NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP Report 373

Use of Antistripping Additives in Asphaltic Concrete Mixtures

FIELD EVALUATION

Transportation Research Board
National Research Council

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DAVID G. TUNNICLIFF
Consulting Engineer
Omaha, NE
and
RICHARD E. ROOT
Chicago Testing Laboratory
Northbrook, IL

Subject Areas

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

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FOREWORD

By Staff
Transportation Research Board

This report will be of interest to materials engineers, research engineers, and others interested in improving the performance of asphalt concrete pavements. It contains the results of a thorough field study of the long-term performance of antistripping additives and the ability of laboratory tests to predict that performance. Two previous phases of this research have been completed, and *NCHRP Report 274*, "Use of Antistripping Additives in Asphaltic Concrete Mixtures—Laboratory Phase," was published; a laboratory test, developed as part of the study, has been approved by ASTM and designated ASTM D 4867, "Test Method for Effect of Moisture on Asphalt Concrete Paving Mixtures"; and a precision study on the laboratory test has been completed.

This report describes the field evaluation phase of the research, which demonstrated that antistripping additives in asphalt concrete mixtures were effective at controlling stripping over a 6- to 8-year period and that ASTM D 4867 is an effective laboratory test for evaluating moisture damage and additive effects.

Moisture is often the major factor associated with the deterioration of asphalt concrete pavements. The most serious consequence of the adverse action of moisture is the loss of adhesion, commonly called "stripping," between the aggregate and asphalt cement resulting in substantial reduction in the tensile strength of the asphalt concrete paving material. Because the asphalt-aggregate adhesion properties of mixtures are very complex, many tests have been used to evaluate these properties. *NCHRP Report 274* describes the development and verification of a laboratory test procedure for predicting the performance of pavements built with moisture-susceptible aggregates, and subsequent work provided information on the precision of the laboratory test. The objectives of the research described herein were to (1) obtain information on the long-term performance of antistripping additives and (2) determine the ability of laboratory tests to evaluate the long-term performance of antistripping additives.

Antistripping additives have been used extensively even though no generally accepted procedures were available to evaluate or predict their effectiveness. In response to this need, the laboratory test procedure described in *NCHRP Report 274* was developed. A field evaluation phase of the research was begun in 1984 and extended in 1992 to evaluate the effectiveness of both antistripping additives and ASTM D 4867. Nineteen test sections have been constructed in eight states with and without antistripping additives. Laboratory tests have been conducted using the actual aggregates, asphalts, and additives from the construction projects to predict pavement performance. The pavements were studied over a 6- to 8-year period to compare actual performance with the predictions. Antistripping additives added to asphalt concrete mixtures were effective at controlling stripping over that period, and ASTM D 4867 is an effective laboratory test for predicting moisture damage and the effects of additives.

Because the test sections have not experienced much moisture damage, the researchers recommend further evaluations to confirm performance trends. On the basis of this study, an interim limiting tensile strength ratio of 75 percent is suggested for test results with

ASTM D 4867. This suggested interim limiting tensile strength ratio needs further research and states are encouraged to build their own sections to verify its usefulness. Because the Strategic Highway Research Program has recommended 6-in.-diameter specimens, research on specimen size is also needed to modify ASTM D 4867.

Readers will note that Appendixes A, C, and E are not published herein. For a limited time, copies will be available on a loan basis or for purchase ($20.00) on request to NCHRP, Transportation Research Board, Box 289, Washington, DC 20055.

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ACKNOWLEDGMENTS

The research reported herein was performed under NCHRP Contracts 10-17 and 10-17/1 by David G. Tunnicliff, Consulting Engineer, Omaha, Nebraska, and Chicago Testing Laboratory, Inc., Northbrook, Illinois. David G. Tunnicliff was the contractor for this study. The work at Chicago Testing Laboratory was under a subcontract with David G. Tunnicliff.

Additional work was performed by the Asphalt Institute, College Park, Maryland; Western Research Institute, Laramie, Wyoming; and Braun Intertec Pavement, St. Paul, Minnesota, under subcontracts with David G. Tunnicliff. Field test sites were provided by state highway agencies in Georgia, Virginia, Arkansas, Maine, Illinois, Arizona, Alabama, and Texas. Nineteen laboratories that participated in the precision study of a test method are acknowledged anonymously in order to preserve the integrity of the precision study.

David G. Tunnicliff was the principal investigator and authored this report. Richard E. Root, President of Chicago Testing Laboratory, Inc., was co-principal investigator.

The work was done under the general supervision of Dr. Tunnicliff. Work at Chicago Testing Laboratory was supervised by Mr. Root. Erlin, Hime Associates, Northbrook, Illinois, did petrographic analysis of aggregates for Chicago Testing Laboratory, Mr. Virgil Kress, Petrographer. Work at the Asphalt Institute was supervised by Mr. V.P. Puzinauskas, Director of Research. Work at Western Research Institute was supervised by Mr. Henry Plancher, Senior Research Scientist. Work at Braun Intertec Pavement was supervised by Mr. Erland Lukanen, Senior Project Engineer.

USE OF ANTISTRIPPING ADDITIVES IN ASPHALTIC CONCRETE MIXTURES

FIELD EVALUATION

SUMMARY

Damage to asphaltic concrete pavements caused by moisture has been a recognized form of pavement distress for many years. To minimize moisture damage, additives—usually called antistripping additives—designed to improve adhesion between asphalt cement and aggregate surfaces have been widely used. In spite of wide use for many years, information on the long-term performance of antistripping additives is lacking, and no laboratory test method is known to be able to evaluate it. The objectives of the field evaluation phase of NCHRP Project 10-17 were to obtain information on long-term additive performance by means of a field study and to determine how well laboratory tests evaluate long-term additive performance.

Nineteen full-scale pavement test sections were built in eight states. In each state, the test project included a control section without additive and a test section including additive. In three cases, two test sections were used. Test projects were selected on the basis of the cooperating agency's preliminary tests and experience. Subsequent tests were performed on the actual materials used in the test projects.

The test method selected to evaluate long-term additive performance was the method developed in the laboratory phase of NCHRP Project 10-17 (published as *NCHRP Report 274*), now ASTM Method D 4867, and a precision study of this method involving 17 laboratories was conducted. The precision study revealed that D 4867 is significantly more precise than any other test available that might have been used. Tests on materials from the test projects revealed a range in potential for moisture damage among the control mixtures, and a range of improvement caused by the additives, resulting in less potential for moisture damage in the test mixtures.

In addition, an extensive program of tests on both aggregates and asphalt cements was included to evaluate thoroughly many factors that may affect moisture damage. The important findings from this program are two: there is potential for moisture damage in the experimental mixtures; and none of the additives increases the potential for moisture damage or converts otherwise satisfactory mixtures into mixtures likely to fail by some other mode.

Field evaluation includes testing cores and condition surveys. At this time, the experimental pavements range in age from approximately 6 to 8 years. There have been no

premature, catastrophic failures. Agreement concerning pavement condition between cores and condition surveys is very good.

Principal conclusions are as follows: (1) The long-term performance of the nine additives after 6 to 8 years was found to be satisfactory in eight cases. In the one unsatisfactory case, performance of the additive was not expected to be good, but the actual performance was worse than anticipated. In another case, an increased additive dosage was found to produce no added benefit. (2) The original laboratory tests using ASTM Test Method D 4867 correctly predicted the pavement performance found by the field evaluation on six of the eight projects. On one project, the control section performed better than expected. On another project, the pavement was never wet, was judged to be impermeable, and had little distress. Altogether, the expected performance was found on 16 of 19 experimental sections. ASTM Test Method D 4867 appears to be suitable for purposes of evaluating moisture damage of paving mixtures.

CHAPTER 1

INTRODUCTION AND RESEARCH APPROACH

INTRODUCTION

In the laboratory phase of NCHRP Project 10-17, stripping in asphalt pavements is defined as the displacement of asphalt cement films from aggregate surface by water (*1*). Preferential wetting is recognized as the primary mechanism causing stripping, and antistripping additives, most of which are surfactants designed at least partly to render aggregate surfaces more easily wetted by asphalt cement than by water, are used widely (*1*). Other materials such as hydrated lime, which function somewhat differently, are also used (*1*)(*2*). Although antistripping additives have been used for many years, information on their long-term effects on pavement performance is lacking.

Fourteen test methods used to evaluate antistripping additives have been identified (*1*). There are numerous modifications of many of these resulting in a very large number of test methods. In spite of the many test methods, none is known to be capable of evaluating long-term antistripping additive performance.

The objectives of the field evaluation phase of NCHRP Project 10-17 are to obtain information on the long-term performance of antistripping additives and to determine the ability of laboratory tests to evaluate the long-term performance of antistripping additives. To this end, a field study involving full-scale experimental pavement sections was initiated.

RESEARCH APPROACH

Test Pavements

Pavements for use in the field evaluation were selected in cooperation with state highway agencies that were interested in participating in the field study. The design of the experiment permitted the use of any pavement on which the cooperating agency required the use of an antistripping additive. Initially, the test layer was to be at least 2 in. thick; however, during the time in which the test pavements were built, nearly all asphalt paving was thin overlays consisting of lifts less than 2 in. thick. Consequently, the thickness requirement was relaxed as necessary. A certain pavement layer was not specified in advance. If the cooperating agency expected moisture damage without an additive, then the mixture could be used in the experiment regardless of its location in the cross section. As a result, the test projects included six surface courses, one surface course under an open-graded friction course, and one leveling course.

All test pavements were required to contain a control section where no additive was used and a test section where an additive at the dosage required by the job mix formula was used. In two cases, a second test section containing a different additive was built, and in another case a second test section containing the same additive at a different dosage was built. Control and test sections were to be located in the same lane as close together as possible.

The decisions that an additive was needed, what additive would be used, and at what dosage were made in advance by the cooperating agencies. The research was designed to work with these decisions, whatever they might be.

The research was designed to include various aggregate types, asphalt cement sources and grades, additives, and climatic conditions. Cooperating states were selected so that these factors were suitably diverse.

Test Methods

Of the 14 test methods noted, 2 were selected for use in the field study. The principal one is ASTM Method D 4867, developed in the laboratory phase of NCHRP Project 10-17 (*1*). This method was selected because the equipment is available in many laboratories, the procedures are relatively simple compared to other methods that test compacted specimens, the test results are available faster than from other methods, and investigators believed the precision was at least as good as that of other methods.

Method D 4867 is applicable to compacted specimens of either laboratory or plant mixtures, with or without additive. A set of specimens is partly saturated with water and conditioned in that state for 24 hr, and a second set is not saturated or conditioned. Tensile strength of both sets is determined, and the effect of moisture is indicated by comparing the strength of the conditioned set to that of the unconditioned set.

This method was used by the research agency on laboratory-mixed job mix formulas with and without additive, laboratory-mixed job mix formulas at other additive dosages, plant-mixed mixtures, and cores from test projects not tested by the cooperating agencies. Cooperating agencies were invited to perform the same series of tests except at alternate dosages.

In addition to its application in the research, ASTM D 4867 was subjected to a precision study conducted in accordance with ASTM Practice C 802 in which 17 laboratories tested five different laboratory mixtures. A complete description of the precision study is contained in Appendix A.

The second test method was a boiling water test, ASTM Method D 3625-83, which was used by the research agency and the cooperating agencies on all laboratory and plant mixtures. In the test, loose mixture is placed in water which is then boiled for a short time. Moisture damage is estimated on the basis of the area of coated aggregate that can be observed. This is not the current version of D 3625, which requires the use of distilled water and evaluates specimens after decanting the water. Instead of the standard coating above or below 95 percent, moisture damage was judged on a numerical scale of 0 to 5, corresponding to no to very severe moisture damage.

This particular boiling water test was selected for use in the research because, of the many versions of boiling water tests in use, D 3625 is the only one that is a consensus standard. Also, it is considered to be more reliable than other tests involving loose mixture, such as static immersion tests.

Supplemental Data

Supplemental data, designed to obtain information on the experimental materials and mixtures pertinent to moisture damage, which would not be available otherwise, were included in the research. These data help to characterize the materials and to determine what either beneficial or detrimental effects, if any, the additives have on the asphalt cements. This information includes

1. Petrographic analysis of aggregates determined in accordance with ASTM Practice C 295;
2. Tests of both control and treated asphalt cements for compliance with ASTM Specification D 3381;
3. Determination of asphalt fractions in both control and treated asphalt cements in accordance with ASTM Method D 4124;
4. Chemical classification of additives; and
5. Chemical and physical tests of control and treated asphalts, aggregates, and interactions, including (a) aggregate composition by X-ray fluorescence (*3*), (b) nitrogen analysis to determine the ability of the aggregates to absorb and retain nitrogen (*1*)(*3*)(*4*), (c) water susceptibility (*1*)(*3*)(*5*), (d) microcalorimetry (*1*)(*3*)(*6*), (e) functional group analysis of the asphalts by selective chemical reactions and differential infrared spectrometry (*3*)(*7*), (f) rolling thin film oven (RTFO) aging in accordance with ASTM Method D 2872, (g) asphaltene settling before and after RFTO aging (*1*)(*8*), (h) rheological properties at 25°C (77°F) and 60°C (140°F) initially and after RTFO aging, and at 60°C (140°F) 13 months later, determined by a Rheometrics Mechanical Spectrometer (*9*)(*10*), and (i) tensile-elongation properties before and after RTFO aging to indicate low-temperature effects (*10*).

Test Project Evaluation

Coring. Control and test sections were evaluated by testing cores. Cores were taken by a wet coring process, blotted to a surface-dry condition immediately, and sealed in plastic bags until tested. Tests were to be completed as soon as possible after the cores were taken. This system was designed to remove most or all water that might have been added to the core by the coring process, preserve the in-place moisture in the core, and complete testing before water added by coring had been present long enough to cause moisture damage.

Sampling Plan. A random sampling plan based on a 4-ft grid and complying with ASTM Practice D 3665 was used to select core locations. One cooperating agency preferred its own stratified, random sampling plan, which was acceptable. The sampling plan provided for coring twice a year for 5 years, but rather than core on a time scale, cooperating agencies were encouraged to core when local conditions and experience indicate that moisture damage is most likely to have occurred. Coring at least once per year was requested. A procedure for recoring in the case of disintegrated cores was included in the sampling plan.

Testing. An initial set of cores was taken at age 1 day or as soon thereafter as possible. These cores were intended to represent the condition of the pavement as-built before moisture damage or any other damage could occur. Their tensile strength was determined using the ASTM D 4867 with no partial saturation or conditioning. D 4867 does not provide for testing cores, but it can be used for that purpose if saturation and conditioning procedures are specified. Subsequent sets of cores were divided into six subsets as follows:

Set 1—split by cold chisel immediately in the field and evaluated visually for moisture damage by the research agency.

Set 2—tested for in-place moisture content by ASTM Method D 1461.

Set 3—tested for in-place moisture content for tensile splitting strength by ASTM D 4867.

Set 4—vacuum saturated at 77°F beyond the in-place moisture content using procedures from D 4867, conditioned in water for 24 hr at 77°F, and tested for tensile splitting strength according to ASTM D 4867.

Set 5—vacuum saturated at 140°F, conditioned in water at 140°F for 24 hr, and tested for tensile splitting strength at 77°F, all in accordance with ASTM D 4867.

Set 6—conditioned at 140°F in a forced-draft oven for at least three conditioning cycles of 3 hr each until there was no weight loss for three consecutive cycles, and tested for tensile splitting strength according to ASTM D 4867.

Set 1 provided an evaluation before any extraneous influences had an opportunity to damage the core. Set 2 was used to characterize the condition of the pavement when cored. Set 3 was intended to represent the actual in-place tensile strength of the pavement. Set 4 served to indicate the condition of the pavement had it been more thoroughly saturated when cored and to suggest the future potential for moisture damage. Set 5 provided more severe saturation and conditioning in an effort to obtain higher degrees of saturation after it was determined that Set 4 often did not result in high degrees of saturation. Set 6 was intended to provide at least partial healing of whatever moisture damage may have occurred and restore a higher in-place strength following procedures suggested by the Virginia Transportation Research Council (*11*). Sets 2, 3, and 4 were used throughout the experiment. Sets 1, 5, and 6 were used only for the final cores in 1993.

Climatological Data. Climatological data for each test project were taken from weather reports issued by the federal weather stations located closest to the projects (*12*).

Traffic Data. Traffic count data, such as AADT, were furnished by the cooperating agencies from their customary traffic data.

Condition Surveys

Condition surveys were conducted in 1988 and 1989 in accordance with NCHRP procedures (*13*)(*14*). The surveys were repeated in 1992 and 1993 using SHRP procedures (*15*). Distress in the form of patching, potholes, rutting, shoving, bleeding, and raveling were considered likely to be caused at least partly by moisture damage. Other forms of distress including various types of cracking and polishing were also measured even though moisture damage is probably not the major cause of distress.

Test Projects

Georgia. The test project is an asphalt concrete overlay placed on an old asphalt concrete pavement on GA-54 in Clayton County, beginning at the junction with State Route 3 in Jonesboro and extending 3.36 mi northerly to I-75. The typical overlay cross section was a spot leveling course approximately 0.5 in. thick, and a surface course approximately 1.5 in. thick. Control and test sections were placed in the northbound travel lane on Nov. 27, 1984. Figure B-1 in Appendix B provides a location sketch of the Georgia project. The job mix containing lime (additive No. 1) was the approved job mix for this project and was used throughout except for the control section and the additive No. 2 test section.

In 1991 the entire project was overlaid for reasons not related to moisture damage. In 1992 the GA-138 intersection was relocated from a point south of the start of the project to a point approximately 0.6 of a mile from GA-3 almost in the middle of the section used for coring the lime mixture. At that time the new intersection was overlaid. Because the lime section now had two overlays, a new section was designated north of the original section.

Virginia. The test project is an asphalt concrete overlay placed on an old asphalt concrete pavement on US-220 in Henry County, beginning at the North Carolina state line and extending northerly toward Martinsville. The typical overlay cross section was a surface course approximately 1.5 in. thick. Control and test sections were placed in the northbound travel lane. The control section was placed July 22, 1985, and the test section was placed on July 23, 1985. The location sketch appears in Figure B-2. The approved job mix contained additive No. 3 and was used on the entire project except the control section.

Arkansas. The test project is an asphalt concrete overlay placed on an old asphalt concrete pavement on US-64 in Cross County, immediately east of Wynne. The typical overlay cross section is the surface course approximately 2 in. thick. Control and test sections were placed in the westbound lane on Aug. 5, 1985. The location is sketched in Figure B-3. The approved job mix contained additive No. 4 and was used throughout except for the control section.

Maine. The test project is an asphalt concrete overlay placed on an old asphalt concrete pavement on US-1 in Aroostook County, between Lille and Grand Isle. The typical overlay cross section was the surface course approximately 1.25 in. thick. Control and test sections were placed in the southbound lane on Aug. 21, 1985, approximately 0.5 mi north of Lille. Figure B-4 is the location sketch. The approved job mix contained no additive and was used throughout. Additive No. 5 was used only in the additive section.

In 1992 the control section was overlaid to correct roughness caused by a box culvert that heaved the previous winter and had nothing to do with moisture damage. A new control section north of the additive section was designed for the 1993 cores and condition survey.

Illinois. The test project is an asphalt concrete overlay placed on an old portland cement concrete pavement on US-50 in Lawrence County west of Lawrenceville. The typical overlay cross section was a leveling course approximately 1 in. thick and a surface course approximately 1.5 in. thick. The mixture used for leveling has no history of moisture damage and contained no additive. Control and test sections were placed in the surface course of the eastbound lane on June 11, 1986. Figure B-5 shows the location. A control section, a section containing 0.5 percent additive No. 3, and a section containing 0.75 percent additive No. 3 for purposes of investigating dosage effects were designated. The job mix with 0.5 percent additive was the approved job mix for the project and was used for the surface course except for the control and special dosage sections.

Arizona. The test project is an asphalt concrete overlay placed on an old asphalt concrete pavement on I-40 in Navajo County approximately 15 mi east of Holbrook. The typical overlay cross section was a surface course approximately 2.5 in. thick with an open-graded friction course approximately .5 in. thick. Control and test sections were placed in the surface course of the eastbound travel lane. The control section was built on Sept. 18, 1986, and the test sections were built on Sept. 19, 1986. A control section, a test section containing portland cement (additive No. 6), and a test section containing additive No. 7 were placed. The location sketch appears in Figure B-6. The job mix for the remainder of the project used different aggregates and contained hydrated lime to prevent moisture damage.

Alabama. The test project is an asphalt concrete overlay placed on an old asphalt concrete pavement on AL-96 in Fayette County between the intersection with AL-18 in Fayette and the Lamar County line. The typical overlay cross section was a surface course approximately 1.5 in. thick. Control and test sections were placed in the westbound lane on Oct. 1, 1986. Figure B-7 depicts the location. The job mix containing additive No. 8 was used for the entire project except for the control mix.

Texas. The test project was an asphalt concrete overlay placed on an old portland cement concrete pavement on I-635 in Dallas County and the city of Balch Springs. The entire project extends from the interchange with I-30 to a point south of Seagoville

Road and includes both roadways. The typical overlay cross section was a latex-modified asphalt cement seal coat placed on the old portland cement concrete pavement, an asphalt concrete leveling course approximately 1.5 in. thick, and an asphalt concrete surface course approximately 1.5 in. thick. The experimental sections are in the leveling course. The job mix formula for the surface course has no history of moisture damage and does not contain an additive. Control and test sections were placed in the right-hand northbound lane on May 19, 1987. The location sketch is in Figure B-8. The job mix with additive No. 9 was used on the entire project except for the control section.

Job Mix Formulas and Quality Control

Information on mixture composition, mixture characteristics, and control tests for the test projects, obtained from the cooperating agencies, appears in Appendix B, Tables B-1, B-2, and B-3.

