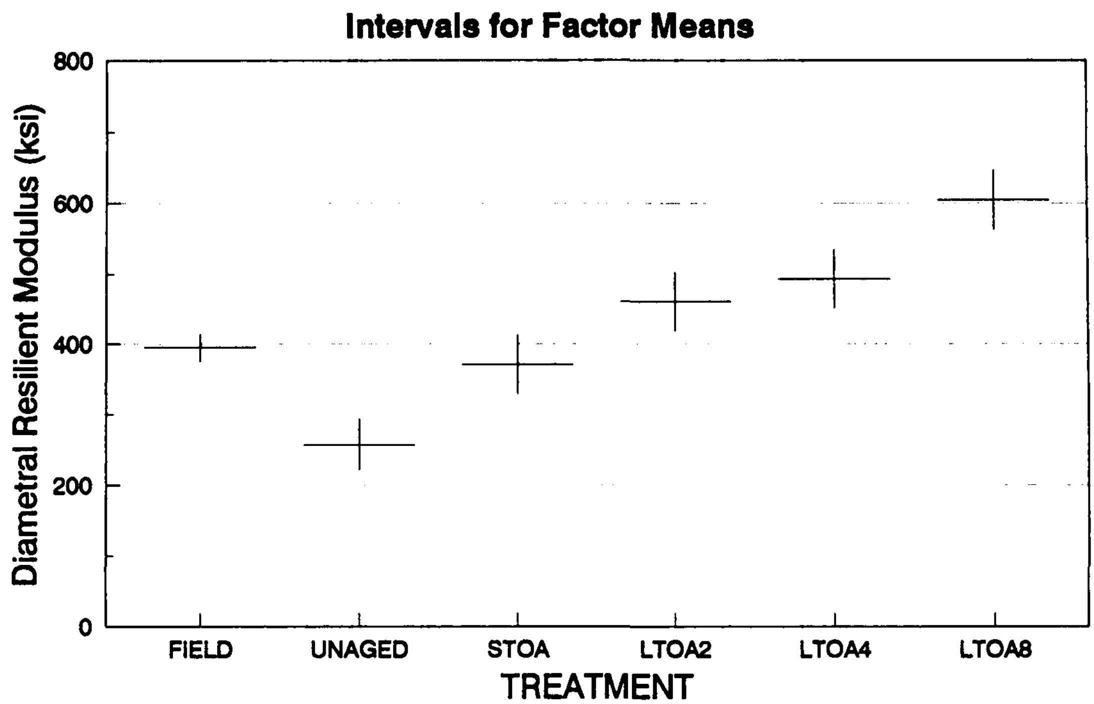

Figure 4.10b Michigan SPS-6 LSD Comparison, 85°C (185°F) Aging

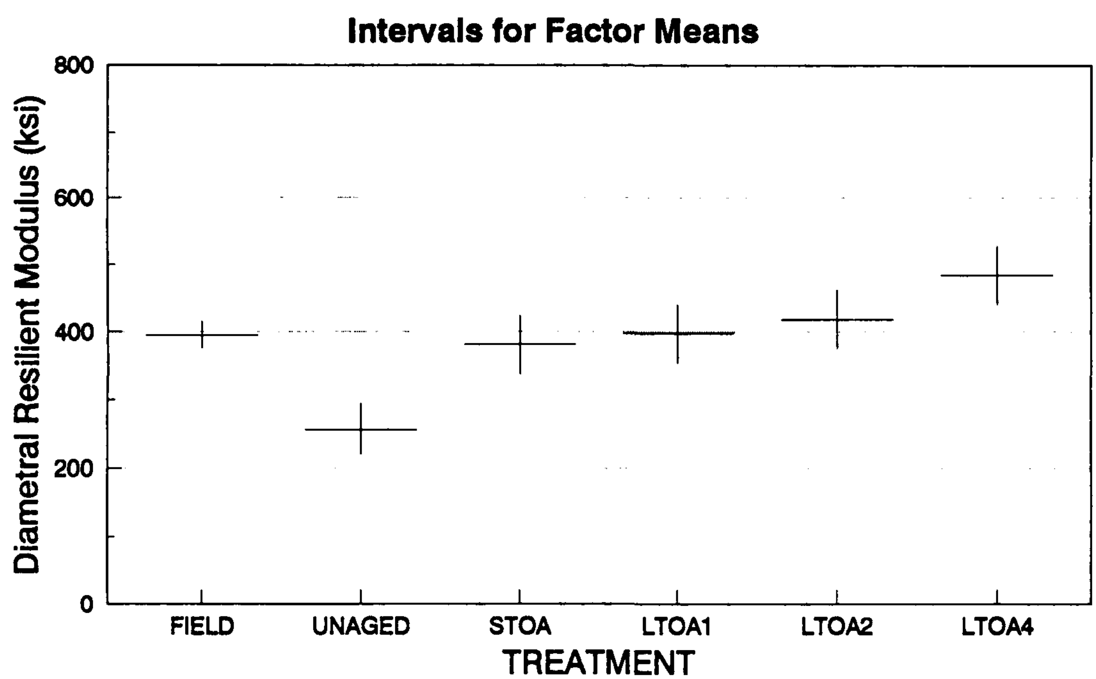

Figure 4.10c Michigan SPS-6 LSD Comparison, 100°C (212°F) Aging

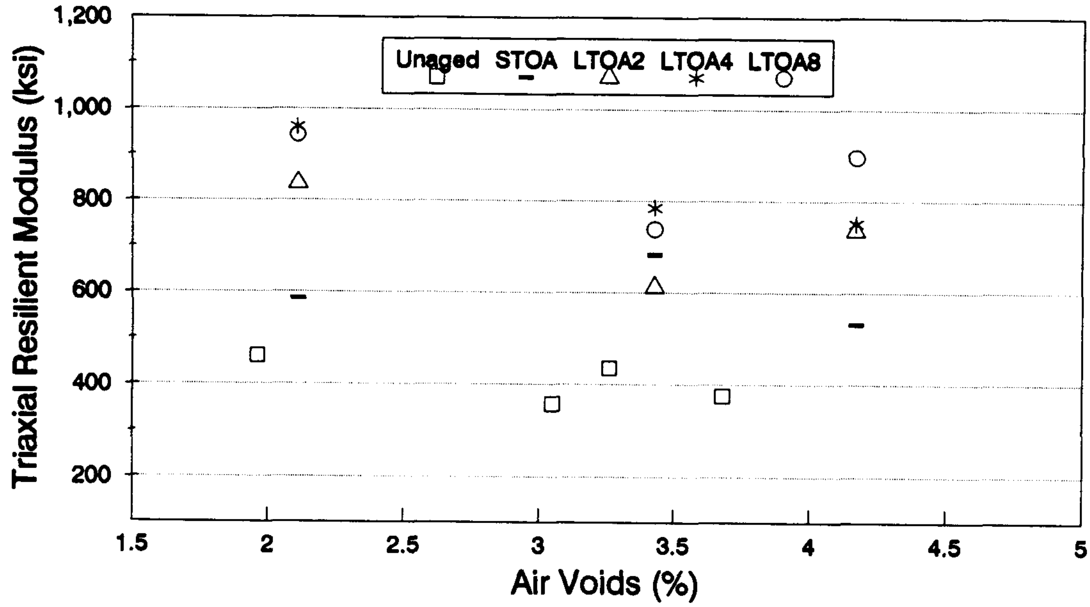

Figure 4.10d Michigan SPS-6 Triaxial Resilient Modulus, 85°C (185°F) Aging

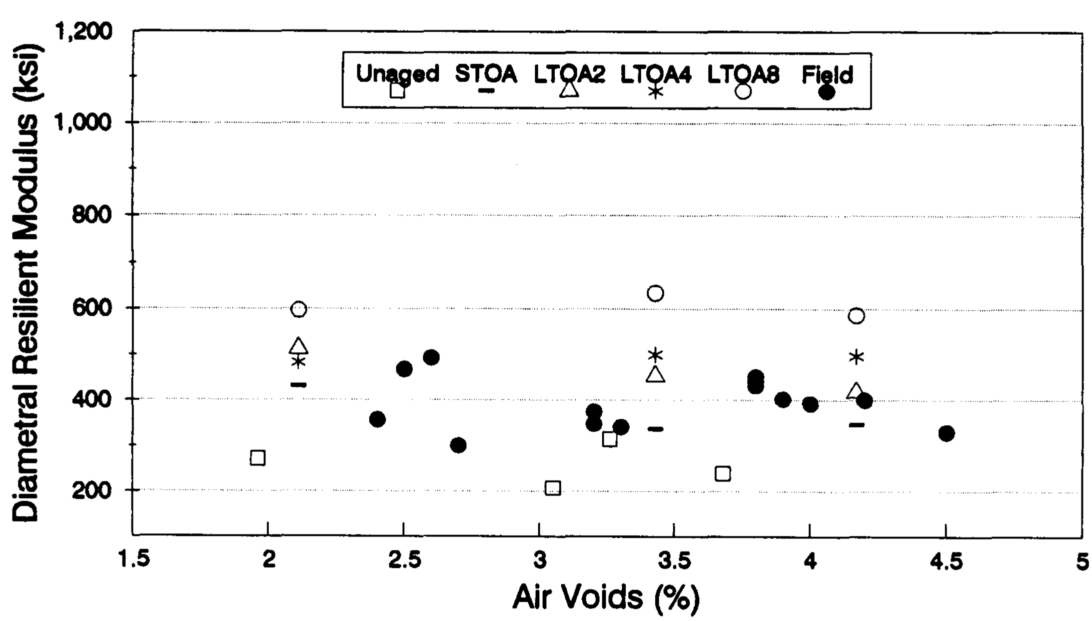

Figure 4.10e Michigan SPS-6 Diametral Resilient Modulus, 85°C (185°F) Aging

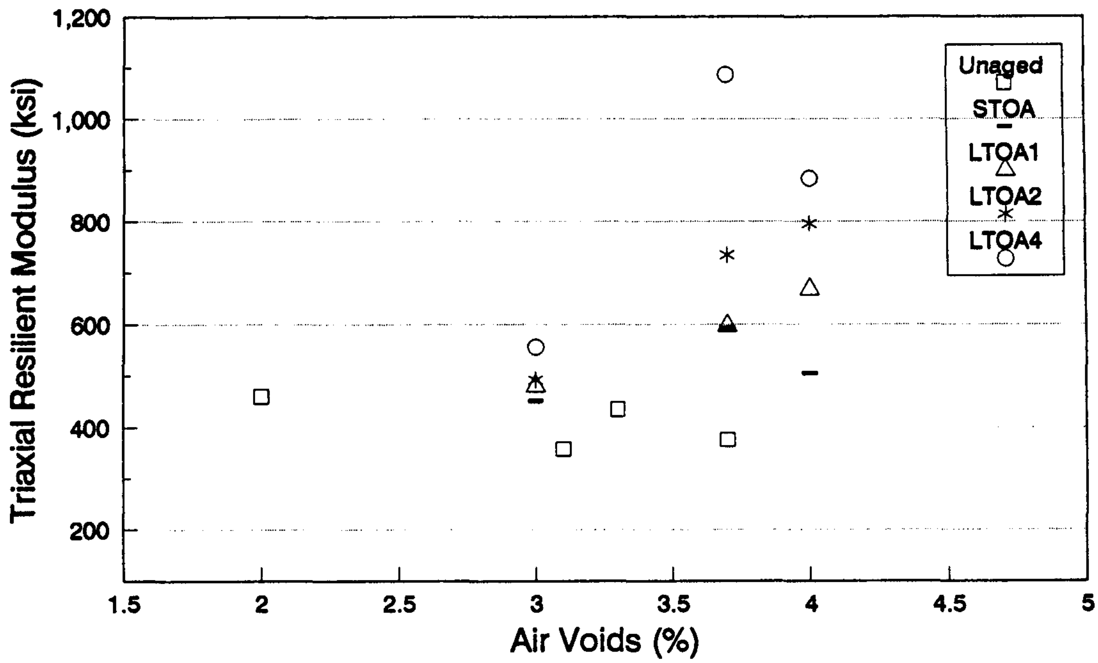

Figure 4.10f Michigan SPS-Triaxial Resilient Modulus, 100°C (212°F) Aging

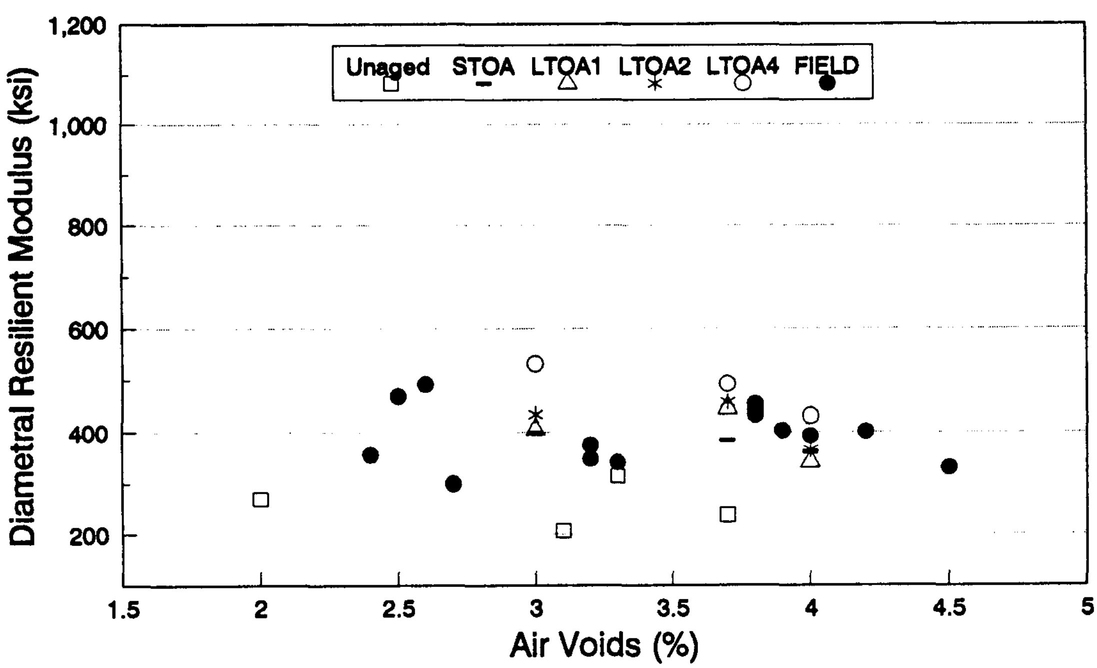

Figure 4.10g Michigan SPS-6 Diametral Resilient Modulus, 100°C (212°F) Aging

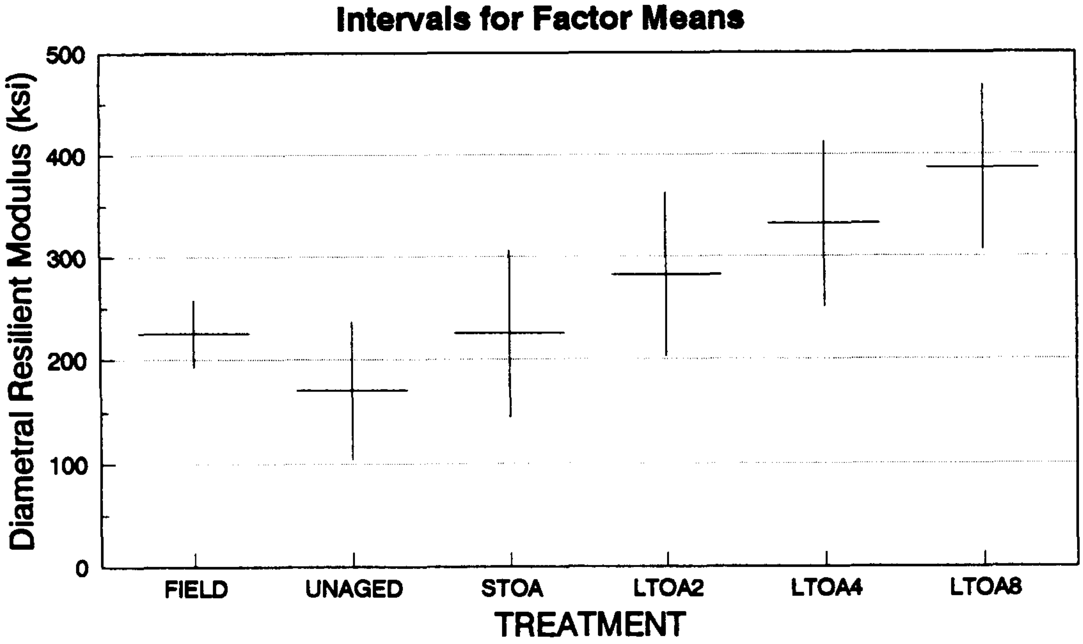

Figure 4.11a Minnesota SPS-5 Tukey Comparison, 85°C (185°F) Aging

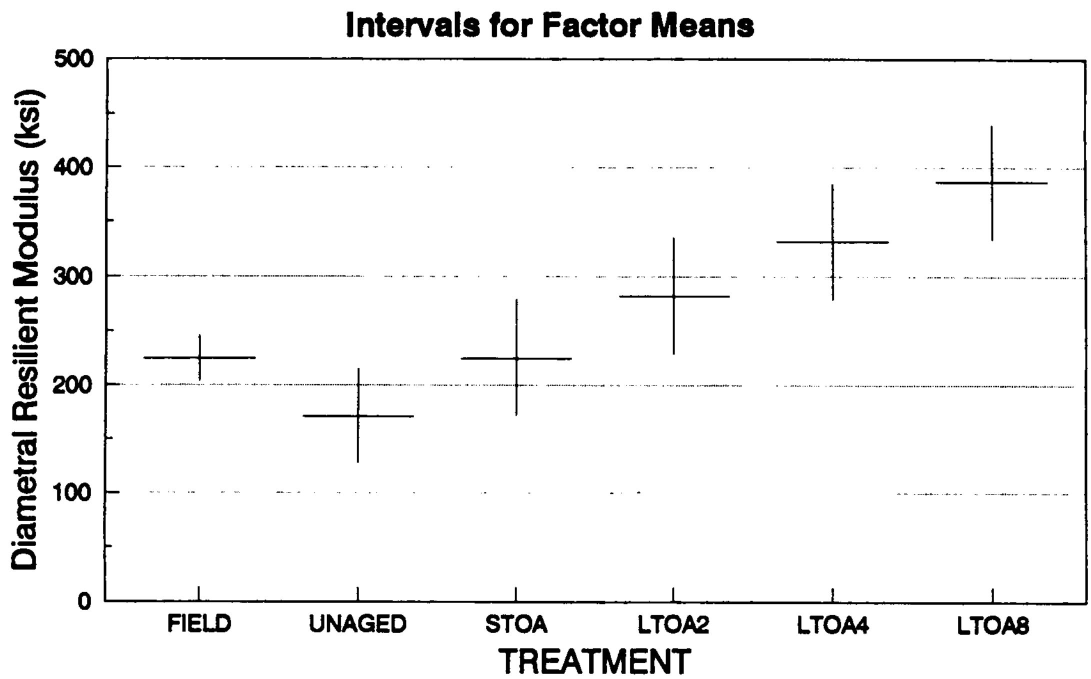

Figure 4.11b Minnesota SPS-5 LSD Comparison, 85°C (185°F) Aging

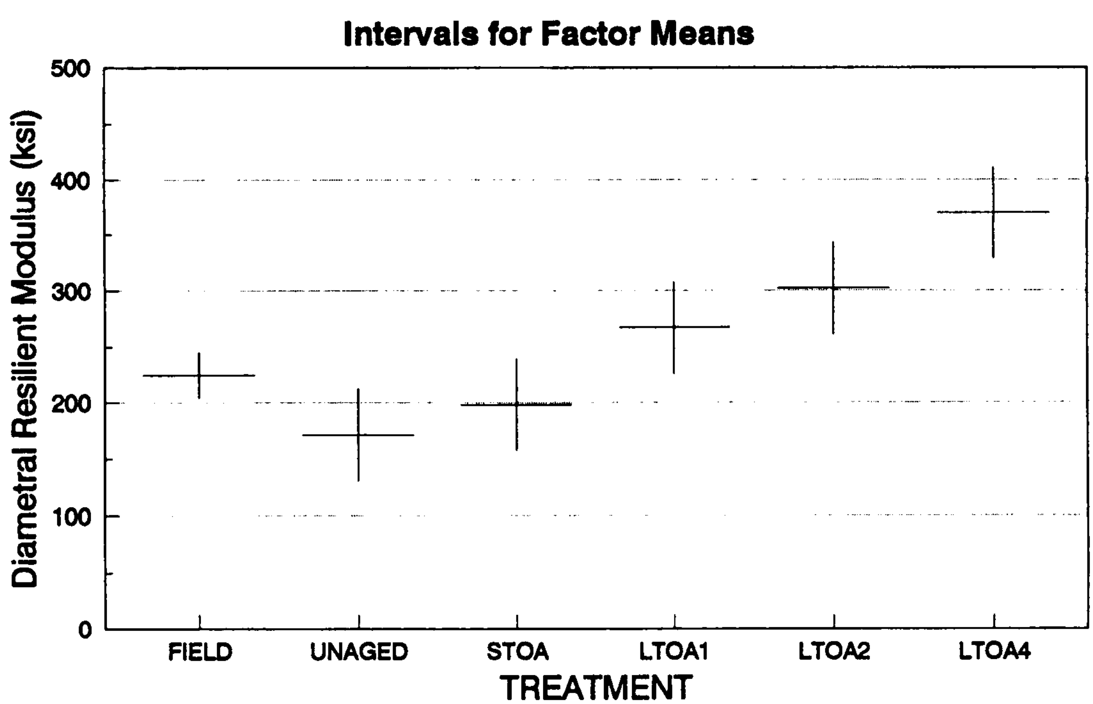

Figure 4.11c Minnesota SPS-5 LSD Comparison, 100°C (212°F) Aging

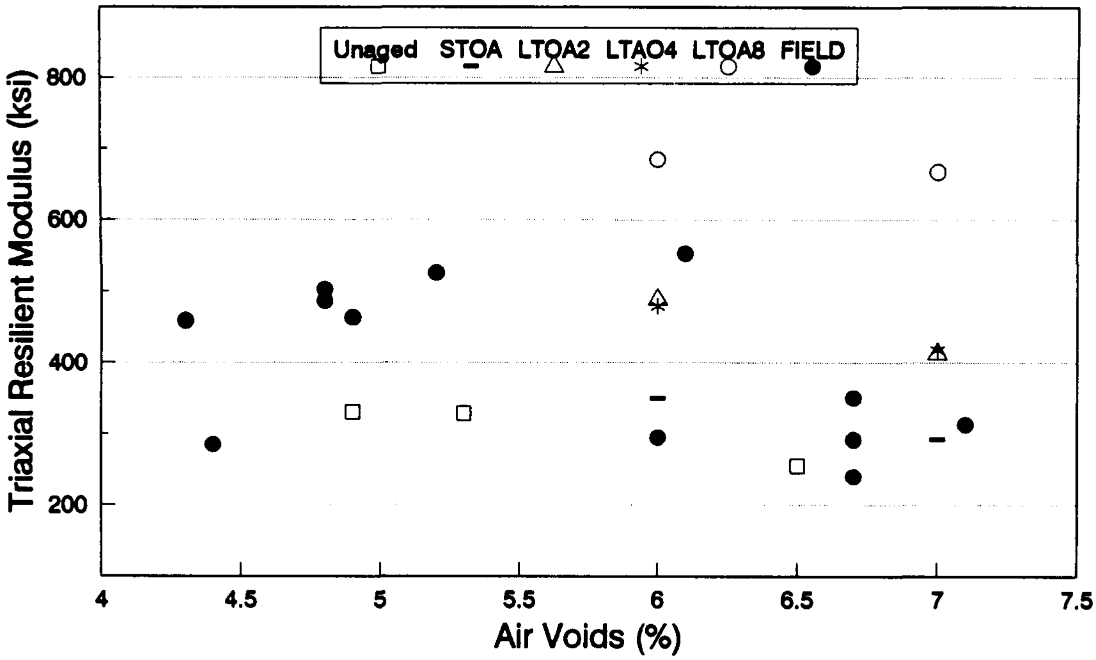

Figure 4.11d Minnesota SPS-5 Triaxial Resilient Modulus, 85°C (185°F) Aging

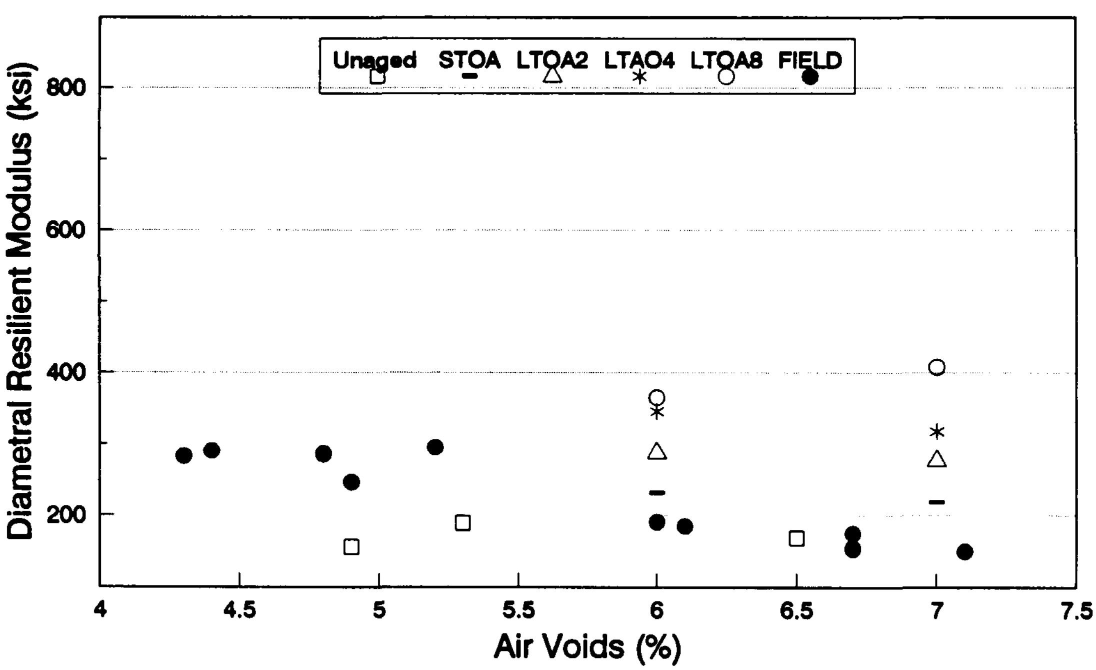

Figure 4.11e Minnesota SPS-5 Diametral Resilient Modulus, 85°C (185°F) Aging

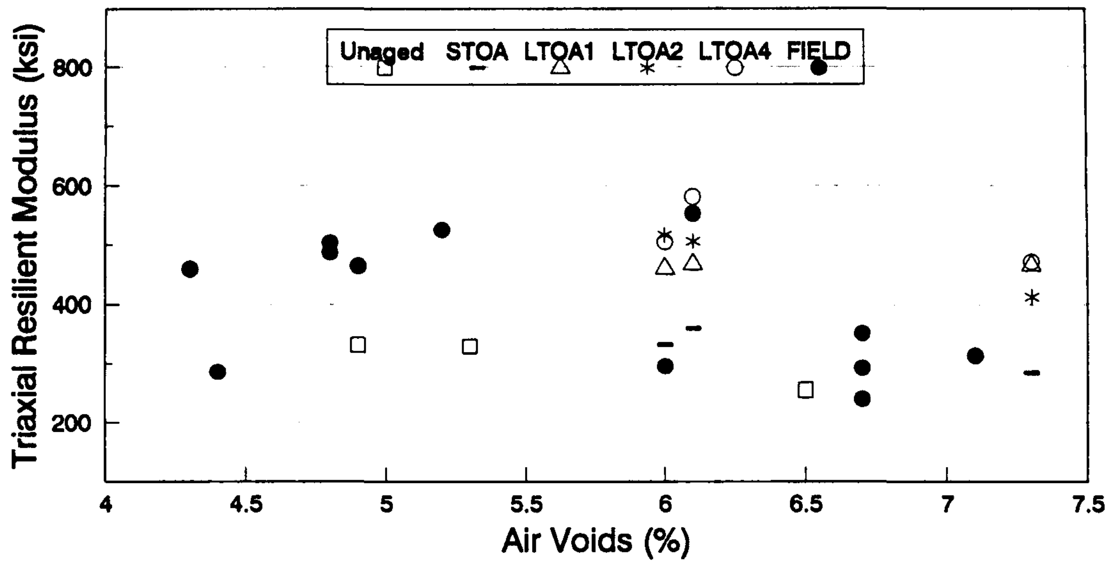

Figure 4.11f Minnesota SPS-5 Triaxial Resilient Modulus, 100°C (212°F) Aging

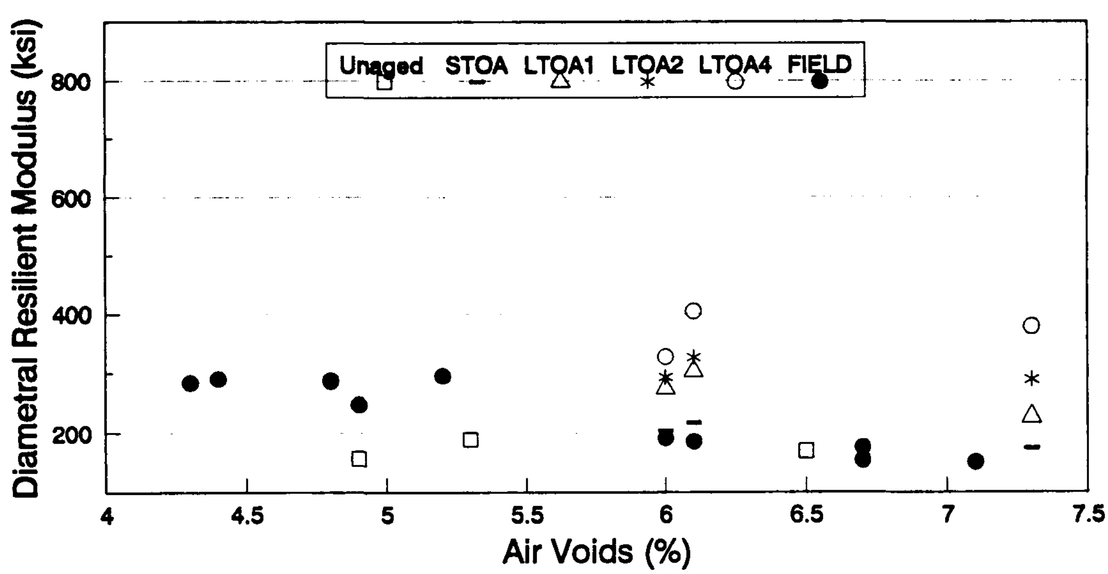

Figure 4.11g Minnesota SPS-5 Diametral Resilient Modulus, 100°C (212°F) Aging

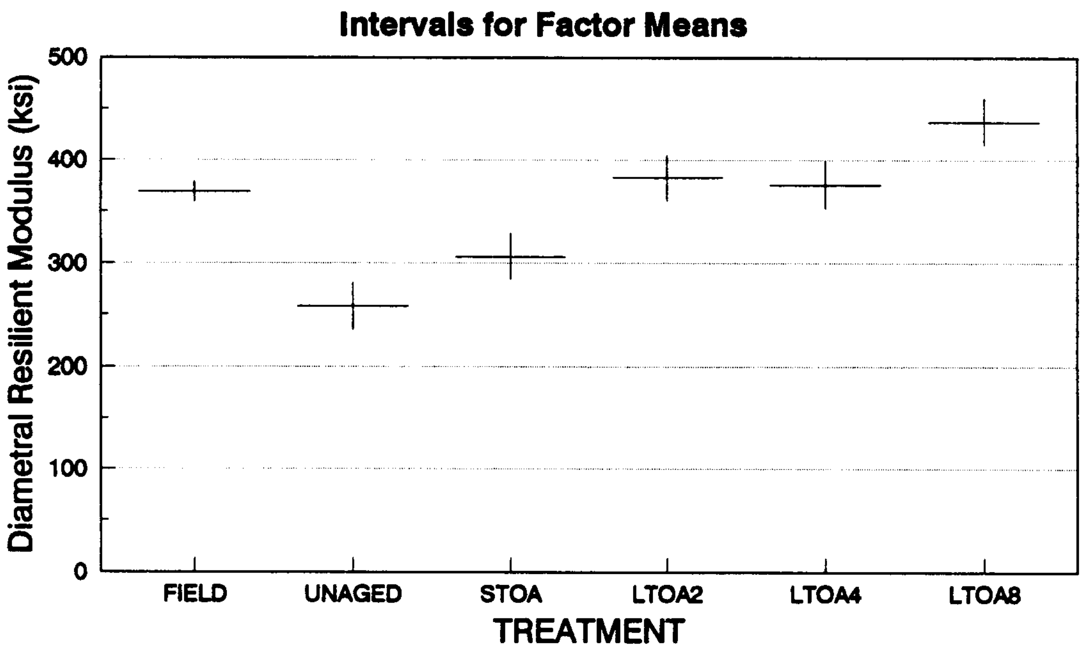

Figure 4.12a Wisconsin AAMAS Tukey Comparison, 85°C (185°F) Aging

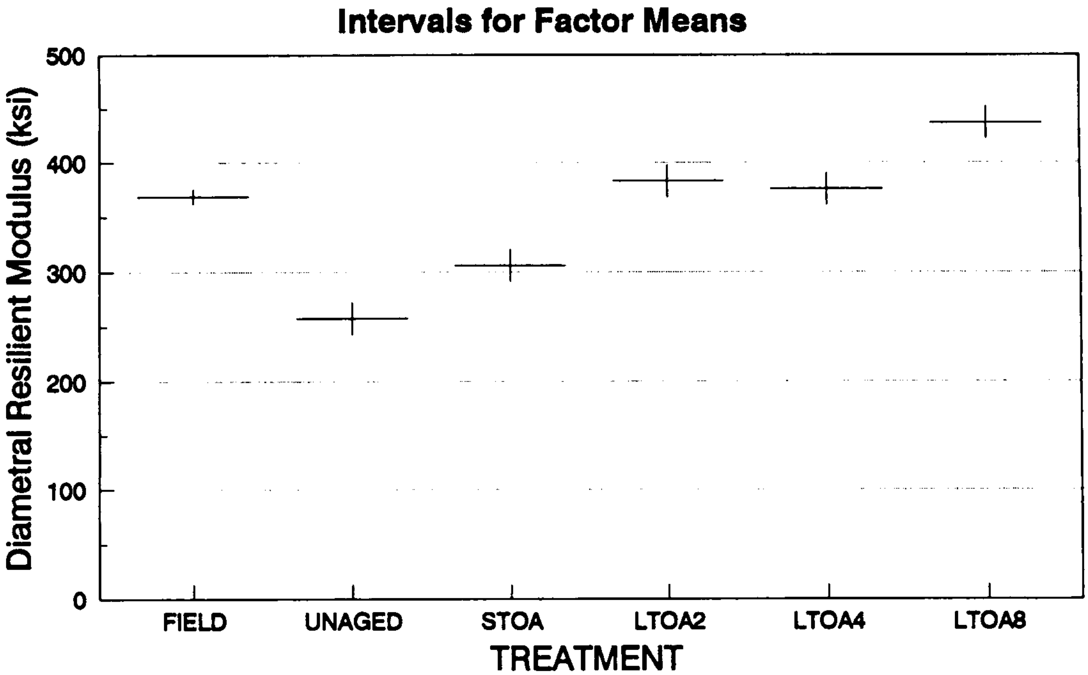

Figure 4.12b Wisconsin AAMAS LSD Comparison, 85°C (185°F) Aging

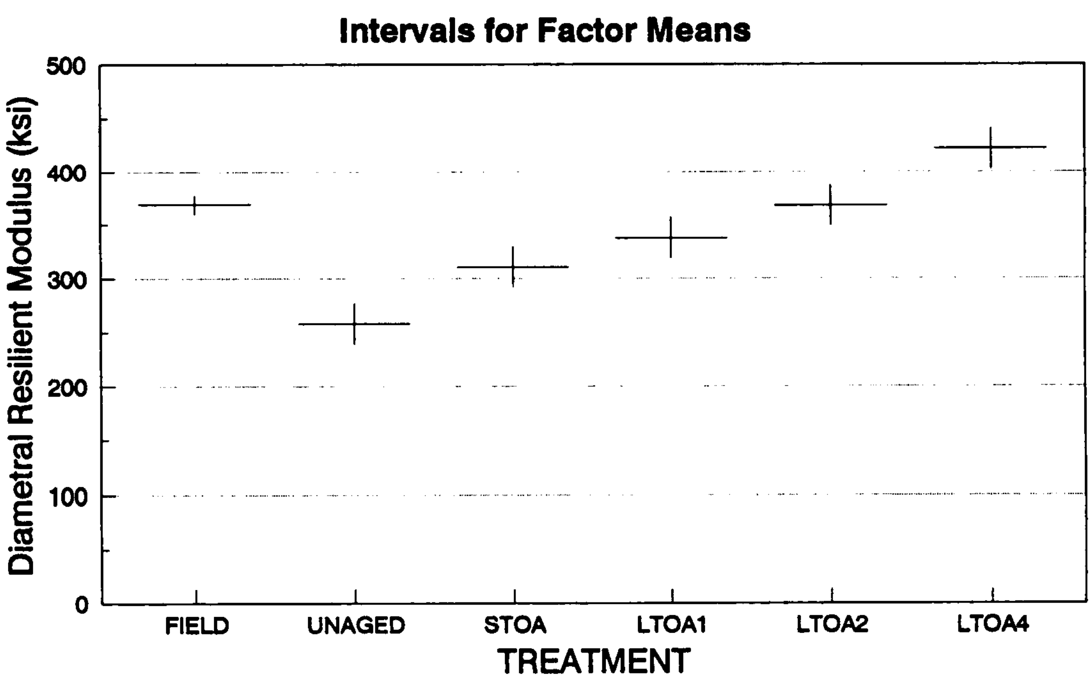

Figure 4.12c Wisconsin AAMAS LSD Comparison, 100°C (212°F) Aging

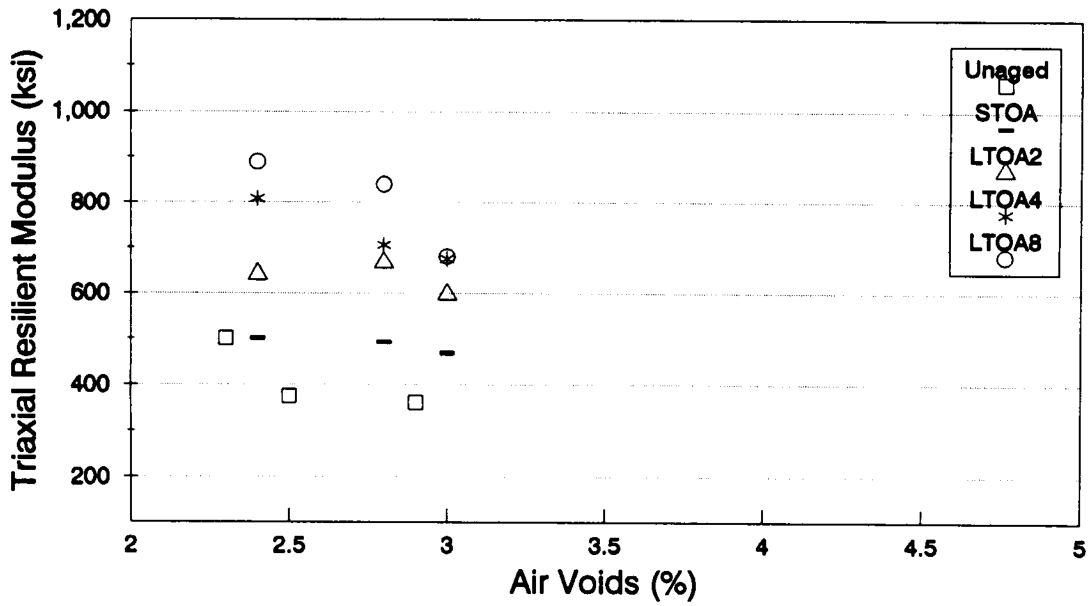

Figure 4.12d Wisconsin AAMAS Triaxial Resilient Modulus, 85°C (185°F) Aging

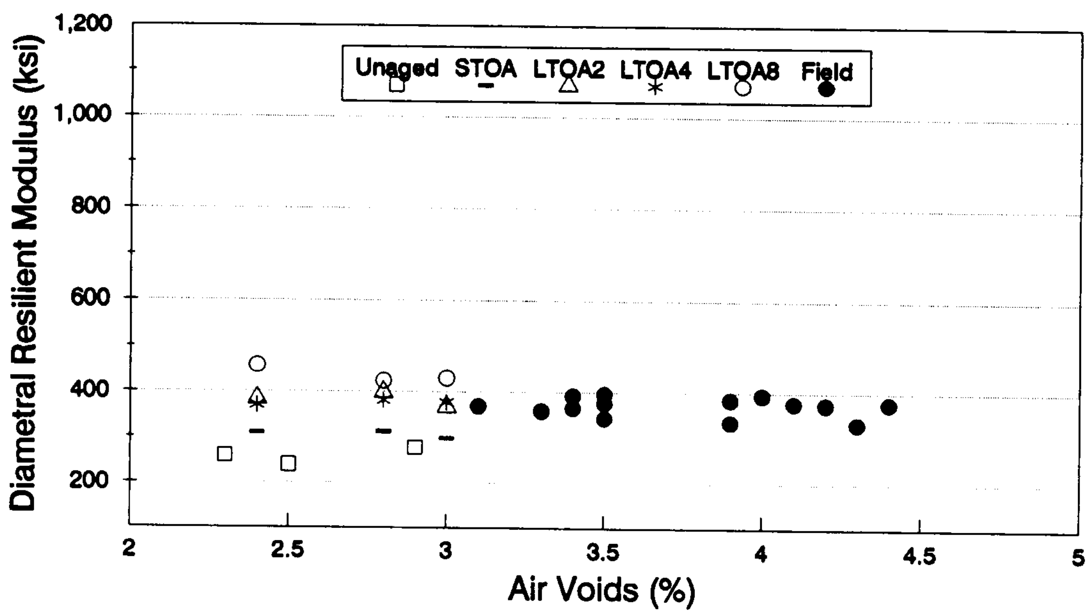

Figure 4.12e Wisconsin AAMAS Diametral Resilient Modulus, 85°C (185°F) Aging

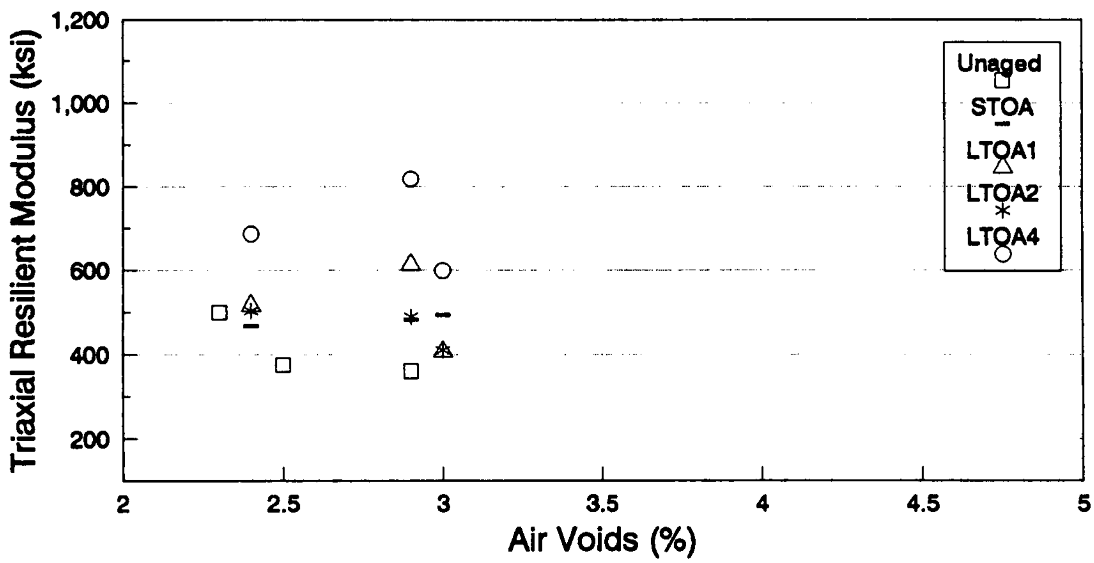

Figure 4.12f Wisconsin AAMAS Triaxial Resilient Modulus, 100°C (212°F) Aging

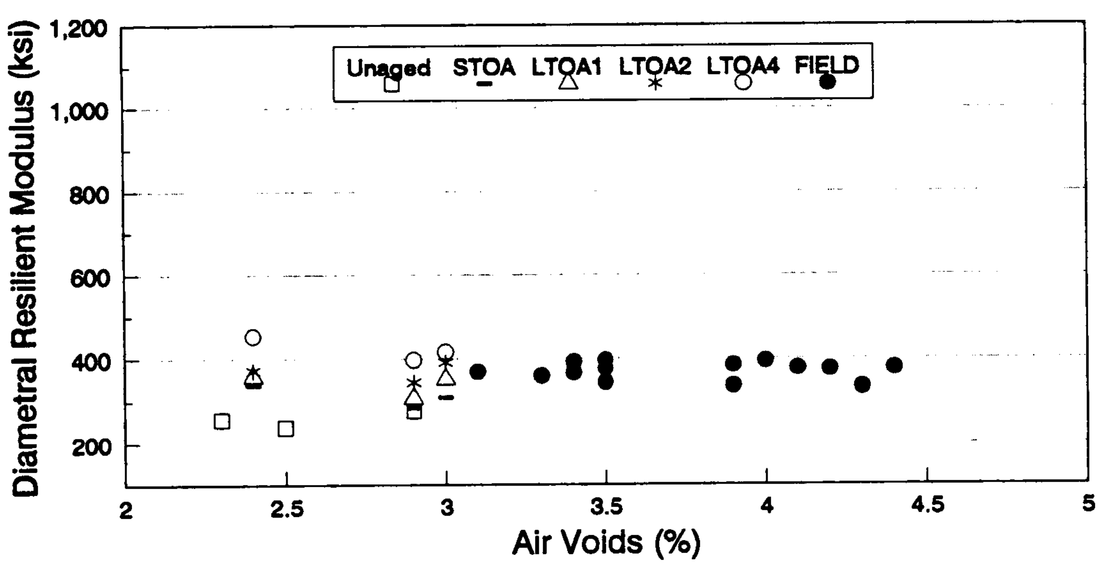

Figure 4.12g Wisconsin AAMAS Diametral Resilient Modulus, 100°C (212°F) Aging

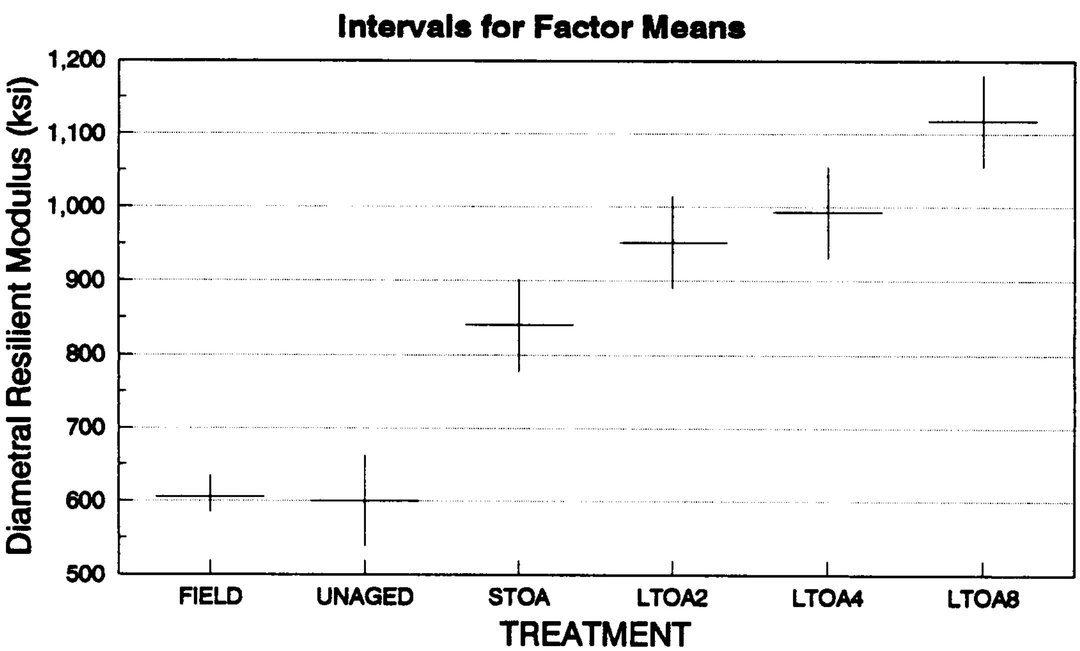

Figure 4.13a Combined California AAMAS Tukey Comparison, 85°C (185°F) Aging

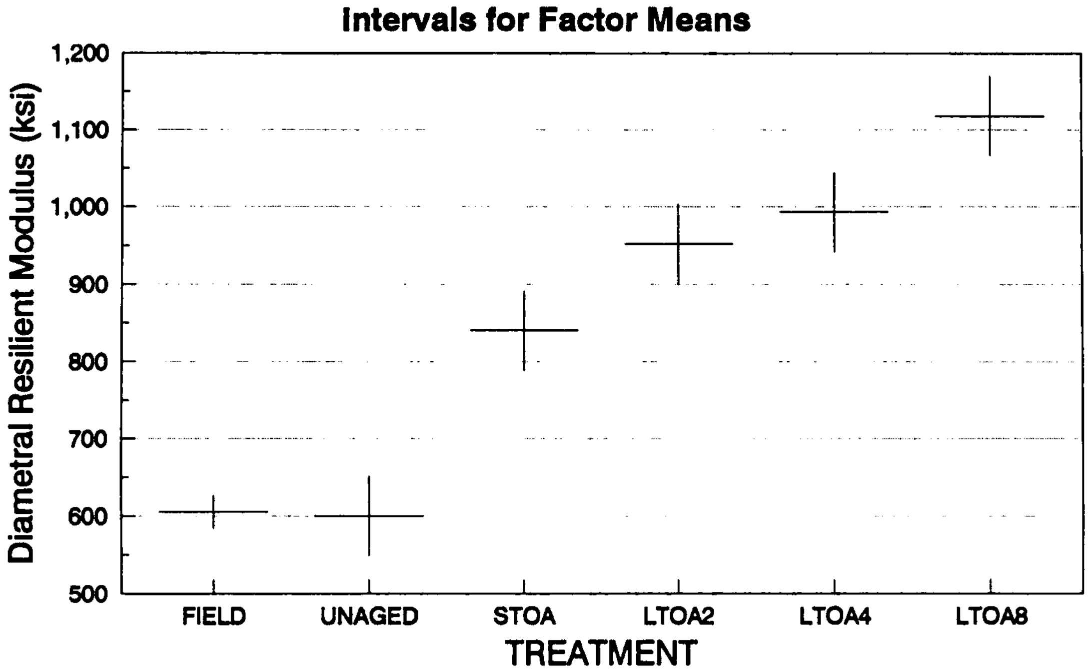

Figure 4.13b Combined California AAMAS LSD Comparison, 85°C (185°F) Aging

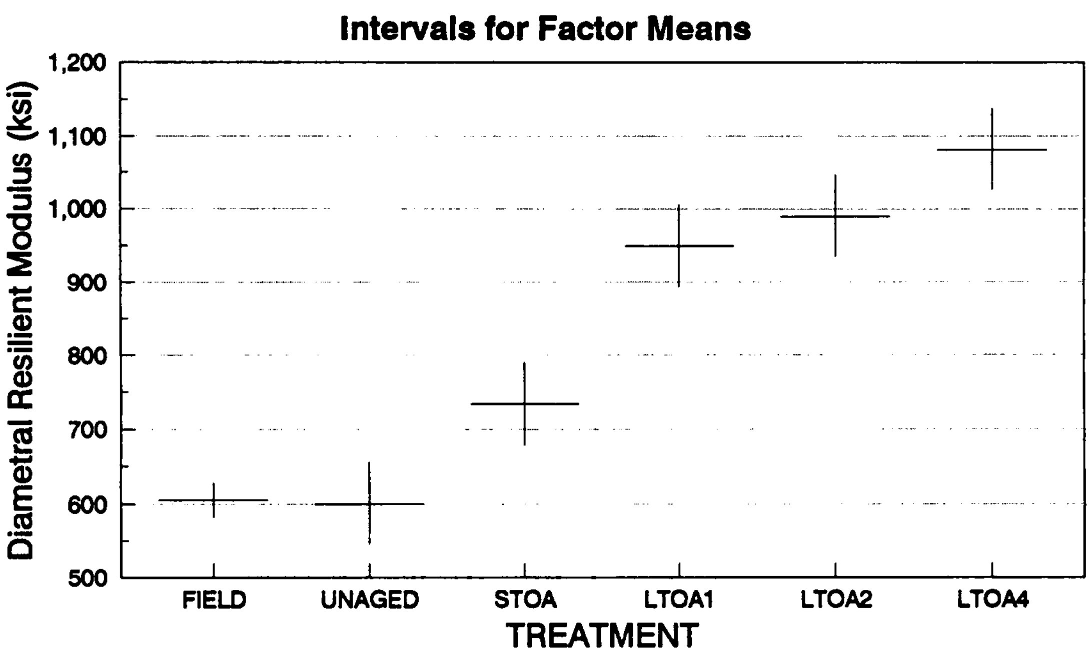

Figure 4.13c Combined California AAMAS LSD Comparison, 100°C (212°F) Aging

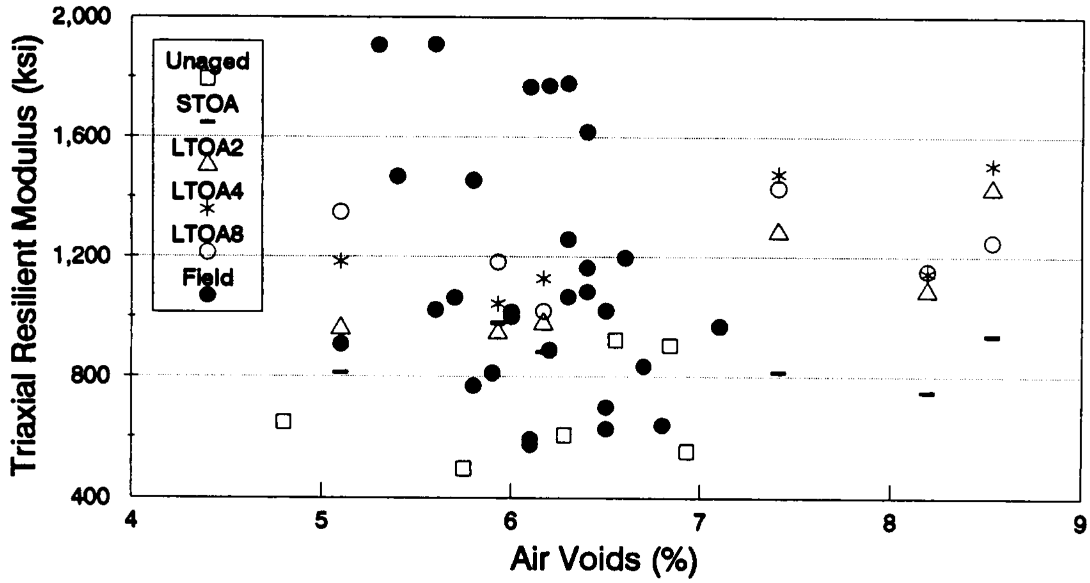

Figure 4.13d Combined California AAMAS Triaxial Resilient Modulus, 85°C (185°F) Aging

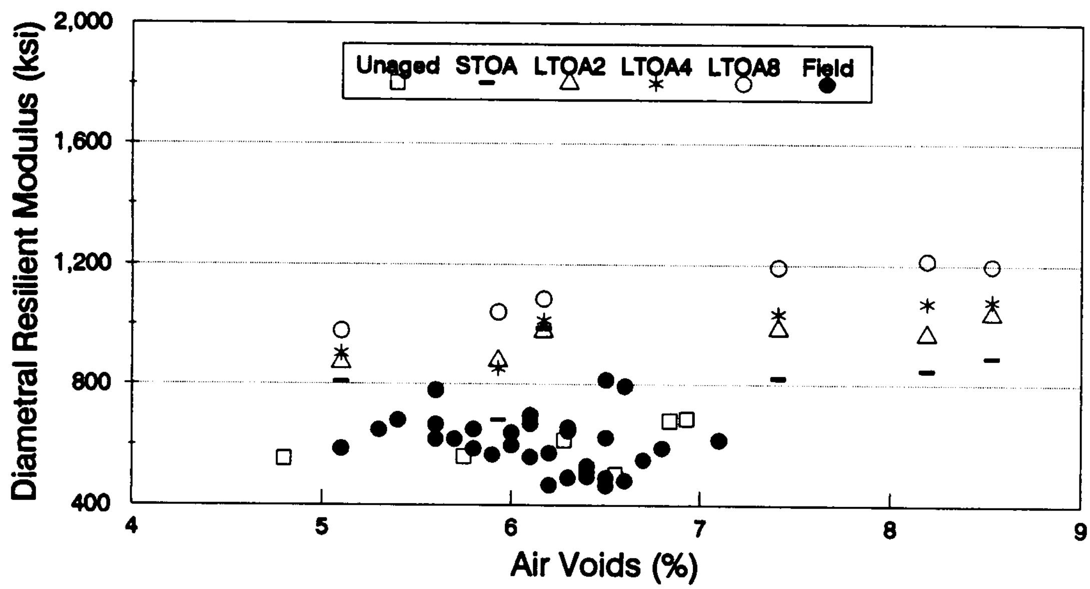

Figure 4.13e Combined California AAMAS Diametral Resilient Modulus, 85°C (185°F) Aging

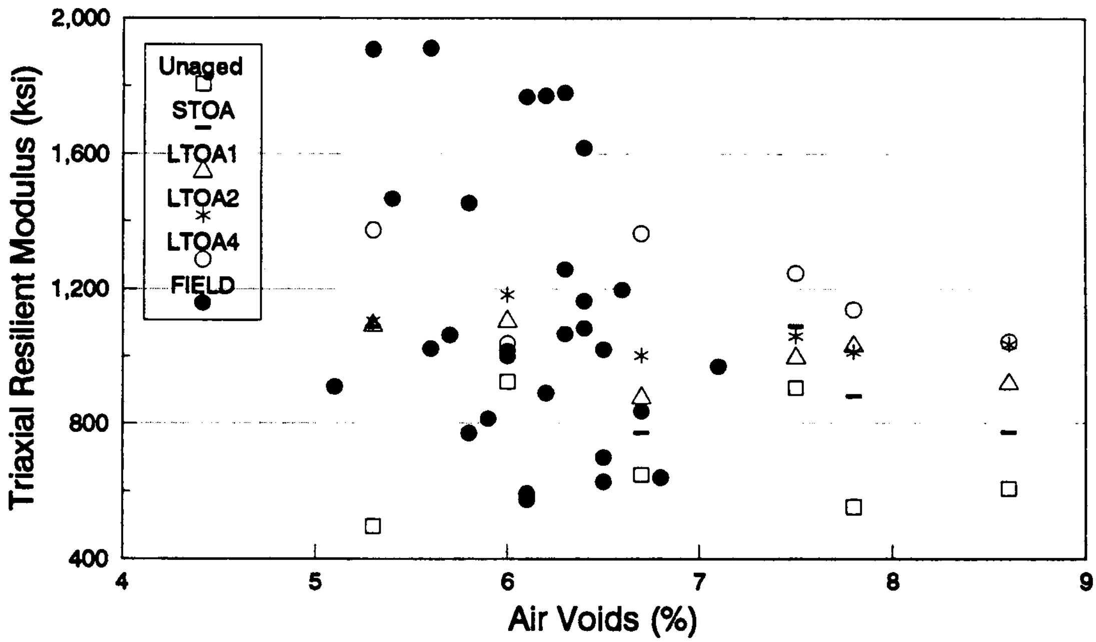

Figure 4.13f Combined California AAMAS Triaxial Resilient Modulus, 100°C (212°F) Aging

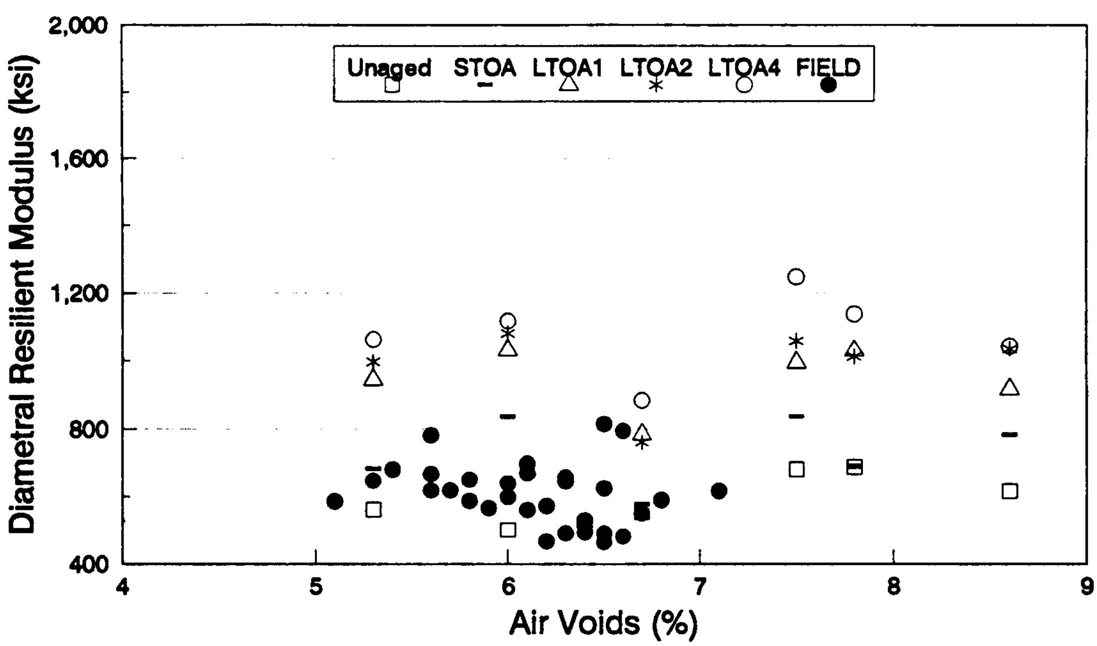

Figure 4.13g Combined California AAMAS Diametral Resilient Modulus, 100°C (212°F) Aging

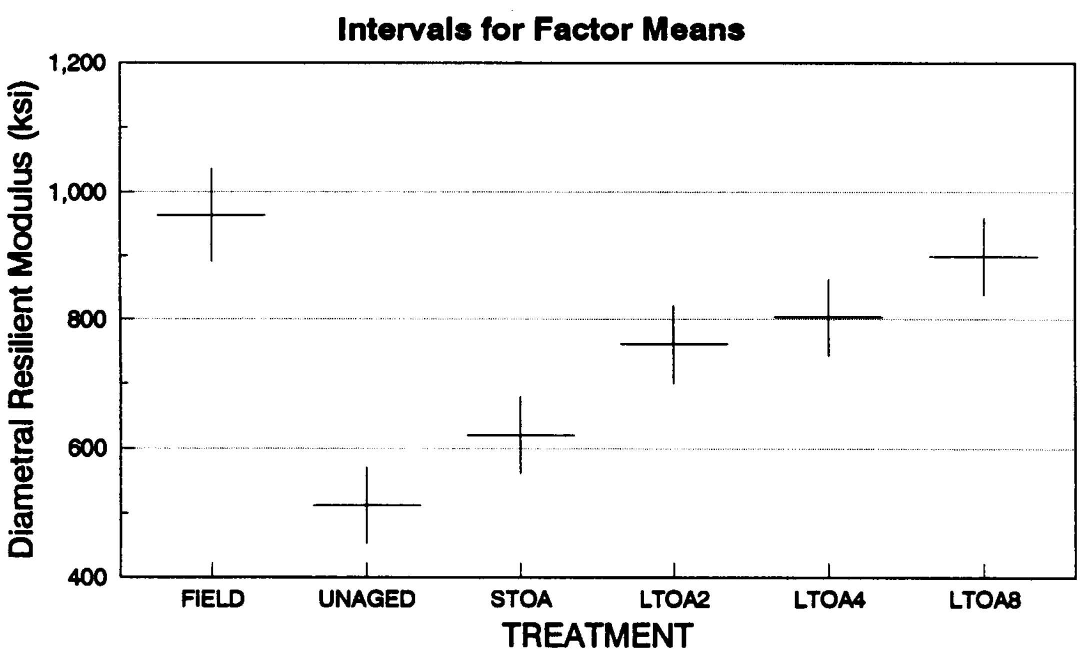

Figure 4.14a Combined France Sections Tukey Comparison, 85°C (185°F) Aging

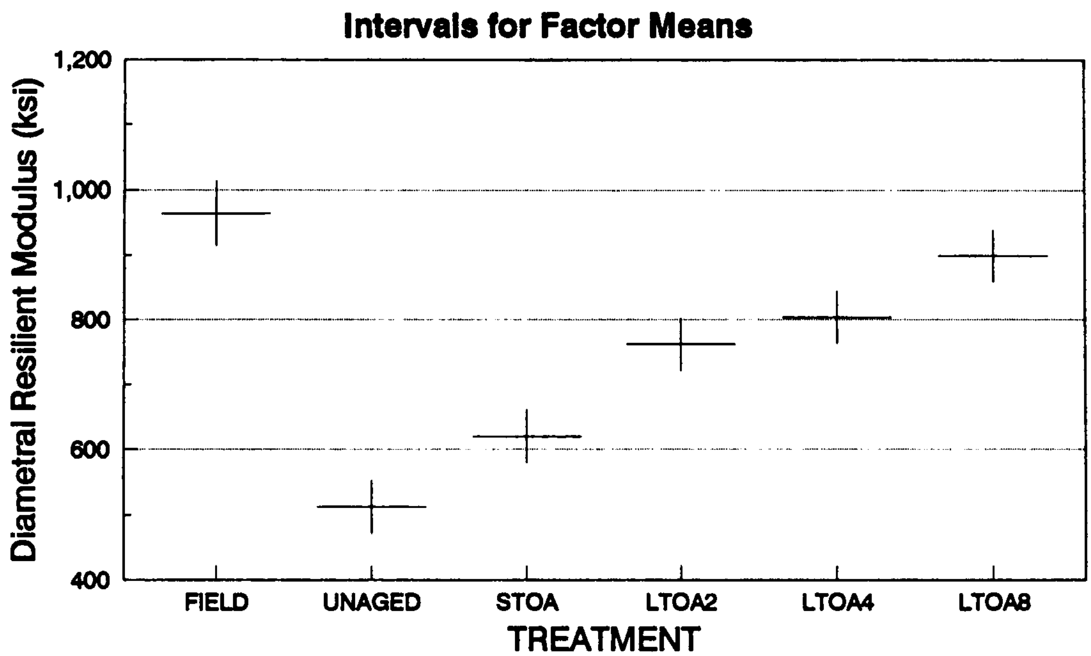

Figure 4.14b Combined France Sections LSD Comparison, 85°C (185°F) Aging

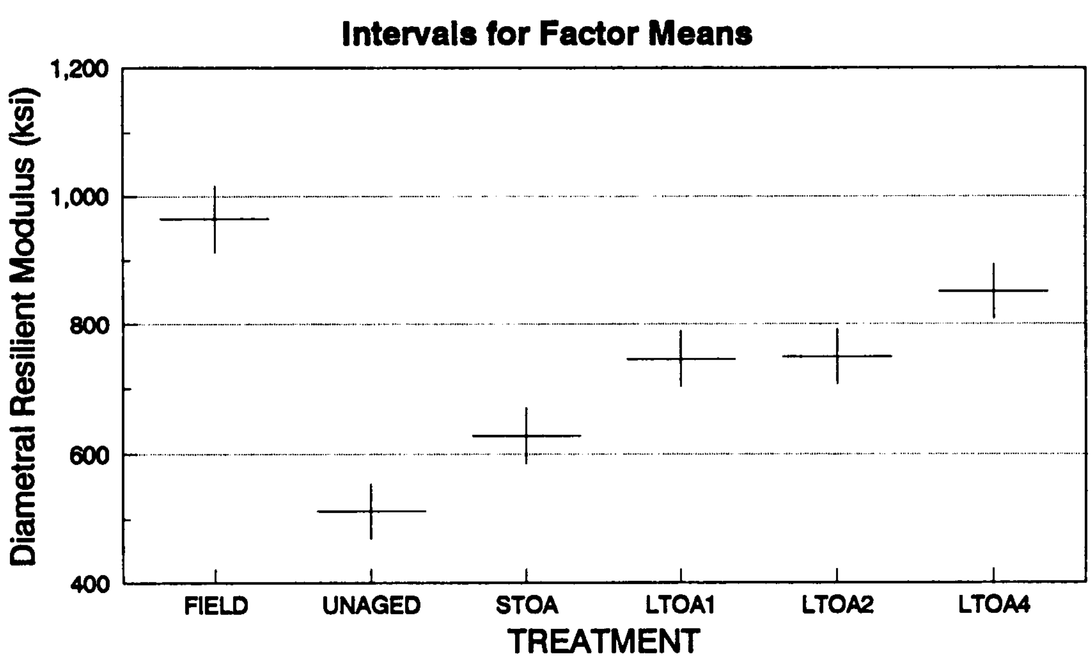

Figure 4.14c Combined France Sections LSD Comparison, 100°C (212°F) Aging

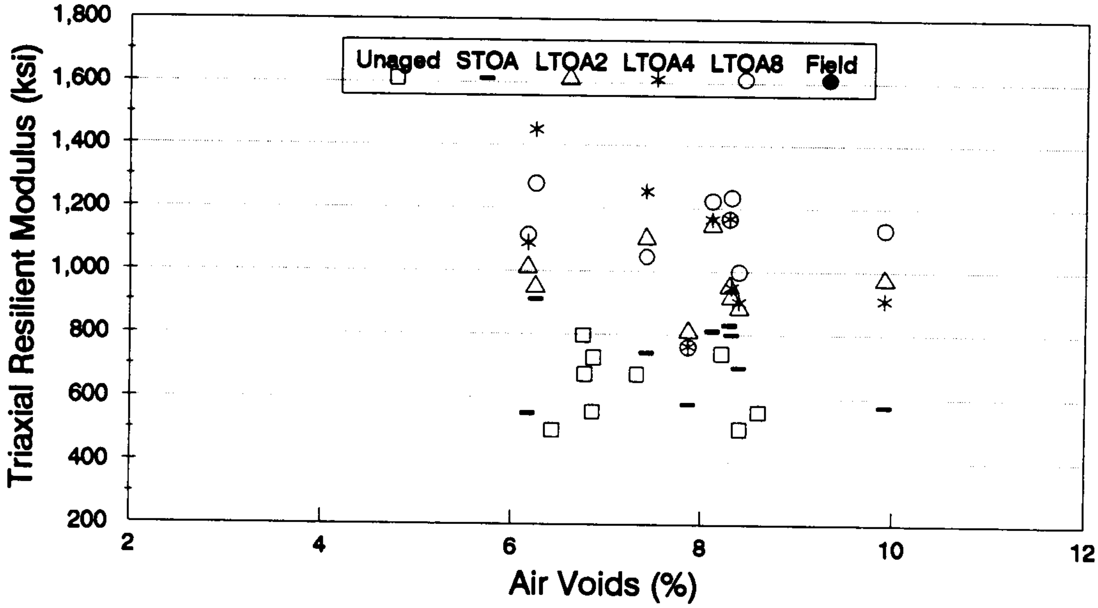

Figure 4.14d Combined France Sections Triaxial Resilient Modulus, 85°C (185°F) Aging