CHAPTER 2

FINDINGS

TEST METHOD

The precision study of ASTM Method D 4867 resulted in Section 12, "Precision and Bias," in that method. The complete report on the precision study appears in Appendix A. The maximum allowable difference in tensile strength ratio between results of tests on samples of the same mixture by two different laboratories was 23 percent. This compares favorably with the maximum allowable difference in index of retained strength between results of tests on samples of the same mixture by two different laboratories of 50 percent for the immersion-compression test, ASTM Method D 1075. This between-laboratory difference of 23 percent compares very favorably with the within-laboratory, single-operator maximum allowable difference of 28 percent for the moisture damage test method in *NCHRP Report 246* (*16*).

For reasons appearing in Appendix A, within-laboratory precision of the ASTM D 4867 was determined on tensile strength rather than on tensile strength ratio. The maximum allowable difference in tensile strength between results of tests on duplicate specimens of the same mixture by the same operator in one laboratory was found to be 23 psi derived from a standard deviation of 8 psi. These values are useful for any laboratory wishing to judge the precision of its own work without running duplicate tests.

TEST PAVEMENTS

Mixture composition data in Table B-1 reveal a desirable variety of materials and additives, and in this respect the test pavements appear to be satisfactory for research purposes. Mix design characteristics in Table B-2 indicate that most of the mixtures generally comply with common mixture design criteria; therefore, the pavements can be expected to perform satisfactorily except for moisture damage. The principal exception is Maine, where the Hveem stability of the job mix of 18 is significantly lower than customary criteria. This job mix reflects agency experience with local materials and climate, and under those conditions satisfactory performance is expected. Cooperating agency quality control data from their routine procedures in Table B-3 show satisfactory agreement between job mixes and field mixtures.

LABORATORY-MIXED JOB MIX FORMULAS

In routine moisture damage testing, decisions concerning additives are often based on tests run on laboratory-mixed job mix formulas. This same testing was used in the research for the express purpose of trying to determine how well the test results evaluate long-term additive performance. The research tests differed from routine tests in that the research used samples of the same materials that were used in the experimental sections, while routine tests are usually run in advance. Tests for the research were run by the research agency and those cooperating agencies choosing to participate in this phase of the research. Tensile test results are tabulated in Table B-4 for the research agency and Table B-5 for the cooperating agencies. Boiling water test results are in Table B-9.

Usually four specimens of each mixture and each condition were tested. This permitted examination of the precision of each tensile strength determination by checking for outliers in accordance with ASTM Practice E 178 at the 5 percent level. An additional criterion was applied, however, before any data were discarded. If the standard deviation of the test results was less than 8 psi, the value found in the previously noted precision study, then the result was retained even though it would be an outlier according to E 178. The statistic used in E 178 is the deviation of an individual test result from the mean of the set divided by the standard deviation of the set. An outlier can be identified in a set of data with very little spread in the data, while in another set with a much larger spread no outlier might be found, a result that would cause rejection of the most precise data. No tests on laboratory mixtures failed both these criteria.

Control Mixtures

Data from Appendix B are summarized in Table 1. The column headed Probability is the probability that the tensile strength of the set of dry specimens is different from the tensile strength of the set of wet specimens based on Student's *t*-test (*1*). A probability of more than 20:1 is statistically significant and evidence that the potential for moisture damage is real. All the control mixtures in Table 1 have a probability of more than 20:1 that moisture damage is likely. Visual ratings of tensile strength specimens are on a scale of 0 to 5 with 0 representing no stripping and 5 representing severe stripping. The same scale is used for boiling water tests. The boiling water test, ASTM Method D 3625, rates coating above or below 95 percent, which is between 1 and 2 on the numerical scale.

In terms of tensile strength ratio, the test results in Table 1 reveal a desirable range in potential for moisture damage among the test projects. Three projects are highly susceptible to moisture damage: those in Georgia, Virginia, and Arizona. On the other end of the moisture damage scale, the Maine project was included partly because an antistripping additive is not usually

TABLE 1. Laboratory-mixed control mixtures

Project	Testing Agency	Tensile Strength Ratio (%)	Probability	Visual Rating	Boiling Water Rating
GA	Research	42	>1000:1	3	2
GA	Coop	45	>1000:1	4	
VA	Research	54	>1000:1	2	1
VA	Coop	54	>1000:1	3	
AR	Research	70	>1000:1	4	3.5
ME	Research	78	>100:1	2	2.5
IL	Research	85	>20:1	3	1.5
AZ	Research	38	>1000:1	3.5	2
AL	Research	86	>100:1	0.5	1.5
TX	Research	79	>100:1	2	0
TX	Coop	70	>1000:1	3	0

used in this job mix and, although moisture damage is expected, it is expected to be very slight. This project was intended to assure that the research included little moisture damage, but the tensile strength ratio indicates that moisture damage may be more severe than expected. The least susceptible mixtures are those in Alabama and Illinois, both of which were expected to be much more susceptible to moisture damage on the basis of the cooperating agencies' preliminary tests and previous experience. Although the range in potential for moisture damage is desirable, more projects at mid-range would be better than so many at the top. One other aspect of tensile strength ratio should be noted. Agreement between cooperating and research agency results is judged to be excellent.

Visual stripping ratings of the tensile test specimens also indicate a desirable range in potential for moisture damage. These ratings differ from tensile strength ratios in that the same potential for moisture damage is not indicated for all projects. The Arkansas, Maine, and Illinois mixtures looked worse than their tensile test ratios indicated, and the Arizona and Virginia mixtures looked better.

Boiling water ratings also indicate a desirable range in potential for moisture damage but differ from both visual ratings and tensile ratios. In particular, the Virginia mixture appears to be less susceptible to moisture damage in the boiling water test, and the Alabama mixture appears to be more susceptible than indicated by visual ratings and tensile tests. Unlike the visual ratings, many of the projects appear to be near the low potential end of the moisture damage scale.

Treated Mixtures

Data from Appendix B on treated mixtures are summarized in Table 2. Most of the treated mixtures indicate little potential for moisture damage when measured by tensile ratios. The exceptions include the Georgia mixture treated with additive No. 2 and the Arizona mixture treated with additive No. 7, both of which appear to be highly susceptible to moisture damage, and the Maine mixture, which is probably somewhat susceptible.

The probability that moisture damage is real is generally lower for treated mixtures in Table 2 than for control mixtures in Table 1. In only one case, Illinois, is the probability negligible. In three cases—Georgia with lime, Virginia, and Texas—there is disagreement between testing agencies at the 20:1 level.

Visual ratings and boiling water ratings for the treated mixtures are generally somewhat lower than for the control mixtures, indicating reduced moisture damage in the treated mixtures. Agreement between visual ratings and boiling water ratings is not good for the Arkansas mixture and the Arizona mixture with additive No. 7. Tensile strength ratios agree fairly well with the visual ratings and boiling water ratings with the notable exception of the Illinois mixture.

Comparing Laboratory Mixtures

One other comparison should be made to determine whether or not the experimental sections on each project differ from each other with respect to moisture damage potential. This comparison is made by applying Student's *t*-test to tensile strength ratios. There is no correct mathematical procedure for doing this because tensile strength ratios were not replicated and the standard deviation of a single measurement is zero. An estimate of the standard deviation of each tensile strength ratio was made by pooling the standard deviations of the tensile strengths of the dry and conditioned specimens. Table 3 lists the experimental sections to be compared, their tensile strength ratios, and the probability that the mixtures are different with respect to moisture damage potential. At the 20:1 level the experimental sections in Maine and Alabama are expected not to differ at all. All other experimental sections are indicated to be different and can be expected to perform differently with respect to moisture damage.

PLANT-MIXED JOB MIX FORMULAS

Samples of each experimental mixture were taken while the experimental section was being built, and subsequently each mixture was tested using ASTM D 4867 by the research agency and those cooperating agencies wanting to participate in this phase of the research. Boiling water tests were run in the field while the experimental sections were being built. The principal purpose of these tests was to determine whether or not the potential for moisture damage in the actual experimental mixtures was the same as indicated by the laboratory-mixed specimens.

Results of these tests are in Appendix B, Tables B-6, B-7, and B-9. Outliers were investigated using the procedure that had

TABLE 2. Laboratory-mixed treated mixtures

Project	Additive	Testing Agency	Tensile Strength Ratio (%)	Probability	Visual Rating	Boiling Water Rating
GA	Lime	Research	93	>20:1	1	1
GA	Lime	Coop	94	<20:1	0	
GA	2	Research	58	>1000:1	2	1.5
GA	2	Coop	78	>1000:1	1	
VA	3	Research	88	>100:1	0.5	1
VA	3	Coop	101	<10:1	0	
AR	4	Research	89	>100:1	1	2.5
ME	5	Research	78	>100:1	1.5	1
IL	3	Research	102	<10:1	1.5	2
AZ	P C	Research	89	>1000:1	0.5	1.5
AZ	7	Research	57	>1000:1	2.5	1
AL	8	Research	89	>100:1	0	1
TX	9	Research	100	<10:1	0	0
TX	9	Coop	89	>20:1	0.5	0

TABLE 3. Comparison of laboratory-mixed mixtures

Project	Testing Agency	Comparison	Tensile Strength Ratio (%) Control	Treated	Probability
GA	Research	Control vs Lime	42	93	>100:1
GA	Coop	Control vs Lime	45	94	>1000:1
GA	Research	Control vs Ad 2	42	58	>20:1
GA	Coop	Control vs Ad 2	45	78	>1000:1
GA	Research	Lime* vs Ad 2	93	58	>100:1
GA	Coop	Lime* vs Ad 2	94	78	>100:1
VA	Research	Control vs Ad 3	54	88	>100:1
VA	Coop	Control vs Ad 3	54	101	>1000:1
AR	Research	Control vs Ad 4	70	89	>100:1
ME	Research	Control vs Ad 5	78	78	<10:1
IL	Research	Control vs Ad 3	85	102	>100:1
AZ	Research	Control vs P C	38	89	>1000:1
AZ	Research	Control vs Ad 7	38	57	>20:1
AZ	Research	P C** vs Ad 7	89	57	>1000:1
AL	Research	Control vs Ad 8	86	89	<10:1
TX	Research	Control vs Ad 9	79	100	>100:1
TX	Coop	Control vs Ad 9	70	89	>1000:1

*Lime used for control.
**P C used for control.

been applied to the laboratory-mixed specimens, ASTM Practice E 178 at the 5 percent level, and a standard deviation larger than 8. Only one test failed both these criteria. That was the research agency's test of moisture-conditioned specimens for the Arizona plant mixture with portland cement, where one low tensile strength was replaced with the average of the remaining three. This specimen became seriously supersaturated during conditioning for unknown reasons.

Control Mixtures

Test results on plant-mixed control mixtures are listed in Table 4. Compared with laboratory-mixed control mixtures in Table 1, tensile ratios in Table 4 are generally somewhat higher, an indication of less potential for moisture damage. In Virginia the ratios are significantly higher, not only indicating less potential for moisture damage but also suggesting that the field and laboratory mixtures may not have been of the same composition. Agreement between results from the research agency and the cooperating agencies remains very good. The largest discrepancy is Geórgia, and that difference is less than 23 percent, the allowable between-laboratory difference found in the precision study.

The probabilities that dry and conditioned specimens of the plant mixtures are different is generally lower than for the same mixtures in Table 1. The Maine and Alabama plant mixtures show practically no difference and little, if any, potential for moisture damage. The Virginia and Arkansas plant mixtures are somewhat less likely to suffer moisture damage than the corresponding laboratory mixtures. The remaining four plant mixtures have the same probability of moisture damage as their corresponding laboratory mixtures.

TABLE 4. Plant-mixed control mixtures

Project	Testing Agency	Tensile Strength Ratio (%)	Probability	Visual Rating	Boiling Water Rating
GA	Research	71	>1000:1		0
GA	Coop	54	>1000:1	2	0
VA	Research	83	>100:1	1.5	0
VA	Coop	81	>100:1	2	0
AR	Research	87	>100:1	4	2
AR	Coop	72	>1000:1	3	
ME	Research	93	<10:1	1	0
ME	Coop				0
IL	Research	89	>20:1	2	1
IL	Coop	82			1
AZ	Research	31	>1000:1	3	2.5
AL	Research	105	<10:1	0.5	3
TX	Research	89	>1000:1	0.5	2.5
TX	Coop	81	>1000:1	0.5	0.5

TABLE 5. Plant-mixed treated mixtures

Project	Additive	Testing Agency	Tensile Strength Ratio (%)	Probability	Visual Rating	Boiling Water Rating
GA	Lime	Research	92	>20:1		0
GA	Lime	Coop	88	>1000:1	0	0
GA	Ad 2	Research	74	>1000:1		0
GA	Ad 2	Coop	66	>1000:1	2	0
VA	Ad 3	Research	78	>1000:1	1	0
VA	Ad 3	Coop	80	>100:1	2	0
AR	Ad 4	Research	98	<10:1	3.5	1
AR	Ad 4	Coop	85	>1000:1	2.5	
ME	Ad 5	Research	95	<10:1	0.5	0
ME	Ad 5	Coop				0
IL	Ad 3	Research	94	>20:1	0.5	0
IL	Ad 3	Coop	102			1
AZ	P C	Research	63	>1000:1	2.5	1.5
AZ	Ad 7	Research	42	>1000:1	3	2
AL	Ad 8	Research	103	<10:1	1	2
TX	Ad 9	Research	91	<10:1	0.5	2.5
TX	Ad 9	Coop	96	<10:1	0	0

Visual ratings and boiling water ratings are generally somewhat lower in Table 4 than in Table 1, indicating somewhat less potential for moisture damage in the plant mixtures.

Treated Plant Mixtures

Test results from plant-mixed treated mixtures are tabulated in Table 5. Tensile ratios from Table 5 are very similar to ratios for treated laboratory mixtures in Table 2, an indication of approximately equal potential for moisture damage. The largest discrepancy in tensile ratios between plant and laboratory mixtures is the Arizona portland cement mixture where the ratio for the plant mixture is significantly lower than the laboratory-mixed ratio. The indications are that there is more potential for moisture damage in the plant mixture than in the laboratory mixture, and that the two mixtures may not have been of the same composition. The tensile ratio for the Arizona plant mixture containing additive No. 7 is also lower than the ratio for the corresponding laboratory mixture, but the discrepancy is not large enough to be a strong indication of more potential for moisture damage or different mixture composition. Agreement between tensile ratios obtained by the research agency and the cooperating agencies remains very good.

Probabilities in Table 5 that the dry and conditioned treated plant mixtures are different from each other do not agree entirely with probabilities for laboratory mixtures in Table 2. Treated plant mixtures from Maine, Alabama, and Texas show little difference between dry and conditioned specimens, and little potential for moisture damage. Arkansas and Illinois mixtures are very close to the same category depending on how the differences between research agency and cooperating agency results are interpreted. Among the treated laboratory mixtures, only Illinois fell into this category. The Virginia treated plant mixture indicates somewhat more probability that dry and conditioned specimens are different than the treated laboratory mixture did.

Visual ratings and boiling water ratings of the treated plant mixtures in Table 5 are comparable to the ratings of laboratory mixtures in Table 2. The largest discrepancy is the visual rating

TABLE 6. Comparison of plant-mixed mixtures

Project	Testing Agency	Comparison	Tensile Strength Ratio (%) Control	Treated	Probability
GA	Research	Control vs Lime	71	92	>1000:1
GA	Coop	Control vs Lime	54	88	>1000:1
GA	Research	Control vs Ad 2	71	74	<10:1
GA	Coop	Control vs Ad 2	54	66	>100:1
GA	Research	Lime* vs Ad 2	92	74	>20:1
GA	Coop	Lime* vs Ad 2	88	66	>1000:1
VA	Research	Control vs Ad 3	83	78	<10:1
VA	Coop	Control vs Ad 3	81	80	<10:1
AR	Research	Control vs Ad 4	87	98	>20:1
AR	Coop	Control vs Ad 4	72	85	>20:1
ME	Research	Control vs Ad 5	93	95	<10:1
IL	Research	Control vs Ad 3	89	94	<10:1
IL	Coop	Control vs Ad 3	82	102	>20:1
AZ	Research	Control vs P C	31	63	>20:1
AZ	Research	Control vs Ad 7	31	42	<10:1
AZ	Research	P C** vs Ad 7	63	42	>20:1
AL	Research	Control vs Ad 8	105	103	<10:1
TX	Research	Control vs Ad 9	89	91	<10:1
TX	Coop	Control vs Ad 9	81	96	>20:1

*Lime used for control.
**P C used for control.

of the treated Arkansas mixture where the treated plant mixture is rated about like the untreated mixtures. Both treated Arizona plant mixtures are rated lower than the Arizona laboratory mixtures, which is consistent with the corresponding tensile ratios. In the total picture, the treated plant mixtures indicate less potential for moisture damage than do treated laboratory mixtures.

Comparison of Plant Mixtures

Data comparing the plant mixtures used in the experimental sections on each project appear in Table 6. Probabilities in Table 6 were calculated on the same basis as that used for Table 3. The probability that control and treated sections in Virginia, Maine, Arizona (additive No. 7), and Alabama are different with respect to potential for moisture damage is very small. Research agency results also indicate little difference in moisture damage potential between control and additive sections for Georgia (additive No. 2), Illinois, and Texas, but cooperating agency results show significant differences at the 20:1 level. With laboratory mixtures, only Maine and Alabama had a probability that the difference between experimental sections was less than 10:1.

EFFECT OF ADDITIVE DOSAGE

Dosage effects were studied by testing laboratory mixtures treated with additive dosages which bracketed the job mix dosage, and by one test section in Illinois which contained 0.25 percent more additive than the job mix. The purpose of studying dosage was to determine how critical it is in the experimental mixtures. Experimental data from Tables B-4 and B-8 are in Table 7. Probabilities comparing low dose with job mix dose and job mix dose with high dose were calculated on the basis used for probabilities in Tables 3 and 6. At the 20:1 level, only the high dosage in Maine was found to be significant. In two cases, Georgia with additive No. 2 and Arizona with additive No. 7, increasing the dosage results increased tensile ratios, but the ratio is still so low that the additive appears ineffective. These two trends are continuing to increase at the highest dosage tested, suggesting that an even higher dosage might have been significant. The highest dosage in Arkansas results in increased tensile ratios, but the job-mix dosage results in relatively high ratios not much lower than the ratios at the highest dosage. Increasing dosages seems to serve no useful purpose at all in the Georgia lime mixture, Virginia, Illinois, the Arizona portland cement mixture, Alabama, and Texas.

The plant mixture from the Illinois test section containing 0.75 percent additive No. 3 resulted in tensile strength ratios of 100 percent and 102 percent by the research agency and the cooperating agency respectively. These ratios are not much different from the ratios for the laboratory mixtures in Table 7 and no reason to use the higher dosage.

The principal finding from the dosage study is that additive dosage was not particularly important in any of the experimental mixtures. Dosages prescribed by the cooperating agencies' job mix formulas are about as good as any other dosage that might have been used. Also, any small discrepancies that may have occurred between dosages actually used in the field study and job mix dosages probably would not affect performance of the test sections to a measurable degree.

SUPPLEMENTAL DATA

Results of the supplemental studies appear in Appendix C along with a discussion of the findings. The principal findings are these:

1. Aggregate petrography and chemical analysis both show that minerals and compounds commonly associated with mois-

TABLE 7. **Effect of additive dosage**

		Tensile Strength Ratio (%)			
Project	Additive	No Dose	Low Dose	Job Mix Dose	High Dose
GA	Lime	42	89	93	93
GA	Ad 2	42	46	58	62
VA	Ad 3	54	84	88	87
AR	Ad 4	70	82	89	94
ME	Ad 5	78	79	78	86
IL	Ad 3	85	96	102	99
AZ	P C	38	90	89	90
AZ	Ad 7	38	48	57	62
AL	Ad 8	86	94	89	93
TX	Ad 9	79	93	100	100

ture damage are present in abundance in all the mixtures so moisture damage can be expected.

2. Nitrogen analysis shows that all the aggregates can be made less susceptible to moisture damage by the additives.

3. With one exception, the asphalt cements and the treated asphalt cements comply with standard specifications, and the noncompliance cannot be expected to cause moisture damage.

4. Compounds and functional types known to cause moisture damage are not present in any of the asphalts in proportions expected to be detrimental.

5. None of the additives cause significant beneficial or detrimental effects in the asphalt cements with respect to performance not related to moisture damage.

PAVEMENT EVALUATION

Pavement Cores

Effect of In-Place Voids and Moisture. Air voids, determined by ASTM Method D 3203, were expected to decrease markedly at early ages and then remain approximately constant. Voids are important because as voids decrease, tensile strength should increase, saturation levels for the same moisture content increase, and entry of water into the pavement becomes more difficult.

In addition to an increase in tensile strength associated with decreasing void content, tensile strength must increase as the pavement ages and the asphalt becomes more viscous. The increase in tensile strength associated with aging should be continuous and irreversible.

Moisture content was expected to be inversely proportional to tensile strength if moisture damage were present. Moisture detected by ASTM Method D 1461 should be greater than moisture in the permeable voids, because it includes internal moisture that may have been retained by the aggregate at the time of construction. A reduction in tensile strength associated with moisture content would be observable only if the effects of decreasing voids and aging were overcome by moisture damage.

Void and moisture data from the cores appear in Tables D-1 through D-8. To investigate observed effects of voids and moisture on tensile strength, the initial data when voids are high and strength low were excluded and the remaining data were analyzed by calculating linear regression lines and correlation coefficients. At the 20:1 level, a significant relationship between

TABLE 8. **Average in-place voids, moisture, and saturation**

Project	Air Voids (%)	Moisture Content (%)	Degree of Saturation (%)
GA Cont.	5.26	0.21	8.2
Lime	4.45	0.18	10.2
Ad 2	4.83	0.17	8.7
VA Cont.	6.22	1.45	52.5
Ad 3	5.27	1.45	66.8
AR Cont.	3.57	0.43	25.3
Ad 4	3.40	0.37	27.7
ME Cont.	2.36	0.38	54.2
Ad 5	2.48	0.52	46.4
IL Cont.	2.02	0.34	40.0
0.5%	2.18	0.32	37.0
0.75%	2.04	0.22	18.2
AZ Cont.	6.38	0.92	35.8
P C	5.44	0.74	33.6
Ad 7	5.96	0.90	37.0
AL Cont.	6.10	0.55	19.3
Ad 8	4.03	0.46	23.5
TX Cont.	2.56	0.37	33.3
Ad 9	3.53	0.30	21.3

voids and tensile strength was found in only two cases, Maine with additive and Alabama as control. The slope of the Maine relationship was practically zero, showing that even though there was good correlation, tensile strength was independent of void content. The Alabama relationship had a negative slope, showing that voids influenced tensile strength even without the initial set of cores.

A significant relationship between moisture content and tensile strength was found in three cases at the 20:1 level. These cases were both Maine sections and Illinois with 0.75 percent additive. In all three cases, the slope of the relationship was positive, an indication that the increasing moisture content resulted in increasing tensile strength. The increase in tensile strength could occur only if there were no moisture damage. Among the 19 experimental sections, there were 8 relationships with positive slopes. Six of these contained additives that were supposed to be beneficial. The remaining 11 relationships with negative slopes suggest that had the pavements been wetter, more moisture damage would have been observed.

Average voids, moisture content, and levels of saturation, excluding the initial data, are tabulated in Table 8. Air voids fall

TABLE 9. Tensile strength of in-place cores

	Age (Years)						
Project	0	1	2	3	4	5	*
GA Cont.	63	125	149	153	152	167	122
Lime	76	219	199	176	173	232	130
Ad 2	93	157	164	164	142	160	162
VA Cont.	58	75	103	84	97		122
Ad 3	66	76	81	59	83		77
AR Cont.			184		225		157
Ad 4			178		174		195
ME Cont.	52	57	69	62	88		86
Ad 5	61	59	60	70	79		113
IL Cont.	84	177	141	191	186		179
0.5%	81	152	139	161	172		175
0.75%	78	160	146	182	152		171
AZ Cont.	102	100	185	223			180
P C	139	159	208	218			262
Ad 7	123	127	201	227			83
AL Cont.	87	116	210	219			255
Ad 8	85	141	217	239			274
TX Cont.	90	139	162				112
Ad 9	85	156	187				157

*1993 cores. Age 8 years in Georgia, Virginia, Arizona, and Maine. Age 7 years in Illinois and Arizona. Age 6 years in Alabama and Texas.

within limits considered indicative of satisfactory pavements. Control sections in Virginia, Arizona, and Alabama with over 6 percent voids are borderline, but not high enough to suggest a high probability of premature failure. Voids in the Georgia control section are consistently higher than in the two treated sections. This situation may be caused by the mineral filler effect of hydrated lime in the lime section and the lower viscosity of the treated asphalt cement, which is shown in Tables C-2, C-4, and C-14, in the additive No. 2 section.

The average moisture content in Virginia over the life of the project was 1.5 percent. In Arizona it was 0.9 percent. At all other projects, very little moisture was found.

The degree of saturation is the volume of moisture in the core expressed as a percentage of the volume of air voids. It represents the combined influence of in-place voids and moisture content. No significant correlation between saturation and tensile strength was found for any of the experimental sections. Saturation levels high enough so that moisture damage might be expected were found in Virginia and Maine. In Maine this occurred because of low void content rather than high moisture content.

In-Place Tensile Strength. Tensile splitting strength of cores taken from the eight projects appears in Tables D-1 through D-8, and the strength of Set 3 cores that were tested at in-place moisture content is summarized in Table 9. Age of the pavements in Table 9 is the age in months from Appendix D rounded to the closest year to achieve a manageable number of columns in the table. Cores from Virginia at 27 and 39 months and cores from Arizona at 13 months are not included in Table 9 because they were taken in the fall and may reflect effects of drying and healing. Some Maine cores also were taken in the fall but are included in Table 9 anyway because the Maine cores seem not to be affected.

Standard deviations in Tables D-1 through D-8 are large in some cases. Because a random sampling plan was used, some variability in the data from cores is inevitable. For example, specimens made from loose mixture are sorted into subsets of approximately equal void content, but cores taken from random locations for assigned purposes cannot be sorted. Also, cores are used to compare control sections with test sections, but there is no way to ensure that cores from the two sections are identical in all respects except moisture damage. Additional variability in cores results from the fact that field mixtures cannot enjoy the proportioning precision of laboratory mixtures.

Tensile strength of cores rather than a tensile strength ratio, is used to compare control and additive sections on each project. Strength is preferred because even at age 0 there is significant variability in the strength of the cores. In some cases in Appendix D there is more difference within a core set than between control and test sets. Also, if a basis for a ratio such as strength at age 0 were selected, it would have to be assumed that the difference between control and test strengths would be applicable at any age. By using tensile strength only, the only assumption is that the stronger cores show less moisture damage.

Tensile strength of cores at in-place moisture content should decrease rapidly at early ages if there is moisture damage in the pavement. In the absence of early moisture damage, tensile strength of cores at in-place moisture content should increase at early ages because of decreasing void content and aging of the asphalt cement. After reaching a maximum value, tensile strength should decrease if and when moisture damage occurs. The rate of decrease should be a function of the severity of the moisture damage and would be tempered by effects of favorable drying conditions. Failure of the pavement would not be expected until tensile strength falls below the strength at age 0.

The three Georgia sections are illustrated in Figure 1. There is little evidence of moisture damage in any of the sections until age 5 years where the decrease in tensile strength in the control and lime sections indicates moisture damage. The control section with the lowest tensile strength at 8 years shows the most damage. In addition to tensile strength, the Set 1 cores, which were split and examined visually immediately, revealed slight moisture damage, rated 1 on the 0 to 5 scale, in the control section

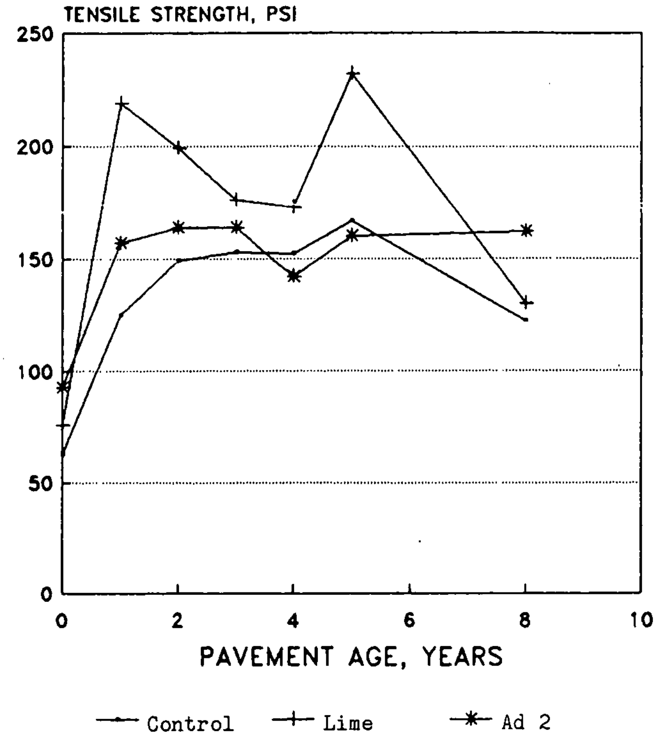

Figure 1. In-place Georgia cores.

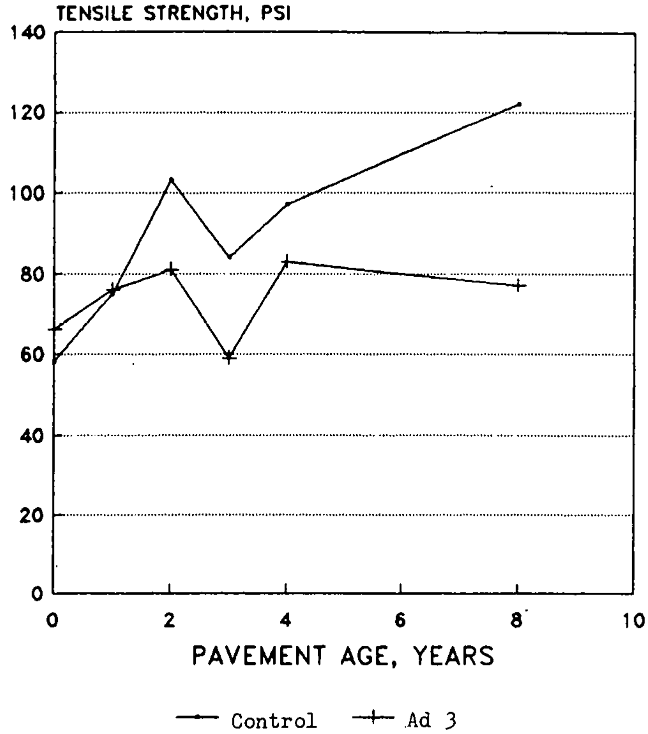

Figure 2. In-place Virginia cores.

and no damage in either test section. On the basis of both tensile strength and visual examination, the most evidence of moisture damage was found in the control section. In the lime section, some moisture damage is indicated by the loss in tensile strength from 5 to 8 years. No evidence of moisture damage was found in the additive No. 2 section.

Significant moisture damage was expected in the control and additive No. 2 sections but was not found with the cores. Data in Table D-1 shows that from 7 months on the pavement was never wet. Somehow this pavement went through its first winter and emerged almost completely dry. It has never been thoroughly saturated since then. In addition, efforts to saturate cores in the laboratory for Sets 4 and 5 were not very successful. Apparently, the pavement had become highly impermeable. Water could not get into the pavement and the expected moisture damage could not occur.

The Virginia control section in Figure 2 shows no evidence of moisture damage. Slight moisture damage may have occurred in the additive No. 2 section after age 4 years because of the reduction in tensile strength at 8 years. No sign of moisture damage was found in the Set 1 cores in either section. Although there is little evidence of moisture damage in either section, the tensile strength of the control section is the highest after 1 year, an indication of less damage in that section.

The strength of the Arkansas control cores in Figure 3 decreases significantly from 4 to 8 years, indicating that moisture damage has occurred. Strength of the additive No. 4 cores increases during the same time period, showing that the additive is preventing or inhibiting moisture damage. Set 1 cores revealed no sign of moisture damage in either section. The increasing strength after 4 years and the higher strength at 8 years show better performance in the additive section.

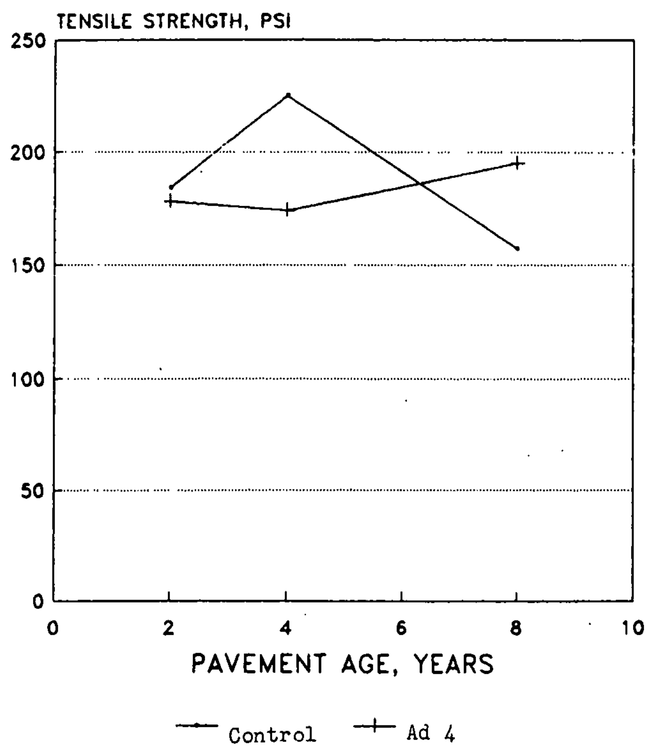

Figure 3. In-place Arkansas cores.

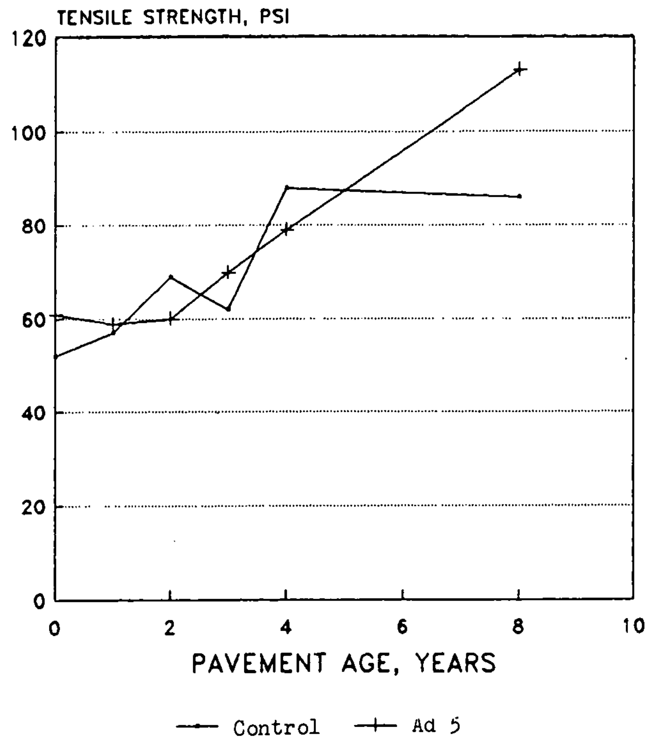

Figure 4. In-place Maine cores.

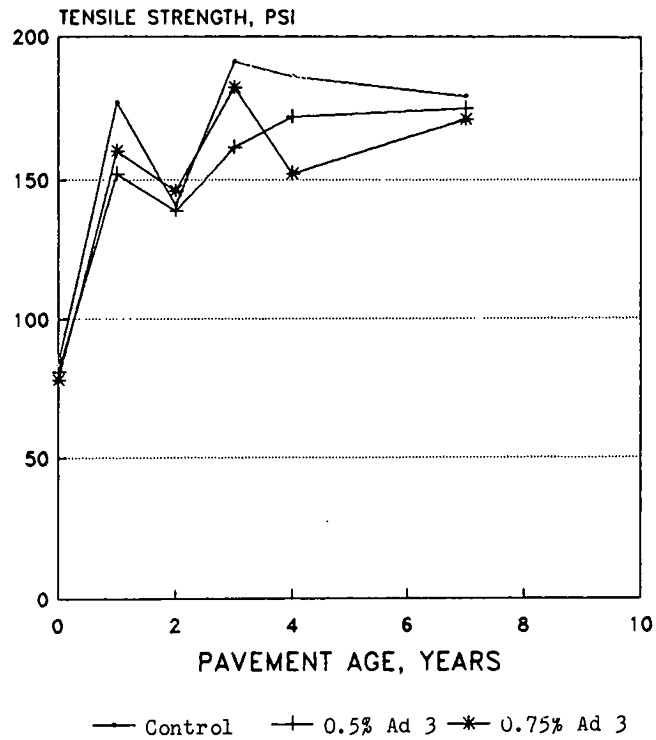

Figure 5. In-place Illinois cores.

The Maine cores in Figure 4 show that the control section experienced a very small decrease in strength from 4 to 8 years. The additive No. 5 section gradually increases in strength from 2 through 8 years. No evidence of moisture damage was observed in the Set 1 cores from either section. The loss of strength in the control section, 2 psi, is too small to support a finding of moisture damage. Also, the entire pattern from 0 through 8 years shows that the higher strength continually reverses from one section to another. Performance of the two sections is considered to be equal.

The gradual reduction in strength in the Illinois control section in Figure 5 after 3 years shows that some moisture damage was occurring. Strength of the 0.5 percent additive No. 3 section gradually increases through 7 years, indicating no moisture damage. The 0.75 percent additive section reveals an erratic strength pattern but little evidence of moisture damage. The difference in strength at 7 years is too small to indicate moisture damage. No evidence of moisture damage was found in any of the Set 1 cores. Because of the strength loss after 3 years, the control section is considered to have experienced the most damage. The two additive sections appear to be approximately equal with no evidence of moisture damage in either section.

Arizona in Figure 6 shows a significant loss in strength in the cores from the control section from 3 to 7 years; the loss indicated that moisture damage had occurred. A few uncoated sand grains were observed in the control Set 1 cores resulting in a visual moisture damage rating of 1. Strength of the portland cement section in Figure 6 increases throughout the 7 years indicating no moisture damage. The Set 1 cores from the portland cement section revealed no evidence of moisture damage. The tensile strength of the additive No. 7 cores in Figure 6

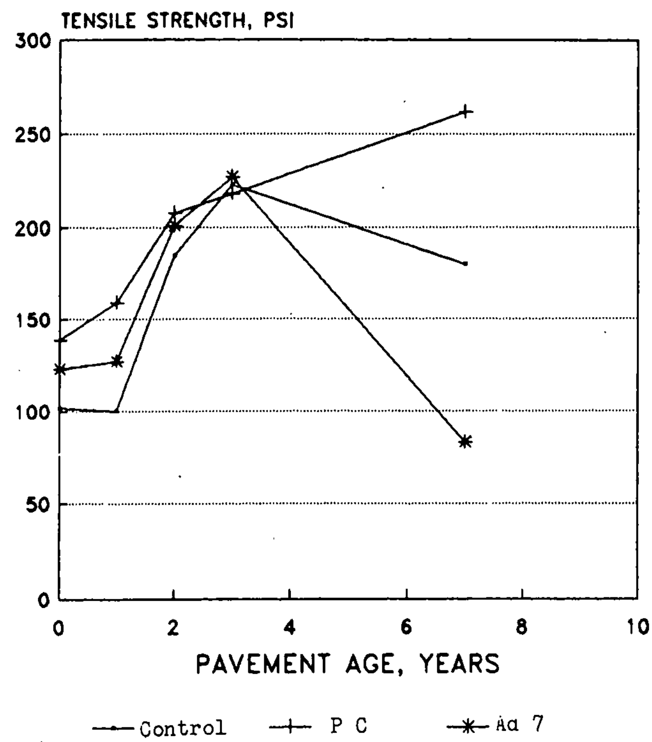

Figure 6. In-place Arizona cores.

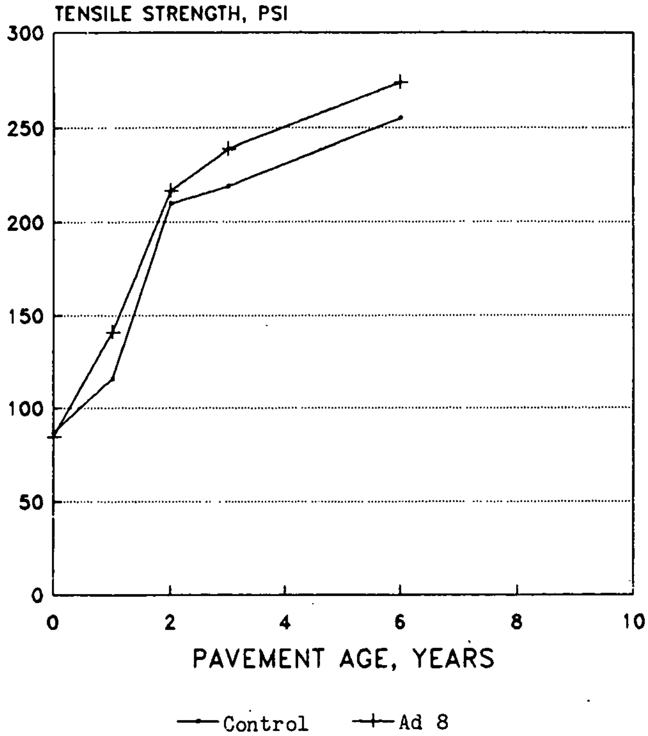

Figure 7. In-place Alabama cores.

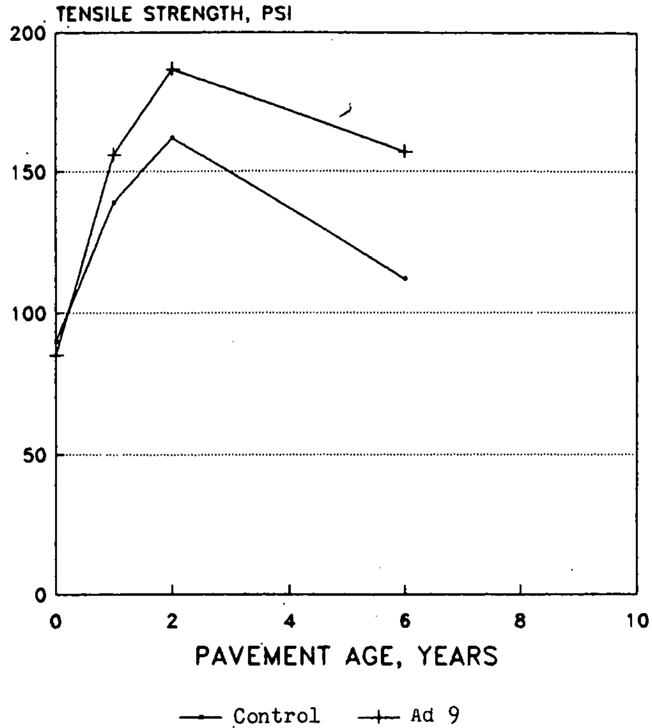

Figure 8. In-place Texas cores.

decreases very rapidly from 3 through 7 years, indicating severe moisture damage. Three disintegrated cores from this section were assigned a strength of 0. The open-graded friction course from these cores was recovered intact, but the underlying test layer could not be recovered at all. The Set 1 cores that were recovered could not be split with cold chisel. Instead, they shattered. There were numerous uncoated sand grains in these cores, resulting in a visual moisture damage rating of 3. The three disintegrated cores from this section had no coated particles and had to be visually rated at 5. On the basis of both tensile strength and visual moisture damage ratings, the portland cement section revealed no evidence of moisture damage, the control section showed some moisture damage, and the additive No. 7 section had severe moisture damage.