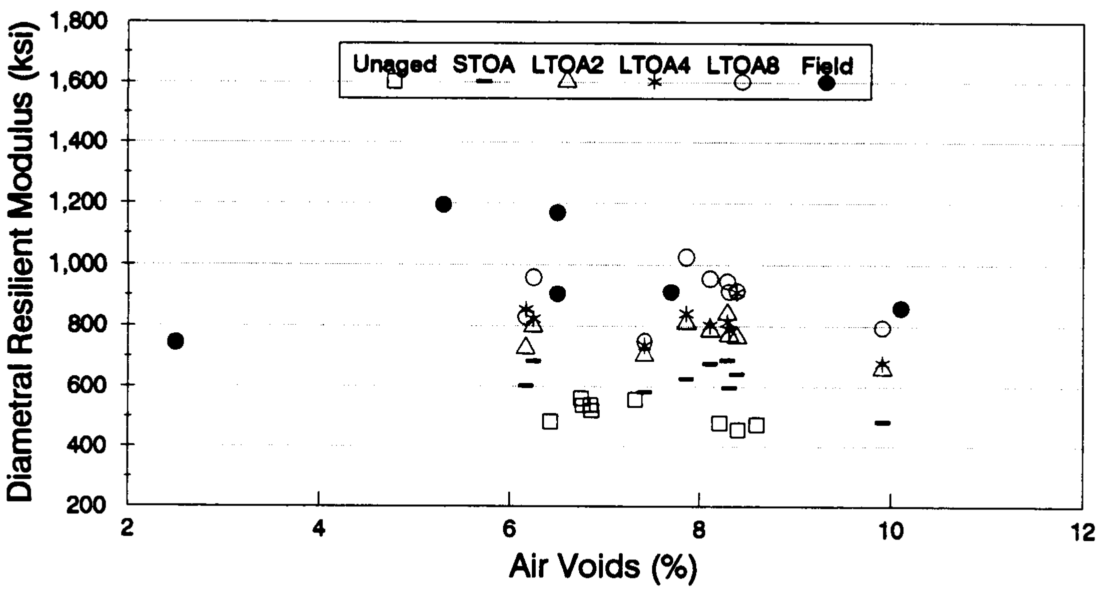

Figure 4.14e Combined France Sections Diametral Resilient Modulus, 85°C (185°F) Aging

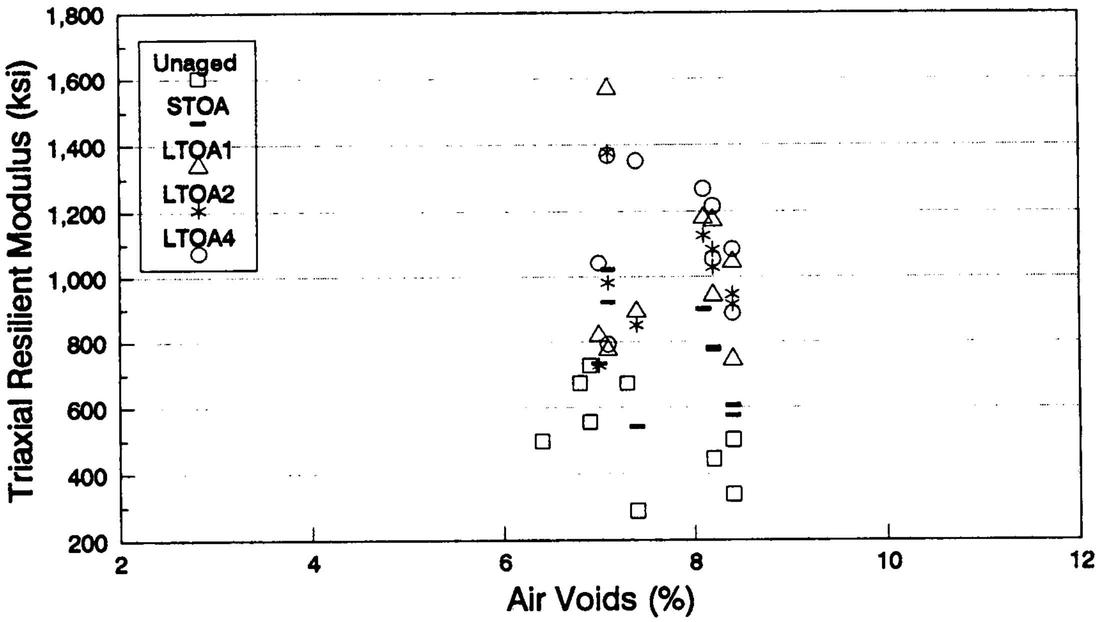

Figure 4.14f Combined France Sections Triaxial Resilient Modulus, 100°C (212°F) Aging

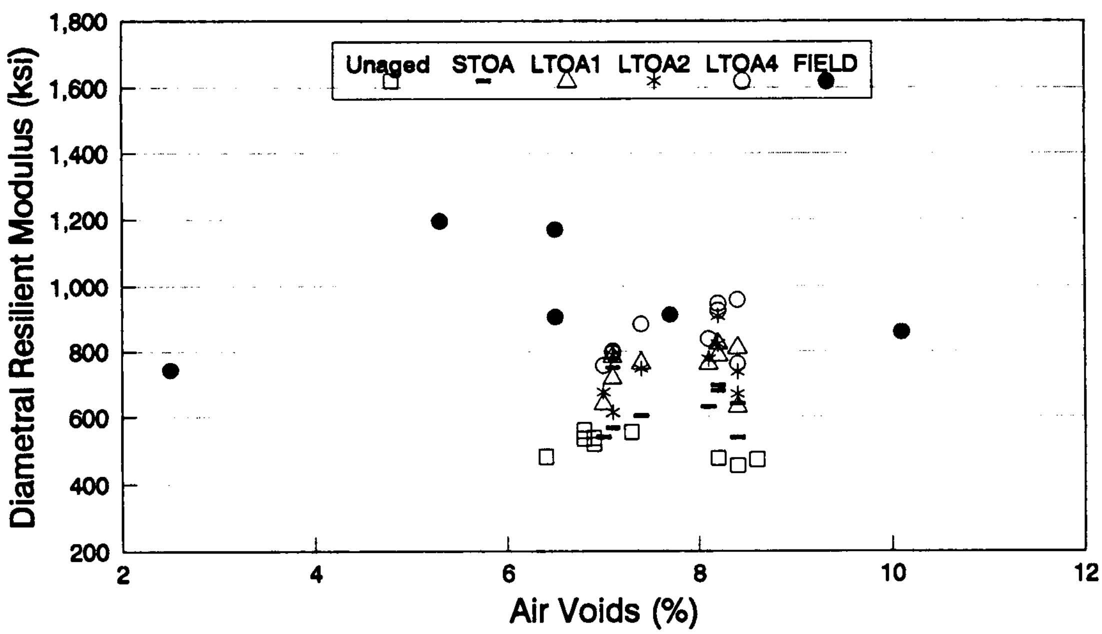

Figure 4.14g Combined France Sections Diametral Resilient Modulus, 100°C (212°F) Aging

5

Test Results—Supplementary Study

5.1 Lab Results

The resilient modulus values for the laboratory-prepared specimens in the diametral and triaxial configurations are summarized in the tables of Appendix F. Plots of the resilient modulus values versus air voids and aging treatment are shown in figures 5.1 through 5.7 at the end of this chapter. Figures a and b from each site compare the 85°C (185°F) leasst significant difference (LSD) analysis of field plots versus aging treatment with the 100°C (212°F) LSD analysis. Figures c and d plot diametral and triaxial resilient modulus values at 85°C (185°F) versus air voids. Figures e and f also plot modulus versus air voids, but at 100°C (212°F).

Table 5.1 shows a comparison of the Tukey and the LSD intervals for long-term oven aging (LTOA) at 85°C (185°F). The LSD method narrowed the "not significantly different" gap on all sites but two. Table 5.1 also compares the LTOA at 100°C (212°F) "not significantly different" treatments with the LTOA at 85°C (185°F), both using LSD. Several of the sites contained borderline intervals, causing the two aging procedures to differ slightly. The same statistical analysis method used in the expanded study was applied for this supplemental study.

5.2 Field Results

The cores received from the Washington Department of Transportation (WDOT) were in good condition. Delineation of layers was determined based on construction thicknesses, and the layers were then separated by sawing. For several sites, the layers studied were less than 102 mm (4 in.); therefore they were not tested in triaxial resilient modulus. An earlier study at Oregon State University (OSU) determined that cores less than 102 mm (4 in.) in height had variable modulus values. The results of the field modulus values appear in Appendix F.

Table 5.1 Lab Modulus Means "Not Significantly Different" from Field Mean

Site	Age (yr)	Tukey (85°C (185°F))	LSD (85°C (185°F))	LSD (100°C (212°F))
1801	18	LTOA 4, 8	LTOA 8	None
6048	14	Unaged + all	STOA LTOA 2, 4, 8	STOA LTOA 1*, 2, 4
6049	19	LTOA 2, 4, 8	LTOA 4, 8	LTOA 4
1002	3	Unaged, STOA, LTOA 2	STOA	STOA
1006	9	LTOA 8	None	Not tested
1008	13	None	None	None
6056	5	STOA LTOA 2, 4, 8	LTOA 2, 4	LTOA 1*, 2

*Not modulus tested, but assumed to fall within the field LSD interval.

Key: None = All of the aging treatments are significantly different from the field.
All = All of the aging treatments are not significantly different from the field.

5.2.1 Washington Site 1801 (18 years old)

For the 100°C (212°F) aging data, the mean field modulus is significantly different from all of the aging treatments. The LTOA for 4 days at 100°C (212°F) was 19 ksi short of the field modulus interval. For the 85°C (185°F) aging specimens, the LTOA at 8 days was not significantly different from the field modulus. For both aging groups, the most extreme treatment mean did not match the field average modulus, even though for the 85°C (185°F) aging, there was no significant difference.

The lab voids for both aging groups were within 1 percent of the field values. This site also used the same asphalt content (6 percent) and close to the same fines content as the field (tables D2 and D6a). An extraction on a field core showed that the lab aggregate used was also very similar to the field.

Field Data: This section had some severe longitudinal cracking in spots, and a few transverse cracks but was in good condition otherwise. A field check showed that the cores were mostly drilled from uncracked sections of the road.

The pavement section rating in 1991 was 73, with deductions for raveling and longitudinal cracking. The average daily traffic (ADT, table 5.2) of 3,251 in 1991 indicates that this site was subjected to a relatively low traffic load. It is located in a dry–no freeze zone in eastern Washington.

5.2.2 Washington Site 6048 (14 years old)

This site had a relatively large standard error of field diametral modulus values, 76 ksi, with values ranging from 292 ksi to 1195 ksi. The cores were retested on December 9, 1992, as a check and yielded the same large modulus range. Due to the large LSD field interval, all of the treatments (except for the unaged) were "not significantly different" from the field modulus values for both 100°C (212°F) and 85°C (185°F) aging. The LTOA1 at 100°C (212°F) is assumed to have fallen within the field LSD interval even though it was not tested. The lab voids were on average 2 percent higher than the field (table D5).

The field core aggregate was different from the lab. The +9.5-mm (+0.4-in.) sizes were similar, but for the −9.5-mm (−0.4-in.) sizes, the field core contained significant rounded aggregate. The lab batched material contained 100 percent fractured material. It was thought that the aggregates rounded shape may have caused stripping in the pavement, but a visual inspection of several cores (broken in half by tensile failure) showed that they suffered very little stripping.

Field Data: No field visit was made to this site. The section had the second lowest pavement rating (63) of all of the Washington sites in 1991 (see table 5.2). Deductions to the rating were for flushing and longitudinal cracking. The site contained 6-mm (0.24-in.) ruts. The section also had a high average daily traffic of nearly 21,000.

Table 5.2 Field Site Traffic Data

Site	Age (years)	ADT	ESALs Since Construction	Pavement Rating (1991)
1801	18	3,251	708,000	73
6048	14	20,668	2,224,000	63
6049	19	81,246	10,683,000	79
1002	3	1,872	197,000	66 (1986)*
1006	9	3,123	467,000	68
1008	13	6,723	1,059,000	49
6056	5	3,786	283,000	76

*This rating is just before the overlay in 1987, indicating the condition of the field cores tested at OSU.

Key: ESAL = Equivalent single axle load.
ADT = Average daily traffic (one way).

This site had the second highest average yearly rainfall of all the Washington sites, 1.4 m (55.1 in.). The high traffic combined with the high rainfall could account for the high modulus variability, i.e., weak, damaged cores.

Two cans of asphalt were used for mixing this site, both from June 1976. The refinery was U.S. Oil in Spokane, Washington (see list of refineries, table D3). The date of construction was October 15, 1976. Specimens fabricated from can 2 had average modulus values of 557 ksi for short-term oven aging (STOA), while can 1 specimens had a 507-ksi average modulus for STOA. Hence, it appears that the asphalt in the two cans was slightly different.

5.2.3 Washington Site 6049 (19 years old)

Three specimens were initially prepared with the original asphalt and had voids 5.2 percent higher than the field. These mixes also contained fines 1.6 percent higher than the field, in an effort to lower the voids. More fines were added for a second group of three, resulting in 1.5 percent lower voids (see table D6a, WDOT site 6049, blend 2). The initial three specimens and one Rice gravity specimen were used for 100°C (212°F) aging, while the second group of three specimens was used for controls and 85°C (185°F) aging (two were used as recompacted controls; see previous discussion). The initial STOA diametral modulus values are significantly higher for the three samples with the higher fines content, 467 ksi compared to 349 ksi, resulting in a higher 8-day modulus than the 4-day-at-100°C (212°F) modulus.

The LTOA4 at 100°C (212°F) and LTOA4 and LTOA8 at 85°C (185°F) are comparable to the field mean. Neither the 702-ksi 4-day-at-100°C (212°F) average nor the 733-ksi 8-days-at-85°C (185°F) average match the field average of 768 ksi. The higher lab voids can be assumed to have reduced the modulus average (see section 2.3.4, expanded study, Bell and Sosnovske). In theory, at 5 percent higher voids the lab modulus average was about 75 ksi too low. Therefore, with the 75 ksi added, the lab modulus would match the field modulus. The lab and field contained a mix of rounded and fractured aggregates, but the field core contains some material larger than 20 mm (0.8 in). The core used for the extraction had a diametral modulus of 880 ksi, compared with the 768-ksi field average. It is possible that the large aggregate present helped to increase the modulus and that the same could hold true for some of the other site 6049 cores. Several other site 6049 cores checked for stripping also contained large aggregate, but they were not the same high strength as the first core.

<u>Field Data</u>: This site had the highest pavement rating of all the Washington sites, 79, with deductions for raveling and longitudinal cracking. A visual inspection showed that the road was in good shape and did not show any severe signs of distress.

This site was 19 years old at the time of coring. The slight cracking combined with a high ADT of 81,426 in 1991 could account for weaker cores and highly variable field core diametral modulus values. One possible reason for the high rating of the road after 19 years, even with the high traffic, is that the weather did not cause significant damage to the road. The average yearly rainfall in the area is 1.2 m (47 in.), but the average yearly temperature variation is only 18 Celsius degrees. Sites 6048 and 6049 were both in the same general climatic area, with high traffic. Site 6049 contained five times as much traffic though, with 10,683,000 ESALs (equivalent single axle loads). Site 6048 failed at a much younger age. Poor placement and construction procedures may have contributed to the difference between these two sites.

5.2.4 Washington Site 1002 (3 years old)

The pavement layer considered for this site was exposed for only 3 years, 1984 to 1987, before being covered with a surface treatment. It is also one of the lab-crushed sites. A visual comparison of a batched sample (after crushing and handpicking out elongated pieces) with an extracted field core showed that the aggregates were similar in shape and size. The field core rock contains more holes (volcanic) than the batched sample. Originally, the crushed particles had a lot of holes in them. But due to high lab voids contents, they were handpicked out to try to reduce the voids. This still reduced the voids only to 7.7 percent, compared with the field average of 4.4 percent.

As noted earlier, to lower the voids for this site, a 1.5 percent increase in fines was targeted, but after several tries a wet sieve analysis showed a 2.2 percent increase in fines over the field gradation (table D6b). This could have accounted for the STOA specimens matching the 3-year-old field cores in modulus; i.e., the STOA specimens had a higher strength with a higher fines content. With 45 ksi added to the lab specimens modulus (due to the 3 percent higher voids content), all of the aging treatments would be above the field average modulus. For both the 100°C (212°F) and 85°C (185°F) aging, the field modulus mean was similar to the modulus values of the STOA specimens from the lab.

Field Data: The field rating in 1986, just before the overlay, was only 66. This indicates that the pavement was not in sound condition. This poor condition could also account for the cores having diametral modulus values similar to the STOA lab specimens, even though they had been aged for 3 years in the field. The overall rating of the road in 1992 was 64, after a high of 85 in 1990. The ADT for this dry-freeze site was 1,872 in 1991, the lowest of the seven Washington study sites.

Due to all the factors affecting the modulus values for this site (material variability, poor condition of field cores, high voids and fines), the correlation between field and lab aging is not sound.

5.2.5 Washington Site 1006 (9 years old)

This site was 9 years old at the time of coring in August 1992. All of the aging treatments at 85°C (185°F) are significantly different from the field value of 852 ksi, the highest of all supplementary sites. The 100°C (212°F) aging procedure was not done for this site.

An interesting correlation can be made between this site and site 1801. This site, containing Pave Bond Special (PBS), has an aging rate of only half that of site 1801. Table 5.3 shows that both lab sites after 8 days of aging at 85°C (185°F) have very similar modulus values. Site 1006 had an unaged modulus almost twice that of site 1801, and thus was able to match 1801's modulus even though it had only half the aging ratio. Therefore, if field conditions (traffic and weather) were similar, site 1006 should have achieved modulus values similar to site 1801 for the same time in the field. But after 9 years, site 1006 shows a higher modulus than the 18 year old site 1801. This lab data tends to show that the PBS in the 1006 field samples is not the cause of the high modulus gain in only 9 years of field aging.

The climatological data for sites 1006 and 1008 (table 5.4) shows that they have the highest temperature deviation (difference between high and low normal monthly averages) of all the Washington sites. Site 1006 had a 30-Celsius-degree deviation and site 1008 had a 24.4-Celsius-degree deviation. The two sites also have by far the lowest rainfall of all the sites older than 9 years, from three to six times less rainfall. Therefore, it is possible that this temperature gradient and the low rainfall are responsible for the high amount of aging in a shorter time, relative to the older sites. A phenomenon that occurs in this country is that states with a high average yearly temperature deviation have interstates and highways that are in poorer condition than do states with mild climates.

No lab cores could be extracted for this site due to their late arrival at OSU. Also, the field site was not visited due to its location in northern Washington.

Field Data: The 1991 field rating was 68, with 30 percent of the section having a "high" severity longitudinal cracking rating.

This site has a relatively low average daily traffic value of 3,123. This low amount of traffic could possibly account for the higher modulus values for the field cores. By having less traffic, it is possible that the pavement was damaged less, resulting in cores that had higher moduli.

5.2.6 Washington Site 1008 (13 years old)

The lab voids for this 13-year-old site were (on the average) the same as the field specimens. The field cores had a low standard error of 15 ksi and the second highest modulus average of all the sites, 825 ksi. As noted for site 1006, this site had a high field modulus for a lower aging time (13 years) compared with the other WDOT sites older than 9 years. As mentioned, it also had a high yearly temperature gradient and relatively low amount of rainfall.

No amount of aging matched the field mean, with 555 ksi resulting for LTOA4 at 100°C (212°F) and 590 ksi for LTOA8 at 85°C (185°F). This site had a significantly lower ADT in 1991 (6,723) than sites 6048 and 6049, which could account for the higher field modulus values, i.e., less traffic fatigue and damage to the road. There was no significant difference between the lab and the field aggregate.

Table 5.3 Lab Aging Ratios for LTOA for 8 Days at 85°C (185°F) versus Unaged

Site	Age (Years)	Asphalt Type	Average Field Modulus (ksi)	LTOA 8 /Unaged (ksi)	Aging Ratio
1801	18	85/100	826	780/180	4.3
6048	14	AR4000	639	810/300	2.7
6049	19	85/100	768	740/240	3.1
1002	3	AR4000	418	650/240	2.7
1006	9	AR4000	852	750/325	2.3
1008	13	AR4000	825	590/250	2.4
6056	5	AR4000	421	510/200	2.6

Table 5.4 Climatological Data—Temperature (°C) and Rainfall (m)

Site	Closest Weather Station	Normal Average Temperature	Average Low Temperature	Average High Temperature	Temperature Change	Average Rainfall
1801	Skamania Fish Hatchery	9.1	0.6	17.2	16.6	2.4
6048	Monroe	10.8	3.9	19.4	15.5	1.4
6049	Tacoma no.1	11.7	2.2	20.0	17.8	1.2
1002	Dayton 1 WSW	10.6	0.0	21.1	21.1	0.5
1006	Methow 2S	9.6	-6.7	23.3	30	0.4
1008	Spokane WSO Airport	8.4	-3.3	21.1	24.4	0.5
6056	Pullman 2 NW	8.4	-2.2	18.9	21.1	0.6

This site also contained PBS and had a low lab aging ratio (table 5.3). The PBS contained in the lab cores 1006 and 1006 tends to reduce the aging rate, while at the same time increasing the initial unaged modulus. Table 5.3 shows that sites 1006 and 1008 have the two lowest aging ratios, while also having two of the highest unaged modulus averages. Even though the two sites have low aging ratios, the combination of their high initial moduli and their extreme temperature fluxuations between seasons results in high field moduli after relatively low aging time in the field.

Field Data: The visual survey showed frequent transverse cracks present throughout the section and a lot of rutting. Also, a few patches were present. The 1991 rating for the section was only 49, with deductions for alligator cracking, longitudinal and transverse cracking, patching, and raveling.

The cores were taken from an uncracked and fairly good section of the road and showed a low standard deviation when tested. Although the field cores had a high average modulus, meaning that they were stiffer due to aging, this does not seem to have alleviated the slight rutting present on the road. The ruts measured in the pavement survey averaged 8 mm (0.3 in.). The aging due to oxidation in the field shows up in the form of cracks, both longitudinal and transverse.

Two cans of asphalt were used for this site (both containing PBS), with no significant difference in modulus noted between cans for STOA specimens (table D3).

5.2.7. Washington Site 6056 (5 years old)

This site was a 5-year-old overlay at the time of coring. It is also the second site to use lab-crushed aggregate for lab specimens. The lab specimens with LTOA2 at 100°C (212°F) and LTOA2 and LTOA4 at 85°C (185°F) had modulus values similar to the field. It appears that LTOA1 at 100°C (212°F) would have fallen within the field LSD interval had it been tested; therefore, it will be included with an asterisk.

The lab-crushed aggregate was handpicked to remove the elongated pieces, but it still contained many elongated, flat pieces. An extraction done on a field core also showed some elongation in the aggregate, but not to the extent of the lab-crushed samples. The lab-crushed sample had a thinner, more elongated shape; i.e., it was flakier than the core aggregate, which was blocky. The type of both aggregates is the same. The lab voids averaged 4 percent higher than the field, most likely due to the bridging effect of the particles. As discussed, a 1 percent higher voids content reduces the specimen strength by about 15 ksi. Therefore, for this site with 4 percent higher voids than the field, 60 ksi should be added to the lab cores modulus averages. This would cause the STOA specimens to be similar to the field for both aging treatments, along with the LTOA2 and LTOA4 for 85°C (185°F) and LTOA2 at 100°C (212°F).

Two cans of asphalt were used for this site, both from Koch Asphalt in Spokane, Washington. Can 1 was dated August 23, 1985; can 2 was dated July 1, 1985; and the construction date was August 23, 1985. Can 1 indicated no additive, while can 2 had 0.5 percent PBS. The three cores with PBS and STOA had an average modulus of 351, while the three cores with no PBS averaged 270. Two PBS cores were used for 85°C (185°F) aging and one for 100°C (212°F) aging. All of the cores were chosen by random selection based on voids distribution.

Field Data: The field was in good shape, with some longitudinal and alligator cracking present, along with some raveling. The 1991 section pavement rating index was 76. The ADT in 1992 was 3,800.

5.3 Discussion

In order to obtain lab specimens with properties as close as possible to the field, this supplementary study slightly altered the mix design process. The asphalt content, compaction temperature, and fines content were all slightly raised to try to achieve lower lab voids. The effects of raising the asphalt content and the compaction temperature are not considered significant because these would most likely fall within the standard deviation of the field values.

The added fines for most of the sites may have altered the strengths (modulus values), but not significantly. As shown in tables D6a and D6b, the fines varied between what the WDOT from field extractions and what Nichols Engineering (conducting long-term pavement performance studies as part of SHRP) obtained from actual 1990-91 core extractions. Since the fines (-200 material) contents from the various sources in the field seem to have a somewhat high deviation, the percentages used for this study do not seem to be significantly off.

Sites 6049, 1002, and 6056 had lab voids contents significantly higher than the field voids. Based on the findings by Bell and Sosnovske (15 ksi diametral modulus decrease for every 1 percent increase in voids over the lab), all of the lab cores for these sites would have higher strengths. This would result in the LSD intervals for these sites shifting up but would not significantly alter the comparisons.

For site 6049, a 75-ksi strength increase due to 5 percent higher voids in the lab would make the LTOA2 specimens similar to the field specimens, along with the LTOA4 and LTOA8 specimens.

With a strength increase, site 1002 would have unaged specimens similar to the field and site 6056 would have STOA specimens added to the "treatments similar to the field modulus" list.

For this study, the data were not normalized to the field voids contents, and the modulus values were analyzed as they are.

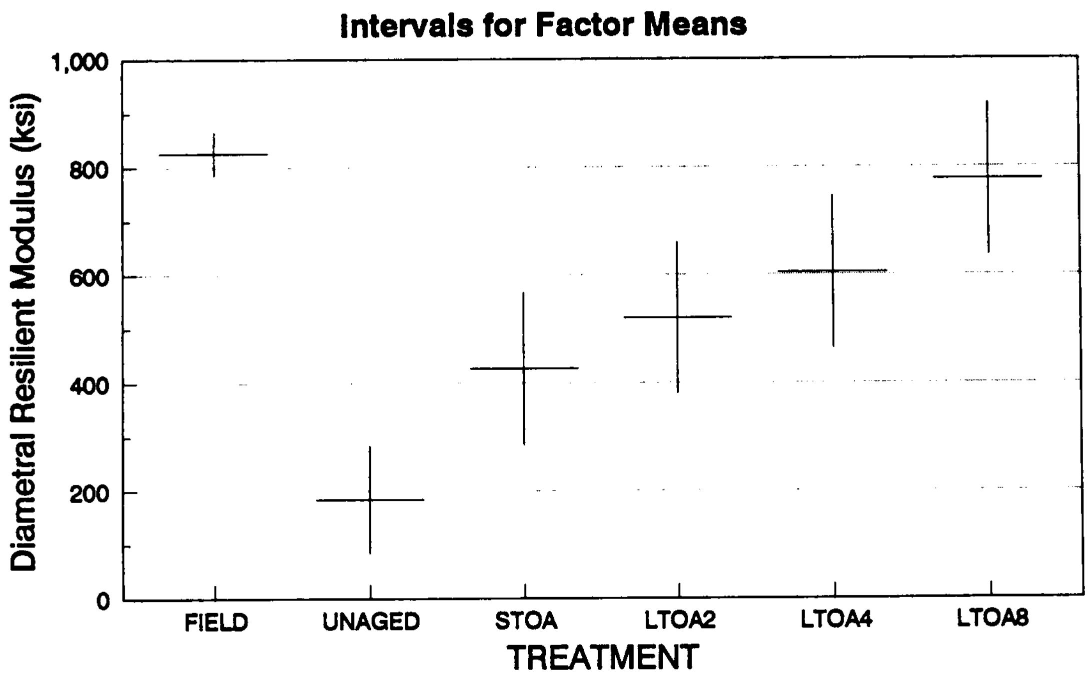

Figure 5.1a Washington Site 1801 LSD Comparison, 85°C (185°F) Aging

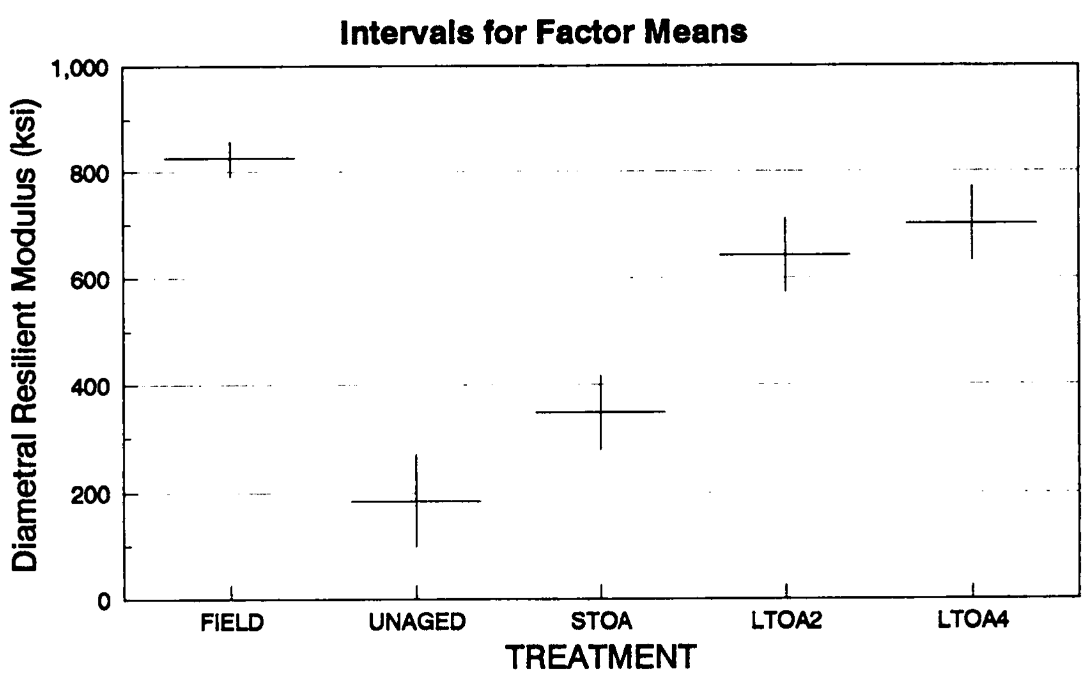

Figure 5.1b Washington Site 1801 LSD Comparison, 100°C (212°F) Aging

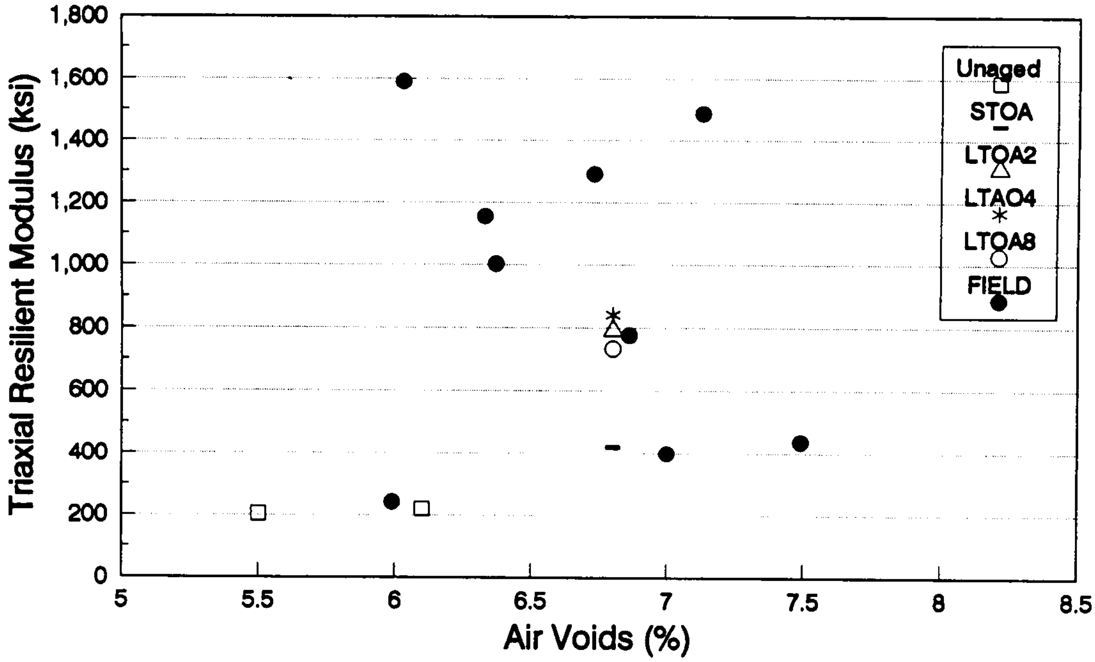

Figure 5.1c Washington Site 1801 Triaxial Resilient Modulus, 85°C (185°F) Aging

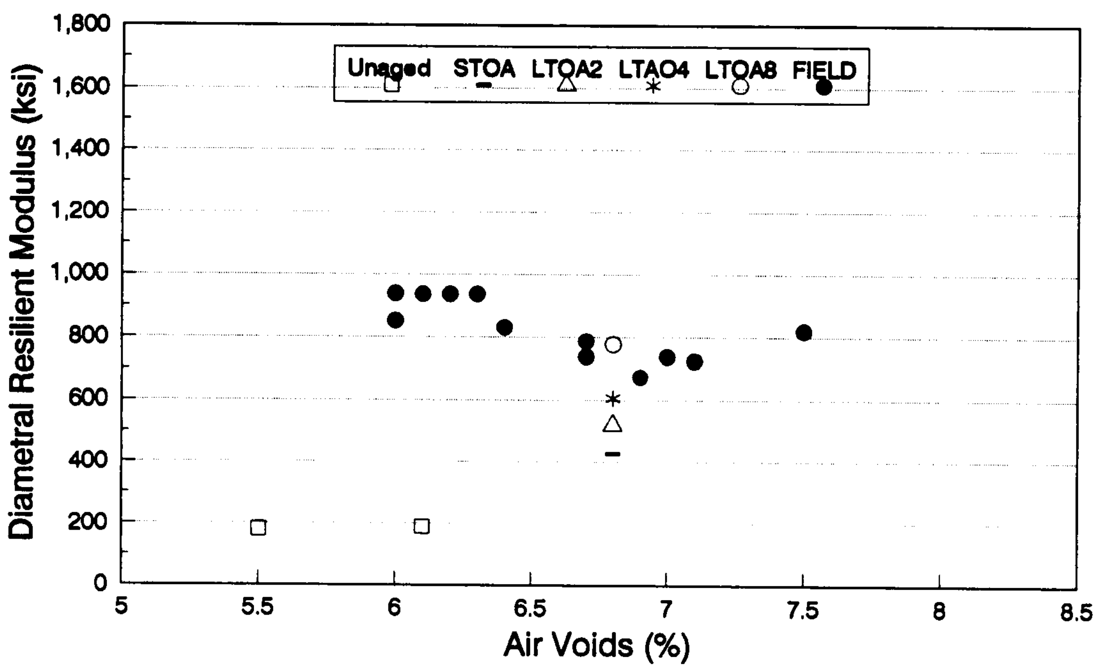

Figure 5.1d Washington Site 1801 Diametral Resilient Modulus, 85°C (185°F) Aging

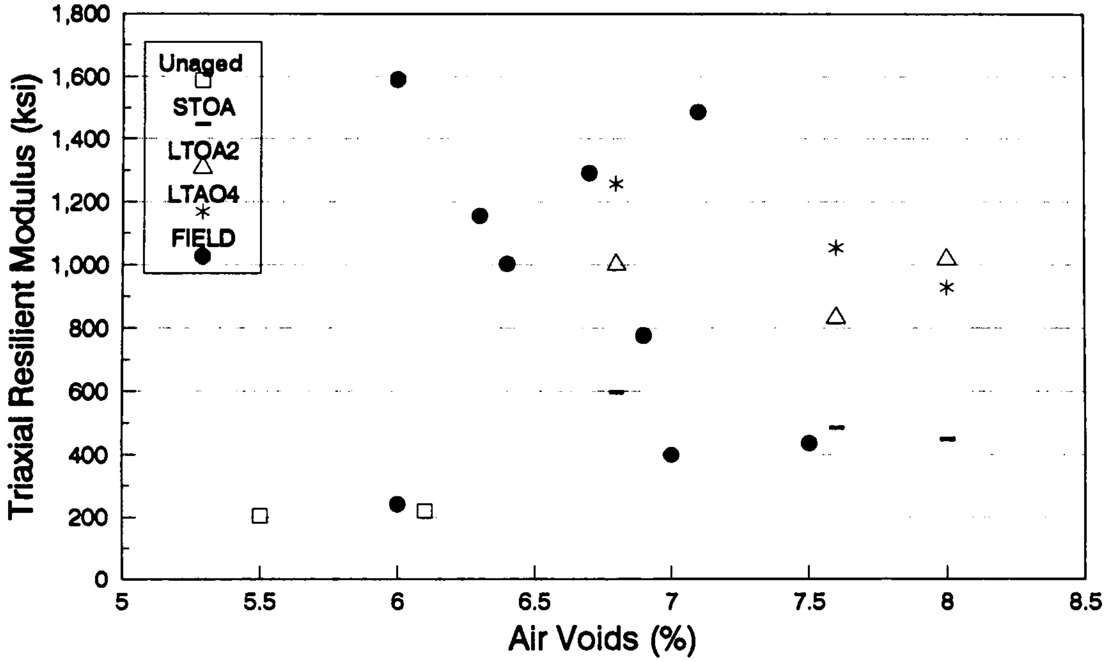

Figure 5.1e **Washington Site 1801 Triaxial Resilient Modulus, 100°C (212°F) Aging**