The tensile strength of the Alabama control cores in Figure 7 increases throughout the 6 years, showing no evidence of moisture damage. The additive No. 8 cores show the same thing but at a higher strength. No evidence of moisture damage was observed in the Set 1 cores from either section. Because the strength of the additive cores is consistently higher, the additive section is considered to have less moisture damage.

In Figure 8 the strength of the Texas control cores increases through 2 years and then decreases significantly to 8 years, showing that moisture damage had occurred. The Set 1 cores from the control section revealed some uncoated sand grains and a visual moisture damage rating of 1. The additive No. 9 cores have the same strength pattern but at a higher tensile strength that still shows that there had been moisture damage. The additive Set 1 cores received a visual rating of 1 because of some uncoated sand grains. The additive section is considered to have experienced less moisture damage because of its higher strength.

Laboratory-Conditioned Cores. Set 4 cores were vacuum saturated and conditioned at 77°F in the laboratory. The purpose of these cores was to determine the remaining potential for moisture damage and to indicate what the in-place strength might have been had the pavement been wetter when cored. These cores were expected to have lower strength than the Set 3 cores if moisture damage was present or if there was the possibility of more damage in the future. Set 5 cores were taken only in 1992 and were vacuum saturated and conditioned at 140°F. This was considered to be more severe conditioning than the Set 4 cores received, and higher saturation levels and lower strength were expected. This set was used because some of the cores taken before 1992 were not thoroughly saturated by the Set 4 procedure and some experienced no loss of strength.

Set 6 cores were taken only in 1992 and were conditioned by drying at 140°F to constant weight. This procedure was intended to heal moisture damage and, if moisture damage was present, to result in higher strength than the Set 3 cores had.

Data on tensile strength of conditioned cores from Tables D-1 through D-8 are summarized in Table 10. As with the data in Table 9, age in months has been rounded to years, and cores taken in the fall of the year in Virginia and Arizona are omitted. Values in parentheses in Table 10 are contrary to expectations, which means that the strengths of Set 4 and Set 5 cores are greater than the strength of the corresponding Set 3 cores, and the strength of Set 6 cores is less than the strength of the corresponding Set 3.

To examine the magnitude of the effect of conditioning, values in Table 10 must be compared with Table 9. This comparison is also presented in Figures D-1 through D-11. Magnitude is of more interest with respect to Set 6 in most cases.

The Georgia control cores show little detrimental effect from

TABLE 10. Tensile strength of conditioned cores

Age, Yrs	0	1	2	3	4	5	*	*	*
Set	4	4	4	4	4	4	4	5	6
Project									
GA Cont.	(72)	(131)	(182)	142	(161)	151	(139)		155
Lime	73	144	181	(178)	(185)	160	(158)		157
Ad 2	(100)	139	(174)	(196)	(166)	(164)	(153)		(158)
VA Cont.	40	73	72	(86)	(51)		95		234
Ad 3	57	58	66	(69)	(89)		(103)		229
AR Cont.			163		(227)		(247)	(191)	216
Ad 4			161		173		151	108	210
ME Cont.	44	48	65	60	75		(96)	79	101
Ad 4	(72)	38	59	61	68		(125)	81	114
IL Cont.	61	112	117	139	150		(216)	(210)	183
0.5%	63	99	113	127	136		(239)	(211)	177
0.75%	68	110	110	134	145		(221)	(201)	(163)
AZ Cont.	52	54	77	107			122	115	271
P C	133	137	169	190			(268)	183	(250)
Ad 7	84	79	151	137			(185)	(181)	264
AL Cont.	(101)	107	(211)	205			204	200	269
Ad 8	(126)	126	173	221			249	230	321
TX Cont.	(141)	(153)	150				(133)	(136)	125
Ad 9	(171)	147	152				132	156	163

*1993 cores. Age 8 years in Georgia, Virginia, Arkansas, and Maine. Age 7 years in Illinois and Arizona. Age 6 years in Alabama and Texas.

the Set 4 conditioning, suggesting that there was little potential for moisture damage and that moisture damage is unlikely even with wetter pavement. Set 6 shows that some moisture damage had occurred. The lime cores show some damage caused by the Set 4 conditioning. The additive No. 2 cores show little effect from Set 4 conditioning and no evidence of moisture damage from Set 6. Conditioning helps to confirm the finding from in-place cores that the additive No. 2 section reveals the least damage but does not help to distinguish between lime and control sections.

Set 4 conditioning on Virginia control cores indicates that there was potential for moisture damage most of the time. Set 6 is much stronger than Set 3, showing that significant moisture damage had occurred. The additive No. 3 cores show nearly the same thing. There is little effect from conditioning that facilitates comparison of the two sections.

The Arkansas Set 4 control cores show some potential for moisture damage at 2 years but no potential later. Set 5 also shows no potential for moisture damage although the more rigorous conditioning did result in lower strength than Set 4. Set 6 shows that moisture damage had occurred. The additive No. 4 Set 4 cores indicate potential for moisture damage from 2 through 8 years, and Set 5 indicates more potential at 8 years caused by the more severe treatment. Set 6 shows that some moisture damage had occurred but less than the damage in the control cores. Laboratory conditioning indicates that the most moisture damage was in the control section.

Both control and additive No. 5 Set 4 cores in Maine show some potential for moisture damage through 4 years and no potential at 8 years. Set 5 shows that severe conditioning reveals some potential for moisture damage in both sections. Set 6 shows that some damage had occurred in both sections. Little distinction between control and additive sections is found with laboratory conditioning.

Set 4 cores from all three Illinois sections indicate that had the pavement been wetter through 4 years there would have been more moisture damage and there is potential for moisture damage. At 7 years no potential is indicated. The Set 5 cores also indicate no potential for damage. Set 6 shows that slight moisture damage had occurred in the control and 0.5 percent additive sections and no damage in the 0.75 percent section. The indication is that control had the most damage, and 0.75 percent additive had the least, but the differences among the sections are too small to be conclusive.

In Arizona, Set 4 reveals potential for moisture damage in all three sections through 3 years, and at 7 years in the control section. No potential is indicated for the portland cement and additive No. 7 sections at 7 years. The more severe Set 5 conditioning shows that moisture damage is possible at 7 years in the control and portland cement sections but not in the additive No. 7 section. Even if the disintegrated cores were excluded, Set 4 and Set 5 would not indicate potential for moisture damage at 8 years in the additive No. 7 section. Set 6 shows significant moisture damage in the control section and very significant damage in the additive No. 7 section, but none in the portland cement section. Laboratory conditioning indicates the same order of performance that was found with in-place cores: portland cement best, control intermediate, and additive No. 7 worst.

Set 4 in Alabama indicates that there is potential for moisture damage in both sections after 2 years and that had the pavement been wetter there would have been more moisture damage. Set 5 shows that there would be more damage with more severe conditioning in both sections. Set 6 shows that there had been some moisture damage in the control section and much more in the additive section. The sections are very similar, but the additive No. 8 section has more evidence of moisture damage.

The Texas control section shows potential for moisture damage from Set 4 conditioning only at 2 years, and no potential from Set 5 conditioning. The additive section shows potential for moisture damage by both Set 4 and Set 5, although Set 5 shows very little potential. Set 6 indicates that some damage had occurred in both sections. The laboratory conditioning reveals little difference between the two sections.

Climatological Data

Climatological data are summarized in Table D-9. Data for each project are taken from National Oceanic and Atmospheric Administration (NOAA) weather stations located where weather conditions at the test sites are best characterized. The data recorded are the weather conditions occurring between each coring.

Temperatures are reported in departure from normal to indicate how temperature at the site varied from the cooperating agency's experience. Hotter than normal temperatures are assumed to provide better than usual drying conditions, a situation that would inhibit moisture damage. Lower than normal temperatures are assumed to provide the opposite.

At five sites higher than normal temperatures were recorded during the early life of the pavements before the first coring. The first few months after construction are considered to be a critical period with respect to moisture damage (*1*). Arizona and Texas reported lower than normal temperatures during this time. Temperature data are not recorded by the weather stations near the Alabama site. Except in Arizona and Texas, higher than normal temperatures were reported before 1988. In 1988, Maine and Arizona had higher than normal temperatures.

Precipitation is reported in terms of a) total for the period, b) departure from normal, c) monthly average, and d) high day. Departure from normal indicates how precipitation varied at the site compared with the cooperating agency's experience. At five sites—Georgia, Virginia, Arkansas, Illinois, and Texas—precipitation was below normal during the critical early months. Only in Arizona has precipitation been above normal consistently, and even that is still very little moisture. Monthly average is used because total precipitation is distorted by the varying time periods. Very wet months have not been observed anywhere. High day provides an indication of the possibility of thorough saturation. Virginia has experienced two of the three highest high days and, as noted previously, it also has the wettest pavement.

Traffic Data

Traffic data appear in Table D-10. Presumably, higher traffic counts and heavier loads are associated with more moisture damage.

Condition Surveys

Condition survey data from Tables D-11 through D-18 are summarized in Table 11. In general, large differences between sections on the same project were not observed; however, there were differences that can be correlated with cores and laboratory tests.

TABLE 11. Condition survey summary

Project	Condition Rating*	Moisture-Related Damage for Low Rating
GA Cont.	3	Rutting and raveling in 1988
Lime	1	
Ad 2	2	Rutting in 1992
VA Cont.	1	
Ad 3	1	
AR Cont.	2	Rutting in 1992 and rate of rut development
Ad 4	1	
ME Cont.	1	
Ad 5	1	
IL Cont.	1	
0.5%	1	
0.75%	1	
AZ Cont.	2	Rutting in 1992
P C	1	
Ad 7	3	Patching, rutting, and raveling in 1992 and 1993
AL Cont.	2	Rutting and rate of rut development
Ad 8	1	
TX Cont.	2	Rutting and rate of rut development
Ad 9	1	

*Condition rating for each project: 1 = best section, 3 = poorest section

In Georgia there were rutting and raveling in the control section in 1988 that could not be observed after the overlay in 1991. The only difference in 1992 was slight rutting in the additive No. 2 section.

There was some raveling in Virginia in 1989 with more in the control section than in the additive section. In 1992 raveling had become equal between the sections, but the additive section had more rutting. Although probably not moisture related, there was more cracking in the control section in 1992.

Rutting was found in both 1988 and 1992 in Arkansas and is considered most serious in the control section because of the rate of rut development.

In Maine there were no significant differences between sections in either 1988 or 1993 and nothing attributable to moisture.

In Illinois some rutting and raveling were present in 1988, but by 1992 the rutting had disappeared. Raveling was the same in all three sections, so there were no moisture-related differences.

Rutting and raveling in the additive No. 7 section in 1992 and 1993 identify the most moisture damage in Arizona. Rutting in 1992 in the control section is less than in the additive No. 7 section but more than in the portland cement section. All three sections exhibited the same rutting in 1988, which shows that the rate of rut development from 1988 to 1992 was the most rapid for the additive No. 7 section, followed by the control section, and was practically negligible for the portland cement section.

There were rutting and raveling in both Alabama sections in both 1988 and 1992. More rutting in the control section indicates the most moisture damage.

In Texas slight raveling in 1989 was not detected in 1992. The distinction between sections related to moisture is rut depth in the control section.

CHAPTER 3

INTERPRETATION, APPRAISAL, APPLICATION

LABORATORY DATA SUMMARY

Data obtained from laboratory mixtures by the research agency are considered the data most pertinent to the objectives of the research. Tests on plant mixtures generally agree with tests on laboratory mixtures but show smaller differences between control and test mixtures. Tests by cooperating agencies are incomplete in that some cooperating agencies chose not to run the tests, but the tests that were run agree very well with tests by the research agency. In addition to the laboratory mixtures, supplemental data that involve complete asphalt and aggregate systems, whether or not the systems are true mixtures, are also considered important. These include the water susceptibility test that is run on a mixture but not the job mix aggregate gradation, and microcalorimetry that uses aggregate immersed in asphalt instead of a mixture. A summary of data from these sources is tabulated in Table 12 where control and test sections can be compared on each project.

Moisture Damage Potential

Georgia. Tensile tests show that the control mixture has the greatest potential for moisture damage. It is followed by the additive No. 2 mixture and the lime mixture, which has the least potential. This same order is found with the other tests except water susceptibility, which shows control and additive No. 2 mixtures to be equal. Large differences between mixtures are not indicated by visual ratings, boiling water, and microcalorimetry. The lime was more than 3 years old but functioned as expected in the water susceptibility test. Its age may have led to an unusually low result in microcalorimetry. This group of tests is conclusive in indicating that differences among the experimental pavement sections caused by moisture damage should occur.

Virginia. Tensile tests, visual ratings, and microcalorimetry show that the control mixture has more potential for moisture damage than the test mixture. Tensile tests on plant mixtures in Tables 4 and 5 show much less difference between control and additive mixtures than the difference for laboratory mixtures in Table 8. Boiling water and water susceptibility reveal no difference between mixtures. Boiling water tests on the plant mixtures in Tables 4 and 5 show no difference between mixtures and no evidence of moisture damage. It is not clear that large differences between control and additive sections in the field should be expected.

TABLE 12. Summary of laboratory-mixed moisture damage test results

Project	Tensile Strength Ratio (%)	Visual Rating	Boiling Water Rating	Water Suscept., Cycles	Bonding Energy, m cal/gr Peak-Tail
GA Cont.	42	3	2	2	121.62-0.46
Lime	93	1	1	>50	133.24-0.68
Ad 2	58	2	1.5	2	122.20-0.54
VA Cont.	54	2	1	4	134.07-0.60
Ad 3	88	0.5	1	4	150.06-0.60
AR Cont.	70	4	3.5	3	120.25-0.57
Ad 4	89	1	2.5	3	195.01-0.86
ME Cont.	78	2	2.5	11	377.31-1.23
Ad 5	78	1.5	1	10	342.04-1.06
IL Cont.	85	3	1.5	6	137.66-0.60
Ad 3	102	1.5	2	15	194.93-1.04
AZ Cont.	38	3.5	2	2	342.67-1.23
P C	89	0.5	1.5	>50	348.07-2.67
Ad 7	57	2.5	1	3	391.04-2.22
AL Cont.	86	0.5	1.5	10	154.14-0.74
Ad 8	89	0	1	17	213.33-1.01
TX Cont.	79	2	0	46	155.89-0.74
Ad 9	100	0	0	>50	208.53-0.96

Arkansas. The water susceptibility test shows that the control and test mixtures have equal potential for moisture damage. All other tests show that the control mixture has more potential than the test mixture. This is a reasonably conclusive indication that differences in pavement performance caused by moisture damage should be observed in the field.

Maine. Tensile tests show that the control and test mixtures have equal potential for moisture damage. Visual ratings and boiling water ratings show that the control mixture has more potential for moisture damage, and water susceptibility and microcalorimetry show that the test mixture has more potential for moisture damage. There is no clear indication that either experimental section would suffer more moisture damage than the other.

Illinois. Boiling water indicates more moisture damage potential in the test mixture, and all other tests indicate more potential in the control mixture. This is a reasonably conclusive indication that moisture damage should be more severe in the control section than in the test section. Illinois also includes a test section containing a high additive dosage. Data in Table 7 show little effect of dosage, leading to the conclusion that moisture damage in the two test sections will be about equal.

Arizona. The control mixture has the highest potential for moisture damage in all tests. The next highest potential for moisture damage is indicated for the additive No. 7 mixture by tensile test, visual ratings, and water susceptibility test, but this mixture has the lowest potential indicated by boiling water and microcalorimetry. The data are conclusive in indicating that the control section should experience the most moisture damage. The additive No. 7 section should be expected to suffer more moisture damage than the portland cement section.

Alabama. The control mixture exhibits the highest potential for moisture damage in all five tests. The difference between control and test mixtures is small in tensile tests, visual ratings, and boiling water and it is not large in water susceptibility. Some differences between the experimental sections caused by moisture damage may be observed with the most damage occurring in the control section.

Texas. The control and test mixtures have equal moisture damage according to boiling water and nearly equal potential in water susceptibility. In both cases, very little moisture damage is indicated. The remaining tests show that the control mixture has the highest potential for moisture damage. These tests indicate that the control section should suffer more moisture damage than the test section.

Project Summary

On seven of the eight projects, the control mixtures exhibit the most potential for moisture damage. Consequently, the corresponding control sections can be expected to exhibit more moisture damage than their test sections. Where two test sections, Georgia and Arizona, were used, the mixtures with liquid additives show more moisture damage potential than the lime and portland cement mixtures, and the corresponding test sections can be expected to show more moisture damage. The eighth project, Maine, reveals little, if any, difference in moisture damage potential between control and test mixtures, and little difference between experimental pavement sections caused by moisture damage is expected.

Project Ranking

No attempt has been made to rank projects or experimental sections by moisture damage potential. Such a ranking is not pertinent to this research and serves no useful purpose. For example, considering only tensile ratios in Table 12, the Arizona control mixture has the lowest ratio and is therefore the most susceptible to moisture damage. Arizona control is followed by Georgia control, Virginia control, Arizona additive No. 7, Georgia additive No. 2, Arkansas control, and so on. It might be assumed that this ranking should be reflected in the severity of moisture damage occurring in the experimental sections in the field, meaning that at equal ages the most severe damage would be found in the Arizona control section, followed in order by Georgia control, Virginia control, etc. Such a ranking would be appropriate if all the sections were in the same location subject to the same traffic, climate, and moisture exposure. Because the sections are not in the same location, they cannot be ranked. Valid comparisons can be made between sections on each project but not between projects.

Test Method Assessment

Tensile strength ratios in Table 12 were determined by ASTM Method D 4867. That test method is considered the most reliable one used in this research for evaluating moisture damage and the effects of additives, for reasons already stated (*1*). Experience with this method in the research shows that it can be used with confidence. More than 20 different laboratories used ASTM Method D 4867 in this research. The precision study showed that it is much more precise than other test methods applicable to complete mixtures and compacted specimens. In the field study, agreement between cooperating agency laboratories and the research agency was found to be very good. Difficulty with the method is confined mostly to interpretation of test results. What constitutes an unacceptable degree of moisture damage is not defined by the method. The need for this information may be filled by the field evaluation phase of this research.

Of the five methods of evaluating mixtures in Table 12, one, the visual rating, is not a test method. It is a part of the D 4867 that requires the technician to evaluate moisture damage visually following the tensile test. In the opinion of the research agency, this visual rating is important because it forces the technician to observe the specimen carefully. A good correlation between tensile ratios and visual ratings should be found for individual mixtures. In Table 12, testers found such a correlation.

One problem with visual ratings, however, is the true meaning of the numbers. For example, tensile ratios of Georgia additive No. 2 and Virginia control are very close, and both mixtures have visual ratings of 2. Maine control and Texas control also have comparable tensile ratios and visual ratings of 2. There are large differences in tensile ratios among the four mixtures, and it is apparent that 2 in Georgia and Virginia does not mean the same as 2 in Maine and Texas. This kind of discrepancy limits the usefulness of visual ratings, but visual ratings can still be useful on individual mixtures.

Limitations on the usefulness of boiling water tests are discussed in the literature (*1*). Experience with boiling water in this research confirms these limitations. In Table 12, correlation between tensile ratios and boiling water is not as good as with visual ratings. Instead of the numerical ratings in Table 12, ASTM Method D 3625-83 rates mixtures on good or bad basis at the 95 percent coated level. Using the 95 percent criterion, the good mixtures include both Georgia treated mixtures, both Virginia mixtures, Maine treated, Illinois control, both Arizona treated mixtures, both Alabama mixtures, and both Texas mixtures. The bad mixtures are Georgia control, both Arkansas mixtures, Maine control, Illinois treated, and Arizona control. This criterion is not helpful in attempting to interpret the experimental data. A better way of evaluating boiling water test results is needed.

Limitations on the water susceptibility test are also in the literature (*1*). In this research, the most formidable problem is the use of an aggregate gradation that does not remotely approach the job mix gradation. The resulting aggregate surface area is not the actual job mix surface area. Additives operate at the asphalt-aggregate interface, and the incorrect surface area makes it impossible to use the correct additive dosage in the test. Also, additives such as lime and portland cement act like both antistripping additives and mineral filler in the test; this behavior gives them an advantage over additives that are not also mineral fillers. The Georgia and Arizona mixtures are good examples of this in Table 12. Georgia lime and Arizona portland cement performed very well in the water susceptibility test, but Georgia additive No. 2 and Arizona additive No. 7 performed very poorly in spite of the fact that these two additives are shown by other data to provide at least some improvement. Other examples of poor agreement with other data in Table 8 include Virginia and Arkansas, where the additives are shown to be useless in water susceptibility. The water susceptibility test may be a useful moisture damage test without additives, but until its surface area problem is solved, it should not be used with additives.