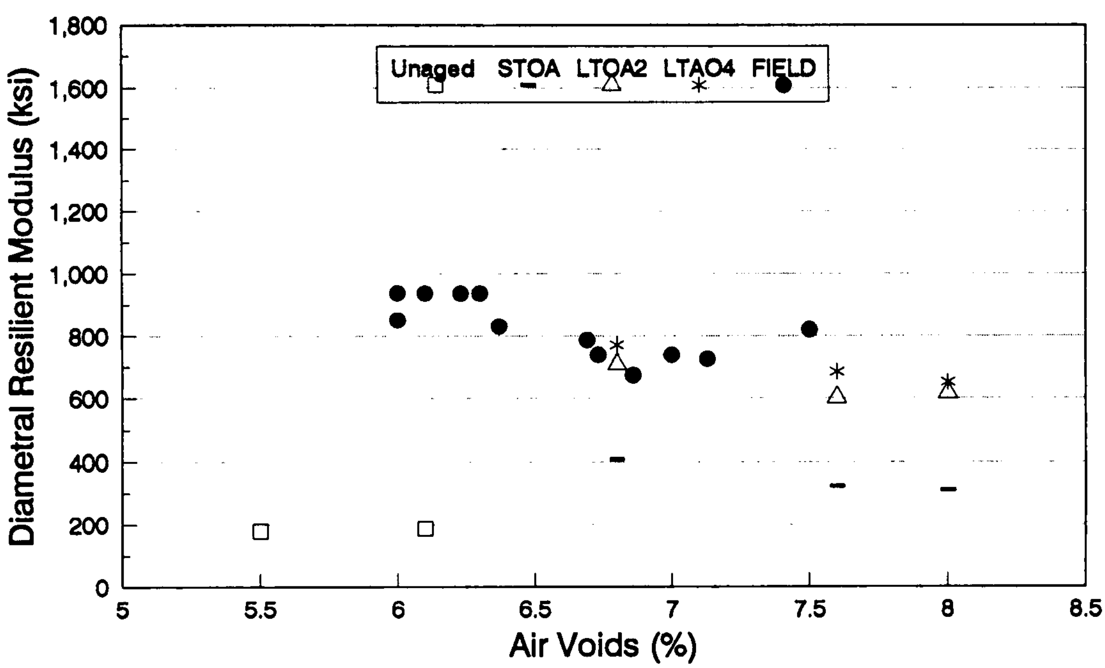

Figure 5.1f **Washington Site 1801 Diametral Resilient Modulus, 100°C (212°F) Aging**

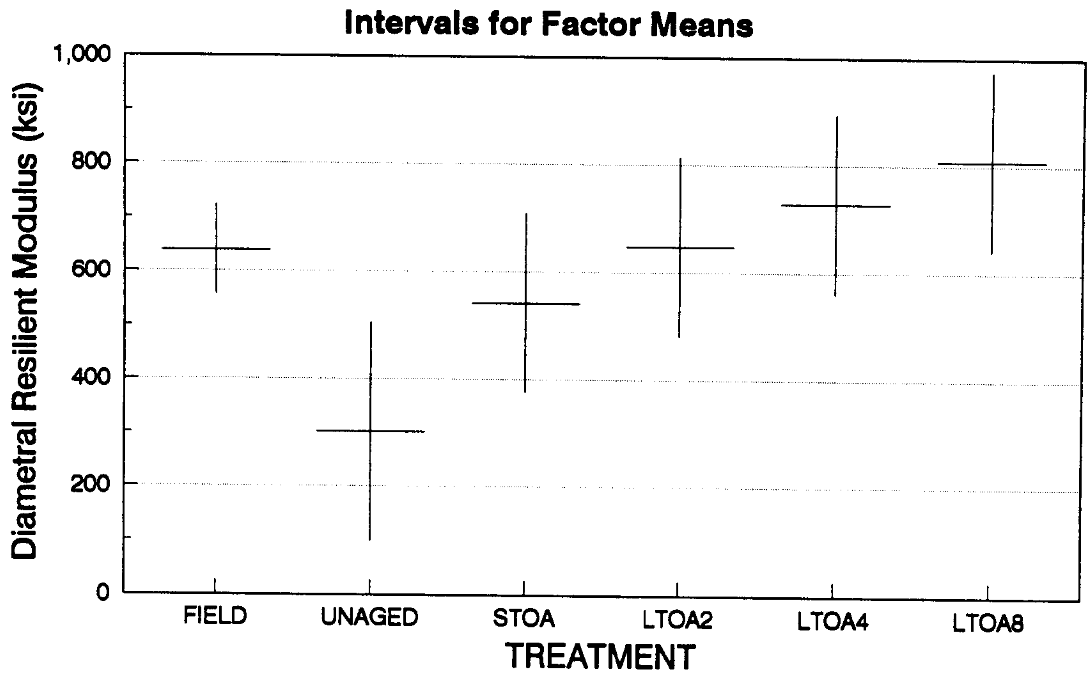

Figure 5.2a Washington Site 6048 LSD Comparison, 85°C (185°F) Aging

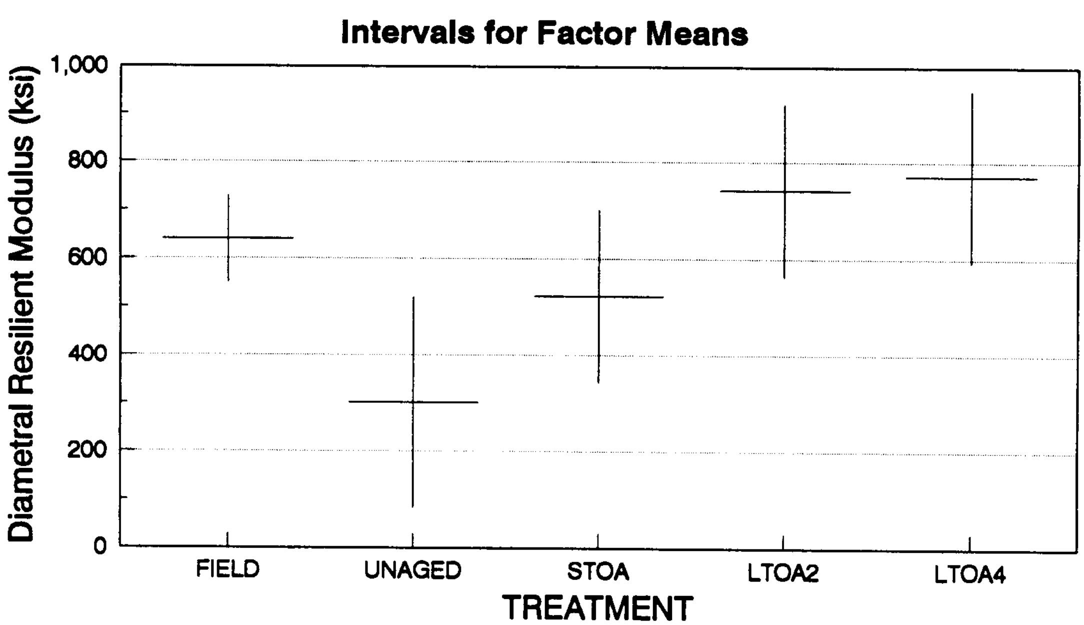

Figure 5.2b Washington Site 6048 LSD Comparison, 100°C (212°F) Aging

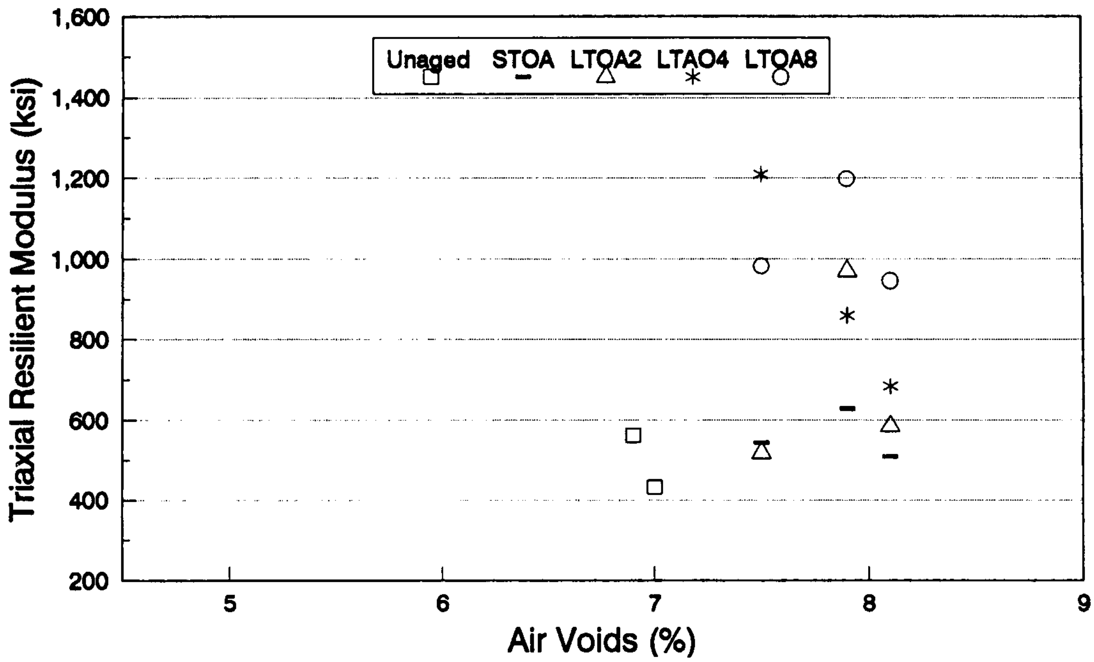

Figure 5.2c Washington Site 6048 Triaxial Resilient Modulus, 85°C (185°F) Aging

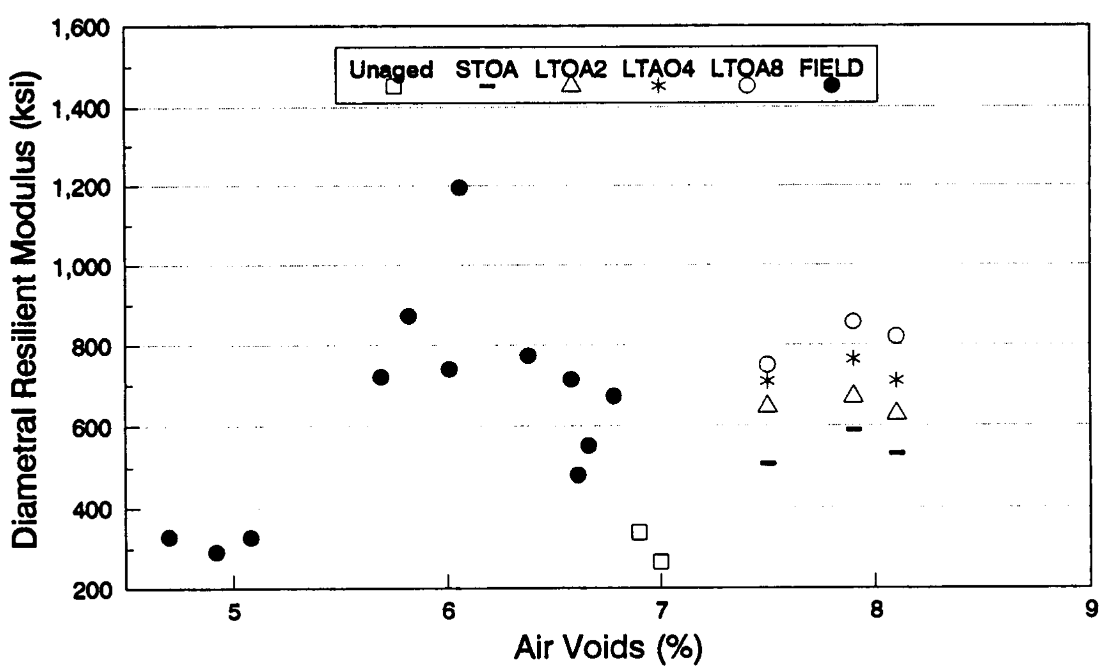

Figure 5.2d Washington Site 6048 Diametral Resilient Modulus, 85°C (185°F) Aging

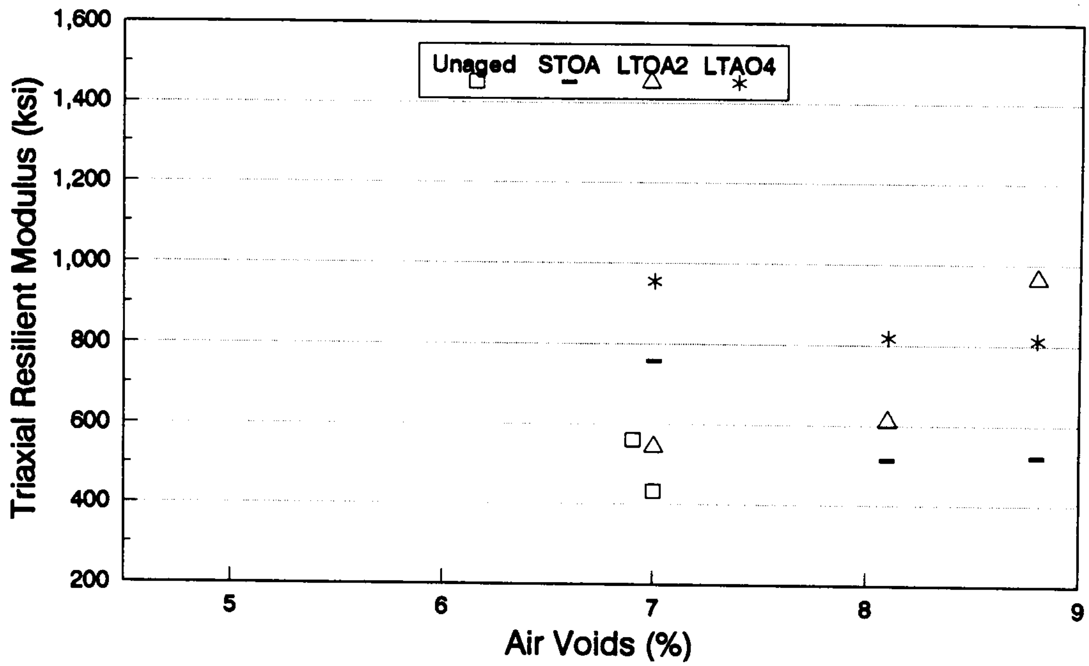

Figure 5.2e Washington Site 6048 Triaxial Resilient Modulus, 100°C (212°F) Aging

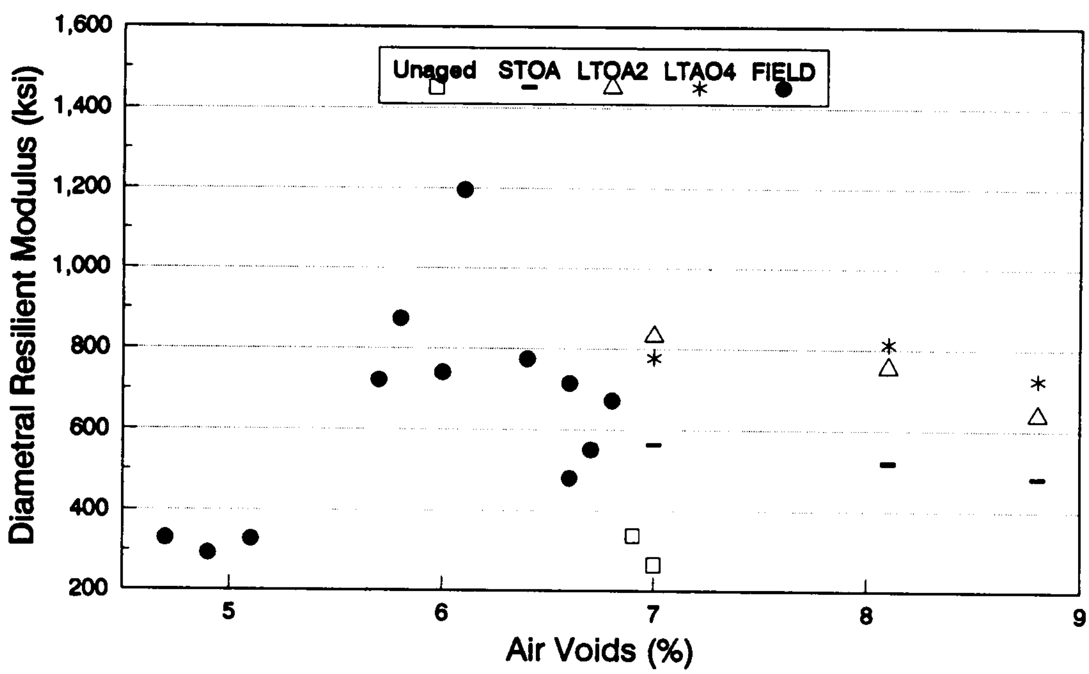

Figure 5.2f Washington Site 6048 Diametral Resilient Modulus, 100°C (212°F) Aging

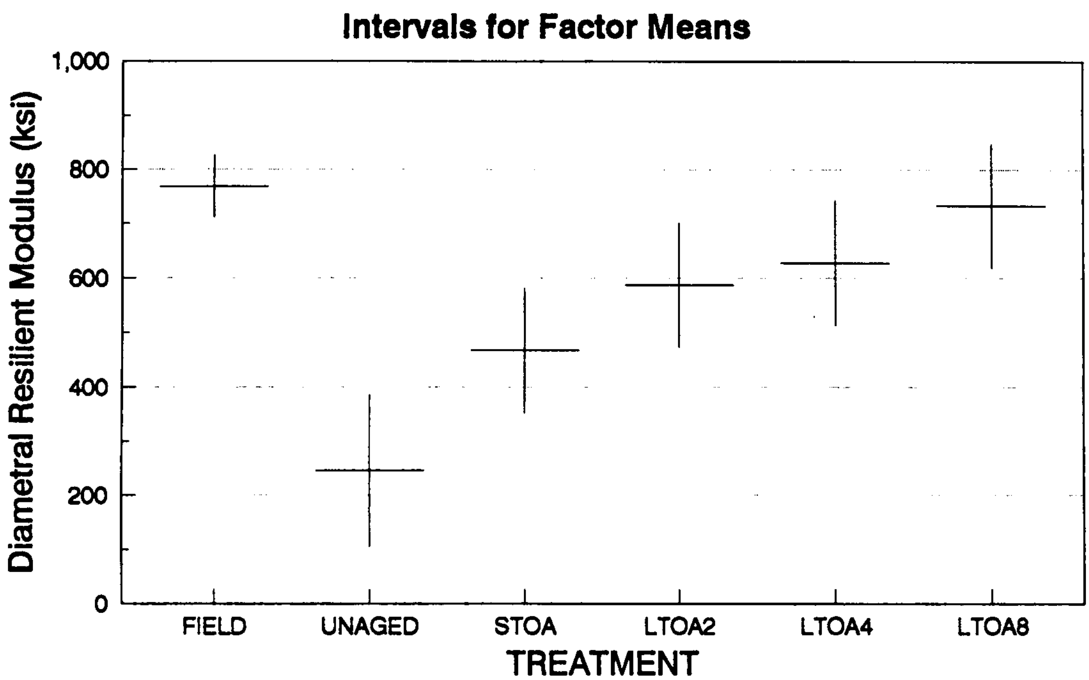

Figure 5.3a Washington Site 6049 LSD Comparison, 85°C (185°F) Aging

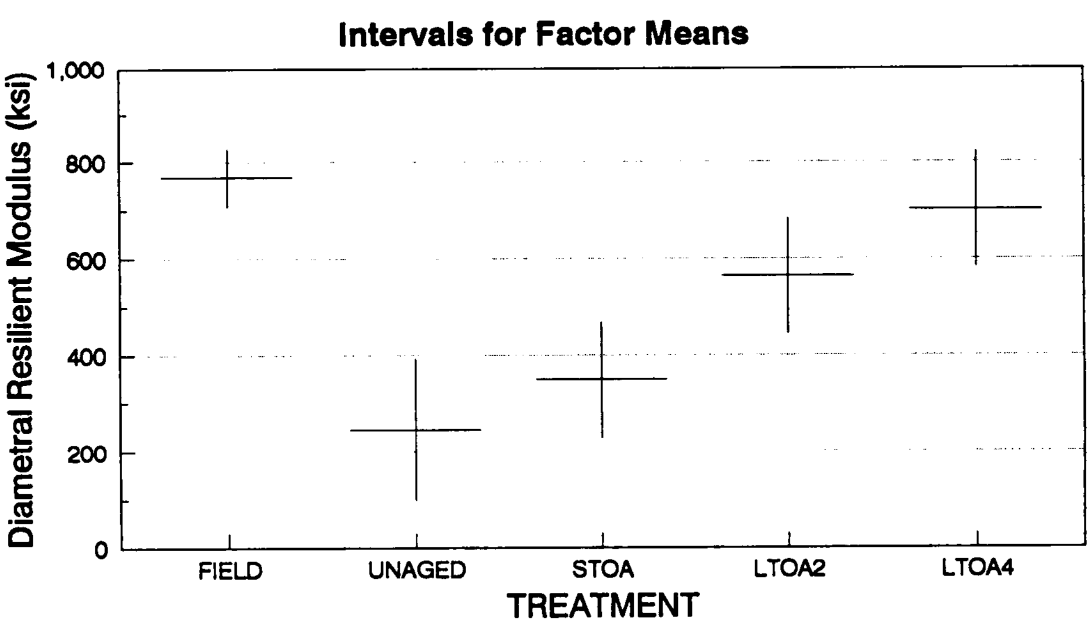

Figure 5.3b Washington Site 6049 LSD Comparison, 100°C (212°F) Aging

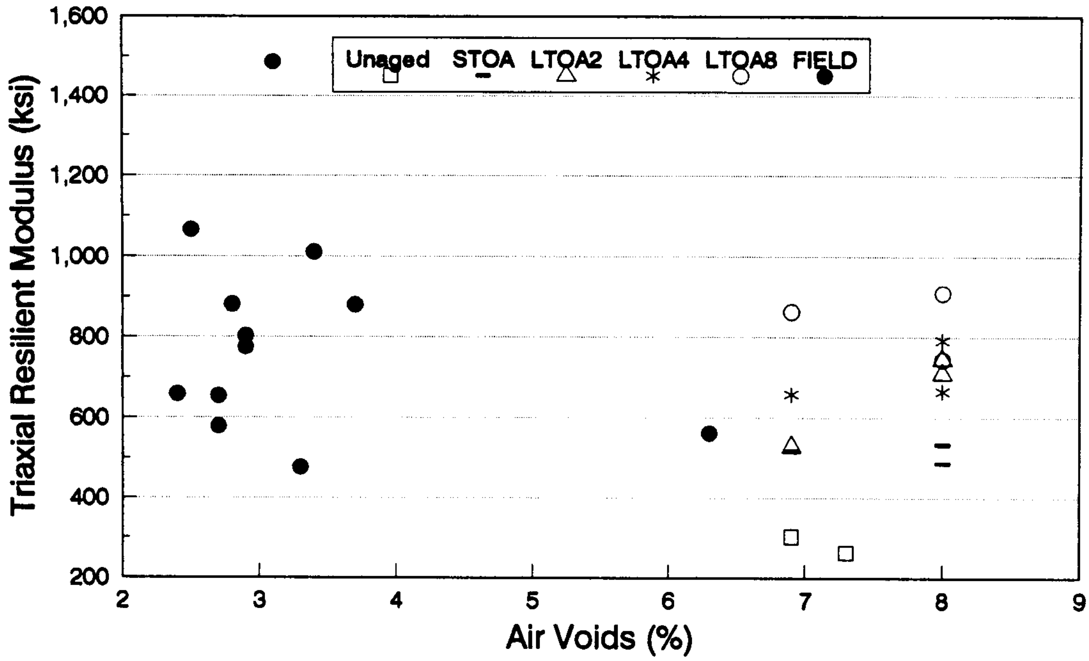

Figure 5.3c Washington Site 6049 Triaxial Resilient Modulus, 85°C (185°F) Aging

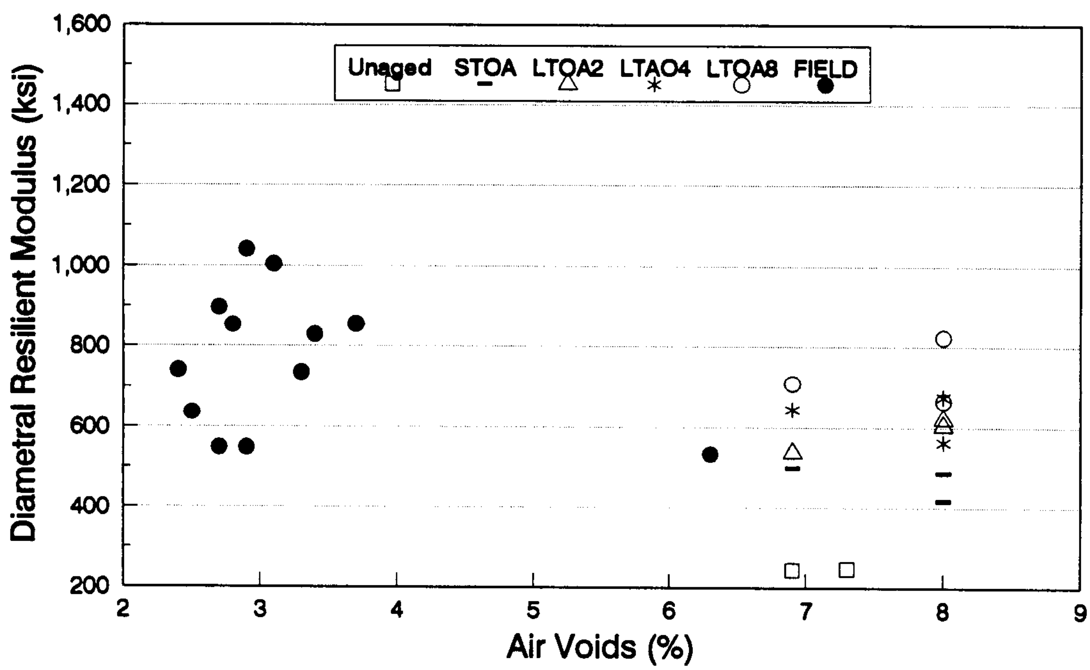

Figure 5.3d Washington Site 6049 Diametral Resilient Modulus, 85°C (185°F) Aging

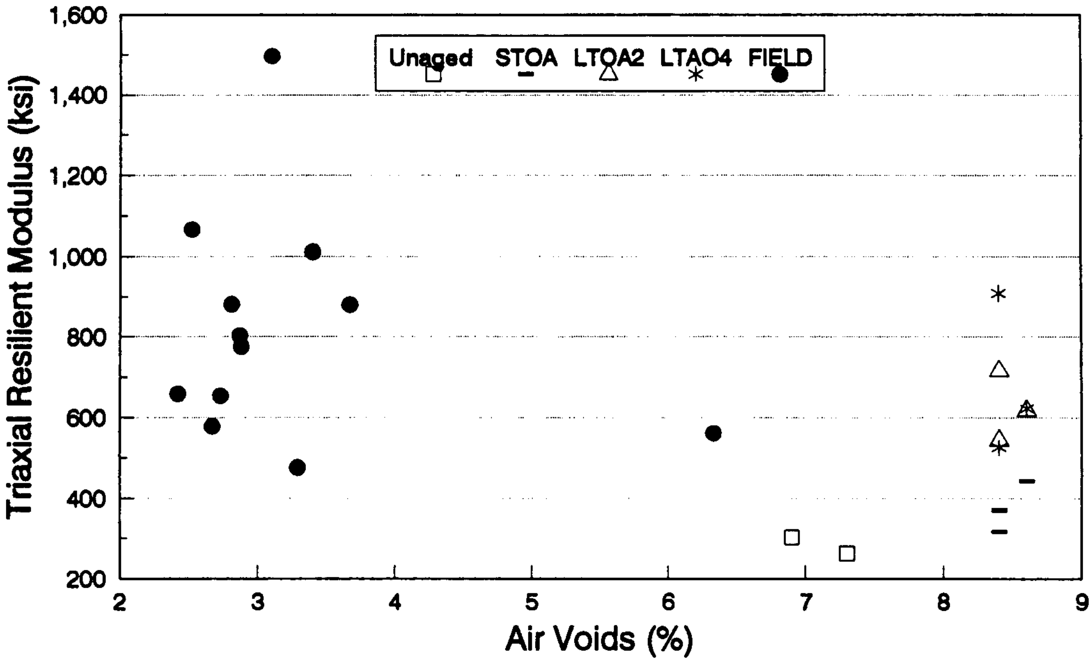

Figure 5.3e Washington Site 6049 Triaxial Resilient Modulus, 100°C (212°F) Aging

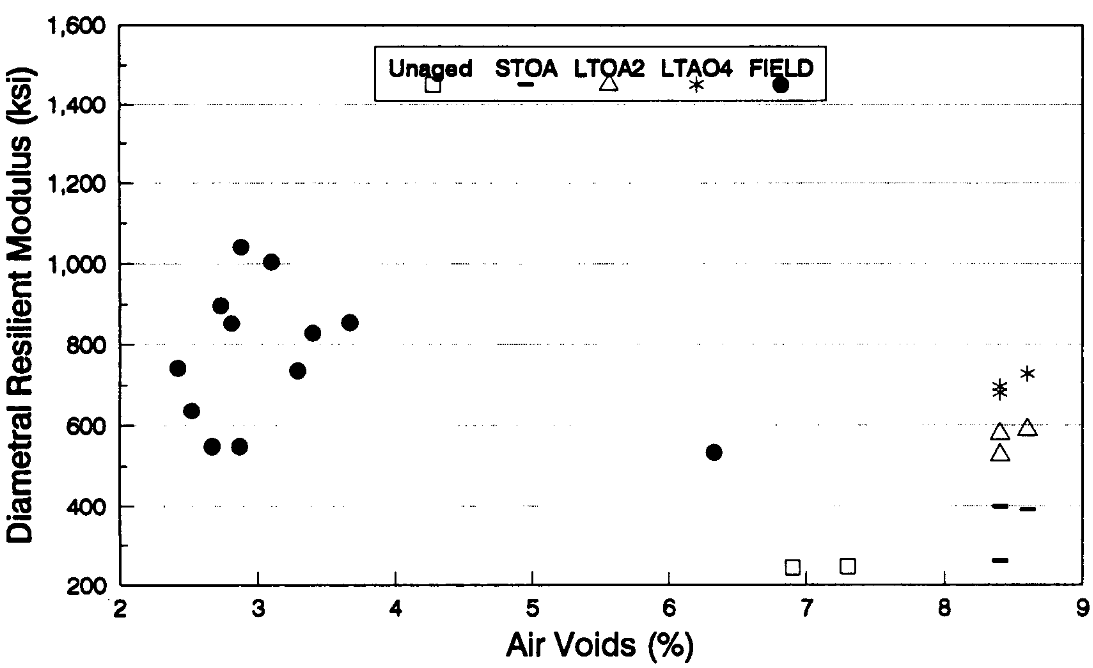

Figure 5.3f Washington Site 6049 Diametral Resilient Modulus, 100°C (212°F) Aging