Microcalorimetry presents problems similar to those of the water susceptibility test with respect to surface area (*1*). In addition, data in Table 12 raise questions concerning its applicability to powders such as lime and portland cement. Both Georgia lime and Arizona portland cement show improved bonding energy compared with their control mixtures, but the increase in both cases is very small compared with the improvement in resistance to moisture damage that is shown by other data and expected by experience. This suggests that microcalorimetry may not be capable of measuring the true effects of these additives. However, as already noted, the lime was more than 3 years old when these tests were run and may have been altered chemically by absorbing carbon dioxide from the atmosphere. The portland cement was more than 1 year old and may have partially hydrated because of exposure to the atmosphere. Very small samples of lime and portland cement are used in these tests, making exposure very critical. The small effect of these powders may have been caused by altered chemical properties rather than the inability of microcalorimetry to measure their true effect.

Another question raised by microcalorimetry is the true meaning of the bonding energy measured. All three Arizona mixtures have high bonding energy, but the control mixture is not supposed to have much resistance to moisture damage. Outside of Arizona, no treated mixture has bonding energy as high as Arizona control. Bonding energies of the Maine mixtures are comparable to the Arizona mixtures and much higher than any others. If bonding energy is a measure of adhesion at the asphalt-aggregate interface, then the Arizona and Maine mixtures should perform very well with or without additives, and none of the Georgia or Virginia mixtures should perform at all. Other data show no relationship between bonding energy and other moisture damage evaluations when various aggregate sources are involved (*3*). Instead of considering absolute values of bonding energy, it may be more appropriate to study the effect of an additive on an individual asphalt-aggregate system. When this is done with the data in Table 12, the additive in Maine appears to be ineffective, but in all other cases the additives result in increased bonding energy. If microcalorimetry is to be useful in moisture damage testing and additive evaluation, a better understanding of the meaning of the data is needed.

SUPPLEMENTAL DATA

Interpretation of the supplemental data appears in Appendix C. Only the interpretations most pertinent to the objectives of this project are reported here. Aggregate tests indicate that there was more limestone present in the Illinois and Texas mixtures than originally expected, which means that these mixtures may be less susceptible to moisture damage than originally indicated by cooperating agency tests. On the other hand, tests on the Alabama aggregate show that it is nearly all materials usually associated with moisture damage, and if its performance should be different from original expectations by the cooperating agency, it should be expected to suffer more moisture damage. That conclusion would be contrary to all data in Table 12. All the aggregates have the capability of absorbing and retaining significant amounts of nitrogen, and all of the liquid additives can supply nitrogen, which should reduce the mixture's susceptibility to moisture damage. None of the asphalt cements should be expected to be highly susceptible to moisture damage with or without additive. None of the treated asphalt cements are expected to cause pavement damage not caused by moisture.

PAVEMENT EVALUATION

Ranking Experimental Sections

The experimental sections on each project are ranked in Table 13 to indicate the relative amount of moisture damage found by condition surveys and cores and the expected damage indicated by laboratory tests. Condition survey rankings are the same as the condition ratings in Table 11. In-place cores are ranked on the basis of the data in Table 9 and the associated discussion. Conditioned cores are ranked in two categories, laboratory saturated and laboratory healed. Laboratory-saturated cores, Sets 4 and 5, showing the least potential for moisture damage, are ranked best or 1. Healed cores, Set 6, showing the smallest difference from in-place cores, Set 3, are ranked best. Expected damage is taken from Table 12 using D 4867 only.

TABLE 13. **Ranking experimental sections**

Project	Condition Surveys	Set 3 Cores	Sets 4 and 5 Cores	Set 6 Cores	D 4867
GA Cont.	3	3	1	3	3
Lime	1	2	2	2	1
Ad 2	2	1	3	1	2
VA Cont.	1	1	2	1	2
Ad 3	1	2	1	2	1
AR Cont.	2	2	1	2	2
Ad 4	1	1	2	1	1
ME Cont.	1	1	1	2	1
Ad 5	1	1	1	1	1
IL Cont.	1	2	1	3	3
0.5%	1	1	1	2	1
0.75%	1	1	1	1	2
AZ Cont.	2	2	3	2	3
P C	1	1	1	1	1
Ad 7	3	3	2	3	2
AL Cont.	2	2	1	1	2
Ad 8	1	1	2	2	1
TX Cont.	2	2	1	2	2
Ad 9	1	1	2	1	1

Interpretation

Georgia. The condition surveys found distress in the control section that may be caused by moisture. Core Sets 3 and 6 show that some moisture damage had occurred in the control section by 99 months. Sets 4 and 5 indicate that there had been little potential for moisture damage in the control section throughout the 8 years. That moisture damage would be detected had been indicated by the original laboratory tests. Cores from the lime section indicated the most potential for moisture damage among the three sections and showed that some moisture damage had occurred but slightly less than in the control section. Condition surveys of the lime section revealed the least distress related to moisture. The original laboratory tests predicted much less moisture damage in the lime section than in the control section. The additive No. 2 cores revealed practically no evidence of moisture damage and showed little potential for it. The condition survey found somewhat more distress in the additive section, perhaps caused by moisture, than was found in the lime section. The original laboratory tests predicted performance more like that of the control section.

Moisture damage more severe than was found in the control and additive sections had been expected on the basis of the original tests. In-place moisture data in Table D-1 show that from 7 months on the pavement was never very wet. Climatological data in Table D-9 shows that less than normal precipitation fell during the first 4 years, which accounts at least partly for the low moisture content of the pavement. Then in 1991 the pavement was overlaid, and subsequent moisture tests show that no moisture was trapped in the test layer at that time. In addition, attempts to saturate cores in the laboratory for Sets 4 and 5 were not very successful. Apparently, the test pavement had become highly impermeable at an early age, and the expected moisture damage could not occur because of lack of moisture.

Virginia. Core Set 6 compared with Set 3 shows that much moisture damage had occurred in both control and additive sections with more damage indicated in the additive section. In all other respects, on the basis of both cores and condition surveys, the two sections not only are very similar to each other but also show little evidence of moisture damage. Set 3 cores indicate slightly more damage in the additive section, and Sets 4 and 5 indicate more potential in the control section. The original laboratory tests indicated that moisture damage could be expected in both mixtures, with much more in the control than in the additive mixture. Tests on the plant mixtures, appearing in Tables 4 and 5, showed that the two mixtures were very similar with respect to moisture damage potential. Both laboratory and plant mixtures were tested by the research agency and the cooperating agency, and the two agencies' results agree very well on both mixtures. There may have been a difference in mixture composition between the laboratory and plant mixtures. What this difference might be is a matter of speculation. One possibility is that the plant control mixture may have contained additive, either inadvertently or as a residual effect caused by plant components being incompletely purged of additive.

Arkansas. Set 3 cores show that moisture damage occurred in the control but not the additive section. Set 6 cores show moisture damage in both sections with more damage in the control section. Sets 4 and 5 show more potential for moisture damage in the control section. The condition surveys reveal more distress in the control than in the additive section. The original laboratory tests showed that moisture damage could be expected in both sections with more damage in the control than in the additive section.

Maine. The condition surveys revealed little, if any, difference between sections attributable to moisture damage. Set 3 and Set 6 cores show that slight moisture damage had occurred in the control section. The same sets show no evidence of moisture damage in the additive section. Sets 4 and 5 show little potential for moisture damage in either section. The original laboratory tests indicated that both sections may suffer moisture damage with little difference between sections.

Illinois. Condition surveys found no significant difference among the three sections. Set 3 and Set 6 cores show that there had been slight moisture damage in the control section and the 0.5 percent additive section with somewhat more evidence of damage in the control section. Neither set revealed any moisture damage in the 0.75 percent additive section. Set 4 indicated some, but approximately equal, potential for damage in all three sections through 4 years, and no potential after that. The original laboratory tests indicated that some moisture damage should be found in the control section and that there would be none in the additive sections.

Data in Table D-5 show that the Illinois pavement was never very wet, and in-place saturation levels were never high. Set 4 conditioning produced high levels of saturation and low tensile strengths, but comparable degrees of saturation were never approached in the field. Apparently, more moisture damage would have occurred, at least in the control section, had the pavement been wetter.

Arizona. Set 3 and Set 6 cores show some moisture damage in the control section, none in the portland cement section, and significant moisture damage in the additive No. 7 section. Sets 4 and 5 indicate potential for moisture damage in the control section, less potential in the additive No. 7 section, and even less in the portland cement section. Condition surveys found some distress in the control section, practically none in the portland cement section, and the most distress in the additive No. 7 section. The original laboratory tests indicated that very severe distress caused by moisture would be found in the control section, little distress would be found in the portland cement section, and severe distress would be found in the additive No. 7 section. The field evaluation reverses the order of the control and additive sections from that expected on the basis of the original tests. Both control and additive No. 7 mixtures were shown to be highly susceptible to moisture damage, and probably neither would be used in practice except in an experiment. Even so, as reported in Table 3, the difference between their tensile strength ratios is significant at the 20:1 level, and their order should not reverse. The expected performance was found in the portland cement and additive No. 7 sections, but not in the control section, which performed too well.

Alabama. Set 3 cores show no evidence of moisture damage in either control or additive section, but the additive section has consistently higher strength, an indication of less damage. Set 6 cores show some moisture damage in both sections, with the additive section indicating more damage. Sets 4 and 5 show that both sections are susceptible to moisture damage, with the additive section slightly more susceptible. Condition surveys found more distress in the control section than in the additive section. The original laboratory tests predicted slightly less moisture damage in the additive section.

Texas. Condition surveys revealed more distress in the control section. Set 3 and Set 6 cores indicate moisture damage in both control and additive sections with the more severe damage in the control section. Sets 4 and 5 indicate moisture damage is more likely in the additive section. The original laboratory tests show that the control section should experience more moisture damage than the additive section.

Appraisal

With respect to the long-term performance of the nine additives investigated in this study, only one was found to perform poorly. Additive No. 7 in Arizona did not perform as well as expected. At 79 months, its test section exhibited distress not found elsewhere and delivered the only disintegrated cores found in the entire research. Had this section been a surface not protected by an open-graded friction course, it might have had to be replaced entirely before the 1993 evaluation was made. The Maine additive did not improve pavement performance, but it did not lead to undue distress, either. This additive performed as expected on the basis of both experience and laboratory tests, and there is no basis for claiming that its performance was poor. The other seven additives were performing well in 1993, and there were no indications that rapid deterioration of their test sections should be expected in the immediate future.

The other matter to be addressed is whether or not the original laboratory tests correctly predicted additive performance. On 16 of the 19 experimental sections the original tests, ASTM D 4867, indicated the observed performance correctly. In Georgia, the control section had the poorest performance, which was expected, but its performance was much better than expected. The lime section was not supposed to suffer more than a little moisture damage, and that is how it performed. The additive No. 2 section performed much better than expected. The performance of one section, lime, is considered to be what was predicted. In Arizona, it was expected that portland cement would perform well and additive No. 7 would perform poorly, both of which occurred. The control section performed better than expected, and accounts for the third incorrect prediction. In Virginia, it is considered that tests on the plant mixture are what should be used to predict field performance, and they correctly indicated the observed field performance. On all other projects, the additive sections were supposed to perform better than the corresponding control sections, and they did.

Decisions concerning long-term additive performance are easily reached. The only question is whether or not age 6 to 8 years is a long enough term, and that is beyond the scope of this research.

Decisions concerning the efficacy of laboratory tests are more difficult. Serious distress was never found in the condition surveys, and only the Arizona Set 3 cores from the additive No. 7 section showed a significant loss of tensile strength. As a result, small differences from the field evaluation must be compared to relatively large differences from the laboratory tests. One reason for the small differences in the field is the low moisture content at six projects. At 17 of the 19 experimental sections, Set 4 cores show that more moisture damage would have occurred if the pavement were wetter at some time during its life. Without much moisture, moisture damage may be occurring at a very slow rate that is probably difficult to measure.

Another reason for small differences in the field is that control mixtures in Illinois, Alabama, and Texas did not exhibit as much potential for moisture damage based on the initial laboratory tests as expected on the basis of preliminary evaluations by the cooperating agencies. Small differences in the field evaluation, both in tensile strength of cores and condition surveys, were observed, and that is what the initial laboratory tests predicted.

There are factors that may influence pavement performance and could obscure moisture damage. In this research, all eight job mix formulas in Table B-3 are considered to be very satisfactory and should result in good pavements. Quality control during construction of the experimental sections, indicated by test results in Table B-3, was also very good; the result was pavements that conform to the job mix formula and should be good pavements. Although high-quality pavements are a credit to the cooperating agencies and their contractors, such pavements also may inhibit moisture damage so that damage proceeds at a very slow rate, a rate that has been found in the field evaluation.

That there would be small differences in performance of the field sections was also indicated by exhaustive supplemental tests that show that one test section in Maine and one in Arizona may rut more than their corresponding control sections and that the test section in Alabama may be more durable than the control. The rutting occurred in Arizona by $\frac{1}{32}$ of an inch after almost 7 years. There was no rutting in Maine and nothing indicating better durability of one Alabama section compared to the other.

Swell was determined on Set 4 and Set 5 cores that were vacuum saturated in the laboratory. Swell data are not reported in Tables D-1 through D-8 because the values are too small to be meaningful. Had significant swell been found in the laboratory, more moisture damage would have been expected and probably found in the field. The report on the precision study in Appendix A shows clearly that swell can be an important contributor to moisture damage. Without swell, moisture damage must develop relatively slowly.

The conclusion of this appraisal is that the original objectives of the research have been satisfied.

Pavement Evaluation Methodology

The methodology used in the pavement evaluation is considered to be satisfactory. There may be questions concerning the use of a wet coring process to obtain cores for measuring moisture content and tensile strength. In this research, over 250 cores have been taken for determination of moisture content. Each core was blotted to a saturated surface-dry condition immediately and then sealed in a plastic bag to prevent further moisture loss. This procedure was intended to minimize any effect of coring water and to preserve the in-place moisture content.

For cores of the size used in this study, saturated surface-dry moisture is probably no more than 1 gram per core, equivalent to about 0.002 percent moisture. Moisture content was determined by ASTM Method D 1461, which removes all moisture; yet data in Tables D-1 through D-8 show clearly that little moisture was found in most of the cores. The exceptions were Virginia and Arizona, where void content was also high enough to admit water. It is impossible that the wet-coring process added significant moisture to the cores in this study.

The usual wet-coring process adds cooling water through the center of the barrel, where it falls onto the specimen. Subsequently, centrifugal force throws the water outward into the pavement, not inward into the specimen. It is unlikely that much water could be added to the specimen under these conditions. If moisture damage is severe, free water is probably present in the pavement, and accurate moisture content determinations cannot be made. If moisture damage is very severe, it may result in disintegrated cores having 0 strength, which is the correct value. In that case, moisture content is of no importance.

In-place moisture content is a necessary part of a field study of moisture damage, although it has not been used for this purpose outside of this study as far as the research agency knows. It would be difficult, if not impossible, to arrive at definitive conclusions in this study if it were not known that six of the eight pavements studied were not wet. Moisture content data were helpful in the interpretation of both core data and condition survey data. Standard deviation of moisture content was calculated from the core data, but it is not reported in Tables D-1 through D-8 because the values are so small. This suggests that one moisture determination per section, rather than the three that were used, may be enough.

The tensile strength of cores proved to be highly variable, as shown by standard deviations reported in Tables D-1 through D-8. The precision study found a standard deviation of 8 for within-laboratory precision. Many standard deviations in the tables are much larger than that. Also, outlier criteria were employed in the analysis of laboratory-compacted specimens, both laboratory and plant-mixed. No such criteria were applied to the core data partly because of the high standard deviations that would have excluded too much data.

Reasons for the variability were considered in an attempt to find the cause, without success. For example, tensile strength was correlated with void content of individual cores. If high void content corresponded with low strength, then the conclusion could be that the core was faulty, perhaps because of an imperceptible crack. That correlation did not exist. As often as not, low voids had low strength and vice versa. Researchers also determined that the variability was not related to the laboratories. All the laboratories reported data with high standard deviations for some core sets. The decision was that high variability is inherent with cores taken at random locations. More variability than is found in laboratory-mixed specimens has to be expected and accepted from cores. Laboratory-mixed specimens should be less variable because of the precision of proportioning that cannot be duplicated in the field. There appear to be other causes of variability in cores. Standard deviations of plant-mixed, laboratory-compacted specimens in Tables B-6 and B-7 are much smaller than standard deviations of cores. In fact, plant-mixed standard deviations are not much different from laboratory-mixed standard deviations. Specimens compacted in the laboratory are sorted into sets of approximately equal void content before tensile strength is determined. Sorting cannot be applied to cores taken for specified purposes from random locations, and more variability has to result.

In the absence of some reason other than the variability itself, and with the realization that core data should be highly variable, there was no attempt to apply any kind of outlier criteria.

Cores also may tend to overstate the in-place condition of the pavement. If the test layer is the surface and the random location happens to be a crack, the core will usually be taken from an adjacent point where the pavement is not cracked. A crack is a tensile failure whether or not moisture is a factor. When a core is taken where the pavement has not failed, the core represents the best condition rather than the worst. If an underlying layer is the test layer, and the core has a crack and is not considered to be a disintegrated core, another core would probably be taken. Regardless of the location of the test layer, the result is the same. One solution to this is to use a condition survey in conjunction with each coring.

A Limiting Tensile Strength Ratio

It has been concluded that ASTM Method D 4867 correctly predicted long-term additive performance and that the methodology used to evaluate field performance was satisfactory. With that background, it is possible to suggest a limit on tensile strength ratio of laboratory specimens below which excessive moisture damage can be expected and a new mix design or use of an additive should be considered.

In this study, all experimental sections for which the tensile strength ratio of their original laboratory specimens was 75 percent or more performed well. Accordingly, 75 percent can be suggested as the limit on tensile strength ratio. It is not recommended for that purpose because too many of the pavements were not wet enough and several of the sections had ratios much below 75 percent but performed well anyway. Until data from wet pavements become available, 75 percent can serve as an interim limit but should be used with discretion.

In the laboratory phase of this research, a procedure for evaluating laboratory test results was developed to assist in making decisions concerning the need for and effectiveness of additives (*1*). Essentially, that procedure requires that the difference between sets of specimens be statistically significant. The use of the limit of 75 percent should be in conjunction with the statistical procedure.

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

The primary objectives of this research were to obtain information on long-term performance of antistripping additives and to determine how well laboratory tests evaluate long-term additive performance. These objectives have been satisfied, and the following conclusions have been reached.

1. The experimental pavements provided a satisfactory basis for a field experiment that can satisfy the primary objectives of the research.
2. Eight of the nine additives performed satisfactorily throughout the 6 to 8 years of the study.
3. The original laboratory tests using ASTM Method D 4867 correctly predicted the performance of 16 of the 19 experimental sections.
4. For purposes of evaluating moisture damage and additive effects, ASTM Method D 4867 is the most satisfactory method known that uses laboratory-mixed compacted specimens of actual paving mixtures because it is easiest, fastest, and most precise.
5. When plant-mixed samples are reheated before testing, they often indicate less potential for moisture damage than laboratory-mixed samples of the same mixture that are not reheated.
6. The wet coring process used in this study is a satisfactory method for obtaining pavement specimens to determine moisture content and tensile strength.
7. Determination of moisture content of pavements should always be included in field moisture damage studies.
8. The effect of antistripping additives on aged asphalts is different than on the original asphalts, and the difference is enough so that testing of aged, treated asphalts should be considered.
9. Laboratory testing involving hydrated lime and asphalt cement should be concluded promptly before the hydrated lime has an opportunity to convert to calcium carbonate.

RECOMMENDATIONS

Future Evaluations

Only 1 of the 19 experimental sections has failed, and it was still in service in 1993. Future evaluation of the pavements is possible and can provide useful information. Recommendations on when to evaluate the sections and how to do it follow.

It is expected that trends in tensile strength and pavement condition that have already been observed will continue and that the sections exhibiting the most distress now will deteriorate more rapidly than those with less distress. If that is the case, there is no need for future evaluations, but it is not certain that that will occur. To determine what the terminal condition of the sections is, it is recommended that a condition survey following Strategic Highway Research Program (SHRP) procedures be conducted by each cooperating agency whenever the pavements are scheduled for resurfacing or replacement (*15*). Although there is no formal way of reporting the results, the agency will know and can report at opportune moments such as discussions of technical papers.

Other procedures such as cores would appear to be useful only if the condition surveys did not reveal the expected results.

The use of SHRP equipment in the long-term pavement performance studies such as the falling weight deflectometer might also be considered. Appendix E presents an analysis of the use of such equipment for evaluation of what is basically thin overlays on old asphalt concrete or portland cement concrete pavements. Mostly because of the precision of the results produced by today's state-of-the-art equipment and analysis procedures, it is concluded that distress in one thin layer is not likely to be detected. The use of SHRP equipment for future evaluation of the sections in this study is not recommended; however, SHRP equipment and procedures are still being refined and improved. Meaningful future evaluations may be possible.

A Limiting Tensile Strength Ratio

Based on this study, a limiting tensile strength ratio of 75 percent has been suggested for use with ASTM Method D 4867 as a tentive limit below which excessive moisture damage can be expected. More field data are needed before this limit can be used with a high degree of confidence. To verify or modify such a limit, pavement sections with ratios below 75 percent need to be built in conjunction with pavements with ratios above 75 percent. This can be done in the same way that was used in this study. If an antistripping additive is needed because the mixture has a ratio below 75 percent, the additive can be omitted from a short section, such as 500 feet, so that its performance can be compared with adjacent sections having ratios above 75 percent. Monitoring can be accomplished through routine pavement management programs, perhaps modified to include the special study.

It should not be necessary to use pavement cores in such studies when surface courses are the test layer. When an underlying layer is the test layer, whatever moisture damage may be developing is of little consequence until its effects are manifest on the surface where they can be detected by pavement management evaluations. At that time cores could be helpful in determining the source of the problem.

To implement a study of a limiting tensile strength ratio, an agency would have to determine what aspects of its pavement management program are applicable to moisture damage. Then comparison of those aspects from a section with a ratio below 75 percent to the same aspects from a section with a ratio above 75 percent can be expected to indicate whether or not the ratio is suitable.

Specimen Size

In this study, laboratory-compacted specimens 4 in. in diameter and approximately 2.5 in. in height were used. The size of specimens is beyond the scope of this study, but some of the results of the SHRP studies raise questions concerning specimen size. SHRP recommends the use of specimens of compacted mixtures 6 in. in diameter. Limited tests of specimens 6 in. in diameter by the Asphalt Institute supervised by R. B. McGennis show that on a mixture routinely tested for moisture damage a ratio of 90 percent is obtained. On the same mixture with specimens 4 in. in diameter, a ratio of 70 percent is obtained.

Specimens 6 in. in diameter of the same height-to-diameter ratio as the specimens 4 in. in diameter routinely used in the past have a mass approximately three times the mass of 4-in. diameter specimens. Size of specimens should make no difference in D 4867 because the degree of saturation is controlled regardless of size, and the dimensions of the specimen enter into the calculation of tensile strength. However, the internal temperature of conditioned specimens is not monitored. It appears as if 6-in. specimens are not conditioned at 140°F for a long enough time to be heated enough internally to cause the same moisture damage that occurs in 4-in.-diameter specimens.

Research is needed to determine how to condition specimens 6 in. in diameter and approximately 3.75 in. in height. One approach would be to determine the internal temperature of 4-in.-diameter specimens and the rate of temperature increase when saturated and conditioned following D 4867 procedures. This could be done by inserting a thermocouple into the center of the specimen. The same procedure could be applied to 6-in.-diameter specimens except that the time needed to achieve the same internal temperature or to hold that temperature for the same period of time, rather than the standard 24 hours, would have to be determined. Then tensile strength ratios from specimens 4 in. in diameter conditioned by standard procedures could be compared with ratios from 6-in.-diameter specimens of the same mixture conditioned on the basis of their internal temperature.

Another approach would be to condition 6-in.-diameter specimens for progressively longer periods of time at 140°F until ratios comparable to ratios from 4-in.-diameter specimens are achieved.

Either way, the time required to condition 6-in.-diameter specimens to yield tensile strength ratios comparable to ratios from 4-in.-diameter specimens would be found.

It might be determined that the time required for 6-in.-diameter specimens is too long to be practical, or that the time is too erratic. Another approach would be to find a limiting tensile strength ratio for specimens 6 in. in diameter that would be expected to provide performance comparable to the performance provided by the ratio of 75 percent suggested above for 4-in.-diameter specimens.

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APPENDIXES A, C, and E

Appendixes A, C, and E contained in the report submitted by the research agency are not published herein but, for a limited time, are available for loan or purchase ($20.00) from the NCHRP, Transportation Research Board, Box 289, Washington, DC.

The appendix titles are as follows:

Appendix A—Test Method and Precision Study

Appendix C—Supplemental Data

Appendix E—Detection of Stripping by Non-Destructive Testing

APPENDIX B

LOCATION SKETCHES
MIXTURE COMPOSITION AND CHARACTERISTICS
EXPERIMENTAL DATA

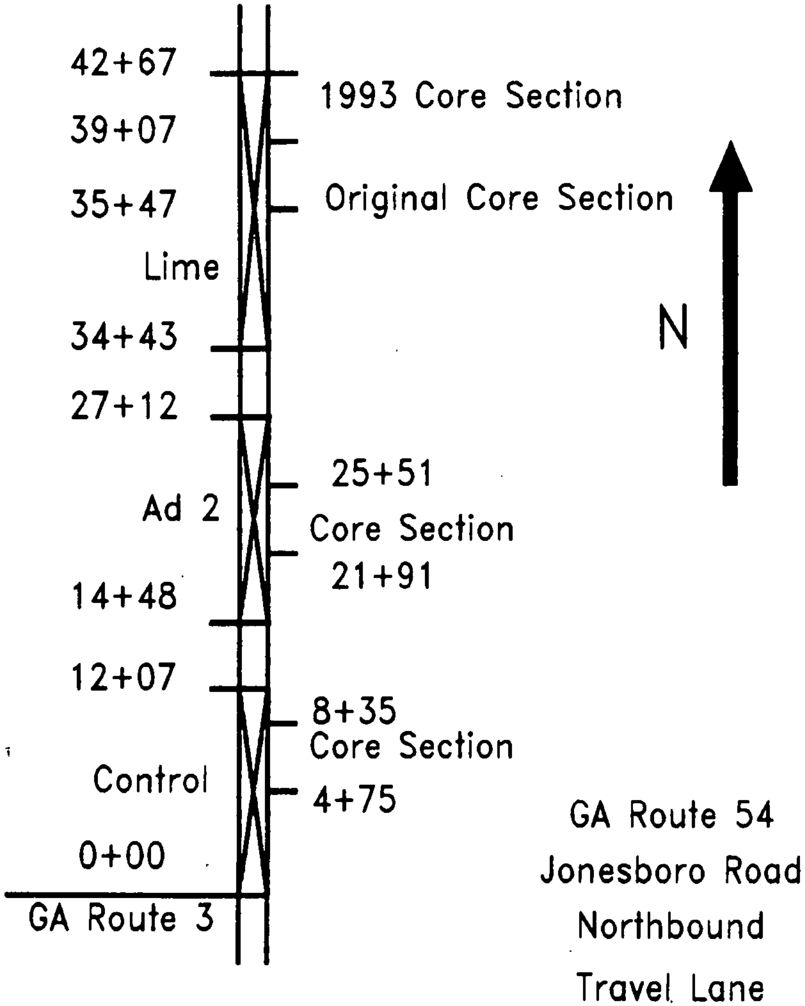

Figure B-1. Georgia Project

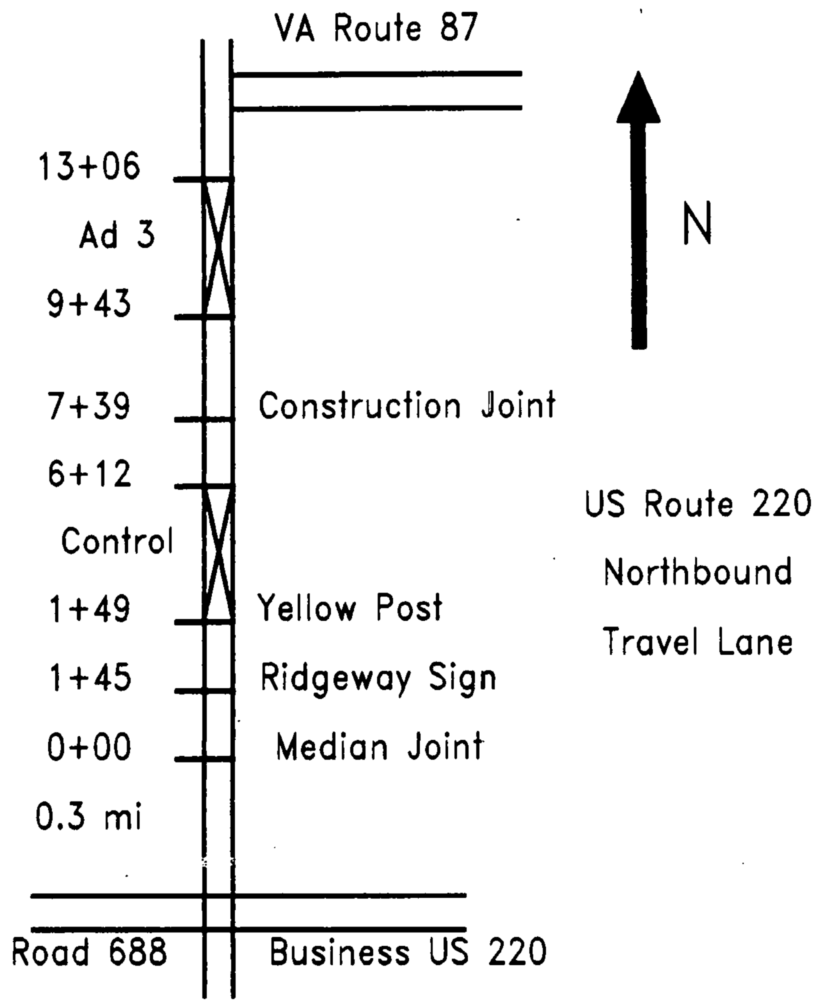

Figure B-2. Virginia Project

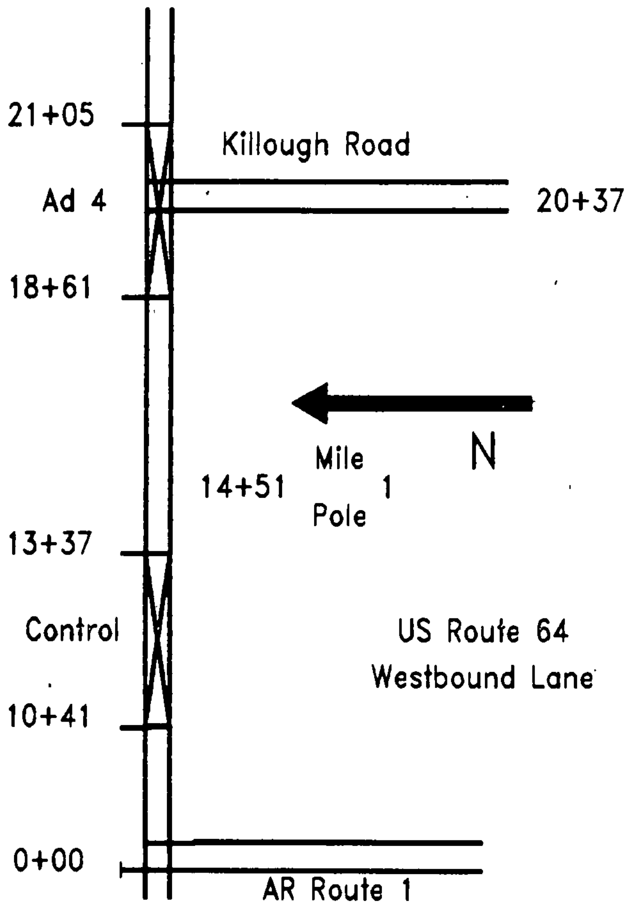

Figure B-3. Arkansas Project

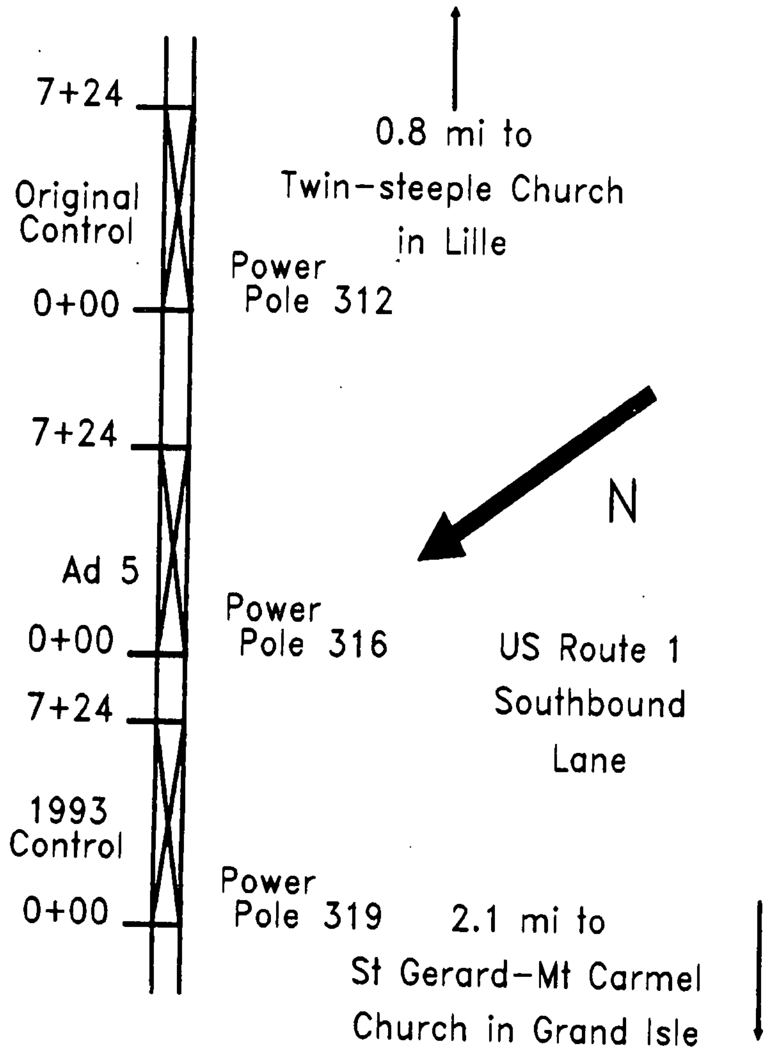

Figure B-4. Maine Project

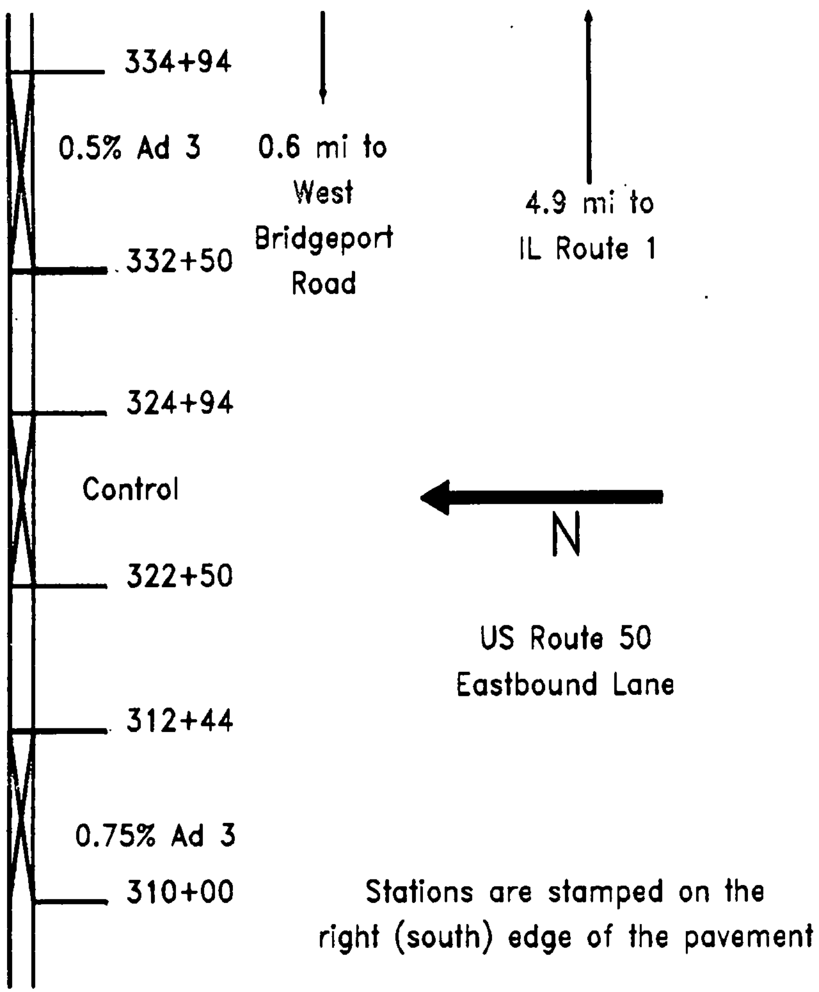

Figure B-5. Illinois Project

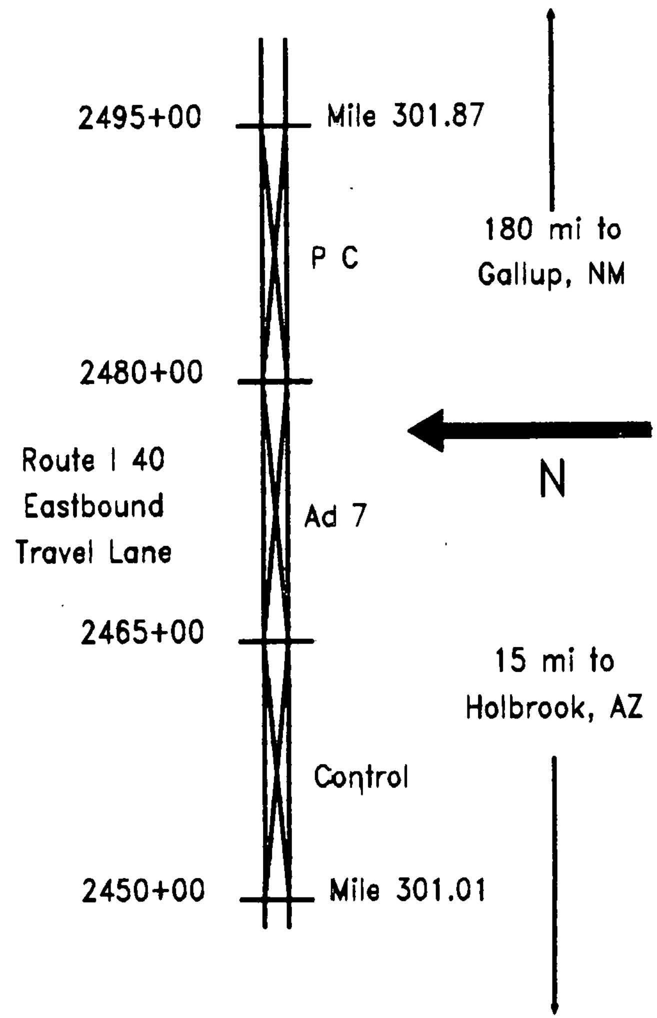

Figure B-6. Arizona Project

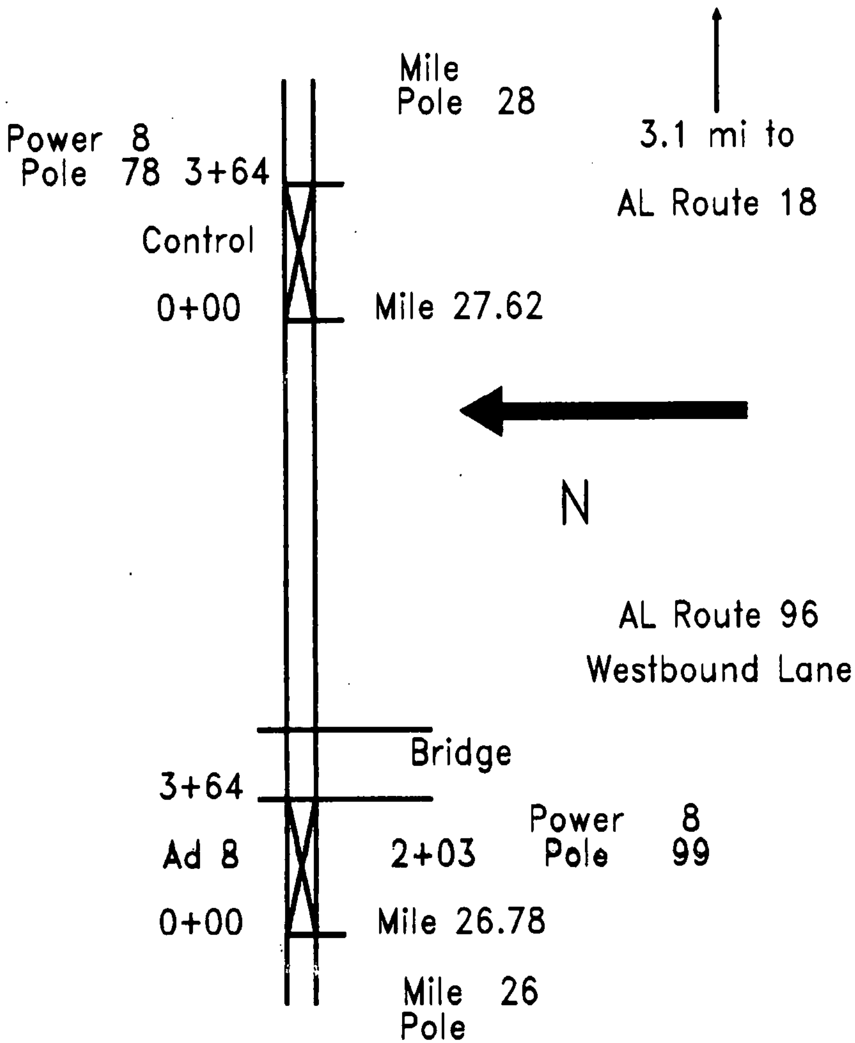

Figure B-7. Alabama Project

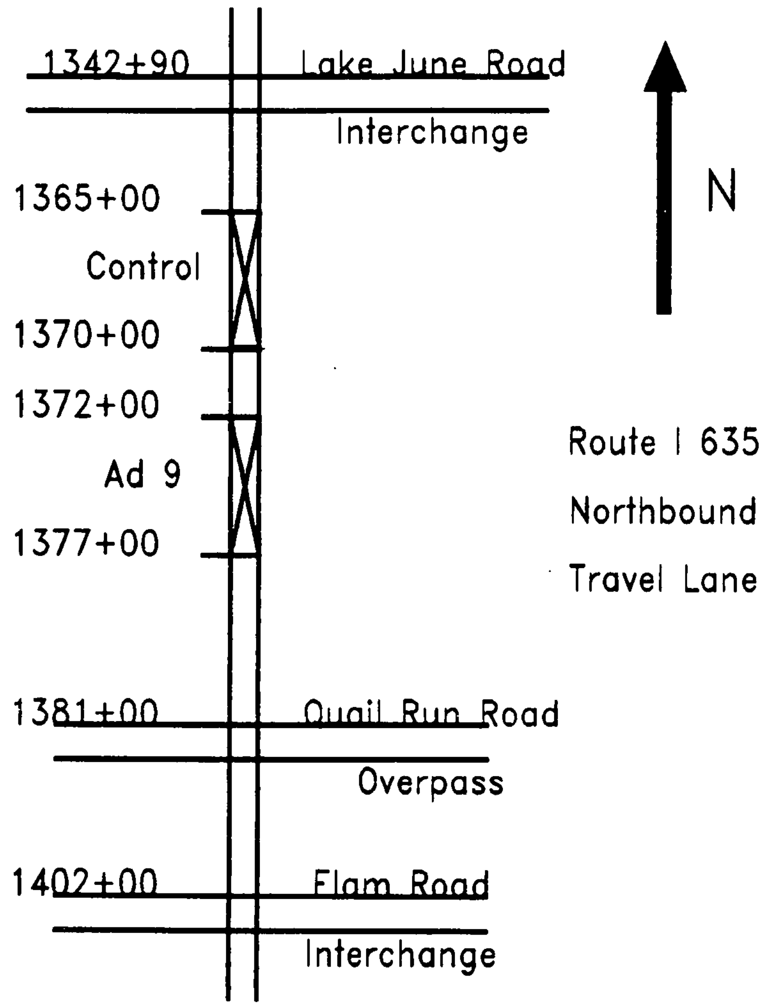

Figure B-8. Texas Project

Table B-1

COMPOSITION OF EXPERIMENTAL JOB MIXES

Project	Component	Type	ASTM Spec.	Percent*	Source
GA	Crse.Agg	Granite-Gneiss		31	Florida Rock Industries Mountain View, GA
	Fine Agg	Granite-Gneiss		68	Florida Rock Industries Mountain View, GA
	Additive	Hydrated Lime Type N	C 206	1	Tenn-Luttrel Lime Co. Luttrel, TN
	Asphalt Cement	AC-20S**	D 3381	5.6	Shell Oil Co. Atlanta, GA
	Additive	Liquid		0.5	Additive 2, Table C-3
VA	Crse.Agg	Granite		50	Martinsville Stone Fielddale, VA
	Fine Agg	Granite		45	Martinsville Stone Fielddale, VA
	Fine Agg	Natural Sand		5	South Central Sand Co. Danville, VA
	Asphalt Cement	AC-20	D 3381	5.6	Shell Oil Co. Bristol, VA
	Additive	Liquid		0.5	Additive 3, Table C-3
AR	Crse.Agg	Cr.Gravel		63	St. Francis Mtls. Co. White Hall, AR
	Fine Agg	Conc. Sand		20	St. Francis Mtls. Co. White Hall, AR
	Fine Agg	Natural Sand		17	Stalcup Pit, Earle, AR
	Asphalt Cement	AC-30	D 3381	5.8	Ergon, Memphis, TN
	Additive	Liquid		0.75	Additive 4, Table C-3
ME	Crse.Agg	Glacial Gravel		45	Daigle Pit, Lille, ME
	Fine Agg	Natural Sand		55	Daigle Pit, Lille, ME
	Asphalt Cement	AC-10	D 3381	6.4	Irving Oil, St. John, NB
	Additive	Liquid		0.5	Additive 5, Table C-3
IL	Crse.Agg	Cr. Gravel		63	Lawrence Gravel Palestine, IL
	Fine Agg	Natural Sand		31.5	Mt. Carmel Sand & Gr. Lawrenceville, IL
	Min.Fil.	Limestone Dust		5.5	Bloomington Stone Bloomington, IN
	Asphalt Cement	AC-20	D 3381	5.7	Marathon Oil Co. Louisville, KY
	Additive	Liquid		0.5	Additive 3, Table C-3
AZ	Crse.Agg	Basalt		30	Hennesy Butte, #5588
	Intermed.	Basalt		14	Hennesy Butte, #5588
	Fine Agg	Basalt Scrs.		16	Hennesy Butte, #5588
	Fine Agg	Washed Sand		40	Francis Day Pit
	Asphalt Cement	AC-30	D 3381	5.5	Suharo Petroleum & Asphalt, Phoenix, AZ

Table B-1 (Continued)

Project	Component	Type	ASTM Spec.	Percent*	Source
	Additive	Type II Portland Cement	C 150	2.0	Ideal Basic Industries Tijeras, Mexico
AZ	Crse.Agg	Basalt		30	Hennesy Butte, #5588
	Intermed.	Basalt		14	Hennesy Butte, #5588
	Fine Agg	Basalt Scrs.		18	Hennesy Butte. #5588
	Fine Agg	Washed Sand		38	Francis Day Pit
	Asphalt Cement	AC-30	D 3381	5.6	Suharo Petroleum & Asphalt, Phoenix, AZ
	Additive	Liquid		0.5	Additive 7, Table C-3
AL	Crse.Agg	Cr. Gravel		50	S. T. Bun Const. Co. Fayette, AL
	Fine Agg	Washed Sand		42	S. T. Bun Const. Co. Fayette, AL
	Fine Agg	Fine Sand		8	Greer Pit, Vernon, AL
	Asphalt Cement	AC-30	D 3381	6.3	Hunt Refining Co. Tuscaloosa, AL
	Additive	Liquid		0.5	Additive 8, Table C-3
TX	Crse.Agg	Limestone		35	Texas Industries Bridgeport, TX
	Crse.Agg	Pea Gravel		25	Texas Industries Ferris Pit
	Fine Agg	Limestone Scrs.		20	Texas Industries Bridgeport, TX
	Fine Agg	Field Sand		20	Texas Industries Beckett Road
	Asphalt Cement	AC-10 with 3% Rubber Solids		4.5	Fina, Big Spring, TX
	Additive	Liquid		1.0	Additive 9, Table C-3

*Percentage of weight of aggregate for hydrated lime and portland cement. Percentage by weight of asphalt cement for liquids.

** Also required to comply with ASTM Specification D 946 for Penetration Grade 60-70.

Table B-2

JOB MIX CHARACTERISTICS

Project	Marshall Stability lbs.	Marshall Flow	Hveem Stability	Air Voids, %	VMA, %	Voids Filled, %
Georgia	2310	9		4.2	17.6	76.7
Virginia	2380	12		4.8	18.4	73.9
Arkansas	1253	7		4.7	17.8	73.6
Maine			18	3.4	16.8	78.0
Illinois	2100	8		3.0	14.2	80.0
Arizona						
Control	2680	12		6.7	18.5	64.2
P C	2595	12		5.0	17.1	70.6
Liquid	2937	12		6.7	18.4	63.4
Alabama	1625	10		4.0	16.9	76.3
Texas			42	4.5		

Table B-3

QUALITY ASSURANCE TEST RESULTS BY COOPERATING AGENCIES

Agency	GA		VA		AR		ME		IL		AZ		AZ		AZ		AL		TX	
Sect.		All		All		All		All		All	Control		P C		Liquid			All		All
n		2		6		2		2		2		3		4		4		2		2
Mix	Job Mix	Fld Mix	Job Mix	Fld Mix	Job Mix	Fld Mix	Job Mix	Fld Mix	Job Mix	Fld Mix	Job Mix	Fld Mix	Job Mix	Fld Mix	Job Mix	Fld Mix	Job Mix	Fld Mix	Job Mix	Fld Mix
Sieve Size	Aggregate Gradation, Percent Passing																			
3/4"	100	100			100	100			100	100	100	100	100	100	100	100	100	100	100	100
1/2"	98	99	100	100	91	92	100	100	98	98	96	96	96	97	96	96	100	99	88	
3/8"	85	84		90	82	85	97	96	80	82	82	83	82	86	82	84	84	86	75	72
#4			54	51	60	61	56	53	49	49	59	57	60	61	59	53	63	62	53	49
#8	46	46		34			42	42	35	33	46	44	47	48	46	45	50	48		
#10					46	44													36	36
#16							31	34	26	25	35	34	36	36	35	34				
#30			20	22			20	25	18		23	22	23	24	23	22	35	35		
#40					28	27													23	23
#50	20	21		15			11	15	10	9	10	10	11	12	10	10	20	21		
#80					14	13													6	8
#100									7	6	4	4	4	6	4	4	8	8		
#200	6	7	5.0	6.0	6	5	2	5.4	5.1	3.5	2.5	2.3	2.5	3.8	2.5	2.3	4.2	4.8	1.2	2.4
%AC	5.6	5.7	5.8	5.7	5.8	5.8	6.4	6.7	5.7	5.3	5.6	5.5	5.5	5.6	5.5	5.5	6.75	6.6	4.5	4.4
%Void		6.5		7.8		9.4		3.8		4.6		8.7		8.1		8.7		8.3		5.7

Table B-4

TENSILE TEST RESULTS, LABORATORY-MIXED SPECIMENS, JOB MIX FORMULA
n = 4 dry and 4 conditioned specimens per test
Testing Agency: Research

Test Sect.	Air Vd., %	Sat.', %	Swl.', %	Sat.", %	Swl.", %	Ten. Str., psi Mean	Std. Dev.	TSR, %	Visual
GA Ctrl	7.7	dry				136.9	2.6		
	7.7	61	.21	83	.94	56.9	4.2	41.6	3
GA Lime	7.9	dry				123.0	8.5		
	7.9	62	.26	73	.21	113.8	3.1	92.6	1
GA Ad 2	7.3	dry				133.7	13.6		
	7.3	63	.26	83	.69	78.1	11.0	58.4	2
VA Ctrl	6.8	dry				115.8	7.4		
	6.8	61	.38	78	.79	63.0	6.1	54.4	2
VA Ad 3	7.0	dry				118.4	3.6		
	7.0	61	.40	68	.01	104.3	5.7	88.0	.5
AR Ctrl	7.3	dry				125.3	6.2		
	7.4	63	.20	79	.14	87.5	7.5	69.8	4
AR Ad 4	6.8	dry				140.9	2.7		
	6.9	63	.30	78	.31	125.7	5.5	89.3	1
ME Ctrl	6.8	dry				66.6	5.0		
	7.0	60	.33	86	.93	52.0	2.5	78.1	2
ME Ad 5	7.3	dry				57.6	4.5		
	7.2	62	.45	88	.83	44.8	1.4	77.8	1.5
IL Ctrl	8.5	dry				68.8	5.3		
	8.7	62	.83	74	.64	58.6	3.0	85.1	3
IL Ad 3	7.0	dry				71.5	5.3		
	6.9	60	.40	73	.35	73.1	4.0	102.2	1.5
AZ Ctrl	7.6	dry				273.5	11.7		
	7.7	68	.37	101	2.17	102.7	11.5	37.5	3.5
AZ P C	9.2	dry				220.2	9.3		
	9.0	64	.16	83	.61	196.1	5.5	89.1	.5
AZ Ad 7	7.9	dry				250.2	3.5		
	7.8	63	-.07	94	1.36	141.6	6.0	56.6	2.5
AL Ctrl	8.1	dry				162.3	4.4		
	8.2	63	.01	76	.09	139.0	8.8	85.6	.5
AL Ad 8	7.2	dry				148.5	3.4		
	7.4	63	.07	73	.18	132.5	5.4	89.2	0
TX Ctrl	7.9	dry				89.5	6.6		
	7.8	63	.38	78	-.02	70.2	7.4	78.5	2
TX Ad 9	7.9	dry				83.9	4.2		
	8.0	62	.24	76	-.13	84.0	3.0	100.0	0

Sat.' and Swl.'are percentage saturation and percentage swell respectively after partial saturation. Sat." and Swl." are percentage saturation and percentage swell respectively after conditioning.

Table B-5

TENSILE TEST RESULTS, LABORATORY-MIXED SPECIMENS, JOB MIX FORMULA
n = 4 dry and 4 conditioned specimens per test
Testing Agency: Cooperating

Test Sect.	Air Vd., %	Sat.', %	Swl.', %	Sat.", %	Swl.", %	Ten. Str., psi Mean	Std. Dev.	TSR, %	Visual
GA Ctrl	6.5	dry				112.2	4.0		
	6.5	71	-.13	95	.65	50.8	5.1	45.3	4
GA Lime	6.3	dry				110.2	1.8		
	6.4	71	-.08	82	-.11	103.0	5.2	93.5	0
GA Ad 2	6.3	dry				113.2	2.2		
	6.3	71	-.09	89	.23	88.5	3.6	78.1	1
VA Ctrl	7.0	dry				97.3	8.3		
	6.9	65	-.44	82	.34	52.6	3.8	54.1	3
VA Ad 3	7.1	dry				86.5	3.9		
	6.9	65	-.48	73	-.30	86.9	2.5	100.6	0
TX Ctrl	7.2	dry				81.2	6.6		
	7.1	61	-.52	76	-.16	53.5	4.0	65.8	3
TX Ad 9	6.9	dry				81.7	2.2		
	6.9	63	-.37	82	-.22	72.6	4.6	88.9	.5

Sat.' and Swl.' are percentage saturation and percentage swell respectively after partial saturation. Sat." and Swl." are percentage saturation and percentage swell respectively after conditioning.

Table B-6

TENSILE TEST RESULTS, PLANT-MIXED SPECIMENS, JOB MIX FORMULA
n = 4 dry and 4 conditioned specimens per test
Testing Agency: Research

Test Sect.	Air Vd., %	Sat.', %	Swl.', %	Sat.", %	Swl.", %	Ten. Str., psi Mean	Ten. Str., psi Std. Dev.	TSR, %	Visual
GA Ctrl	7.5	dry				143.6	2.0		
	7.5	61	.25	75	.50	102.3	2.4	71.2	
GA Lime	7.3	dry				144.0	5.4		
	7.3	67	.20	76	.17	132.5	5.3	92.0	
GA Ad 2	8.3	dry				149.4	12.1		
	8.3	61	.35	73	.35	110.2	11.1	73.8	
VA Ctrl	7.4	dry				111.4	7.8		
	7.3	60	.55	69	.08	92.7	5.7	83.2	1.5
VA Ad 3	6.7	dry				125.6	7.4		
	6.6	62	.42	72	.21	97.6	3.6	77.7	1
AR Ctrl	7.6	dry				124.0	1.8		
	7.7	61	.45	75	.23	108.3	5.6	87.4	4
AR Ad 4	7.6	dry				129.0	3.1		
	7.5	59	.39	71	.16	126.5	5.9	98.0	3.5
ME Ctrl	7.4	dry				57.4	4.1		
	7.5	61	.88	77	.77	53.5	5.0	93.1	1
ME Ad 5	7.8	dry				54.8	3.6		
	7.8	63	.87	79	.62	51.9	3.7	94.7	.5
IL Ctrl	6.9	dry				114.3	4.0		
	6.9	63	.21	73	-.20	101.9	5.9	89.1	2
IL Ad 3	6.7	dry				111.8	4.0		
	6.8	61	.11	68	-.41	104.6	2.2	93.5	.5
AZ Ctrl	8.0	dry				249.1	20.6		
	8.2	62	.17	101	1.97	76.7	6.4	30.8	3
AZ P C	8.1	dry				226.7	18.5		
	8.2	63	.09	94	1.86	143.7	15.6	63.4	2.5
AZ Ad 7	7.8	dry				275.6	5.4		
	8.0	63	.06	97	1.56	116.5	6.7	42.3	3
AL Ctrl	7.7	dry				143.4	7.5		
	7.7	62	.28	78	.07	150.4	5.9	104.9	.5
AL Ad 8	6.6	dry				128.7	7.1		
	6.6	63	.16	84	-.12	132.4	4.6	102.9	1
TX Ctrl	6.7	dry				132.9	2.8		
	6.7	61	.18	77	-.02	118.6	1.3	89.2	.5
TX Ad 9	6.8	dry				114.0	8.5		
	6.9	59	.41	75	.09	103.9	8.2	91.1	.5

Sat.' and Swl.' are percentage saturation and percentage swell respectively after partial saturation. Sat." and Swl." are percentage saturation and percentage swell respectively after conditioning.

Table B-7

TENSILE TEST RESULTS, PLANT-MIXED SPECIMENS, JOB MIX FORMULA
n = 4 dry and 4 conditioned specimens per test
Testing Agency: Cooperating

Test Sect	Air Vd., %	Sat.', %	Swl.', %	Sat.", %	Swl.", %	Ten. Str., psi Mean	Ten. Str., psi Std. Dev.	TSR, %	Visual
GA Ctrl	6.0	dry				168.5	2.4		
	6.1	66	-.49	80	-.06	91.0	3.9	54.0	2
GA Lime	6.4	dry				185.8	4.4		
	6.3	76	-.27	93	.31	162.8	6.3	87.6	0
GA Ad 2	6.9	dry				216.6	4.2		
	6.9	70	-.18	89	.46	142.3	3.5	65.7	2
VA Ctrl	7.2	dry				142.3	8.8		
	7.2	65	-.51	77	.00	115.2	5.7	81.0	2
VA Ad 3	6.9	dry				135.9	8.8		
	6.9	65	-.41	78	.07	108.2	4.6	79.6	2
AR Ctrl	7.3	dry				153.4	5.3		
	7.4	77	.01	79	.17	110.3	12.5	71.9	3
AR Ad 4	6.8	dry				145.4	6.4		
	6.9	73	-.03	83	.53	124.0	4.2	85.3	2.5
TX Ctrl	7.0	dry				99.5	6.1		
	7.1	57	-.60	76	-.26	80.1	1.1	80.5	.5
TX Ad 9	6.5	dry				109.0	12.0		
	6.6	58	-.52	75	-.32	104.2	6.1	95.6	0

Sat.' and Swl.' are percentage saturation and percentage swell respectively after partial saturation. Sat." and Swl." are percentage saturation and percentage swell respectively after conditioning.
* n = 5 dry and 5 conditioned specimens per test.

Table B-8

TENSILE TEST RESULTS, LABORATORY-MIXED SPECIMENS,
EFFECT OF ADDITIVE DOSAGE
n = 4 dry and 4 conditioned specimens per test
Testing Agency: Research

Mixture	Air Vd., %	Sat.', %	Swl.', %	Sat.", %	Swl.", %	Ten. Str., psi Mean	Ten. Str., psi Std. Dev.	TSR, %	Visual
GA 0.5%	8.0	dry				124.1	3.4		
Lime	8.0	63	.23	75	.21	110.0	7.8	88.6	1
GA 1.5%	7.6	dry				123.3	4.2		
Lime	7.7	63	.24	71	.10	115.0	2.7	93.3	1
GA .25%	7.7	dry				124.5	8.9		
Ad 2	7.7	66	.29	90	1.16	57.3	3.4	46.0	3
GA 1.0%	7.3	dry				139.9	3.5		
Ad 2	7.5	62	.17	78	.52	86.7	8.3	62.0	2
VA .25%	7.2	dry				95.3	6.4		
Ad 3	7.2	65	.29	75	.26	79.6	5.4	83.5	.5
VA 1.0%	6.5	dry				115.8	11.3		
Ad 3	6.6	65	.30	67	-.27	100.6	7.8	86.9	.5
AR 0.5%	7.0	dry				139.6	12.9		
Ad 4	7.0	61	.38	74	.19	113.9	2.6	81.6	1
AR 1.25%	7.1	dry				136.1	5.9		
Ad 4	7.1	62	.36	74	.20	127.3	3.5	93.5	1
ME .25%	7.2	dry				63.9	2.3		
Ad 5	7.2	66	.27	91	.84	50.4	1.6	79.0	2
ME 1.0%	6.6	dry				54.9	3.8		
Ad 5	6.7	63	.39	86	.77	47.0	1.1	85.5	1.5
IL .25%	8.9	dry				61.8	5.1		
Ad 3	8.7	61	.92	73	.72	59.0	5.5	95.5	2.5
IL 0.75%	7.7	dry				70.4	4.8		
Ad 3	7.6	60	.55	71	.39	69.6	6.4	98.9	1
AZ 1.5%	7.8	dry				284.2	3.5		
P C	7.8	62	.11	78	.25	255.2	15.9	89.8	.5
AZ 2.5%	8.7	dry				223.9	11.9		
P C	8.7	63	.15	80	.41	201.8	4.8	90.1	0
AZ 0.25%	7.6	dry				266.9	20.7		
Ad 7	7.7	65	-.10	98	1.53	126.9	12.4	47.5	2
AZ 0.75%	7.7	dry				272.7	8.0		
Ad 7	7.8	60	.44	84	1.20	168.4	7.0	61.7	2
AL 0.25%	7.6	dry				167.0	6.0		
Ad 8	7.6	59	.15	70	.09	156.8	5.3	93.9	0
AL 0.75%	7.5	dry				156.8	7.4		
Ad 8	7.4	63	.18	76	.16	145.5	0.8	92.8	0
TX 0.5%	7.8	dry				85.2	6.6		
Ad 9	7.8	60	.41	75	-.16	79.5	7.0	93.3	1.5
TX 1.5%	8.0	dry				81.2	3.4		
Ad 9	8.0	64	.32	81	-.17	81.1	6.5	100.0	0

Sat.' and Swl.' are percentage saturation and percentage swell respectively after partial saturation. Sat." and Swl." are percentage saturation and percentage swell respectively after conditioning.

Table B-9
BOILING WATER TEST RESULTS

Test Section	Moisture Damage Rating* Plant Mixed Research Agency	Plant Mixed Cooperating Agency	Laboratory Mixed Research Agency	Laboratory Mixed Cooperating Agency
GA Control	0	0	2	
GA Lime	0	0	1	
GA Ad 2	0	0	1.5	
VA Control	0	0	1	
VA Ad 3	0	0	1	
AR Control	2		3.5	
AR Ad 4	1		2.5	
ME Control	0	0	2.5	
ME Ad 5	0	0	1	
IL Control	1	1	1.5	
IL Ad 3	1	1	2	
AZ Control	2.5		2	
AZ P C	1.5		1.5	
AZ Ad 7	2		1	
AL Control	3		1.5	
AL Ad 8	2		1	
TX Control	2.5	0.5	0	2
TX Ad 9	2	0	0	0

*No moisture damage = 0, severe moisture damage = 5.
95% coating used in ASTM D 3625 is between 1 and 2.