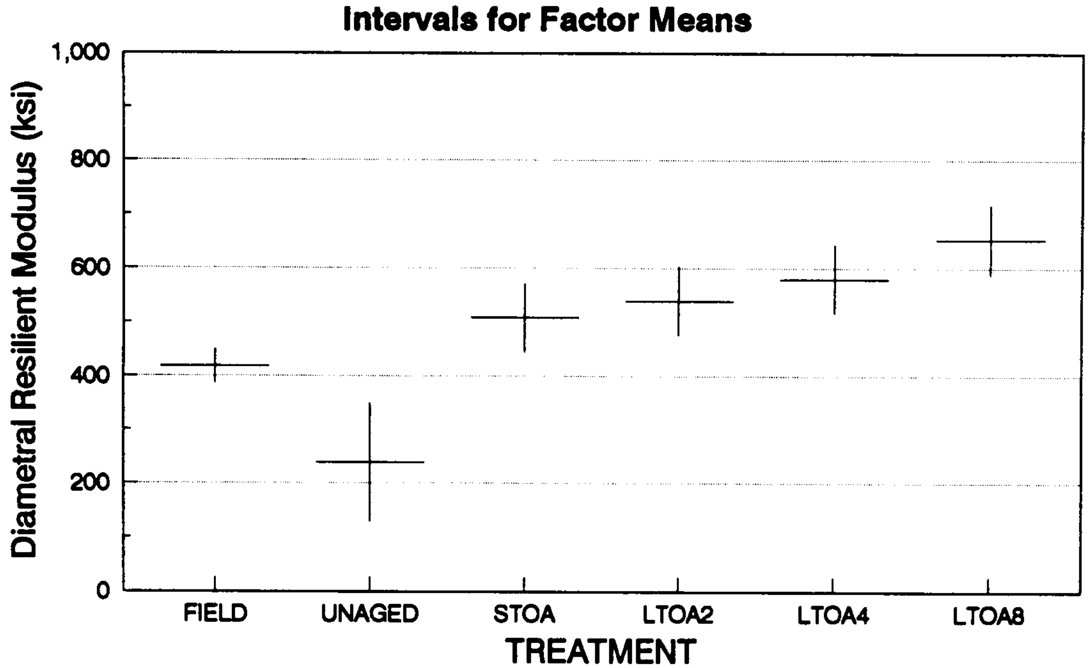

Figure 5.4a Washington Site 1002 LSD Comparison, 85°C (185°F) Aging

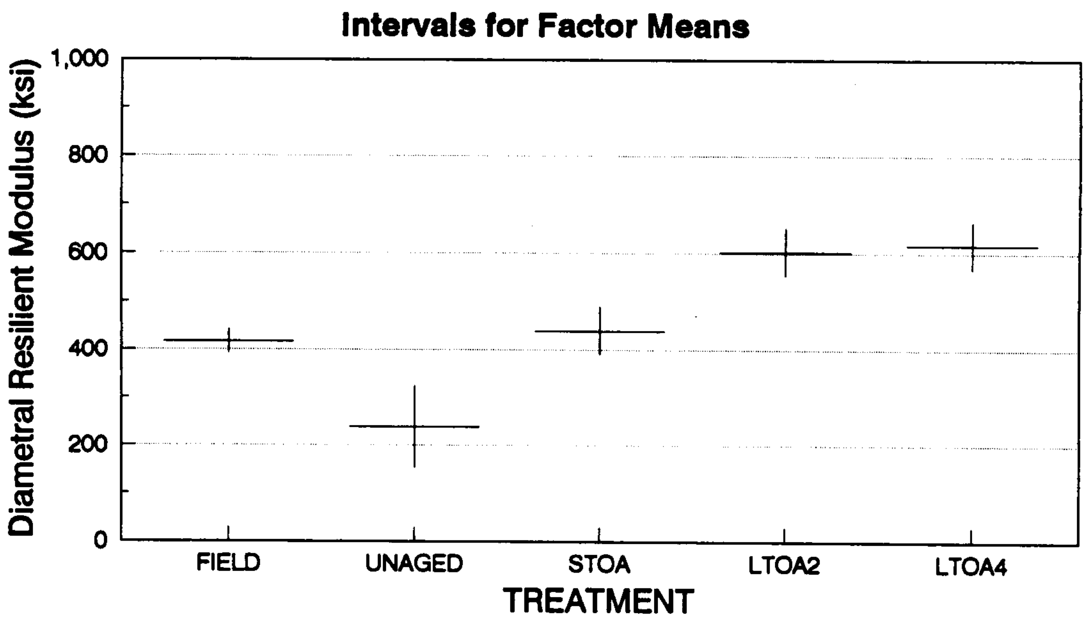

Figure 5.4b Washington Site 1002 LSD Comparison, 100°C (212°F) Aging

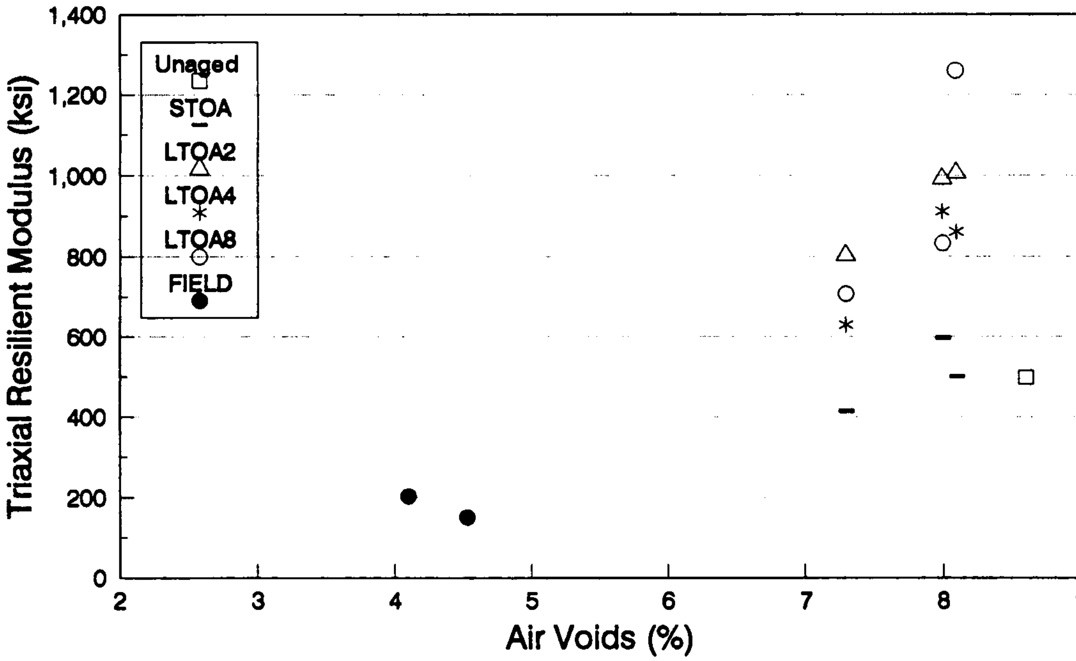

Figure 5.4c Washington Site 1002 Triaxial Modulus, 85°C (185°F) Aging

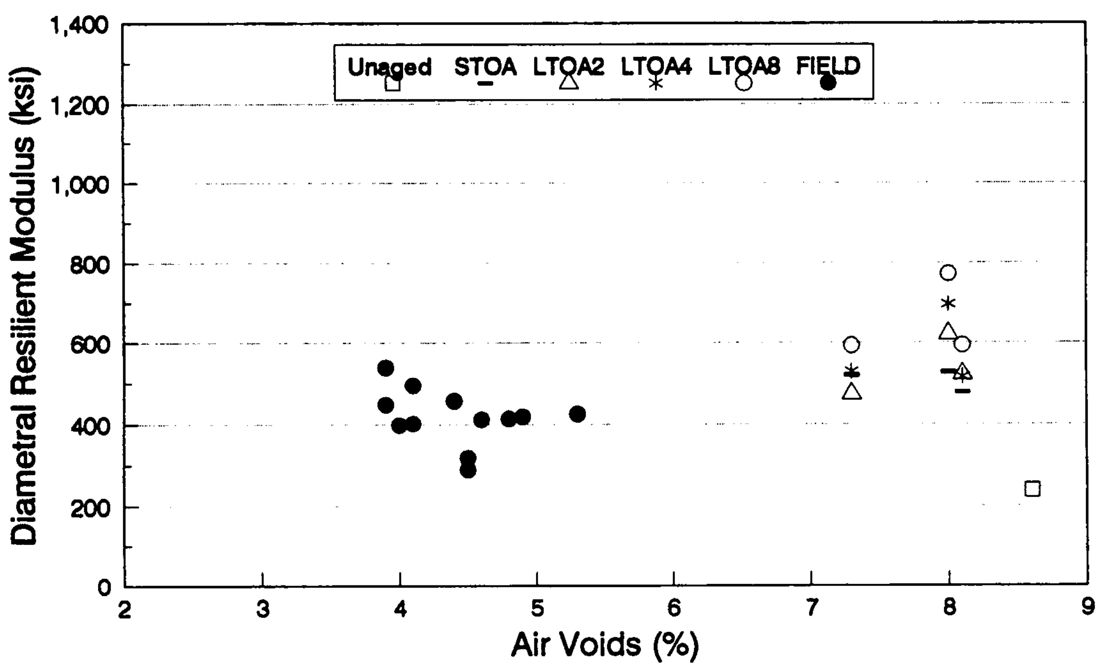

Figure 5.4d Washington Site 1002 Diametral Resilient Modulus, 85°C (185°F) Aging

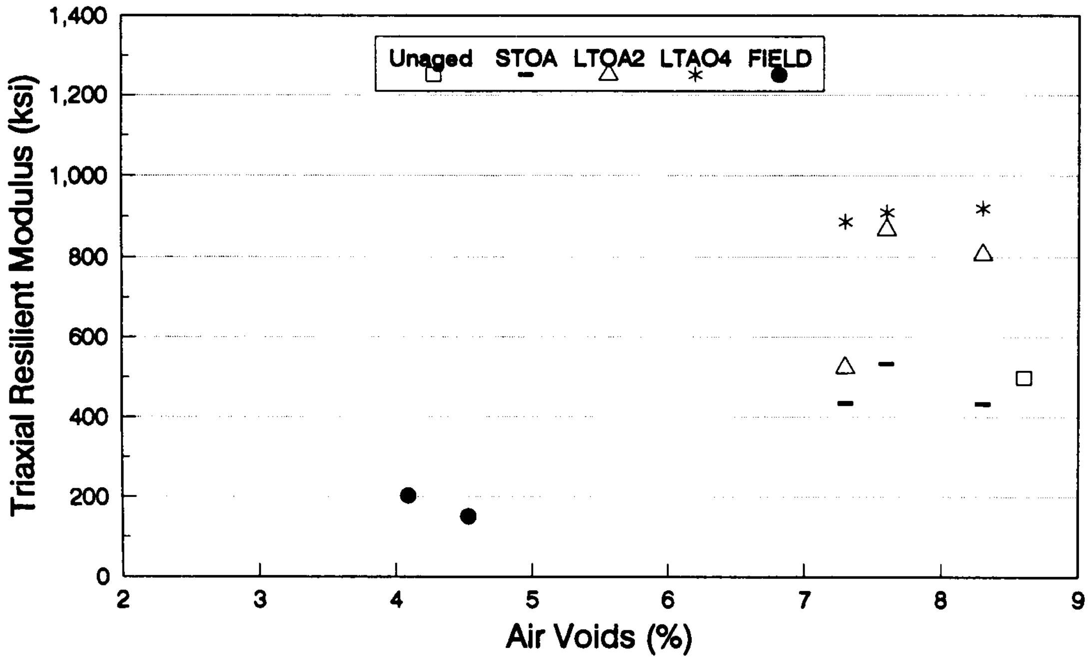

Figure 5.4e Washington Site 1002 Triaxial Resilient Modulus, 100°C (212°F) Aging

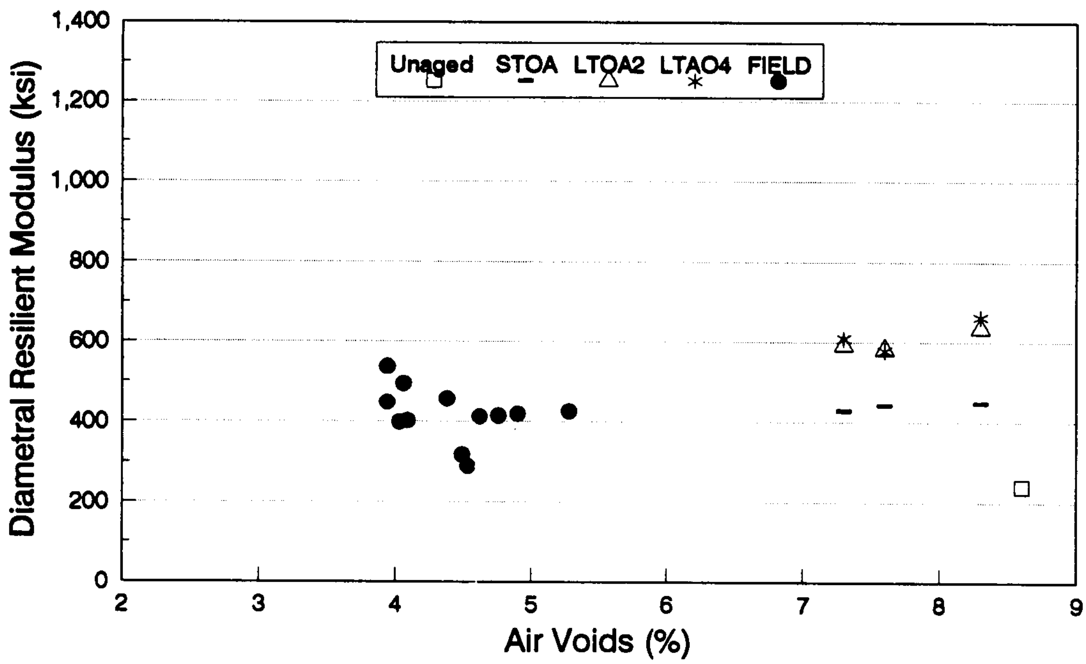

Figure 5.4f Washington Site 1002 Diametral Resilient Modulus, 100°C (212°F) Aging

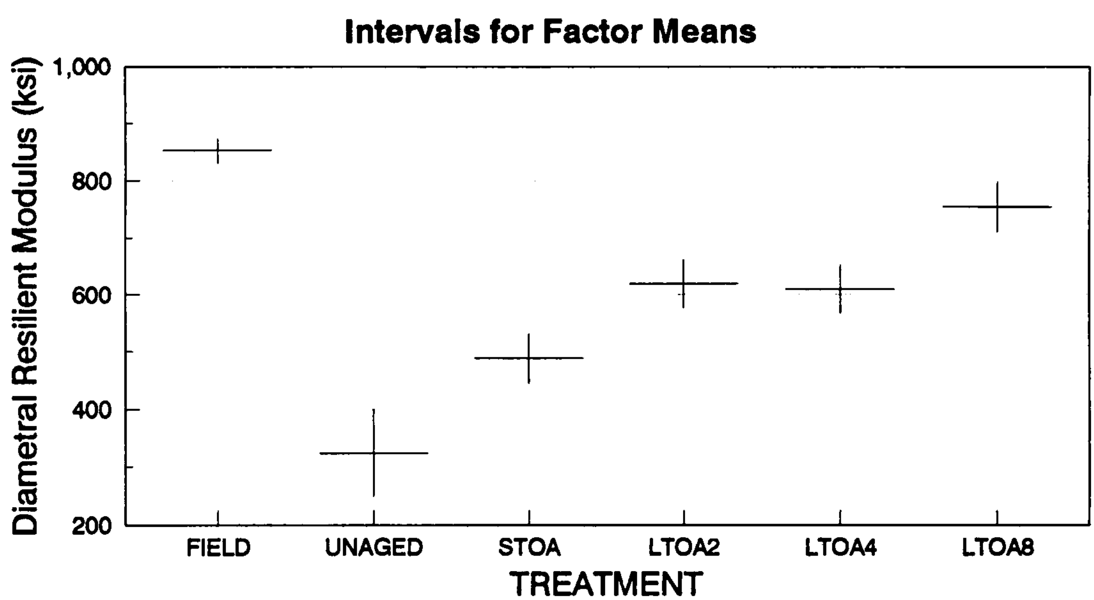

Figure 5.5a Washington Site 1006 LSD Comparison, 85°C (185°F) Aging

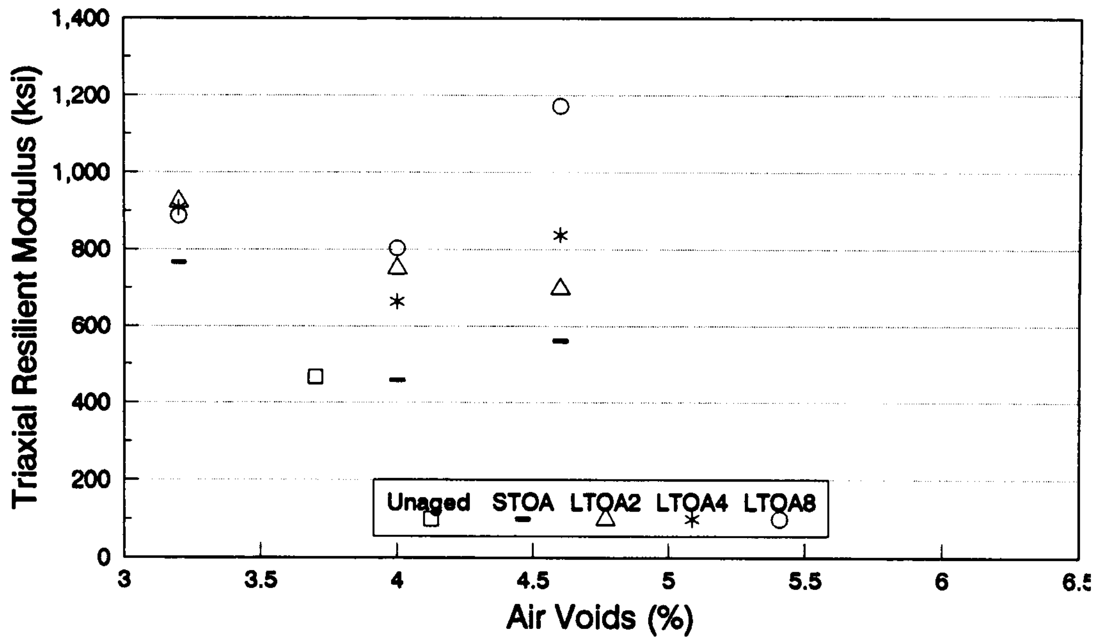

Figure 5.5b Washington Site 1006 Triaxial Resilient Modulus, 85°C (185°F) Aging

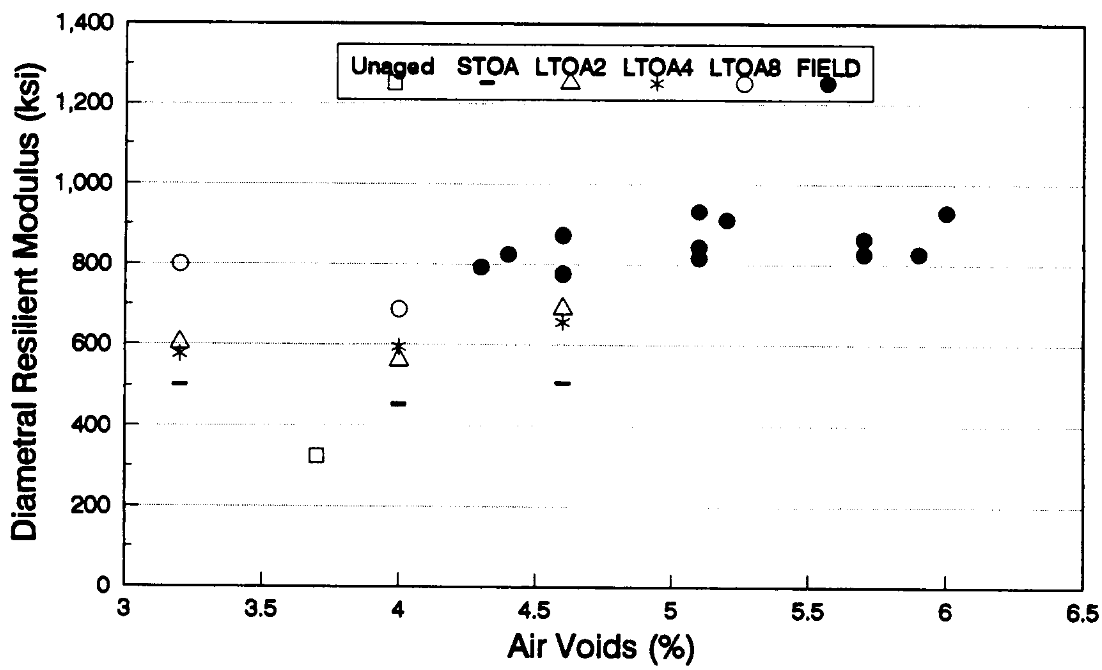

Figure 5.5c Washington Site 1006 Diametral Resilient Modulus, 85°C (185°F) Aging

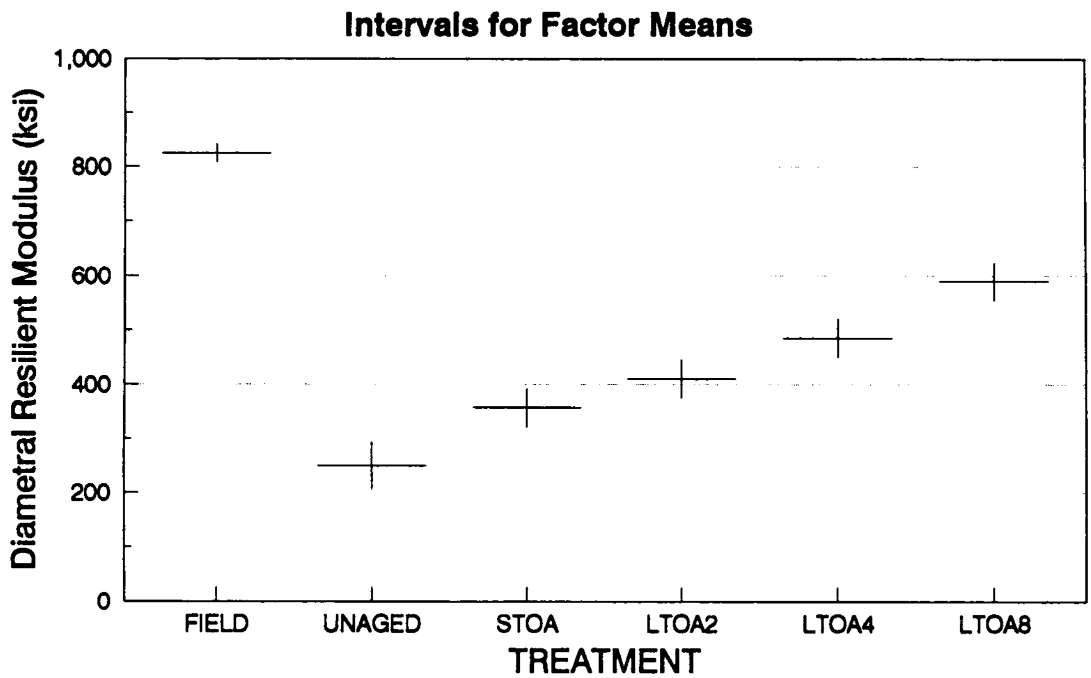

Figure 5.6a Washington Site 1008 LSD Comparison, 85°C (185°F) Aging

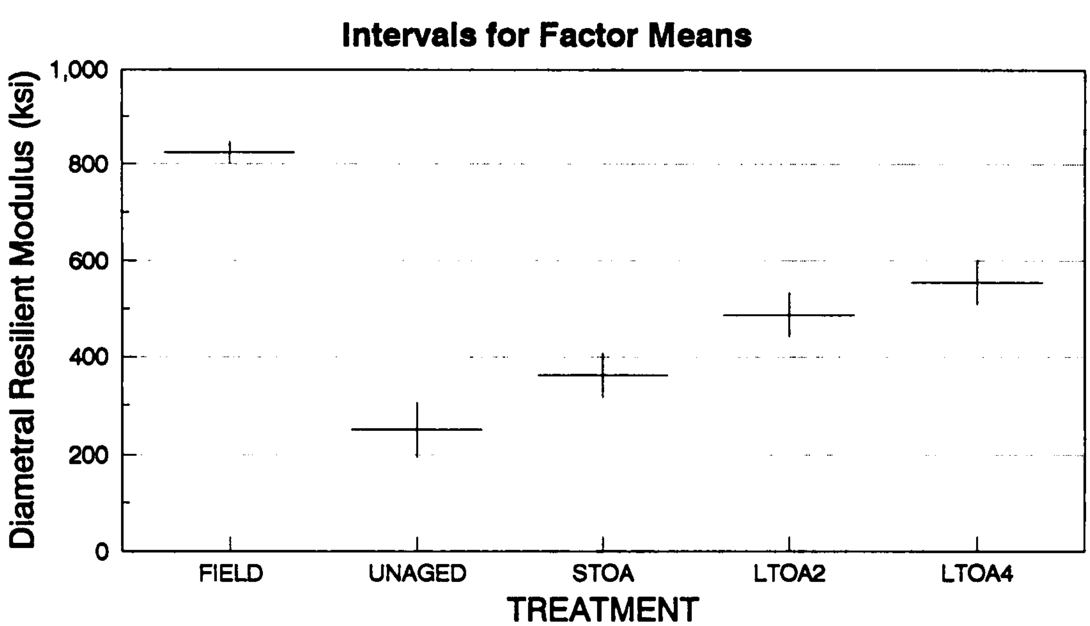

Figure 5.6b Washington Site 1008 LSD Comparison, 100°C (212°F) Aging

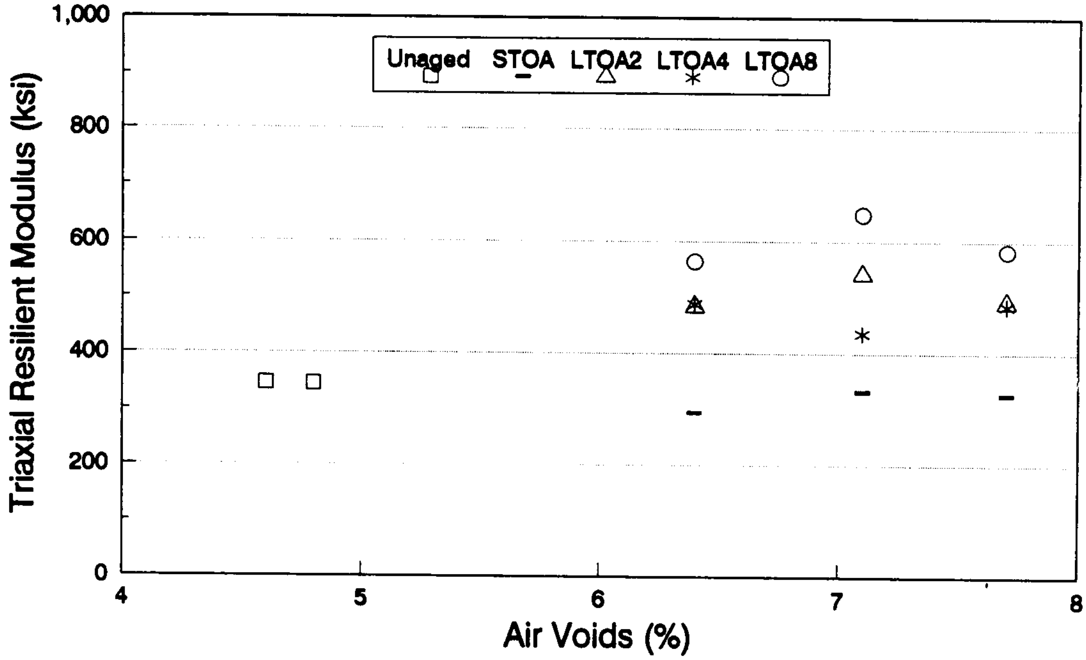

Figure 5.6c Washington Site 1008 Triaxial Resilient Modulus, 85°C (185°F) Aging

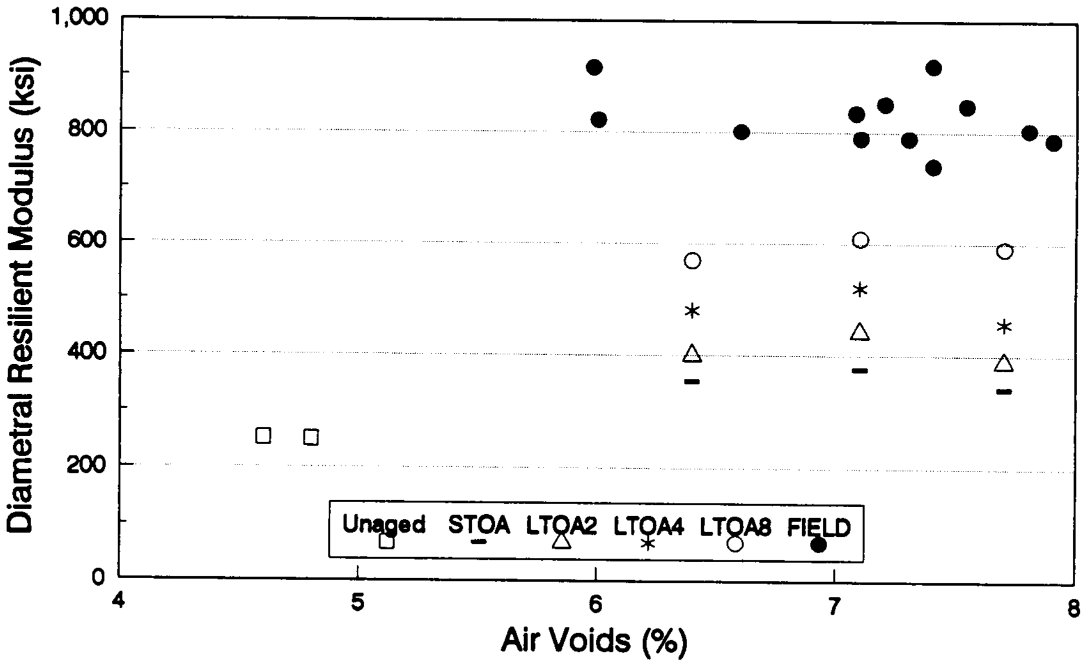

Figure 5.6d Washington Site 1008 Diametral Resilient Modulus, 85°C (185°F) Aging

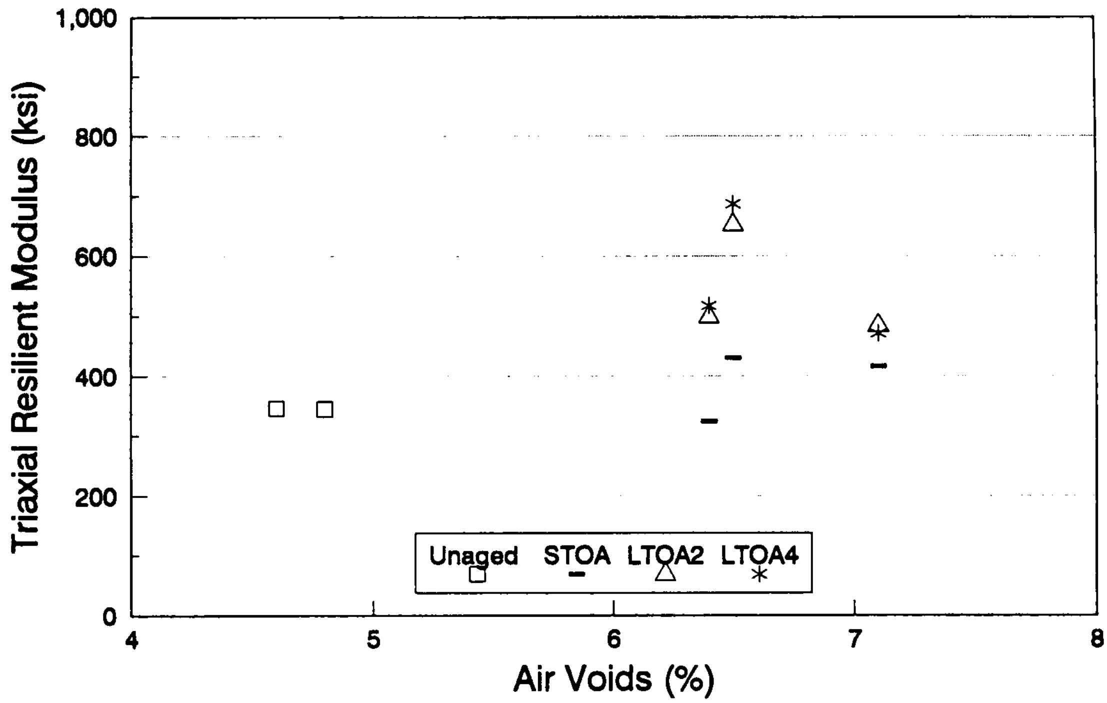

Figure 5.6e Washington Site 1008 Triaxial Resilient Modulus, 100°C (212°F) Aging

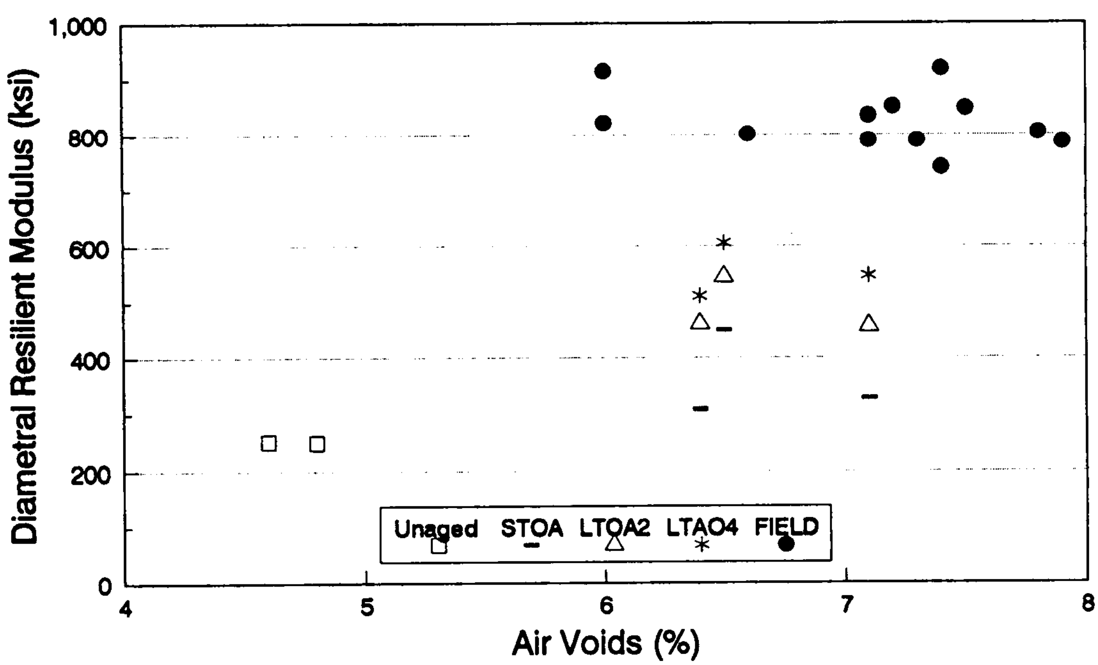

Figure 5.6f Washington Site 1008 Diametral Resilient Modulus, 100°C (212°F) Aging

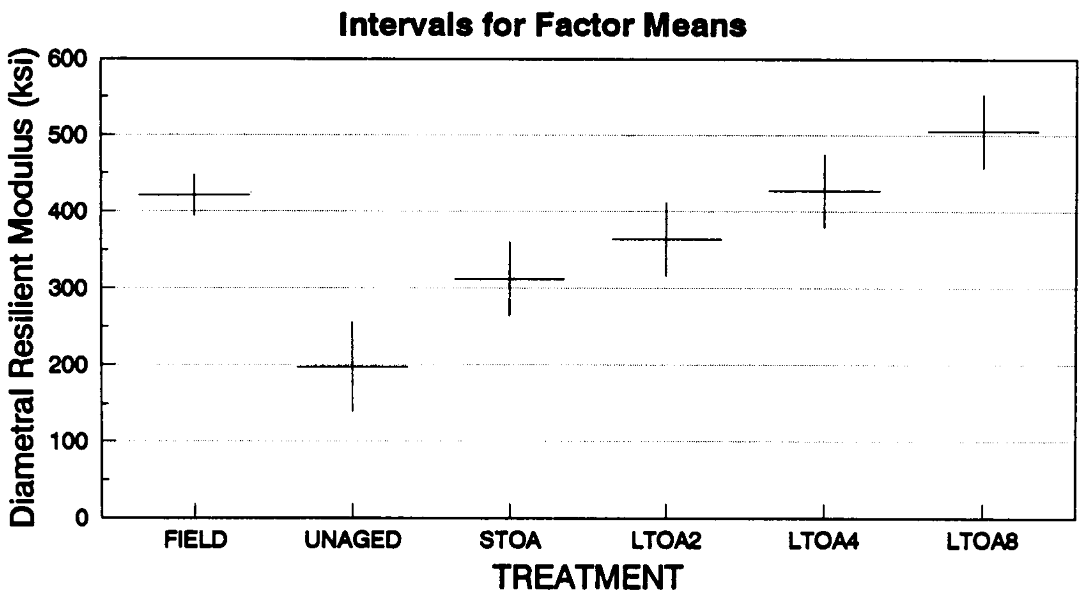

Figure 5.7a Washington Site 6056 LSD Comparison, 85°C (185°F) Aging

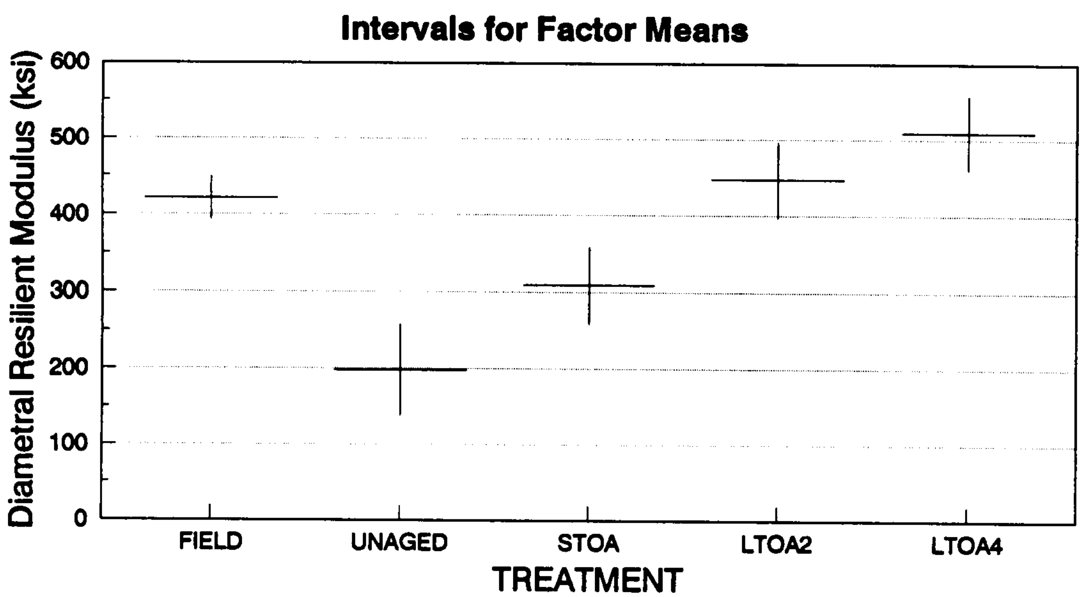

Figure 5.7b Washington Site 6056 LSD Comparison, 100°C (212°F) Aging

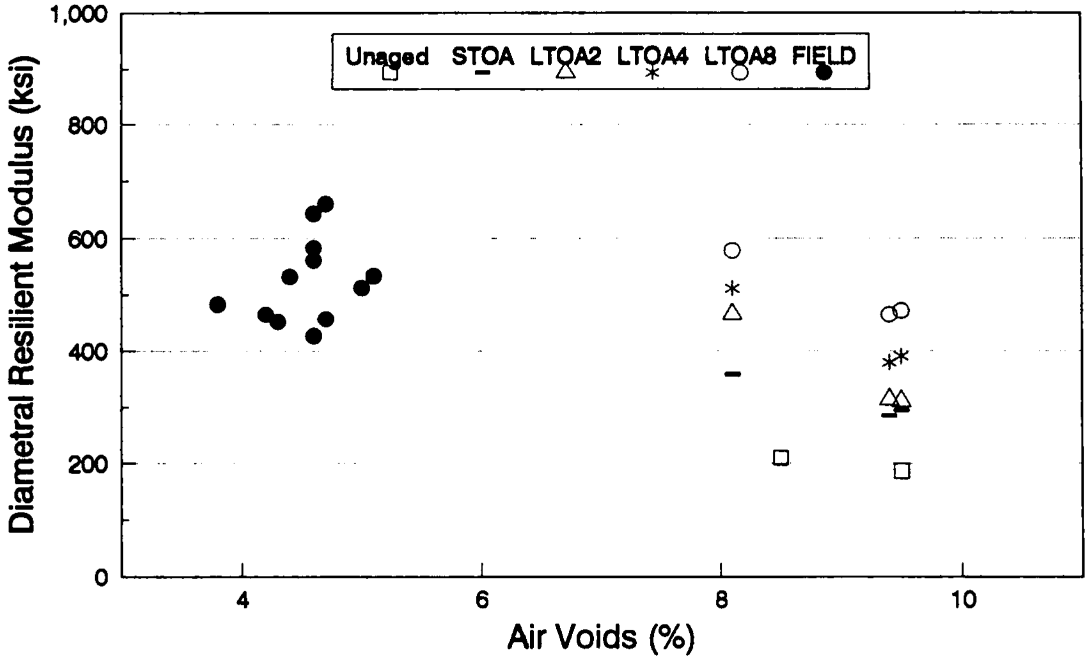

Figure 5.7c Washington Site 6056 Triaxial Resilient Modulus, 85°C (185°F) Aging

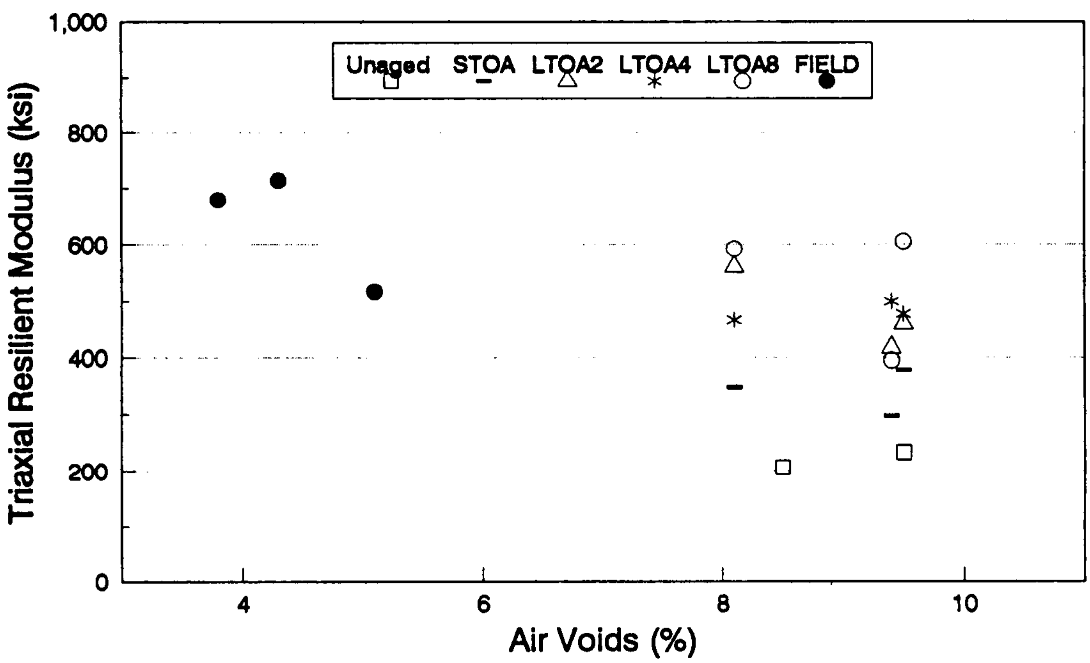

Figure 5.7d Washington Site 6056 Diametral Resilient Modulus, 85°C (185°F) Aging

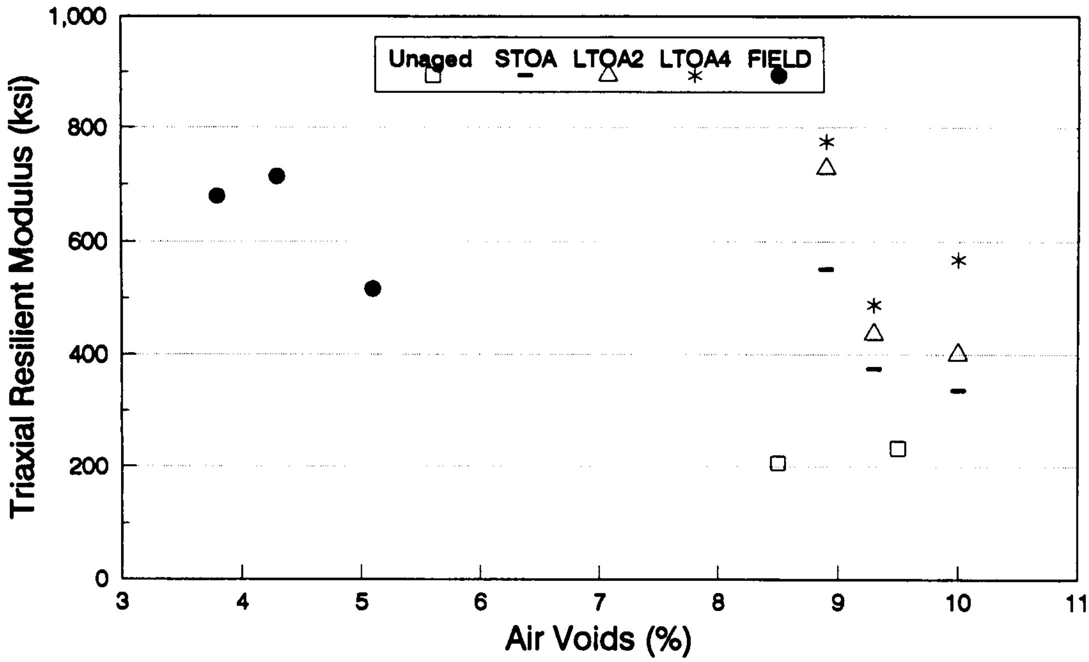

Figure 5.7e Washington Site 6056 Triaxial Resilient Modulus, 100°C (212°F) Aging

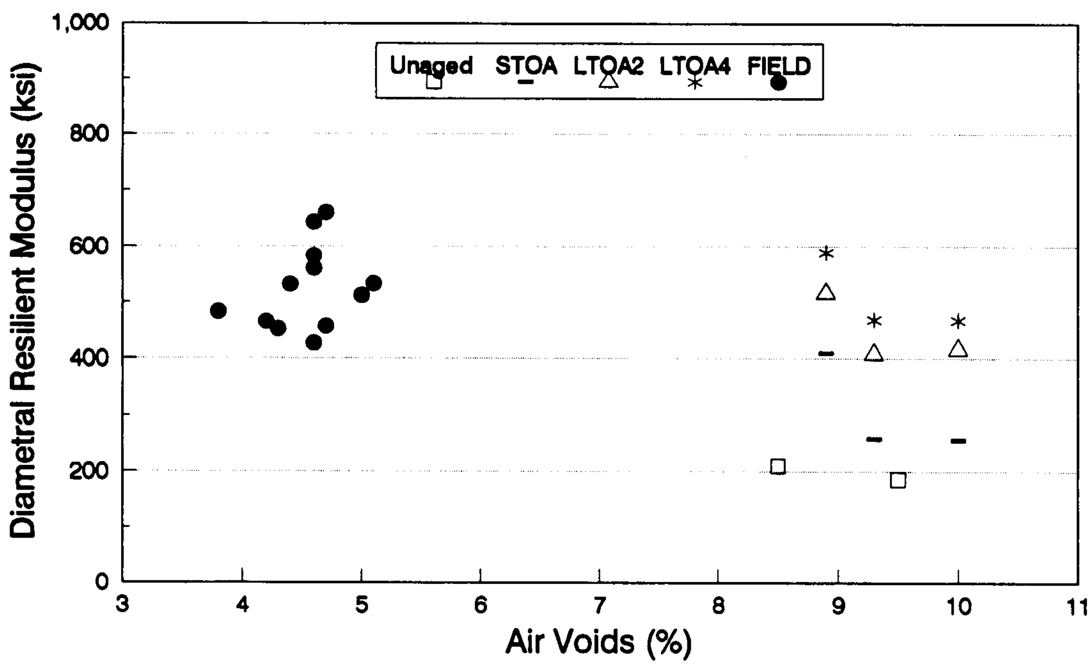

Figure 5.7f Washington Site 6056 Diametral Resilient Modulus, 100°C (212°F) Aging

6

Conclusions and Recommendations

6.1 Conclusions

The following conclusions may be drawn from this study.

1) The triaxial resilient modulus results do not tend to follow the same general trend as the diametral modulus values, that of increased modulus with increased aging time. Also, the variation in triaxial modulus values was larger than the variation in the diametral moduli. This was true even though a large portion of the variation in testing was eliminated by having the same operator using the same equipment for each testing sequence.

2) The California and Georgia Asphalt-Aggregate Mixture Analysis Study (AAMAS) field moduli were much lower than expected, which may be due to the poor mix design identified in the AAMAS study (von Quintus et al., 1991). The wide variation in the Arizona SPS-6 (Special Pavement Study) field moduli and the small number of cores three make it difficult to distinguish whether the unaged or short-term overn aging (STOA) specimens best represent the field modulus after 6 months. Additional coring and testing of this site in the future may resolve this problem. Since the California AAMAS and the Arizona SPS-6 were the only long-term sites in a dry-freeze climatic zone, and the Georgia AAMAS was the only site in a wet–no freeze climate, no aging relationships based on climate can be identified at this time.

3) Discounting the three sites discussed (Arizona SPS-6, California AAMAS, and Georgia AAMAS), the remaining sites all have field moduli significantly higher than the unaged lab specimens. Two of these sites (California GPS-6 and Michigan SPS-6) are only a few months old and can be assumed to have moduli similar to the time when they were compacted. They both have field moduli averages very close to the STOA specimens. These data strengthen the conclusions of the preliminary study in which 4 hours of aging at 135°C

(275°F), STOA, was decided to be representative of the aging due to the construction process.

4) A representation of the mixtures' hardening rate can be seen in the Tukey and least significant difference (LSD) plots in figures 4.1 through 4.14. The Michigan project, which used a low-viscosity asphalt, had a modulus increase of more than 200 percent between the unaged and the 8-day LTOA specimens. The stiffer asphalt-aggregate combination of the Arizona SPS-5 project had a modulus increase of less than 50 percent over the same range. It was expected that heavier, stiffer mixtures would age more slowly, since there are fewer volatiles in the asphalts. While prediction of the aged modulus is not yet possible, comparison of aging rates for asphalt-aggregate combinations with similar asphalt properties can be made using the long-term oven-aging (LTOA) procedures. This is underway within another subtask of the SHRP study.

5) The results of the LTOA at 100°C (212°F) are similar to the LTOA at 85°C (185°F), but the higher temperature achieves similar hardening in less time. No degradation or deformation of the specimens was observed during the 100°C (212°F) aging procedure. However, there was more variability in the data, and the lower temperature is therefore to be preferred.

6) Five of the supplementary sites were older than 9 years and required at least the maximum amount of LTOA to statistically match the field aging, i.e., 8 days of LTOA at 85°C (185°F) or 4 days of LTOA at 100°C (212°F). Of these five sites, numbers 1006 and 1008 (ages 9 and 13 years), had field modulus values significantly higher than any of the aging treatments. Site 1801, age 18 years, was similar to the field at 8 days of 85°C (185°F) (LTOA) but was significantly lower than the field at 4 days of 100°C (212°F) aging. Site 6049, age 19 years, had field values matching 4 days of LTOA at 100°C (212°F), while site 6048, age 14 years, encompassed all aging treatment due to a large spread of field core modulus values. These data indicate that LTOA of 4 days at 100°C (212°F) or 8 days at 85°C (185°F) is representative of all five of these older sites, while conservative for two of them.

7) Due to the large spread of field core modulus values for site 6048, a close correlation to laboratory aging treatments is not possible. Site 6048 was slightly cracked before coring, which could have resulted in the high variability in diametral modulus values between cores. For further study, cores from uncracked sections of the road would be needed.

8) It is apparent that the amount of traffic and the climatic region for a particular highway site play a role in the field modulus values of the cored specimens. The three supplementary sites over 9 years old with low relative traffic counts (1801, 1006, and 1008) had the highest average field modului. Two of those sites (1006 and 1008), the youngest of those sites 9 years and

older, had the highest yearly temperature deviations and also the highest field modulus values.

The two sites over 9 years old with high traffic counts (6048 and 6049) had the lowest field modulus averages and the highest standard deviation between cores. Sites 6048 and 6049 also had two of the highest rainfall averages, indicating that the high moisture combined with the high traffic levels had some effect on the high variability as well as low modulus values among the cores.

9) It appears that climates with high temperature variations age (gain modulus) at a faster rate than wet climates with a low temperature variation. The three wet–no freeze sites have the three lowest average temperature deviations as well as the three highest yearly rainfall averages. The four dry-freeze sites have the four highest temperature deviations as well as the four lowest rainfall averages (table 5.4).

   The three sites over 9 years old in the wet–no freeze zone have two of the three lowest modulus averages. The two dry-freeze sites (1008 and 1006) have the two highest modulus values.

   A comparison between sites 1006 and 1801 strengthens this conclusion. Site 1006, containing Pave Bond Special (PBS), has an aging rate only half that of site 1801. Table 5.3 shows that both lab sites after 8 days of aging at 85°C (185°F) have very similar modulus values. Site 1006 had an unaged modulus almost twice that of site 1801 and thus was able to match 1801's modulus even though it had only half the aging ratio. Therefore, if field conditions (traffic and weather) were similar, site 1006 should have achieved modulus values similar to site 1801 for the same time in the field. But after 9 years, site 1006 shows a higher modulus than the 18-year-old site 1801. (These lab data tend to show that the PBS in the 1006 field samples is not the cause of the high modulus gain in only 9 years.)

10) The PBS contained in lab cores 1006 and 1008 tends to reduce the aging rate, while at the same time increasing the initial unaged modulus. Table 5.3 shows that sites 1006 and 1008 have the two lowest aging ratios. The sites also have two of the highest unaged modulus values. (Site 1006 has by far the highest unaged modulus, 325 ksi.) Even though the two sites have low aging ratios, the combination of their high initial moduli and their extreme temperature fluctuations between seasons results in high field moduli after relatively low aging time in the field.

11) Although 9- and 18-year-old sites, such as 1006 and 1801, achieve similar hardening in the field, this study does not conclude what a field pavement's maximum modulus is, when it reaches its maximum, or what happens after it reaches its maximum. Only theories can be discussed.

For instance, site 1801 may have reached 850 ksi during its first 9 years, then started to deteriorate due to the high rainfall. The asphalt modulus may then have remained about the same, even though the asphalt continued to age. Or this site may have had a modulus of only 600 ksi after 9 years, and then slowly gained modulus until 18 years, when it was cored.

Site 1006, while it now has an 852-ksi modulus, may continue to gain modulus in the field until a certain point, and then also decline in modulus to the mid 800s in its later years. Or, this site may continue to gain modulus its whole field life.

6.2 Recommendations

The following recommendations may be made from the results of this study.

1) To further analyze the effectiveness of the short-term aging period of 4 hours, additional sites should be selected. Of the agencies contacted when searching for retained materials, few indicated the use of diametral resilient modulus for testing newly laid pavements. Since this method is common practice in Oregon, additional Oregon sites are being considered.

2) Increasing the number of sites and the total number of specimens prepared will facilitate the use of regression analysis to determine prediction models. The sites selected should have in-service lives ranging from 1 to 20 or more years to encompass all long-term aging in the field. A reduction in the 95 percent confidence intervals shown on the Tukey HSD (honest significant difference) and LSD plots in this study could lead to correlation of the laboratory procedures and the age of the field cores. This could lead to prediction models in which a known treatment is used to predict the stiffness of field pavements (e.g., for an AC-10 in the dry-freeze region, STOA and 4-day LTOA are very similar to 6 years in service).

3) This study addressed validation of 4-hour-at-135°C (275°F) STOA and the LTOA at 85°C (185°F) and 100°C (212°F). One additional test for long-term aging has been developed at Oregon State University and deserves additional validation study. This is the low-pressure oxidation test (LPO) at varied temperatures. The test involves passing oxygen through a specimen at elevated temperatures of 60°C (140°F) or 85°C (185°F). The pressures involved with this procedure are not high enough to pose safety problems similar to those of high-pressure oxidation studied in the past. Additional specimens were prepared with the intent of using them in a validation effort for low pressure oxidation, but due to time limitations, the test was not completed.

4) To obtain a more accurate model to simulate field aging, more parameters are needed to determine a multiple linear regression relationship. Possible inputs could be traffic, high and low average field temperatures, average rainfall, field age, lab aging time to match the field modulus. Field modulus could be the dependent variable, and the other variables could be independent or explanatory variables. With this data, several regression models could be tried until the best regression fit is obtained. It may be the case that not all of the independent variables are used, but having them available would ensure the best fit.

6.3 Implementation

The following are preliminary guidelines for implementing the results from this study.

Although only five sites older than 9 years old were studied, and all were in Washington, they included dry-freeze and wet–no freeze zones, which cover a good portion of the United States (see figure 2.2). Neither the dry–no freeze portion of the United States nor the wet-freeze zones contained any sites over 5 years old. Since not enough young and old sites were available from each climatic zone, only a few definite recommendations can be made at this time.

1) 0 to 2 years, all zones: STOA

Based on the Oregon preliminary study data and the two expanded sites, California GPS-6 and Michigan SPS-6, it appears that 4 hours of lab oven aging at 135°C (275°F) is a good (although conservative for some sites) estimate of the aging taking place during field mixing and up to 2 years after. Minnesota SPS-5 was over 1 years old and had a field modulus similar to STOA.

Two 2-year-old sites, California AAMAS and Georgia AAMAS, had poor field cores that did not allow a good comparison. The only undamaged 1- to 2-year-old site with a field modulus matching the unaged lab specimens was Arizona SPS-6. Arizona SPS-5, in a more extreme environment than Arizona SPS-6, had a field modulus closer to the 2-day-at-85°C (185°F) long-term specimens.

This recommendation takes into account three climatic zones and is a conservative estimate. As mentioned earlier, to get a true indication of what happens in each zone, a more thorough study is needed.

2) Over 9 years for the dry-freeze zone: 8 days of LTOA at 85°C (185°F)
Over 18 years for the wet–no freeze zone: 8 days of LTOA at 85°C (185°F)

Long-term oven aging at 85°C (185°F) for 8 days appears representative (and conservative) of the sites 9 years or older in the dry-freeze zone and 18 years or older in the wet–no freeze zone. It is not clear what the modulus is for the wet–no freeze sites between 9 and 18 years; therefore no general conclusion can be made for all of these 9-year or older sites. Again, further research in each of these zones is needed.

For the following field aging periods, only an estimate can be made by combining all of the climatic zones. This is only for discussion purposes, and not recommended.

3) 2 to 6 years: LTOA of 2 days at 85°C (185°F)

Four sites were studied in this time range: Wisconsin AAMAS (3 years old), Washington 6056 (5 years old), Washington 1002 (3 years old), and the France LCPC site (5 years old). The Wisconsin field modulus was similar to LTOA of 2 and 4 days at 85°C (185°F), as was the Washington site 6056. The French field modulus was similar to LTOA of 8 days at 85°C (185°F), and the Washington site 1002 had a field modulus matching the STOA specimens. Field cores from the Washington site 1002 were overlain after only 3 years in the field and were considered to be in poor condition (a 61 pavement rating).

A conservative estimate of field aging for this period is LTOA of 2 days at 85°C (185°F).

4) 6 to 9 years: Unknown

No field sites were available from this time period. A hypothesis would be that LTOA of 4 days at 85°C (185°F) would be similar to this amount of field aging.

7

References

AbWahab, Y. Ph.D. Forthcoming dissertation. (1992) Oregon State University, Corvallis, Oregon.

Bell, C.A. (1989). Summary Report on Aging of Asphalt-Aggregate Systems. SHRP-A-305, Strategic Highway Research Program, National Research Council, Washington, DC.

Bell, C.A., Y. AbWahab, M.E. Cristi, and D. Sosnovske (1993). TMAAM: Selection of Laboratory Aging Procedures for Asphalt-Aggregate Mixtures. TM-OSU-A003A-92-22, Strategic Highway Research Program, National Research Council, Washington, DC.

Bell, C.A., Y. AbWahab, J. Kliewer, D. Sosnovske, and A. Wieder (1992). Aging of Asphalt-Aggregate Mixtures. *Proceedings, 7th International Conference on Pavements,* London, Vol. 2, 1-15.

Bell, C.A., and D. Sosnovske (1993). TMAAM: Validation of the A-002A Hypothesis for Aging. TM-OSU-A-003A-92-24, Strategic Highway Research Program, National Research Council, Washington, DC. Forthcoming.

Dow, A.W. (1903). Asphalt Experiments at Washington. *Engineering News Record* 47: 18.

Edler, A.C., M.M. Hattingh, V.P. Servas, and C.P. Marais, (1985). Use of Aging Tests to Determine the Efficacy of Hydrated Lime Additions to Asphalt in Retarding Its Oxidative Hardening. *Proceedings, American Association of Asphalt Paving Technologists,* Vol. 54, 118–139.

Goode, J.F. and L.A. Lufsey (1966). Voids, Permeability, Film Thickness vs Asphalt Hardening. *Proceedings, American Association of Asphalt Paving Technologists,* Vol. 35, 430–463.

Griffin, R.L., T.K. Miles, and C.J. Penter (1955). Microfilm Durability Test for Asphalt. *Proceedings, American Association of Asphalt Paving Technologists,* Vol. 25, 31–62.

Hveem, F.N., E. Zube, and J. Skog (1963). Proposed New Tests and Specifications for Paving Grade Asphalts. *Proceedings, American Association of Asphalt Paving Technologists,* Vol. 32, 247–327.

Kemp, G.R. and N.H. Predoehl (1981). A Comparison of Field and Laboratory Environments on Asphalt Durability. *Proceedings, American Association of Asphalt Paving Technologists,* Vol. 50, 79–99.

Lee, D.Y. (1973). Asphalt Durability Correlation in Iowa. Highway Research Board, Record 468, 43–60.

Lewis, R.H. and W.J. Welborn (1940). Report on the Properties of the Residues of 50-60 and 85-100 Penetration Asphalts from Oven Tests and Exposure. *Proceedings, American Association of Asphalt Paving Technologists,* Vol. 11, 86–157.

Petersen, J.C. (1984). Chemical Composition of Asphalt as Related to Asphalt Durability: State of the Art. *Transportation Research Record* 999: 13–30.

Petersen, J.C. (1989). A Thin-Film Accelerated Aging Test for Evaluating Asphalt Oxidative Aging. *Proceedings, American Association of Asphalt Paving Technologists,* Preprint Volume.

Traxler, R.N. (1961). Relation Between Asphalt Composition and Hardening by Volatilization and Oxidation. *Proceedings, American Association of Asphalt Paving Technologists,* Vol. 30, 359–377.

Traxler, R.N. (1963). Durability of Asphalt Cements. *Proceedings, American Association of Asphalt Paving Technologists,* Vol. 32, 44–58.

Von Quintus, H.L., J.A. Scherocman, C.S. Hughes, and T.W. Kennedy (1991). Asphalt-Aggregate Mixture Analysis System. National Cooperative Highway Research Program, Report 338, National Research Council, Washington, DC.

Welborn, J.Y. (1979). Relationship of Asphalt Cement Properties to Pavement Durability. National Cooperative Highway Research Program, Synthesis 59, National Research Council, Washington, DC.

Appendix A

Mixture Gradations, Mix Design Data, Traffic, Pavement, and Climatic Data—Expanded Validation

The sieve analysis data, tables A1 to A10, are listed in U.S. sieve sizes. Currently, no U.S. set of standard sieve sizes are available in metric units. However, a comparison of standard United Kingdom (U.K.) sizes is given as a guideline in table A20.

Table A1 Arizona SPS-5 Gradation

Size	Percent Required
1" x 3/4"	0
3/4" x 1/2"	7
1/2" x 3/8"	15
3/8" x #4	21
#4 x #30	37
#30-	20

Table A2 Arizona SPS-6 Gradation

Size	Percent Required
1" x 3/4"	6
3/4" x 1/2"	16
1/2" x 3/8"	12
3/8" x #4	17
#4 x #30	27
#30-	22

Table A3a California AAMAS "Batch" Gradation

Size	Percent Required
1" x 3/4"	0
3/4" x 1/2"	8
1/2" x 3/8"	5
3/8" x #4	26
#4 x #30	32
#30-	29

Table A3b California AAMAS "Drum" Gradation

Size	Percent Required
1" x 3/4"	0
3/4" x 1/2"	1
1/2" x 3/8"	13
3/8" x #4	25
#4 x #30	35
#30-	26

Table A4 California GPS-6 Gradations

Size	Percent Required
1" x 3/4"	0
3/4" x 1/2"	4
1/2" x 3/8"	13
3/8" x #4	23
#4 x #30	35
#30-	25

Table A5 France LCPC Gradation

Size	Percent Required
Large Basalt Gravel	45
Small Basalt Gravel	15
Basalt Sand	15
Silica Sand	25

Table A6 Georgia AAMAS Gradation

Size	Percent Required
1" x 3/4"	11
3/4" x 1/2"	19
1/2" x 3/8"	8
3/8" x #4	2
#4+ Fines	11
#4 x #30	30
#30-	19

Table A7 Michigan SPS-6 Gradation

Size	Percent Required
1" x 3/4"	0
3/4" x 1/2"	6
1/2" x 3/8"	11
3/8" x #4	21
#4 x #30	32
#30-	30

Table A8 Minnesota SPS-5 Gradation

Size	Percent Required
1" x 3/4"	0
3/4" x 1/2"	17
1/2" x 3/8"	9
3/8" x #4	11
#4 x #30	41.5
#30-	21.5

Table A9 **Wisconsin AAMAS Gradation**

	Size	Percent Required
Virgin	3/4" x 1/2"	1.6
	1/2" x 3/8"	7.7
	3/8" x #4	13.2
	#4 x #30	19.3
	#30-	13.2
RAP	1-1/2" x 1"	1.4
	1" x 3/4"	1.9
	3/4" x 1/2"	5.2
	1/2" x 3/8"	5.1
	3/8" x #4	11.1
	#4 x #30	14.9
	#30-	5.4

Table A10a Summary of Aggregate Gradations

	Arizona, SPS-5		Arizona, SPS-6		California, AAMAS Batch		
Sieve Size	JMF (Target)	Mix Blend	JMF (Target)	Mix Blend	JMF	Extr (Target)	Mix Blend
1 "	100.0	100.0	100	100	100.0	100.0	100.0
3/4 "	100.0	100.0	95	94	100.0	100.0	100.0
1/2 "	93.0	93.0	79	78	97.0	92.0	92.0
3/8 "	78.0	78.0	65	66	85.0	88.0	87.0
1/4 "	63.0	--	55		--	--	--
No. 4	58.0	56.9	50	49	61.0	64.0	61.0
No. 8	46.0	46.4	40	40.4	47.0	52.0	52.4
No. 10	43.0	--	39		--	--	--
No. 16	34.0	36.7	33	31.6	35.0	41.0	41.0
No. 30	32.0	22.2	24	23	25.0	31.0	30.8
No. 40	16.0	--	18		--	--	--
No. 50	11.0	10.4	13	13.5	16.0	20.0	20.2
No. 100	5.0	3.9	6	7	10.0	13.0	13.0
No. 200	2.9	2.0	4.1	4.2	8.0	9.0	8.3

	Georgia, AAMAS			Minnesota, SPS-5		Michigan, SPS-6	
Sieve Size	JMF	Extr (Target)	Mix Blend	JMF (Target)	Mix Blend	JMF (Target)	Mix Blend
1 "	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3/4 "	92.0	89.0	89.0	100.0	100.0	100.0	100.0
5/8 "	--	--	--	96.0	--		
1/2 "	77.0	70.0	70.0	83.0	83.0	94.2	94.0
3/8 "	68.0	62.0	61.9	75.0	74.0	82.8	83.0
1/4 "	--	--	--	--	--		
No. 4	54.0	52.0	51.1	64.0	63.0	63.0	62.0
No. 8	38.0	39.0	37.1	--	53.7	50.9	51.3
No. 10	--	--	--	51.0	--		
No. 16	26.0	26.0	26.8	--	42.4	41.0	42.1
No. 30	19.0	19.0	19.5	--	27.0	32.2	32.2
No. 40	--	--	--	19.0	--		
No. 50	13.0	14.0	15.1	--	13.8	24.0	19.2
No. 100	9.0	10.0	11.4	--	8.5	15.5	10.6
No. 200	5.0	7.0	7.5	5.0	5.9	6.2	7.2

Table A10b Summary of Aggregate Gradations

	California, AAMAS Drum			California GPS-6	
Sieve Size	JMF Blend	Extr (Target)	Mix Blend	JMF (Target)	Mix Blend
1 "	100.0	100.0	100.0	100.0	100.0
3/4 "	100.0	100.0	100.0	100.0	100.0
1/2 "	97.0	99.0	99.0	96.0	96.0
3/8 "	85.0	85.0	86.0	83.0	83.0
1/4 "	--	--	--	--	--
No. 4	61.0	61.0	61.0	60.0	59.9
No. 8	47.0	53.0	51.6	49.0	47.6
No. 10	--	--	--	--	--
No. 16	35.0	39.0	39.1	38.0	38.2
No. 30	25.0	27.0	28.0	25.0	26.0
No. 40	--	--	--	--	--
No. 50	16.0	18.0	18.3	13.0	14.9
No. 100	10.0	11.0	11.8	6.0	7.7
No. 200	8.0	8.0	7.6	3.0	3.2

	Wisconsin, AAMAS		
Sieve Size	JMF	Extr (Target)	Mix Blend
1 "	100.0	100.0	100.0
3/4 "	100.0	100.0	100.0
1/2 "	98.0	97.0	97.0
3/8 "	90.0	83.0	83.0
1/4 "	--	--	--
No. 4	69.0	58.0	58.4
No. 8	53.0	42.0	42.4
No. 10	--	--	--
No. 16	--	34.0	32.2
No. 30	23.0	25.0	24.6
No. 40	--	--	--
No. 50	--	17.0	17.4
No. 100	--	11.5	10.7
No. 200	9.4	6.0	6.9

Table A11 Field Site Identification

Site	Governing Agency	Mixture Designation
Arizona, SPS-5 (AZ5)	SHRP	Arizona DOT 3/4-in. modified
Arizona, SPS-6 (AZ6)	SHRP	Arizona DOT 3/4-in. modified
California, AAMAS Batch (CAB)	CALTRANS	CALTRANS Type "A" mix
California, AAMAS Drum (CAD)	CALTRANS	CALTRANS Type "A" mix
California, GPS-6b (CAG)	SHRP	Not Available
Georgia, AAMAS (GAA)	Georgia DOT	Georgia DOT "B" mix
Minnesota, SPS-5 (MN5)	SHRP	Not Available
Michigan, SPS-6 (MI6)	SHRP	1500 T (Top Course)
Wisconsin, AAMAS (WIA)	Wisconsin DOT	Recycled
France	LCPC	Not Available

Table A12 Coring Dates for Field Sites

Site	Coring Date
AZ5	January 14, 1991
AZ6	April 12, 1991
CAB	August 1991
CAD	August 1991
CAG	October 1991
GAA	April 1991
MI6	Not Available
MN5	December 12, 1991
WIA	September 19, 1991
France	November 1990

Table A13 Field Sites Materials Identification

Site	Construction Type	Normal Layer Thickness (mm)	Number of Lifts	Normal Lift Thickness (mm)
AZ5	Overlay on AC	127	3	51
AZ6	Not available	Not available	Not available	Not available
CAB	Overlay on AC	114[1]	3[1]	38[1]
CAD	Overlay on AC	114[1]	3[1]	38[1]
CAG	Overlay on AC	89	2	44
GAA	Overlay on AC	102	1[1]	102[1]
MI6	Not available	Not available	Not available	Not available
MN5	Overlay on AC	127	3	44
WIA	Recycled overlay on AC	102	1	102
France	Not available	Not available	Not available	Not available

[1]From visual inspection of field cores.

Table A14 Asphalt and Admixture Contents

Site	Asphalt Content*	Admixture Content
AZ5	4.7 JMF	None
AZ6	4.6 JMF	1.5% Hydrated Lime
CAB	5.61 Extr	None
CAD	4.54 Extr	None
CAG	5.21 JMF	None
GAA	4.33 Extr	1.0 % Lime
MI6	5.6 JMF	0.7 % Flyash
MN5	5.60 JMF	None
WIA	3.16 New Extr 5.30 total	45% RAP 55% New Aggregate
France	5.9	None

*By total weight of mix

Table A15 Asphalt Viscosity Data and Mixing and Compaction Temperatures

Site	Absolute Viscosity at 60°C (Poises)	Kinematic Viscosity at 135°C (cSt)	Mix Temperature (°C)	Compaction Temperature (°C)
AZ5	4140	411	151	1287
AZ6	Not available	Not available	Not available	Not available
CAB	2050	286	151	127
CAD	2050	286	151	127
CAG	1180	278	144	120
GAA	3150	528	157	132
MI6	Not available	Not available	Not available	Not available
MN5	608	223	141	116
WIA	392	187	137	112
France	Not available	Not available	Not available	Not available

Table A16 Traffic Volumes for the Field Sections

Site	ADT	Percent Trucks	Date
AZ5	Not available	Not available	Not available
AZ6	Not available	Not available	Not available
CAB	4000	16	1989
CAD	4000	16	1989
CAG	8200	14	1991-1992
GAA	8800	9.8	1991
MN5	4900	13.4	1986
MI6	Not available	Not available	Not available
WIA	3500	10	1991
France	Not available	Not available	Not available

Table A17 Summary of Pavement Condition Surveys

Site	Survey Type	Survey Date	Comments
AZ5	Manual	8/92	In good condition, some traffic densification
AZ6	Manual	8/92	In good condition
CAB	Manual	8/92	In good condition
CAD	Manual	8/92	In good condition
CAG	Not available	Not available	Overlain with wearing course
GAA	Not available	Not available	Not available
MI6	Not available	Not available	Not available
MN5	Not available	Not available	Not available
WIA	Not available	Not available	Not available
France	Not available	Not available	Not available

Table A18 Monthly Normal Temperature (°C) for the Nearest Recording Station, 30-Year Average (1961–1991)

Site	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
AZ5	10.8	13.1	15.7	19.8	24.7	29.7	32.7	31.4	28.1	22	15.2	10.8
AZ6	na	na	na	na	na	na	na	na	na	na	na	na
CAB	0.06	2.9	5.2	8.2	12.6	17.1	20.8	20.1	16.1	10.6	4.4	0.2
CAD	0.06	2.9	5.2	8.2	12.6	17.1	20.8	20.1	16.1	10.6	4.4	0.2
CAG	12.6	14.9	17.1	20.3	24.7	29.5	32.9	32.7	29.3	23.6	16.9	12.4
GAA	1.6	3.3	7.9	12.4	16.6	20.6	22.5	22.1	18.9	12.9	8.3	3.7
MI6	na	na	na	na	na	na	na	na	na	na	na	na
MN5	na	na	na	na	na	na	na	na	na	na	na	na
WIA	na	na	na	na	na	na	na	na	na	na	na	na
FRA.	na	na	na	na	na	na	na	na	na	na	na	na

na = not available

Table A19 Monthly Normal Precipitation (mm) for the Nearest Recording Station, 30-Year Average (1961–1991)

Site	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
AZ5	19	18	22	7	3	3	22	50	22	20	19	30	235
AZ6	na	na	na	na	na	na	na	na	na	na	na	na	na
CAB	72	63	46	24	29	21	12	11	16	31	70	63	2822
CAD	72	63	46	24	29	21	12	11	16	31	70	63	2822
CAG	9	7	5	1	0.5	0.25	2	9	8	8	7	11	69
GAA	131	133	158	119	122	110	123	112	109	95	115	124	1452
MI6	na	na	na	na	na	na	na	na	na	na	na	na	na
MN5	na	na	na	na	na	na	na	na	na	na	na	na	na
WIA	na	na	na	na	na	na	na	na	na	na	na	na	na
FRA.	na	na	na	na	na	na	na	na	na	na	na	na	na

na = not available

Table A20 Comparison of United States and United Kingdom Sieve Sizes

United States	United Kingdom
1 1/2 in.	37.5 mm
1 in.	28 mm
3/4 in.	20 mm
1/2 in.	14 mm
3/8 in.	10 mm
1/4 in.	6.3 mm
#4	5.0 mm
#8	2.36 mm
#10	2.0 mm
#16	1.18 mm
#30	600 μmeters
#40	300 μmeters
#50	150 μmeters
#100	100 μmeters
#200	75 μmeters

Appendix B

Field Core Information—Expanded Validation

All moduli values are given in kips per square in. (ksi). The conversion from kips to megaPascals is:

1 ksi = 6.89 MPa

Table B1 Arizona SPS-5 Field Samples

SITE	#	Vv (%)	Thickness (mm)	LOCATION	DIAMETERAL Modulus	TRIAXIAL Modulus
AZ5F	1	5.1	103	BWP	1310	1209
AZ5F	2	4.4	95	BWP	1280	1252
AZ5F	3	4.2	102	WP	1171	1414
AZ5F	4	4.7	99	BWP	1329	1645
AZ5F	5	4.8	102	BWP	1156	2688
AZ5F	6	4.2	93	WP	1259	1200
AZ5F	7	4.1	101	BWP	1201	1021
AZ5F	8	4.5	103	BWP	961	1365
AZ5F	9	3.7	102	WP	1108	1627
AZ5F	10	4.0	101	BWP	1248	1476
AZ5F	11	4.5	100	BWP	1104	2462
AZ5F	12	4.0	101	WP	1230	1734
AVERAGE		4.3			1196	1591

WP=Wheel Path
BWP=Between Wheel Path

Table B2 Arizona SPS-6 Field Samples

SITE	#	Vv (%)	Thickness (mm)	LOCATION	DIAMETERAL Modulus	TRIAXIAL Modulus
AZ6F	CO 1	5.0	93	WP	782	852
AZ6F	CO 2	5.0	100	BWP	798	784
AZ6F	CO 3	4.7		WP	DAMAGED	
AZ6F	CO 4	4.5	102	BWP	827	1048
AVERAGE		3.2			401	537

WP=Wheel Path
BWP=Between Wheel Path

Table B3 California AAMAS "Batch"' Field Samples

SITE	#	Vv (%)	THICKNESS (mm)	LOCATION	DIAMETERAL Modulus	TRIAXIAL Modulus
CAAB	1	6.4	102	BWP	511	1618
CAAB	2	6.4	101	BWP	529	1082
CAAB	3	6.3	102	BWP	491	1780
CAAB	4	6.5	101	BWP	464	627
CAAB	5	6.6	102	BWP	481	1196
CAAB	6	6.2	102	BWP	466	1771
CAAB	7	6.3	102	WP	658	1258
CAAB	8	6.5	102	WP	490	698
CAAB	9	6.0	101	WP	598	999
CAAB	10	6.1	102	WP	697	574
CAAB	11	6.5	101	WP	624	1018
CAAB	12	5.9	102	WP	566	812
CAAB	13	5.8	101	WP	587	770
CAAB	14	5.6	101	WP	619	1909
CAAB	15	6.4	100	WP	494	1163
CAAB	16	6.7	101	WP	550	834
AVERAGE		6.25			551	1132

WP=Wheel Path
BWP=Between Wheel Path

Table B4 California AAMAS "Drum" Field Samples

SITE	#	Vv (%)	THICKNESS (mm)	LOCATION	DIAMETERAL Modulus	TRIAXIAL Modulus
CAAD	1	5.1	103	BWP	586	907
CAAD	2	5.4	103	BWP	681	1468
CAAD	3	6.2	103	BWP	572	888
CAAD	4	6.6	69	BWP	794	NT
CAAD	5	5.3	102	BWP	649	1906
CAAD	6	5.6	69	BWP	780	NT
CAAD	7	6.1	103	WP	560	1767
CAAD	8	6.8	103	WP	589	639
CAAD	9	7.1	103	WP	617	967
CAAD	10	6.0	101	WP	640	1014
CAAD	11	5.7	100	WP	619	1062
CAAD	12	5.8	102	WP	651	1455
CAAD	13	6.3	102	WP	646	1065
CAAD	14	5.6	102	WP	667	1021
CAAD	15	6.1	101	WP	669	592
CAAD	16	6.5	50	WP	814	NT
AVERAGE		6.02			658	922

WP=Wheel Path
BWP=Between Wheel Path
NT=Not tested

Table B5 California GPS-6 Field Samples

SITE	#	Vv (%)	Thickness (mm)	Location	Diametral Modulus	Triaxial Modulus
CAL	1	6.1	78	BWP	330	NT
CAL	2	5.7	76	BWP	388	NT
CAL	3	5.8	73	BWP	361	NT
CAL	4	6.3	78	BWP	332	NT
CAL	5	6.2	75	BWP	367	NT
CAL	6	6.2	74	BWP	363	NT
CAL	7	6.4	79	WP	352	NT
CAL	8	5.8	77	WP	355	NT
CAL	9	5.2	67	WP	397	NT
CAL	10	5.3	68	WP	361	NT
CAL	11	5.1	64	WP	374	NT
CAL	12	5.3	69	WP	382	NT
CAL	13	5	67	WP	428	NT
CAL	14	4.9	69	WP	444	NT
CAL	15	5.2	66	WP	442	NT
CAL	16	4.7	70	WP	396	NT
AVERAGE		5.6			380	

WP=Wheel Path
BWP=Between Wheel Path
NT=Not Tested

Table B6 France LCPC Field Samples

SITE	#	Vv (%)	THICKNESS (mm)	LOCATION	DIAMETERAL Modulus	TRIAXIAL Modulus
FRA	4	6.5	76	WP	905	NT
FRA	13	10.1	72	SHOULDER	858	NT
FRB	4	2.5	53	WP	744	NT
FRB	13	6.5	65	SHOULDER	1169	NT
FRC	4	7.7	80	WP	912	NT
FRC	13	5.3	75	SHOULDER	1194	NT
AVERAG		6.5			964	

WP=Wheel Path
BWP=Between Wheel Path
NT=Not Tested

Table B7 Georgia AAMAS Field Samples

SITE	#	Vv (%)	THICKNESS (mm)	LOCATION	DIAMETERAL Modulus	TRIAXIAL Modulus
GAA	A1	8.5	101	WP	327	560
GAA	A2	7.2	54	WP	320	NT
GAA	A3	7.2	100	WP	361	542
GAA	A4	7.2	71	WP	319	NT
GAA	A5	6.2	89	WP	237	NT
GAA	A6	8.1	67	WP	378	NT
GAA	B1	6.3	102	BWP	329	479
GAA	B2	8.3	99	BWP	293	615
GAA	B3	7.3	66	BWP	352	NT
GAA	B4	7.0	73	BWP	360	NT
GAA	B5	9.8	99	BWP	229	296
GAA	B6	8.7	101	BWP	275	425
AVERAG		7.7			306	

WP=Wheel Path
BWP=Between Wheel Path
NT=Not Tested

Table B8 Michigan SPS-6 Field Samples

SITE	#	Vv (%)	THICKNESS (mm)	LOCATION	DIAMETERAL Modulus	TRIAXIAL Modulus
MI6K	1	3.3	39	UNKNOWN	341	NT
MI6K	2	3.2	40	"	374	NT
MI6K	4	2.7	40	"	299	NT
MI6K	5	2.4	39	"	356	NT
MI6K	7	3.2	40	"	348	NT
MI6K	8	4.0	39	"	392	NT
MI6K	9	4.2	38	"	400	NT
MI6K	11	4.5	38	"	330	NT
MI6K	12	6.1	30	"	NT	NT
MI6K	14	6.2	31	"	NT	NT
MI6K	16	6.4	29	"	NT	NT
MI6K	18	3.8	43	"	441	NT
MI6K	19	3.8	45	"	432	NT
MI6K	21	3.8	43	"	452	NT
MI6K	22	2.6	43	"	492	NT
MI6K	24	2.5	42	"	468	NT
MI6K	26	3.9	42	"	402	NT
MI6K	27	5.4	32	"	NT	NT
MI6K	29	5.1	34	"	NT	NT
MI6K	30	4.7	34	"	NT	NT
AVERAGE		4.1			395	

WP=Wheel Path
BWP=Between Wheel Path
NT=Not Tested

Table B9 Minnesota SPS-5 Field Samples

SITE	#	Vv (%)	THICKNESS (mm)	Location	DIAMETRAL Modulus	TRIAXIAL Modulus
MIN5	1	4.8	104	WP	287	487
MIN5	2	4.4	105	WP	290	285
MIN5	3	4.8	101	WP	285	503
MIN5	4	4.9	102	WP	246	464
MIN5	5	4.3	102	WP	283	459
MIN5	6	5.2	102	WP	295	526
MIN5	7	6.7	101	BWP	155	292
MIN5	8	6.7	102	BWP	175	351
MIN5	9	6.1	101	BWP	185	553
MIN5	10	6.7	103	BWP	153	240
MIN5	11	7.1	102	BWP	150	313
MIN5	12	6	101	BWP	191	295
AVERAGE		5.6			225	397

WP=Wheel Path
BWP=Between Wheel Path

Table B10 Wisconsin AAMAS Field Samples

SITE	#	Vv (%)	THICKNESS (mm)	LOCATION	DIAMETERAL Modulus	TRIAXIAL Modulus
WIAF	1	4.2	Damaged	BWP	NT	NT
WIAF	2	3.3	63	BWP	359	NT
WIAF	3	3.4	68	BWP	366	NT
WIAF	4	3.3	70	BWP	358	NT
WIAF	5	4.2	67	BWP	374	NT
WIAF	6	4.4	67	BWP	377	NT
WIAF	7	4.3	69	WP	332	NT
WIAF	8	3.1	65	WP	369	NT
WIAF	9	3.4	66	WP	392	NT
WIAF	10	3.5	63	WP	376	NT
WIAF	11	4.1	79	WP	377	NT
WIAF	12	3.5	77	WP	343	NT
WIAF	13	3.9	78	WP	335	NT
WIAF	14	4.0	75	WP	394	NT
WIAF	15	3.9	74	WP	384	NT
WIAF	16	3.5	71	WP	396	NT
AVERAG		3.4			369	

WP=Wheel Path
BWP=Between Wheel Path
NT=Not Tested

Appendix C

Laboratory Specimen Information—Expanded Validation

All moduli values are given in kips per square in. (ksi). The conversion from kips to megaPascals is:

1 ksi = 6.89 MPa

Table C1 Arizona SPS-5 Lab Specimens

		Vv	THICKNES		Diametral Modulus (ksi)					Triaxial Modulus (ksi)				
SITE	#	(%)	(mm)	TREATMENT	UNAGED	STOA	LTOA-2	LTOA-4	LTOA-8	UNAGED	STOA	LTOA-2	LTOA-4	LTOA-8
AZ5K	9	7.7	113	LTOA 85		901	1075	1074	1110		925	1025	1068	994
AZ5K	10	6.6												
AZ5K	11	7.4												
AZ5K	12	5.9												
AZ5K	13	6.1												
AZ5K	14	5.2												
AZ5K	15	5.7												
AZ5K	16	5.4	111	LTOA 85		1205	1260	1272	1378		1208	1584	1243	1796
AZ5K	17	5.9	113	LTOA 85		1118	1214	1290	1310		1039	901	1099	1363
AZ5K	18	6.7												
AZ5K	19	5.8												
AZ5K	20			UNAGED/RIC										
AZ5K	21	6.1	113	UNAGED	793					1041				
AZ5K	22	5.2	111	UNAGED	979					945				
AZ5K	23	4.7	112	UNAGED	899					991				

ARIZONA SPS-5 LAB SPECIMENS 100C Aging

		Vv	THICKNES		Diametral Modulus (ksi)					Triaxial Modulus (ksi)				
SITE	#	(%)	(mm)	TREATMENT	UNAGED	STOA	LTOA-1	LTOA-2	LTOA-4	UNAGED	STOA	LTOA-1	LTOA-2	LTOA-4
AZ5K	9	7.7	113											
AZ5K	10	6.6	113	LTOA 100		942	1119	1113	1275		858	1170	1333	1381
AZ5K	11	7.4												
AZ5K	12	5.9	113	LTOA 100		1031	972	1249	1291		984	1432	NO DATA	1518
AZ5K	13	6.1												
AZ5K	14	5.2												
AZ5K	15	5.7	112	LTOA 100		998	1158	1189	1348		1149	1756	1577	1805
AZ5K	16	5.4	111											
AZ5K	17	5.9	113											
AZ5K	18	6.7												
AZ5K	19	5.8												
AZ5K	20			UNAGED/RIC										
AZ5K	21	6.1	113	UNAGED	793									
AZ5K	22	5.2	111	UNAGED	979									
AZ5K	23	4.7	112	UNAGED	899									

Table C2 Arizona SPS-6 Lab Specimens

		Vv	THICKNES		Diametral Modulus (ksi)					Triaxial Modulus (ksi)				
SITE	#	(%)	(mm)	TREATMENT	UNAGED	STOA	LTOA-2	LTOA-4	LTOA-8	UNAGED	STOA	LTOA-2	LTOA-4	LTOA-8
AZ6K	1	6.7	106	LTOA 85		885	1063	1142	1222		852	1100	1295	1177
AZ6K	2	7.8	107	LTOA 85		962	1070	1146	1265		784	1181	1097	1182
AZ6K	3	8.1												
AZ6K	4	7.3	107	LTOA 85		842	970	1087	1287		1048	1317	1572	1669
AZ6K	5	7.5												
AZ6K	6			STOA RICE										
AZ6K	7	7.2												
AZ6K	8	7.3												
AZ6K	9	7.2												
AZ6K	10	6.4												
AZ6K	11	6.7	106	UNAGED	659					828				
AZ6K	12	6.7	106	UNAGED	973					889				
AZ6K	13			UNAGED/RIC										
AZ6K	14	6.5	106	UNAGED	749					710				

ARIZONA SPS-6 LAB SPECIMENS 100C Aging

		Vv	THICKNES		Diametral Modulus (ksi)					Triaxial Modulus (ksi)				
SITE	#	(%)	(mm)	TREATMENT	UNAGED	STOA	LTOA-1	LTOA-2	LTOA-4	UNAGED	STOA	LTOA-1	LTOA-2	LTOA-4
AZ6K	1	6.7	106											
AZ6K	2	7.8	107											
AZ6K	3	8.1												
AZ6K	4	7.3	107											
AZ6K	5	7.5	107	LTOA 100		1024	1144	1162	1440		1074	1370	1068	1718
AZ6K	6			STOA RICE										
AZ6K	7	7.2	107	LTOA 100		948	1146	1250	1293		1076	1356	1199	NO DATA
AZ6K	8	7.3												
AZ6K	9	7.2	107	LTOA 100		884	1028	1144	1175		826	1043	1345	1619
AZ6K	10	6.4												
AZ6K	11	6.7	106	UNAGED	659					828				
AZ6K	12	6.7	106	UNAGED	973					889				
AZ6K	13			UNAGED/RIC										
AZ6K	14	6.5	106	UNAGED	749					710				

Table C3 California AAMAS "Batch" Lab Specimens

		Vv	THICKNES		Diametral Modulus (ksi)					Triaxial Modulus (ksi)				
SITE	#	(%)	(mm)	TREATMENT	UNAGED	STOA	LTOA-2	LTOA-4	LTOA-8	UNAGED	STOA	LTOA-2	LTOA-4	LTOA-8
CAAB	1	4.8	109	UNAGED	553					647				
CAAB	2	5.8	110	UNAGED	561					496				
CAAB	3	6.6	111	UNAGED	501					922				
CAAB	4	5.9	110	LTOA 85		683	878	853	1041		978	944	1042	1181
CAAB	5	5.8												
CAAB	6			RICE										
CAAB	7	6.7												
CAAB	8	5.3												
CAAB	9	5.1	109	LTOA 85		809	870	903	978		813	958	1183	1350
CAAB	10	6.0												
CAAB	11	6.2												
CAAB	12	4.9												
CAAB	13	6.2	110	LTOA 85		987	977	1013	1085		881	975	1127	1017

CALIORNIA AAMAS 'BATCH' LAB SPECIMENS 100C AGING

		Vv	THICKNES		Diametral Modulus (ksi)					Triaxial Modulus (ksi)				
SITE	#	(%)	(mm)	TREATMENT	UNAGED	STOA	LTOA-1	LTOA-2	LTOA-4	UNAGED	STOA	LTOA-1	LTOA-2	LTOA-4
CAAB	1	4.8	109	UNAGED	553					647				
CAAB	2	5.8	110	UNAGED	561					496				
CAAB	3	6.6	111	UNAGED	501					922				
CAAB	4	5.9	110											
CAAB	5	5.8												
CAAB	6			RICE										
CAAB	7	6.7	111	LTOA 100		577	783	759	884		771	874	1001	1364
CAAB	8	5.3	110	LTOA 100		684	943	996	1063		1087	1091	1103	1374
CAAB	9	5.1	109											
CAAB	10	6.0	110	LTOA 100		835	1031	1080	1117		1010	1103	1182	1037
CAAB	11	6.2												
CAAB	12	4.9												
CAAB	13	6.2	110											

Table C4 California AAMAS "Drum" Lab Specimens

		Vv	THICKNES		Diametral Modulus (ksi)					Triaxial Modulus (ksi)				
SITE	#	(%)	(mm)	TREATMENT	UNAGED	STOA	LTOA-2	LTOA-4	LTOA-8	UNAGED	STOA	LTOA-2	LTOA-4	LTOA-8
CAAD	1	7.4	109	LTOA 85		821	985	1036	1192		814	1281	1476	1430
CAAD	2	8.5	110	LTOA 85		891	1036	1080	1197		936	1425	1506	1249
CAAD	3	8.2	110	LTOA 85		848	968	1073	1214		750	1082	1145	1152
CAAD	4	8.2												
CAAD	5	7.8												
CAAD	6	7.3												
CAAD	7			STOA RICE										
CAAD	8	8.2												
CAAD	9	7.5												
CAAD	10	8.6												
CAAD	11			UNAGED/RIC										
CAAD	12	6.9	109	UNAGED	688					553				
CAAD	13	6.8	109	UNAGED	681					903				
CAAD	14	6.3	108	UNAGED	616					606				

CALIFORNIA AAMAS 'DRUM' LAB SPECIMENS 100C Aging

		Vv	THICKNES		Diametral Modulus (ksi)					Triaxial Modulus (ksi)				
SITE	#	(%)	(mm)	TREATMENT	UNAGED	STOA	LTOA-1	LTOA-2	LTOA-4	UNAGED	STOA	LTOA-1	LTOA-2	LTOA-4
CAAD	1	7.4	109											
CAAD	2	8.5	110											
CAAD	3	8.2	110											
CAAD	4	8.2												
CAAD	5	7.8	110	LTOA 100		690	1029	1011	1137		879	1591	1177	1376
CAAD	6	7.3												
CAAD	7			STOA RICE										
CAAD	8	8.2												
CAAD	9	7.5	109	LTOA 100		836	994	1058	1247		1088	965	1595	1481
CAAD	10	8.6	110	LTOA 100		782	916	1034	1042		773	NO DATA	990	1209
CAAD	11			UNAGED/RIC										
CAAD	12	6.9	109	UNAGED	688					553				
CAAD	13	6.8	109	UNAGED	681					903				
CAAD	14	6.3	108	UNAGED	616					606				

Table C5 France LCPC "A" Lab Specimens

SITE	#	Vv (%)	THICKNES (mm)	TREATMENT	Diametral Modulus (ksi) UNAGED	STOA	LTOA-2	LTOA-4	LTOA-8	Triaxial Modulus (ksi) UNAGED	STOA	LTOA-2	LTOA-4	LTOA-8
FRAK	1	9.9	113	LTOA 85		483	658	678	794		573	972	908	1132
FRAK	2	7.4	110	LTOA 85		582	705	736	749		742	1102	1253	1046
FRAK	3	7.1												
FRAK	4	8.4		STOA RICE										
FRAK	5	7.2												
FRAK	6	6.2	108	LTOA 85		603	727	853	829		551	1009	1088	1113
FRAK	7	8.4												
FRAK	8	7.0												
FRAK	9	5.5												
FRAK	10	8.9		UNAGED RIC										
FRAK	11	6.9	109	UNAGED	539					556				
FRAK	12	6.4	108	UNAGED	483					498				
FRAK	13	8.4	110	UNAGED	456					502				

FRENCH LCPC "A" LAB SPECIMENS 100C AGING

SITE	#	Vv (%)	THICKNES (mm)	TREATMENT	Diametral Modulus (ksi) UNAGED	STOA	LTOA-1	LTOA-2	LTOA-4	Triaxial Modulus (ksi) UNAGED	STOA	LTOA-1	LTOA-2	LTOA-4
FRAK	1	9.9	113											
FRAK	2	7.4	110											
FRAK	3	7.1	109	LTOA 100		569	718	613	800		922	1568	981	1369
FRAK	4	8.4												
FRAK	5	7.2		STOA RICE										
FRAK	6	6.2	108											
FRAK	7	8.4	111	LTOA 100		541	629	669	762		576	744	946	887
FRAK	8	7.0	110	LTOA 100		543	638	676	757		734	818	728	1042
FRAK	9	5.5												
FRAK	10	8.9		UNAGED/RIC										
FRAK	11	6.9	109	UNAGED	539					556				
FRAK	12	6.4	108	UNAGED	483					498				
FRAK	13	8.4	110	UNAGED	456					502				

Table C6 France LCPC "B" Lab Specimens

		Vv	THICKNES		Diametral Modulus (ksi)					Triaxial Modulus (ksi)				
SITE	#	(%)	(mm)	TREATMENT	UNAGED	STOA	LTOA-2	LTOA-4	LTOA-8	UNAGED	STOA	LTOA-2	LTOA-4	LTOA-8
FRB	1	6.3	107	LTOA 85		684	798	823	959		909	948	1449	1276
FRB	2	8.1	110	LTOA 85		676	785	801	956		811	1145	1164	1223
FRB	3	8.7												
FRB	4	7.8												
FRB	5	8.3	110	LTOA 85		688	839	812	947		830	949	1168	1165
FRB	6	7.1												
FRB	7	7.4												
FRB	8	8.2												
FRB	9	8.1												
FRB	10			UNAGED/RIC										
FRB	11	7.3	109	UNAGED	557					673				
FRB	12	6.8	108	UNAGED	537					674				
FRB	13	6.9	109	UNAGED	520					727				

FRENCH LCPC "B" LAB SPECIMENS 100C Aging

		Vv	THICKNES		Diametral Modulus (ksi)					Triaxial Modulus (ksi)				
SITE	#	(%)	(mm)	TREATMENT	UNAGED	STOA	LTOA-1	LTOA-2	LTOA-4	UNAGED	STOA	LTOA-1	LTOA-2	LTOA-4
FRSK	1	6.3	107											
FRSK	2	8.1	110											
FRSK	3	8.7												
FRSK	4	7.8												
FRSK	5	8.3	110											
FRSK	6	7.1	109	LTOA 100		751	784	789	794		1022	775	1377	792
FRSK	7	7.4												
FRSK	8	8.2	111	LTOA 100		696	787	822	924		781	1171	1083	1054
FRSK	9	8.1	111	LTOA 100		630	762	776	837		900	1179	1126	1267
FRSK	10			UNAGED/RIC										
FRSK	11	7.3	109	UNAGED	557					673				
FRSK	12	6.8	108	UNAGED	537					674				
FRSK	13	6.9	109	UNAGED	520					727				

Table C7 France LCPC "C" Lab Specimens

		Vv	THICKNESS		Diametral Modulus (ksi)					Triaxial Modulus (ksi)				
SITE	#	(%)	(mm)	TREATMENT	UNAGED	STOA	LTOA-2	LTOA-4	LTOA-8	UNAGED	STOA	LTOA-2	LTOA-4	LTOA-8
FRC	1	8.4	110	LTOA 85		642	763	909	916		696	881	901	998
FRC	2	8.3	110	LTOA 85		598	769	785	913		800	915	948	1234
FRC	3	8.4												
FRC	4	7.4												
FRC	5	7.9	109	LTOA 85		626	810	841	1024		581	808	763	760
FRC	6	8.2												
FRC	7	8.0												
FRC	8	8.6												
FRC	9	8.1												
FRC	10	6.7		UNAGED/RICE										
FRC	11	8.2	110	UNAGED	479					739				
FRC	12	8.6	110	UNAGED	474					556				
FRC	13	6.8	111	UNAGED	561					797				

FRENCH LCPC "C" LAB SPECIMENS 100C Aging

		Vv	THICKNESS		Diametral Modulus (ksi)					Triaxial Modulus (ksi)				
SITE	#	(%)	(mm)	TREATMENT	UNAGED	STOA	LTOA-1	LTOA-2	LTOA-4	UNAGED	STOA	LTOA-1	LTOA-2	LTOA-4
FRTK	1	8.4	110											
FRTK	2	8.3	110											
FRTK	3	8.4	110	LTOA 100		640	809	738	957		606	1043	915	1084
FRTK	4	7.4	109	LTOA 100		603	763	748	883		541	892	850	1352
FRTK	5	7.9	109											
FRTK	6	8.2	109	LTOA 100		774	822	907	946		774	941	1028	1215
FRTK	7	8.0												
FRTK	8	8.6												
FRTK	9	8.1												
FRTK	10	6.7		UNAGED/RICE										
FRTK	11	8.2	110	UNAGED	479					338				
FRTK	12	8.6	110	UNAGED	474					288				
FRTK	13	6.8	111	UNAGED	561					445				

Table C8 Georgia AAMAS Lab Specimens

SITE	#	Vv (%)	THICKNESS (mm)	TREATMENT	Diametral Modulus (ksi) UNAGED	STOA	LTOA-2	LTOA-4	LTOA-8	Triaxial Modulus (ksi) UNAGED	STOA	LTOA-2	LTOA-4	LTOA-8
GAA	5	7.7												
GAA	6	8.8												
GAA	7	8.0												
GAA	8	8.8	110	LTOA 85		518	667	649	714		535	694	773	914
GAA	13	7.5												
GAA	14	7.0												
GAA	15			STOA RICE										
GAA	16	7.4												
GAA	17	6.5	107	LTOA 85		487	673	634	689		596	731	823	753
GAA	18	7.5	109	LTOA 85		545	671	629	768		464	588	665	809
GAA	19	6.6												
GAA	20	7.0	108	UNAGED	441					338				
GAA	21	7.7	109	UNAGED	361					288				
GAA	22	8.2	110	UNAGED	461					445				
GAA	23			UNAGED/RICE										

GEORGIA AAMAS LAB SPECIMENS 100C Aging

SITE	#	Vv (%)	THICKNESS (mm)	TREATMENT	Diametral Modulus (ksi) UNAGED	STOA	LTOA-1	LTOA-2	LTOA-4	Triaxial Modulus (ksi) UNAGED	STOA	LTOA-1	LTOA-2	LTOA-4
GAA	5	7.7												
GAA	6	8.8	110	LTOA 100		440	645	642	639		477	566	680	1115
GAA	7	8.0												
GAA	8	8.8	110											
GAA	13	7.5												
GAA	14	7.0												
GAA	15			RICE										
GAA	16	7.4	109	LTOA 100		500	657	731	826		436	648	698	920
GAA	17	6.5	107											
GAA	18	7.5	109											
GAA	19	6.6	108	LTOA 100		572	602	695	928		356	444	510	593
GAA	20	7.0	108	UNAGED	441					338				
GAA	21	7.7	109	UNAGED	361					288				
GAA	22	8.2	110	UNAGED	461					445				
GAA	23			UNAGED/RICE										

Table C9 Michigan SPS-6 Lab Specimens

		Vv	THICKNES		Diametral Modulus (ksi)					Triaxial Modulus (ksi)				
SITE	#	(%)	(mm)	TREATMENT	UNAGED	STOA	LTOA-2	LTOA-4	LTOA-8	UNAGED	STOA	LTOA-2	LTOA-4	LTOA-8
MI6K	1	4.7												
MI6K	2	3.0												
MI6K	3	4.0												
MI6K	4	2.1												
MI6K	5	2.1	106	LTOA 85		430	512	482	596		585	835	959	942
MI6K	6	3.4	107	LTOA 85		337	453	500	634		682	611	785	738
MI6K	7	3.7												
MI6K	8	4.2	108	LTOA 85		347	418	497	586		531	736	751	896
MI6K	9	3.2												
MI6K	10	4.0												
MI6K	11	4.6												
MI6K	12	2.0	105	UNAGED	270					460				
MI6K	13	3.7	107	UNAGED	238					376				
MI6K	14	3.3	107	UNAGED	314					435				
MI6K	15	3.1	107	UNAGED	207					358				

MICHIGAN SPS-6 LAB SPECIMENS 100C Aging

		Vv	THICKNES		Diametral Modulus (ksi)					Triaxial Modulus (ksi)				
SITE	#	(%)	(mm)	TREATMENT	UNAGED	STOA	LTOA-1	LTOA-2	LTOA-4	UNAGED	STOA	LTOA-1	LTOA-2	LTOA-4
MI6K	1	4.7												
MI6K	2	3.0		LTOA 100		399	405	433	531		451	480	492	556
MI6K	3	4.0	106											
MI6K	4	2.1												
MI6K	5	2.1												
MI6K	6	3.4	106											
MI6K	7	3.7	107	LTOA 100		383	444	456	492		593	597	735	1086
MI6K	8	4.2	108											
MI6K	9	3.2	108											
MI6K	10	4.0		LTOA 100		361	342	365	430		505	668	796	883
MI6K	11	4.6	108											
MI6K	12	2.0		UNAGED	270					460				
MI6K	13	3.7	105	UNAGED	238					376				
MI6K	14	3.3	107	UNAGED	314					435				
MI6K	15	3.1	107	UNAGED	207					358				

Table C10 Wisconsin AAMAS Lab Specimens

SITE #	Vv (%)	THICKNESS (mm)	TREATMENT	Diametral Modulus (ksi) UNAGED	STOA	LTOA-2	LTOA-4	LTOA-8	Triaxial Modulus (ksi) UNAGED	STOA	LTOA-2	LTOA-4	LTOA-8
WIAK 3	3.0												
WIAK 4	2.8												
WIAK 5			STOA RICE										
WIAK 7	3.1												
WIAK 9	2.4												
WIAK 10	2.9												
WIAK 11	2.8	102	LTOA 85		312	398	381	424		492	666	705	840
WIAK 12	2.6												
WIAK 13	3.0	102	LTOA 85		298	367	377	430		469	597	674	680
WIAK 16	1.8												
WIAK 17	2.4	101	LTOA 85		309	383	370	458		500	640	808	889
WIAK 20	2.9	101	UNAGED	277					361				
WIAK 21			UNAGED/RICE										
WIAK 22	2.3	101	UNAGED	258					500				
WIAK 23	2.5	101	UNAGED	239					375				

WISCONSIN AAMAS LAB SPECIMENS 100C Aging

SITE #	Vv (%)	THICKNESS (mm)	TREATMENT	Diametral Modulus (ksi) UNAGED	STOA	LTOA-1	LTOA-2	LTOA-4	Triaxial Modulus (ksi) UNAGED	STOA	LTOA-1	LTOA-2	LTOA-4
WIAK 3	3.0	101	LTOA 100		309	351	391	416		494	407	410	599
WIAK 4	2.8												
WIAK 5			STOA RICE										
WIAK 7	3.1												
WIAK 9	2.4	101	LTOA 100		338	357	371	454		468	516	503	686
WIAK 10	2.9	102	LTOA 100		286	307	343	397		483	613	489	818
WIAK 11	2.8	102											
WIAK 12	2.6												
WIAK 13	3.0	102											
WIAK 16	1.8												
WIAK 17	2.4	101											
WIAK 20	2.9	101	UNAGED	277					361				
WIAK 21			UNAGED/RICE										
WIAK 22	2.3	101	UNAGED	258					500				
WIAK 23	2.5	101	UNAGED	239					375				

Table C11 Minnesota SPS-5

		Vv	THICKNESS		Diametral Modulus (ksi)					Triaxial Modulus (ksi)				
SITE	#	(%)	(mm)	TREATMENT	UNAGED	STOA	LTOA-2	LTOA-4	LTOA-8	UNAGED	STOA	LTOA-2	LTOA-4	LTOA-8
MI5K	1	7.80	107											
MI5K	2	6.90	107											
MI5K	3	7.00	108	LTOA 85		219	277	318	408		293	413	418	667
MI5K	5	6.11	107											
MI5K	6	5.84	107											
MI5K	7	7.27	108											
MI5K	8			STOA RICE										
MI5K	9	6.45	108	UNAGED	169					255				
MI5K	10	5.34	107	UNAGED	189					329				
MI5K	11	4.90	106	UNAGED	156					331				
MI5K	12	6.00	107	LTOA 85		232	288	346	366		351	489	480	685
MI5K	13	6.80	108											
MI5K	14	6.00	108											

Minnesota SPS-5 Lab Specimens 100C Aging

		Vv	THICKNESS		Diametral Modulus (ksi)					Triaxial Modulus (ksi)				
SITE	#	(%)	(mm)	TREATMENT	UNAGED	STOA	LTOA-1	LTOA-2	LTOA-4	UNAGED	STOA	LTOA-1	LTOA-2	LTOA-4
MI5K	1	7.80	107											
MI5K	2	6.90	107											
MI5K	3	7.00	108											
MI5K	5	6.11	107	LTOA 100		217	302	326	404		359	467	506	581
MI5K	6	5.84	107											
MI5K	7	7.27	108	LTOA 100		174	226	288	378		284	465	412	471
MI5K	8			STOA RICE										
MI5K	9	6.45	108	UNAGED	169					255				
MI5K	10	5.34	107	UNAGED	189					329				
MI5K	11	4.90	106	UNAGED	156					331				
MI5K	12	6.00	107											
MI5K	13	6.80	108											
MI5K	14	6.00	108	LTOA 100		204	273	292	327		332	460	517	505

Table C12 California SPS-6

		Vv	Thickness		Diametral Modulus (ksi)					Triaxial Modulus (ksi)				
SITE	#	(%)	(mm)	TREATMENT	UNAGED	STOA	LTOA-2	LTOA-4	LTOA-8	UNAGED	STOA	LTOA-2	LTOA-4	LTOA-8
CAG	1	7.30	110											
CAG	2	6.20	109	LTOA 85		406	551	639	735		561	680	719	1180
CAG	3	6.60	109											
CAG	4	6.20	109											
CAG	5	7.60	111											
CAG	6	6.70	110											
CAG	7	6.70	110	LTOA 85		290	439	482	577		346	450	509	466
CAG	8	6.20	109											
CAG	9			STOA RICE										
CAG	10	5.90	110		181									
CAG	11	6.30	110		174									
CAG	12	6.00	110		170									

California GPS-6 Lab Specimens 100C Aging

		Vv	Thickness		Diametral Modulus (ksi)					Triaxial Modulus (ksi)				
SITE	#	(%)	(mm)	TREATMENT	UNAGED	STOA	LTOA-1	LTOA-2	LTOA-4	UNAGED	STOA	LTOA-1	LTOA-2	LTOA-4
CAG	1	7.30	110											
CAG	2	6.20	109											
CAG	3	6.60	109	LTOA 100		355	457	600	699		400	565	637	695
CAG	4	6.20	109											
CAG	5	7.60	111	LTOA 100		384	479	576	624		390	542	632	679
CAG	6	6.70	110											
CAG	7	6.70	110											
CAG	8	6.20	109	LTOA 100		326	459	488	617		380	658	592	796
CAG	9			STOA RICE										
CAG	10	5.90	110		181									
CAG	11	6.30	110		174									
CAG	12	6.00	110		170									

Appendix D

Field and Laboratory Mix Design and Compaction Summaries—Supplementary Validation

The sieve analysis data, table D6, is listed in U.S. sieve sizes. Currently, no U.S. set of standard sieve sizes is available in metric units. However, a comparison of standard United Kingdom (U.K.) sizes is given in table A20 as a guideline.

Table D1 Explanation of Mix Design Designations

WDOT Mix Design	This is the original mix design used by the Washington Department of Transportation. Only 2 sites had mix designs available.
WDOT Field Check	This is the field extraction data done by the Washington DOT during construction. These values were used in this study as the target values.
LTPP WDOT Data	This is data submitted by WDOT to Nichols Engineering in Nevada for the LTPP (Long Term Pavement Performance) studies being done on the SHRP project.
LTPP Field Cores	Cores were drilled at all 7 WDOT sites by Nichols Engineering in 1990. This is the data from these cores.
OSU Extr. Field Cores	This is data from extractions done on the field cores used in this study.
OSU Compacted Samples	These are the values used and obtained at OSU for lab specimens.

Table D2 Mix Design Comparisons: Asphalt %, Voids %, Rice Gravities

Site	1801	6048	6049	1002	1006	1008	6056
Asphalt %							
WDOT Mix Design	*	*	*	5.4	5.2	*	*
WDOT Field Check	6	5.5	5.6	5.6	5.3	5.8	5.9
LTPP WDOT Data	5.6	6.1	5.7	5.4	5.3	6.2	6
LTPP Field Cores	5.4	5.4	*	4.6	5.4	5.8	5.6
OSU Extr. Field Cores	6.7	6.6	6.9	7.3	*	6.3	6.7
OSU Compacted Sample	6	5.7	5.8	5.9	5.3	6	6.2
Voids %							
WDOT Mix Design	*	*	*	4.3	3.3	*	*
WDOT Field Check	3.9	2.4	3.2	5.1	3.5	5.3	3.6
LTPP WDOT Data	3.5	7.8	6.8	4.8	8.6	4.7	4.2
LTPP Field Cores	1.9	5.5	*	2	3	4.7	3.8
OSU Extr. Field Cores	6.6	5.9	3.2	4.4	5.1	7	4.8
OSU Compacted Sample	7.2	7.9	8.1	7.7	4.1	6.8	8.9
Rice Specific Gravity							
WDOT Mix Design	*	*	*	*	*	*	*
WDOT Field Check	2.46	2.483	2.478	2.514	2.491	2.536	2.538
LTPP WDOT Data	*	*	*	*	*	*	*
LTPP Field Cores	2.425	2.492	*	2.462	2.481	2.501	2.542
OSU Extr. Field Cores	2.448	2.434	2.468	2.474	*	2.495	2.544
OSU Compacted Sample	2.457	2.516	2.438	2.449	2.428	2.507	2.572

Table D3 Asphalt Data and Admixtures

Site	Can #	Asphalt Type	Asphalt Source	Admixtures	Date Sampled	Date of Construction
1801	1	85/100	Shell Oil Portland, OR	None	9/12/73	8/29/73 to 9/3/73
6048	1	AR4000W	U.S. Oil Refining Tacoma, WA	None	10/1/76	6/?/76
	2	AR4000W	U.S. Oil Refining Tacoma, WA	None	10/26/76	6/?/76
6049	1	85/100	Sound Refining Tacoma, WA	None	5/22/72	4/18/72
1002	1	AR4000W	Cenex Refining Laurel, MT	None	10/14/83	10/14/83
1006	1	AR4000W	Cenex Refining Laurel, MT	1/2% PBS	10/15/83	10/7/83 to 10/19/83
1008	1	AR4000W	Husky Oil Billings, MT	1/2% PBS	9/27/78	10/78
	2	AR4000W	Husky Oil Billings, MT	1/2% PBS	8/9/78	10/78
6056	1	AR4000W	Conoco, INC. Billings, MT	None	8/23/85	8/85
	2	AR4000W	Conoco, INC. Billings, MT	1/2% PBS	7/1/85	8/85

Table D4 Mixing and Compaction Temperatures and Viscosities

Site	Pen @ 25°C	Viscosity @ 60°C (Poises)	Viscosity @ 135°C (Centistokes)	Mix Temperature (°C)	Compaction Temperature (°C)
1801	99	Not available	1.4	132	110
6048	Not available	3090	Not available	154	130
6049	91	Not available	1.27	130	110
1002	90	2910	3.8	150	126
1006	95	3669	4.23	154	130
1008	109	3450	3.01	148	123
6056	83	3662	4.79	155	130

Table D5 Voids Summary Sheet

Site	AVG Field Voids	AVG Lab Voids (85°C)	AVG Lab Voids (100°C)
1801	6.6	6.8	7.5
6048	6	7.8	8.0
6049	3.2	7.6	8.5
1002	4.4	7.8	7.7
1006	5.1	3.9	4.2
1008	7.1	7.1	6.7
6056	4.6	9.0	8.7

Table D6a Gradations: Washington Sites 1801, 6048, 6049, and 1008

Sieve Size	Washington Site 1801 WDOT Mix Design	WDOT Extr. (Target)	OSU Mix Blend	LTPP WDOT Data	LTPP Cores BOP	LTPP Cores EOP	Washington Site 6048 WDOT Mix Design	WDOT Extr. (Target)	OSU Mix Blend	LTPP WDOT Data	LTPP Cores BOP	LTPP Cores EOP
1 1/4"		100.0	100.0	100.0	100.0	100.0		100.0	100.0	100.0	100.0	100.0
1"		100.0	100.0	100.0	100.0	100.0		100.0	100.0	100.0	98.0	100.0
3/4"		100.0	100.0	100.0	100.0	100.0		100.0	100.0	100.0	•••	•••
5/8"		100.0	100.0	100.0	100.0	99.0		100.0	100.0	100.0	96.0	99.0
1/2"		97.0	97.0	96.0	98.0	91.0		98.0	98.0	98.0	88.0	96.0
3/8"		81.0	81.0	79.0	85.0	79.0		86.0	86.0	88.0	80.0	84.0
1/4"		66.0	66.0	•••	61.0	60.0		68.0	68.0	•••	58.0	59.0
No. 4		59.0	57.7	•••	•••	•••		61.0	57.0	•••	•••	•••
No. 10		40.0	42.0	37.0	44.0	43.0		40.0	44.0	45.0	36.0	40.0
No. 16		32.0	31.4	•••	•••	•••		32.0	34.2	•••	•••	•••
No. 30		20.5	19.0	•••	•••	•••		22.0	21.7	•••	•••	•••
No. 40		16.0	16.0	16.0	18.0	18.0		17.0	18.0	18.0	14.0	16.0
No. 80		9.0	9.0	8.0	10.0	10.0		9.0	12.0	8.0	9.0	9.0
No. 100		8.0	7.9	•••	•••	•••		8.0	10.3	•••	•••	•••
No. 200		5	5.5	5	7	7.6		5.9	7.3	5	6.3	5.9

Sieve Size	Washington Site 6049 WDOT Mix Design	WDOT Extr. (Target)	OSU Mix Blend 1	OSU Mix Blend 2	LTPP WDOT Data	LTPP Cores BOP	LTPP Cores EOP	Washington Site 1008 WDOT Extr. (Target)	OSU Mix Blend	LTPP WDOT Data	LTPP Cores BOP	LTPP Cores EOP
1 1/4"		100.0	100.0	100.0	100.0			100.0	100.0	100.0	100.0	100.0
1"		100.0	100.0	100.0	100.0			100.0	100.0	100.0	100.0	100.0
3/4"		100.0	100.0	100.0	100.0			100.0	100.0	100.0	100.0	100.0
5/8"		100.0	100.0	100.0	100.0			100.0	100.0	100.0	100.0	100.0
1/2"		97.0	97.0	97.0	92.0			97.0	97.0	98.0	97.0	97.0
3/8"		83.0	83.0	83.0	76.0			87.0	87.0	88.0	84.0	88.0
1/4"		69.0	69.0	69.0	•••			71.0	71.0	•••	59.0	63.0
No. 4		62.0	62.0	62.0	•••			63.0	61.6	•••	•••	•••
No. 10		43.0	44.0	44.0	38.0			39.0	44.0	33.0	40.0	44.0
No. 16		36.0	37.3	37.3	••8			31.0	32.9	•••	•••	•••
No. 30		27.0	31.1	31.1	•••			20.5	22.7	•••	•••	•••
No. 40		23.0	24.0	24.0	19.0			16.0	18.0	15.0	16.0	20.0
No. 80		10.0	10.2	11.3	8.0			9.0	10.0	10.0	9.0	13.0
No. 100		9.0	8.9	9.8	•••			8.0	8.7	•••	•••	•••
No. 200		4.8	6.4	7.1	4.0			5.8	6.6	6.0	5.6	8.1

Table D6b Gradations: Washington Sites 1002, 1006, and 6056

Sieve Size	Washington Site 1002 WDOT Mix Design	WDOT Extr. (Target)	OSU Mix Blend	LTPP WDOT Data	LTPP Cores BOP	LTPP Cores EOP	Washington Site 1006 WDOT Mix Design	WDOT Extr. (Target)	OSU Mix Blend	LTPP WDOT Data	LTPP Cores BOP	LTPP Cores EOP
1 1/4"	100.0	100.0	100.0	100.0	100.0	100.0	100	100.0	100.0	100.0	100.0	100.0
1"	95.0	95.0	95.0	94.0	100.0	98.0	100	100.0	100.0	100.0	100.0	100.0
3/4"	***	86.0	84.3	***	100.0	***	100	100.0	100.0	100.0	100.0	100.0
5/8"	80.0	79.0	79.0	85.0	100.0	90.0	100	100.0	100.0	100.0	100.0	100.0
1/2"	72.0	72.0	72.7	80.0	96.0	79.0	95	95.0	95.0	95.0	97.0	96.0
3/8"	***	62.0	63.6	***	85.0	69.0	83	81.0	81.0	80.0	84.0	86.0
1/4"	49.0	49.0	54.0	***	59.0	49.0	68	68.0	***	***	64.0	64.0
No. 4	***	44.0	47.0	***	***	***	***	60.5	61.0	***	***	***
No. 10	30.0	28.0	32.0	30.0	36.0	31.0	38	40.0	***	40.0	44.0	44.0
No. 16	***	24.0	26.4	***	***	***	***	32.5	27.8	***	***	***
No. 30	***	18.0	19.8	***	***	***	***	22.0	22.4	***	***	***
No. 40	13.0	15.0	17.0	15.0	19.0	16.0	15	17.0	***	18.0	19.0	19.0
No. 80	8.0	11.0	13.0	11.0	11.0	11.0	9	10.0	***	11.0	12.0	12.0
No. 100	***	10.0	12.4	***	***	***	***	11.8	11.8	***	***	***
No. 200	5.5	7.2	9.5	8	6.8	7.8	6	6.5	8.7	7	7.7	7.7

Sieve Size	Washington Site 6056 WDOT Mix Design	WDOT Extr. (Target)	OSU Mix Blend	LTPP WDOT Data	LTPP Cores BOP	LTPP Cores EOP	WDOT Mix Design	WDOT Extr. (Target)	OSU Mix Blend	LTPP WDOT Data	LTPP Cores BOP	LTPP Cores EOP
1 1/4"		100.0	100.0	100.0	100.0	100.0						
1"		100.0	100.0	100.0	100.0	100.0						
3/4"		100.0	100.0	100.0	100.0	100.0						
5/8"		100.0	100.0	100.0	100.0	100.0						
1/2"		97.0	96.4	96.0	98.0	99.0						
3/8"		82.0	82.3	82.0	92.0	94.0						
1/4"		67.0	70.0	***	63.0	60.0						
No. 4		59.5	60.9	***	***	***						
No. 10		37.0	40.0	37.0	38.0	36.0						
No. 16		30.0	32.2	***	***	***						
No. 30		21.5	22.8	***	***	***						
No. 40		17.0	19.0	18.0	17.0	18.0						
No. 80		10.0	12.0	10.0	11.0	12.0						
No. 100		9.5	11.5	***	***	***						
No. 200		6.1	7.6	7.0	7.9	9.0						

Table D7 Layer Thickness and Material Types

Site	OSU core Thickness (mm)	Construction Data	Material Type
1801	102	107mm Original Surface (1973)	Dense Graded Hot Mix Asphalt
		107mm HMAC below surface (1973)	Bituminous Bound Base
		91mm Base	Crushed Gravel
		Subgrade	Gravel
6048	61	46mm Resurface (1977)	Dense Graded Hot Mix Asphalt
		107mm Original Surface (1965)	Dense Graded Hot Mix Asphalt
		86mm Base (1965)	Crushed Gravel
		254mm Subbase	Uncrushed Gravel
		Subgrade	Gravel
6049	102	91mm Resurface (1972)	Dense Graded Hot Mix Asphalt
		107mm Original Surface (1966)	Bituminous Bound Base
		91mm Base (1966)	Crushed Gravel
		335mm Subbase	Uncrushed Gravel
		Subgrade	Gravel
1002	84	12mm Surface Treatment (1977)	Porous Friction Course
		107mm Original Surface (1984)	Dense Graded Hot Mix Asphalt
		274mm Base	Crushed Gravel
		Subgrade	Silt Subgrade
1006	76	76mm Reconstruction	Dense Graded Hot Mix Asphalt
		91mm Base	Crushed Gravel
		91mm Subbase	Crushed Gravel
		Subgrade	Gravel
1008	64	91mm New Construction	Dense Grade Hot Mix Asphalt
		76mm Base	Crushed Gravel
		290 Subbase	Crushed Gravel
		Subgrade	Gravel
6056	51	46mm Resurface	Dense Graded Hot Mix Asphalt
		91mm Original Surface	Dense Graded Hot Mix Asphalt
		366mm Base	Crushed Gravel
		Subgrade	Silt Subgrade

Table D8 Mix Classifications and Aggregate Types

Site	Field Mix Classification	Date of Field Checks	Course Aggregate Type
1801	Class B Mix	9/73	Granite
	Class E Mix	8/73	
6048	Class B Mix	6/15/76	Granite
	Asphalt Treated Base	6/9/76	
6049	Class B Mix	4/18/72	Granite
1002	Class E Mix	10/83	Basalt
1006	Class B Mix	10/83	Basalt
1008	Class B Mix	10/78	Basalt
6056	Class B Mix	1985	Basalt

Appendix E

Modulus Values for Laboratory Specimens—Supplementary Validation

All moduli values are given in kips per square in. (ksi). The conversion from kips to megaPascals is:

1 ksi = 6.89 MPa

Table E1 Site 1801

WASHINGTON #1801 LAB SPECIMENS 85C Aging

		Vv	THICKNESS		Diametral Modulus (ksi)					Triaxial Modulus (ksi)				
SITE	#	(%)	(mm)	TREATMENT	UNAGED	STOA	LTOA-2	LTOA-4	LTOA-8	UNAGED	STOA	LTOA-2	LTOA-4	LTOA-8
W1801	1	8.00	111											
W1801	2	7.60	111											
W1801	3	6.80	110											
W1801	4	6.10	110	UNAGED*	188					219				
W1801	5	5.50	109	UNAGED	180					204				
W1801	5a	6.80	111	LTOA 85		426	520	605	777		420	792	841	733

* (used as a rice specimen after modulus testing)

Note: Sample 5a is sample #5 aged at 135C for 4 hours, (after initial modulus testing), then recompacted.
ONLY ONE SAMPLE WAS AVAILABLE TO AGE AT 85C FOR THIS SITE.

WASHINGTON #1801 LAB SPECIMENS 100C Aging

		Vv	THICKNESS		Diametral Modulus (ksi)				Triaxial Modulus (ksi)			
SITE	#	(%)	(mm)	TREATMENT	UNAGED	STOA	LTOA-2	LTOA-4	UNAGED	STOA	LTOA-2	LTOA-4
W1801	1	8.00	111	LTOA 100		310	617	651		450	1017	928
W1801	2	7.60	111	LTOA 100		323	602	684		486	831	1054
W1801	3	6.80	110	LTOA 100		408	709	770		598	1001	1257
W1801	4	6.10	110	UNAGED*	188				219			
W1801	5	5.50	109	UNAGED	180				204			

* (used as a rice specimen after modulus testing)

Table E2 Site 6048

WASHINGTON #6048 LAB SPECIMENS 85C Aging

		Vv	THICKNESS		Diametral Modulus (ksi)					Triaxial Modulus (ksi)				
SITE	#	(%)	(mm)	TREATMENT	UNAGED	STOA	LTOA-2	LTOA-4	LTOA-8	UNAGED	STOA	LTOA-2	LTOA-4	LTOA-8
W6048	1			STOA RICE										
W6048	2	7.90	108	LTOA 85		589	670	765	857		628	969	859	1198
W6048	3	8.10	108											
W6048	4	7.00	107											
W6048	5	8.10	107	LTOA 85		531	627	710	821		509	584	684	945
W6048	6	8.80	108											
W6048	7	7.50	105	LTOA 85		506	646	709	750		543	518	1209	982
W6048	8			STOA RICE										
W6048	9	7.00	107	UNAGED	266					432				
W6048	10	6.90	107	UNAGED	338					561				

WASHINGTON #6048 LAB SPECIMENS 100C Aging

		Vv	THICKNESS		Diametral Modulus (ksi)					Triaxial Modulus (ksi)				
SITE	#	(%)	(mm)	TREATMENT	UNAGED	STOA	LTOA-2	LTOA-4		UNAGED	STOA	LTOA-2	LTOA-4	
W6048	1			STOA RICE										
W6048	2	7.90	108											
W6048	3	8.10	108	LTOA 100		519	756	812			514	611	819	
W6048	4	7.00	107	LTOA 100		564	831	778			758	544	955	
W6048	5	8.10	107											
W6048	6	8.80	108	LTOA 100		483	639	725			521	964	813	
W6048	7	7.50	105											
W6048	8			STOA RICE										
W6048	9	7.00	107	UNAGED	266					432				
W6048	10	6.90	107	UNAGED	338					561				

Table E3 Site 6049

WASHINGTON #6049 LAB SPECIMENS 85C Aging

		Vv	THICKNESS		Diametral Modulus (ksi)					Triaxial Modulus (ksi)				
SITE	#	(%)	(mm)	TREATMENT	UNAGED	STOA	LTOA-2	LTOA-4	LTOA-8	UNAGED	STOA	LTOA-2	LTOA-4	LTOA-8
W604	1	8.40	112											
W604	2	8.60	111											
W604	3		107	STOA RICE										
W604	4	8.40	112											
W604	5	7.30	110	UNAGED	247					263				
W604	6	6.90	110	UNAGED	244					303				
W604	7	6.90	109	LTOA 85		487	620	676	823		486	745	792	744
W604	5a	8.00	110	LTOA 85		416	604	563	666		533	710	666	909
W604	6a	8.00	111	LTOA 85		499	537	645	710		517	528	658	863

NOTE: Samples 5a and 6a are samples 5 and 6 aged for 4 hours @ 135C, (after initial modulus testing), then compacted.

WASHINGTON #6049 LAB SPECIMENS 100C Aging

		Vv	THICKNESS		Diametral Modulus (ksi)				Triaxial Modulus (ksi)			
SITE	#	(%)	(mm)	TREATMENT	UNAGED	STOA	LTOA-2	LTOA-4	UNAGED	STOA	LTOA-2	LTOA-4
W604	1	8.40	108	LTOA 100		398	578	696		371	716	908
W604	2	8.60	107	LTOA 100		390	588	728		443	618	623
W604	3		107	STOA RICE								
W604	4	8.40		LTOA 100		260	526	681		317	544	525
W604	5	7.30	106	UNAGED	247				263			
W604	6	6.90	108	UNAGED	244				303			
W604	7	6.90	106									

Table E4 Site 1002

WASHINGTON #1002 LAB SPECIMENS 85C Aging

		Vv	Thickness		Diametral Modulus (ksi)					Triaxial Modulus (ksi)				
SITE	#	(%)	(mm)	TREATMENT	UNAGED	STOA	LTOA-2	LTOA-4	LTOA-8	UNAGED	STOA	LTOA-2	LTOA-4	LTOA-8
W1002	1			STOA RICE										
W1002	2	7.30	107											
W1002	3	8.10	108	LTOA 85		478	522	516	594		501	1006	861	1259
W1002	4	7.30	107	LTOA 85		520	473	529	593		414	803	630	707
W1002	5	7.60	108											
W1002	6	8.60	109	UNAGED	239					499				
W1002	7	8.30	109											
W1002	6a	8.00	107	LTOA 85		527	622	696	772		598	992	911	833

Note: Sample 6a is sample 6 aged @ 135C for 4 hours after initial modulus testing, then recompacted.

WASHINGTON #1002 LAB SPECIMENS 100C Aging

		Vv	Thickness		Diametral Modulus (ksi)					Triaxial Modulus (ksi)				
SITE	#	(%)	(mm)	TREATMENT	UNAGED	STOA	LTOA-2	LTOA-4		UNAGED	STOA	LTOA-2	LTOA-4	
W1002	1			STOA RICE										
W1002	2	7.30	107	LTOA 100		428	592	609			434	524	887	
W1002	3	8.10	108											
W1002	4	7.30	107											
W1002	5	7.60	108	LTOA 100		442	583	579			534	868	910	
W1002	6	8.60	109	UNAGED	239					499				
W1002	7	8.30	109	LTOA 100		448	634	663			433	807	920	

Table E5 Site 1006

WASHINGTON #1006 LAB SPECIMENS 85C Aging

		Vv	Thickness		Diametral Modulus (ksi)					Triaxial Modulus (ksi)				
SITE	#	(%)	(mm)	TREATMENT	UNAGED	STOA	LTOA-2	LTOA-4	LTOA-8	UNAGED	STOA	LTOA-2	LTOA-4	LTOA-8
W1006	1	4.00	107	LTOA 85		453	563	595	688		458	749	663	803
W1006	2	4.60	107	LTOA 85		508	690	656	775		560	696	837	1172
W1006	3	4.20	107											
W1006	4	3.70	106	UNAGED/RICE *	324					466				
W1006	5	3.20	106	LTOA 85		502	603	577	799		766	923	908	887
W1006	6	4.10	107											
W1006	7	4.30	107											

* Used as an unaged sample, then broken up for a Rice sample.

Table E6 Site 1008

WASHINGTON #1008 LAB SPECIMENS 85C Aging

		Vv	Thickness		Diametral Modulus (ksi)					Triaxial Modulus (ksi)				
SITE	#	(%)	(mm)	TREATMENT	UNAGED	STOA	LTOA-2	LTOA-4	LTOA-8	UNAGED	STOA	LTOA-2	LTOA-4	LTOA-8
W1008	1			STOA RICE										
W1008	2	6.50	106											
W1008	3	4.60	105	UNAGED	251					346				
W1008	4	4.80	105	UNAGED	249					395				
W1008	5	7.10	107	LTOA 85		376	441	520	609		333	541	436	648
W1008	6	7.70	106	LTOA 85		341	389	456	591		327	491	485	583
W1008	7	7.10	107											
W1008	8	6.40	106											
W1008	9	6.20	106											
W1008	10	6.40	106	LTOA 85		353	400	479	569		294	484	487	564

WASHINGTON #1008 LAB SPECIMENS 100C Aging

		Vv	Thickness		DIAMETRAL					TRIAXIAL				
SITE	#	(%)	(mm)	TREATMENT	UNAGED	STOA	LTOA-2	LTOA-4	LTOA-8	UNAGED	STOA	LTOA-2	LTOA-4	LTOA-8
W1008	1			STOA RICE										
W1008	2	6.50	106	LTOA 100		450	545	606			430	652	687	
W1008	3	4.60	105	UNAGED	251					346				
W1008	4	4.80	105	UNAGED	249					395				
W1008	5	7.10	107											
W1008	6	7.70	106											
W1008	7	7.10	107	LTOA 100		328	456	547			416	484	471	
W1008	8	6.40	106	LTOA 100		308	461	511			324	498	517	
W1008	9	6.20	106											
W1008	10	6.40	106											

Table E7   Site 6056

WASHINGTON #6056 LAB SPECIMENS 85C Aging

		Vv	Thickness		Diametral Modulus (ksi)					Triaxial Modulus (ksi)				
SITE	#	(%)	(mm)	TREATMENT	UNAGED	STOA	LTOA-2	LTOA-4	LTOA-8	UNAGED	STOA	LTOA-2	LTOA-4	LTOA-8
	1	10.00	108											
W605	2	9.50	107	LTOA 85		294	311	391	472		378	459	477	605
W605	3	9.30	107											
W605	4			STOA RICE										
W605	5	8.50	106	UNAGED	209					206				
W605	6	9.50	108	UNAGED	186					233				
W605	7	8.10	106	LTOA 85		358	466	511	578		348	561	466	592
W605	8	8.90	105											
W605	9	9.40	107	LTOA 85		285	314	380	465		297	417	499	395

WASHINGTON #6056 LAB SPECIMENS 100C Aging

		Vv	Thickness		Diametral Modulus (ksi)					Triaxial Modulus (ksi)				
SITE	#	(%)	(mm)	TREATMENT	UNAGED	STOA	LTOA-2	LTOA-4		UNAGED	STOA	LTOA-2	LTOA-4	
W605	1	10	4.24	LTOA 100		257	416	468			336	401	568	
W605	2	9.5	4.22											
W605	3	9.3	4.23	LTOA 100		259	408	469			375	437	488	
W605	4			STOA RICE										
W605	5	8.5	4.18	UNAGED	209					206				
W605	6	9.5	4.23	UNAGED	186					233				
W605	7	8.1	4.18											
W605	8	8.9	4.12	LTOA 100		410	516	589			551	729	775	
W605	9	9.4	4.23											

Appendix F

Field Core Modulus Values—Supplementary Validation

All moduli values are given in kips per square in. (ksi). The conversion from kips to megaPascals is:

1 ksi = 6.89 MPa

Table F1 Washington 1801 Field Samples

Site	Specimen #	Vv (%)	Thickness (mm)	Location	Diametral Modulus (ksi)	Triaxial Modulus (ksi)
W1801	1	6	91	WP	851	1590
W1801	2	6.3	88	WP	936	1154
W1801	3	6.2	86	WP	936	NT
W1801	5	6.1	86	WP	936	NT
W1801	6	6	88	WP	938	241
W1801	11	7.5	100	WP	820	436
W1801	13	6.4	99	WP	830	1003
W1801	14	7.1	101	WP	725	1486
W1801	16	6.7	100	WP	786	NT
W1801	17	6.9	101	WP	673	776
W1801	24	6.7	101	WP	739	1290
W1801	25	7	102	WP	738	399
	AVG:	6.6		AVG:	826	931
W1801	B1	5.3	101	BWP	763	1705
W1801	B2	6.7	100	BWP	761	NT
W1801	B3	5.4	97	BWP	786	1415
W1801	B4	5.6	97	BWP	728	776
W1801	B5	5.4	97	BWP	778	956
	AVG:	5.7		AVG:	763	1213

WP = Wheel Path Cores
BWP = Between Wheelpath Cores
NT = Not Tested

Table F2 Washington 6048 Field Samples

Site	Specimen #	Vv (%)	Thickness (mm)	Location	Diametral Modulus (ksi)	Triaxial Modulus (ksi)
W6048	1	6.1	63	WP	1195	NT
W6048	3	5.8	65	WP	873	NT
W6048	4	6	64	WP	741	NT
W6048	7	6.4	64	WP	774	NT
W6048	9	5.7	64	WP	722	NT
W6048	12	4.9	64	WP	292	NT
W6048	13	6.6	64	WP	480	NT
W6048	14	6.7	64	WP	551	NT
W6048	16	4.7	65	WP	329	NT
W6048	19	5.1	64	WP	327	NT
W6048	24	6.8	63	WP	673	NT
W6048	25	6.6	64	WP	715	NT
	AVG:	6.0		AVG:	639	
W6048	B26	7.3	63	BWP	722	NT
W6048	B27	6.3	64	BWP	466	NT
W6048	B28	6.9	62	BWP	590	NT
W6048	B29	6	62	BWP	317	NT
W6048	B30	6.5	64	BWP	507	NT
	AVG:	6.6		AVG:	520	

WP = Wheel Path Cores
BWP = Between Wheelpath Cores
NT = Not Tested

Table F3 Washington 6049 Field Samples

Site	Specimen #	Vv (%)	Thickness (mm)	Location	Diametral Modulus (ksi)	Triaxial Modulus (ksi)
W6049	5	3.4	102	WP	855	880
W6049	7	6.3	101	WP	533	561
W6049	8	2.9	101	WP	1041	776
W6049	10	2.7	102	WP	896	654
W6049	14	2.4	102	WP	742	659
W6049	15	2.7	102	WP	548	578
W6049	16	3.4	100	WP	829	1011
W6049	18	3.1	101	WP	1004	1496
W6049	20	2.8	102	WP	853	881
W6049	21	3.3	101	WP	736	475
W6049	22	2.5	102	WP	636	1066
W6049	25	2.9	102	WP	548	803
	AVG:	3.2		AVG:	768	820
W6049	B26	4.8	102	BWP	495	666
W6049	B27	2.4	102	BWP	521	630
W6049	B28	3.6	102	BWP	595	1340
W6049	B29	4.1	102	BWP	551	1042
W6049	B30	4.2	101	BWP	757	1491
	AVG:	3.8		AVG:	584	1034

WP = Wheel Path Cores
BWP = Between Wheelpath Cores

Table F4 Washington 1002 Field Samples

Site	Specimen #	Vv (%)	Thickness (mm)	Location	Diametral Modulus (ksi)	Triaxial Modulus (ksi)
W1002	4	4.4	71	WP	457	NT
W1002	7	4.1	97	WP	402	202
W1002	9	4	80	WP	398	NT
W1002	10	4.9	62	WP	419	NT
W1002	11	5.3	69	WP	425	NT
W1002	12	4.6	79	WP	412	NT
W1002	13	3.9	73	WP	448	NT
W1002	15	4.5	93	WP	289	150
W1002	17	4.8	76	WP	414	NT
W1002	18	4.1	68	WP	495	NT
W1002	20	4.5	84	WP	317	NT
W1002	23	3.9	72	WP	539	NT
	AVG:	4.4		AVG:	418	176
W1002	B26	5.1	86	BWP	397	NT
W1002	B27	5.1	86	BWP	367	NT
W1002	B28	4.9	70	BWP	372	NT
W1002	B29	4.8	80	BWP	463	NT
W1002	B30	3.8	78	BWP	332	NT
	AVG:	4.7		AVG:	386	NT

WP = Wheel Path Cores
BWP = Between Wheelpath Cores
NT = Not Tested

Table F5 Washington 1006 Field Samples

Site	Specimen #	Vv (%)	Thickness (mm)	Location	Diametral Modulus (ksi)	Triaxial Modulus (ksi)
W1006	3	5.9	72	WP	827	NT
W1006	4	5.7	69	WP	863	NT
W1006	5	5.1	70	WP	817	NT
W1006	9	4.6	80	WP	873	NT
W1006	12	4.3	74	WP	793	NT
W1006	13	4.4	79	WP	825	NT
W1006	14	6	74	WP	930	NT
W1006	19	5.7	77	WP	826	NT
W1006	20	5.1	72	WP	932	NT
W1006	24	5.1	75	WP	844	NT
W1006	25	4.6	79	WP	777	NT
W1006	30	5.2	75	WP	911	NT
	AVG:	5.1		AVG:	852	
W1006	B1	5.1	70	BWP	NT	NT
W1006	B2	5.9	73	BWP	NT	NT
W1006	B3	5.3	69	BWP	NT	NT
W1006	B4	5.1	69	BWP	NT	NT
W1006	B5	5	72	BWP	NT	NT
	AVG:	5.3		AVG:	NT	NT

WP = Wheel Path Cores
BWP = Between Wheelpath Cores
NT = Not Tested

Table F6 Washington 1008 Field Samples

Site	Specimen #	Vv (%)	Thickness (mm)	Location	Diametral Modulus (ksi)	Triaxial Modulus (ksi)
W1008	3	6	65	WP	915	NT
W1008	5	7.5	62	WP	848	NT
W1008	6	7.1	63	WP	835	NT
W1008	8	7.4	59	WP	919	NT
W1008	11	7.9	58	WP	787	NT
W1008	12	7.4	63	WP	741	NT
W1008	14	7.4	64	WP	790	NT
W1008	16	7.2	61	WP	851	NT
W1008	17	7.1	64	WP	790	NT
W1008	18	7.8	66	WP	805	NT
W1008	20	6.6	65	WP	802	NT
W1008	23	6	66	WP	822	NT
	AVG:	7.1		AVG:	825	
W1008	B1	8.3	66	BWP	766	NT
W1008	B2	8.2	64	BWP	751	NT
W1008	B3	9	68	BWP	795	NT
W1008	B4	8.5	68	BWP	812	NT
W1008	B5	8.4	70	BWP	723	NT
	AVG:	8.5		AVG:	769	NT

WP = Wheel Path Cores
BWP = Between Wheelpath Cores
NT = Not Tested

Table F7 Washington 6056 Field Samples

Site	Specimen #	Vv (%)	Thickness (mm)	Location	Diametral Modulus (ksi)	Triaxial Modulus (ksi)
W6056	1	3.8	102	WP	483	679
W6056	3	4.6	103	WP	583	NT
W6056	4	5.1	103	WP	533	516
W6056	8	4.2	91	WP	465	NT
W6056	10	4.6	77	WP	427	NT
W6056	13	4.3	80	WP	452	714
W6056	16	5	81	WP	512	NT
W6056	17	4.7	74	WP	457	NT
W6056	18	4.6	83	WP	643	NT
W6056	19	4.7	80	WP	660	NT
W6056	22	4.4	78	WP	532	NT
W6056	24	4.6	82	WP	561	NT
	AVG:	4.6		AVG:	526	636
W6056	B1	6.5	103	BWP	632	1090
W6056	B2	7	87	BWP	597	NT
W6056	B3	6	80	BWP	521	NT
W6056	B4	6.3	102	BWP	528	333
W6056	B5	6.5	101	BWP	607	521
	AVG:	6.5		AVG:	577	648

WP = Wheel Path Cores
BWP = Between Wheelpath Cores
NT = Not Tested