APPENDIX D

PAVEMENT EVALUATION

Table D-1

TEST RESULTS OF GEORGIA CORES
Testing Agency: Cooperative

Section	Set	Age, Mo.	n	Air Voids, %	In-plc Moist., %	Saturation, %	Tensile Strength, psi	
							Mean	Std. Dev.
Control	-	0	9	7.8	-	-	67	11.6
Lime	-	0	9	6.8	-	-	78	8.4
Ad 2	-	0	9	5.8	-	-	96	12.4
Control	3	0	3	10.0	1.7	38	50	11.9
Control	4	0	3	6.5	-	56	72	1.5
Lime	3	0	3	7.7	1.0	29	69	2.7
Lime	4	0	3	6.4	-	57	73	2.7
Ad 2	3	0	3	6.8	1.2	39	84	.8
Ad 2	4	0	3	4.9	-	54	100	3.4
Control	3	7	3	5.7	.2	8	125	11.3
Control	4	7	3	6.2	-	73	131	12.9
Lime	3	7	3	3.4	.03	2	219	18.5
Lime	4	7	3	4.2	-	56	144	10.2
Ad 2	3	7	3	4.8	.05	2	157	5.2
Ad 2	4	7	3	4.6	-	80	139	22.6
Control	3	18	3	3.8	.3	11	149	85.1
Control	4	18	3	7.3	-	70	182	26.0
Lime	3	18	3	3.4	.4	30	199	15.5
Lime	4	18	3	5.0	-	69	181	72.0
Ad 2	3	18	3	4.5	.4	22	164	29.2
Ad 2	4	18	3	4.6	.8	55	174	12.9
Control	3	30	3	5.5	.5	19	153	38.0
Control	4	30	3	5.0	-	72	142	67.3
Lime	3	30	3	5.5	.5	22	176	15.7
Lime	4	30	3	5.0	-	76	178	33.8
Ad 2	3	30	3	5.2	.4	20	164	12.9
Ad 2	4	30	3	5.1	-	53	196	18.5
Control	3	42	3	6.6	.1	3	152	10.6
Control	4	42	3	6.6	-	55	161	9.9
Lime	3	42	3	4.1	.1	5	173	6.1
Lime	4	42	3	3.9	-	55	185	8.5
Ad 2	3	42	3	5.8	.1	3	142	33.5
Ad 2	4	42	3	5.6	-	58	166	18.4
Control	3	53	3	4.4	.1	6	167	35.2
Control	4	53	3	7.4	-	76	151	88.8
Lime	3	53	3	5.2	.02	1	232	26.9
Lime	4	53	3	4.9	-	50	160	5.9
Ad 2	3	53	3	4.4	.03	2	160	26.7
Ad 2	4	53	4	4.8	-	53	164	25.9
Control	3	99	3	5.6	.04	2	122	34.2
Control	4	99	3	5.2	-	47	139	38.3
Lime	3	99	3	5.1	.01	1	130	31.1
Lime	4	99	3	4.6	-	59	158	31.1
Ad 2	3	99	3	4.3	.05	3	162	17.2
Ad 2	4	99	3	5.8	-	43	153	19.8
Control	5	99	3	5.8	-	24	*	*
Control	6	99	3	5.2	-	-	155	19.8
Lime	5	99	3	4.5	-	24	*	*
Lime	6	99	3	5.2	-	-	157	29.1
Ad 2	5	99	3	4.7	-	29	*	*
Ad 2	6	99	6	4.5	-	-	158	26.2

*Not tested at 77F.

Table D-2

TEST RESULTS OF VIRGINIA CORES

Testing Agency: Cooperative

Section	Set	Age, Mo.	n	Air Voids, %	In-plc Moist., %	Saturation, %	Tensile Strength, psi Mean	Std. Dev.
Control	-	0	9	-	-	-	55	12.3
Ad 3	-	0	9	-	-	-	64	9.8
Control	3	0	3	-			66	.7
Control	4	0	3	9.8		66	40	10.9
Ad 3	3	0	3	-	2.2		71	1.27
Ad 3	4	0	3	10.1	-	71	57	4.5
Control	3	7	3	-	-	-	75	19.7
Control	4	7	3	7.7	1.7	87	73	16.0
Ad 3	3	7	3	-	1.7	-	76	7.1
Ad 3	4	7	3	6.7	-	80	58	9.5
Control	3	20	3	6.8	1.9	-	103	13.1
Control	4	20	3	6.2	-	108	72	6.8
Ad 3	3	20	3	6.6	1.9	-	81	19.8
Ad 3	4	20	3	7.0	-	95	66	28.9
Control	3	27	3	5.7	1.4	-	92	5.7
Control	4	27	3	6.9	-	94	95	16.6
Ad 3	3	27	3	5.4	1.4	-	95	13.4
Ad 3	4	27	3	6.0	-	99	96	9.6
Control	3	33	3	6.9	1.7	60	84	8.1
Control	4	33	3	6.4	-	98	86	16.1
Ad 3	3	33	3	5.6	1.7	76	59	17.5
Ad 3	4	33	3	6.3	-	97	69	5.6
Control	3	39	3	6.1	1.3	51	106	8.1
Control	4	39	3	5.6	-	87	91	18.9
Ad 3	3	39	3	4.8	1.3	65	104	29.8
Ad 3	4	39	3	5.0	-	86	93	9.3
Control	3	44	3	5.8	.9	38	97	21.5
Control	4	44	3	4.6	-	76	51	9.7
Ad 3	3	44	3	4.2	.9	52	83	23.9
Ad 3	4	44	3	4.8	-	77	89	16.9
Control	3	93	3	6.0	1.5	61	122	21.8
Control	4	93	3	5.1	-	100	95	48.5
Ad 3	3	93	3	5.0	1.5	74	77	30.6
Ad 3	4	93	3	5.1	-	103	103	48.3
Control	5	93	3	6.4	-	92	*	*
Control	6	93	3	5.7	-	-	234	60.1
Ad 3	5	93	3	5.1	-	102	*	*
Ad 3	6	93	3	5.6	-	-	229	31.9

*Not tested at 77F.

Table D-3

TEST RESULTS OF ARKANSAS CORES

Testing Agency: Cooperative through 27 months, then Research

Section	Set	Age, Mo.	n	Air Voids, %	In-plc Moist., %	Saturation, %	Tensile Strength, psi Mean	Std. Dev.
Control	3	27	5	3.0	.1	5	184	53.1
Control	4	27	6	3.8	-	72	163	53.1
Ad 4	3	27	5	2.8	.1	10	178	45.8
Ad 4	4	27	6	3.6	-	56	161	54.5
Control	3	47	3	4.2	.5	26	225	58.1
Control	4	47	3	2.6	-	91	227	32.9
Ad 4	3	47	3	4.6	.5	23	174	13.4
Ad 4	4	47	3	2.7	-	92	173	25.9
Control	3	92	3	3.5	.7	45	157	124.6
Control	4	92	3	2.0	-	135	247	53.4
Ad 4	3	92	3	2.6	.5	50	195	34.0
Ad 4	4	92	3	2.7	-	88	151	69.9
Control	5	92	3	2.1	-	128	191	67.0
Control	6	92	3	2.6	-	-	216	40.4
Ad 4	5	92	3	2.6	-	151	108	33.9
Ad 4	6	92	3	3.1	-	-	210	47.2

Table D-4

TEST RESULTS OF MAINE CORES

Testing Agency: Cooperative through 13 months, then Research

Section	Set	Age, Mo.	n	Air Voids, %	In-plc Moist., %	Saturation, %	Tensile Strength, psi Mean	Tensile Strength, psi Std. Dev.
Control	-	0	9	2.4	-	-	53	8.6
Ad 5	-	0	9	2.0	-	-	65	25.6
Control	3	0	3	2.3	.3	30	50	4.8
Control	4	0	3	2.7	-	148	44	2.9
Ad 5	3	0	3	2.0	.2	27	55	.8
Ad 5	4	0	3	1.9	-	177	72	2.6
Control	3	13	3	3.0	.3	21	57	6.5
Control	4	13	3	2.1	-	69	48	.8
Ad 5	3	13	3	2.6	.4	33	59	1.5
Ad 5	4	13	3	2.2	-	55	38	3.5
Control	3	25	3	1.2	.3	63	69	5.9
Control	4	25	3	1.4	-	136	65	4.2
Ad 5	3	25	3	2.2	.3	35	60	10.2
Ad 5	4	25	3	2.5	-	107	59	.3
Control	3	33	3	1.6	.4	55	62	1.9
Control	4	33	3	2.2	-	87	60	8.5
Ad 5	3	33	3	1.9	.3	38	70	7.2
Ad 5	4	33	3	1.8	-	86	61	1.2
Control	3	45	3	1.2	.4	79	88	5.8
Control	4	45	3	1.1	-	113	75	9.8
Ad 5	3	45	3	2.1	.6	64	79	6.6
Ad 5	4	45	3	2.2	-	109	68	6.1
Control	3	91	3	2.0	.5	53	86	23.0
Control	4	91	3	1.8	-	120	96	6.2
Ad 5	3	91	3	3.6	1.0	62	113	5.4
Ad 5	4	91	3	3.2	-	154	125	35.7
Control	5	91	3	1.8	-	147	79	15.7
Control	6	91	3	2.8	-	-	101	12.8
Ad 5	5	91	3	2.6	-	156	81	24.8
Ad 5	6	91	3	2.6	-	-	114	8.1

Table D-5

TEST RESULTS OF ILLINOIS CORES

Testing Agency: Cooperative

Section	Set	Age, Mo.	n	Air Voids, %	In-plc Moist., %	Saturation, %	Tensile Strength, psi Mean	Tensile Strength, psi Std. Dev.
Control	-	0	9	4.0	-	-	83	5.6
.5 Ad 3	-	0	9	4.2	-	-	81	7.2
.75 Ad 3	-	0	9	4.4	-	-	75	10.3
Control	3	0	3	4.6	.3	16	87	10.2
Control	4	0	3	4.8	-	86	61	7.2
.5 Ad 3	3	0	3	4.7	.4	22	81	19.4
.5 Ad 3	4	0	3	4.1	-	89	63	4.0
.75 Ad 3	3	0	3	4.4	.6	30	86	9.5
.75 Ad 3	4	0	3	3.9	-	96	68	6.7
Control	3	9	3	1.9	.3	31	177	4.8
Control	4	9	3	1.6	-	82	112	1.7
.5 Ad 3	3	9	3	2.1	.4	45	152	5.3
.5 Ad 3	4	9	3	2.1	-	62	99	5.7
.75 Ad 3	3	9	3	1.6	.2	2	160	6.3
.75 Ad 3	4	9	3	2.7	-	79	110	8.6
Control	3	22	3	1.6	.3	44	141	3.7
Control	4	22	3	1.1	-	137	117	9.7
.5 Ad 3	3	22	3	2.2	.2	26	139	8.9
.5 Ad 3	4	22	3	2.1	-	105	113	3.7
.75 Ad 3	3	22	3	1.8	.2	20	146	7.0
.75 Ad 3	4	22	3	1.1	-	157	110	18.1
Control	3	34	3	1.1	.3	55	191	13.1
Control	4	34	3	1.6	-	127	139	7.3
.5 Ad 3	3	34	3	2.1	.6	72	161	19.2
.5 Ad 3	4	34	3	2.1	-	99	127	9.6
.75 Ad 3	3	34	3	1.5	.3	36	182	5.4
.75 Ad 3	4	34	3	1.5	-	145	134	23.3
Control	3	46	3	2.1	.3	36	186	5.9
Control	4	46	3	1.6	-	145	150	12.0
.5 Ad 3	3	46	3	1.8	.1	13	172	6.1
.5 Ad 3	4	46	3	1.7	-	144	136	2.6
.75 Ad 3	3	46	3	2.4	.1	9	152	14.4
.75 Ad 3	4	46	3	2.1	-	122	145	7.4
Control	3	82	3	3.4	.5	34	179	6.7
Control	4	82	3	3.0	-	128	216	9.1
.5 Ad 3	3	82	3	2.7	.3	29	175	18.2
.5 Ad 3	4	82	3	2.0	-	138	239	14.8
.75 Ad 3	3	82	3	2.9	.3	24	171	23.1
. Ad 3	4	82	3	2.2	-	124	221	27.8
Control	5	82	3	2.6	-	147	210	35.9
Control	6	82	3	3.8	-	-	183	22.2
.5 Ad 3	5	82	3	2.4	-	123	211	19.8
.5 Ad 3	6	82	3	2.8	-	-	177	27.3
.75 Ad 3	5	82	3	2.4	-	154	201	21.6
.75 Ad 3	6	82	3	2.4	-	-	163	8.0

Table D-6

TEST RESULTS OF ARIZONA CORES
Testing Agency: Cooperative

Section	Set	Age, Mo.	n	Air Voids, %	In-plc Moist., %	Satura-tion, %	Tensile Strength, psi	
							Mean	Std. Dev.
Control	-	0	9	7.4	-	-	100	10.5
P C	-	0	9	6.3	-	-	136	14.7
Ad 7	-	0	9	7.3	-	-	124	17.4
Control	3	1	3	7.0	.8	27	108	15.7
Control	4	1	3	7.9	-	90	52	5.5
P C	3	1	3	6.2	.7	29	146	16.4
P C	4	1	3	6.5	-	87	133	8.0
Ad 7	3	1	3	7.1	1.0	33	117	13.5
Ad 7	4	1	3	7.4	-	105	83	1.8
Ad 7	3	2	3	6.5	1.1	40	125	14.7
Ad 7	4	2	3	7.2	-	92	84	6.5
Control	3	7	3	6.7	1.0	35	100	11.9
Control	4	7	3	7.3	-	79	54	5.3
P C	3	7	3	7.2	1.0	33	159	11.1
P C	4	7	3	6.4	-	82	137	10.3
Ad 7	3	7	3	6.5	1.0	37	127	2.9
Ad 7	4	7	3	7.0	-	85	79	9.4
Control	3	13	3	6.6	.8	30	196	11.8
Control	4	13	3	6.4	-	88	91	7.3
P C	3	13	3	4.7	.6	32	207	9.7
P C	4	13	3	5.3	-	86	178	5.6
Ad 7	3	13	3	6.0	1.0	41	204	22.7
Ad 7	4	13	3	6.1	-	84	151	25.0
Control	3	19	3	6.6	.8	29	185	14.6
Control	4	19	3	7.2	-	84	77	3.5
P C	3	19	3	5.2	.7	35	208	05.0
P C	4	19	3	5.2	-	87	169	8.0
Ad 7	3	19	3	5.1	.8	39	201	6.4
Ad 7	4	19	3	5.9	-	82	124	12.2
Control	3	31	3	6.6	.8	30	223	8.8
Control	4	31	3	6.1	-	87	107	3.8
P C	3	31	3	4.9	.7	33	218	18.9
P C	4	31	3	5.0	-	82	190	6.6
Ad 7	3	31	3	5.8	.7	29	227	12.3
Ad 7	4	31	3	6.2	-	84	137	4.1
Control	3	79	3	5.4	1.2	55	180	47.6
Control	4	79	3	5.8	-	98	122	69.6
P C	3	79	3	5.2	.7	35	262	11.0
P C	4	79	3	3.8	-	84	268	25.9
Ad 7	3	79	3	6.4	1.0	39	83	40.3
Ad 7	4	79	3	6.5	-	84	185	64.0
Control	5	79	3	6.0	-	114	115	37.4
Control	6	79	3	4.5	-	-	271	12.2
P C	5	79	3	3.8	-	135	183	24.4
P C	6	79	3	3.8	-	-	250	30.0
Ad 7	5	79	3	5.4	-	93	181	16.9
Ad 7	6	79	3	5.5	-	-	264	50.7

Table D-7

TEST RESULTS OF ALABAMA CORES
Testing Agency: Research

Section	Set	Mo.	n	Air Voids %	In-plc Moist., %	Satura tion, %	Tensile Strength, psi	
							Mean	Std. Dev.
Control	-	0	9	7.8	-	-	86	15.5
Ad 8	-	0	9	6.6	-	-	92	10.7
Control	3	0	3	8.0	.7	19	91	4.7
Control	4	0	3	7.4	-	87	101	8.3
Ad 8	3	0	3	7.8	.6	16	82	13.4
Ad 8	4	0	3	5.8	-	82	128	13.3
Control	3	7	3	7.9	.6	17	116	13.5
Control	4	7	3	7.4	-	92	107	7.7
Ad 8	3	7	3	4.1	.3	15	141	12.4
Ad 8	4	7	3	5.5	-	82	126	8.0
Control	3	19	3	5.3	.4	16	210	12.4
Control	4	19	3	4.7	-	86	211	10.1
Ad 8	3	19	3	4.5	.4	19	217	25.8
Ad 8	4	19	3	5.0	-	90	173	37.0
Control	3	31	3	5.5	.7	28	219	8.2
Control	4	31	3	5.6	-	89	205	18.3
Ad 8	3	31	3	3.5	.63	37	239	8.6
Ad 8	4	31	3	3.4	-	114	221	12.0
Control	3	77	3	5.7	.5	16	255	20.7
Control	4	77	3	6.8	-	101	204	43.1
Ad 8	3	77	3	4.0	.4	22	274	1.9
Ad 8	4	77	3	4.3	-	106	249	64.7
Control	5	77	3	5.1	-	131	200	46.5
Control	6	77	3	3.7	-	-	269	64.7
Ad 8	5	77	3	4.2	-	114	230	10.8
Ad 8	6	77	3	5.0	-	-	321	10.8

Table D-8

TEST RESULTS OF TEXAS CORES
Testing Agency: Cooperative

Section	Set	Age, Mo.	n	Air Voids, %	In-plc Moist., %	Satura-tion, %	Tensile Strength, psi	
							Mean	Std. Dev.
Control	-	0	9	6.3	-	-	70	8.0
Ad 9	-	0	9	7.4	-	-	63	6.8
Control	3	3	3	3.7	.2	11	150	14.7
Control	4	3	3	3.8	-	71	141	4.6
Ad 9	3	3	3	4.4	.1	6	150	4.3
Ad 9	4	3	3	3.6	-	59	171	9.2
Control	3	11	3	2.8	.2	13	139	7.3
Control	4	11	3	2.3	-	83	153	14.2
Ad 9	3	11	3	3.3	.1	8	156	3.6
Ad 9	4	11	3	3.3	-	56	147	11.0
Control	3	23	3	2.4	.3	35	162	59.3
Control	4	23	3	2.8	-	69	150	56.1
Ad 9	3	23	3	3.8	.2	16	187	32.1
Ad 9	4	23	3	3.4	-	54	152	45.6
Control	3	70	3	2.5	.6	52	112	19.7
Control	4	70	3	2.3	-	98	133	53.8
Ad 9	3	70	3	3.5	.6	40	157	61.3
Ad 9	4	70	3	2.8	-	66	132	8.6
Control	5	70	3	2.5	-	105	136	58.2
Control	6	70	3	2.3	-	-	125	18.5
Ad 9	5	70	3	3.4	-	88	156	31.7
Ad 9	6	70	3	2.9	-	-	163	26.9

Table D-9

CLIMATOLOGICAL DATA

Pro-ject	Date Built	Date Cored	Time Inter-val, Mo.	Temp. F Depart. from Normal	Precipitation, Inches			
					Total	Depart. from Normal	Average per Month	High Day
GA	11-84	5-85	6	+5.6	22.0	-6.6	3.7	1.9
		4-86	11	+12.4	36.8	-4.5	3.3	2.5
		5-87	13	+8.8	51.5	-2.2	4.0	2.1
		5-88	11	-0.8	39.5	-6.3	3.6	2.0
VA	7-85	3-86	8	+10.2	31.5	-2.8	3.9	5.7
		4-87	13	+8.9	46.1	-0.2	3.5	2.6
		11-87	8	+2.9	40.2	+4.6	5.0	5.5
		4-88	4	-2.9	10.0	-3.5	2.5	1.0
		10-88	7	-2.6	25.1	-1.5	3.6	2.1
AR	8-85	4-86	9	+10.0	28.3	-8.9	3.1	3.4
		11-87	19	+12.6	66.0	-9.9	3.5	4.1
		6-88	7	-3.0	29.0	+0.5	4.1	5.6
ME	8-85	9-86	13	+0.1	36.9	+0.5	2.8	1.5
		9-87	13	+3.1	30.6	-4.9	2.4	1.7
		5-88	8	+5.0	16.7	-2.8	2.1	1.8
IL	6-86	3-87	10	+13.3	31.6	-4.0	3.2	2.3
		4-88	13	-2.5	42.9	+7.2	3.3	2.6
AZ	9-86	4-87	7	-2.1	8.6	+6.0	1.2	0.9
		10-87	6	-2.0	6.1	+0.6	1.0	1.0
		5-88	6	+3.7	5.7	+1.5	1.0	0.7
AL	10-86	3-87	6	NA	33.3	+4.5	5.6	2.2
		5-88	14	NA	40.7	-24.1	2.9	1.8
TX	5-87	8-87	3	-0.2	6.9	-0.5	2.3	1.2
		4-88	8	-2.9	19.9	-4.5	2.5	2.2

Table D-10

TRAFFIC DATA

Project	Average Annual Daily Traffic	Annual Growth Factor	Proportion Commercial
GA	20,000		10%
VA	7,910		30%, 75% heavy
AR	4,050		
ME	2,500	1.01	12%
IL	3,600		16%
AZ	10,660	1.033	
AL	2,055	1.02	15%, 75% heavy
TX	65,000*		

*1-way, 4-lanes.

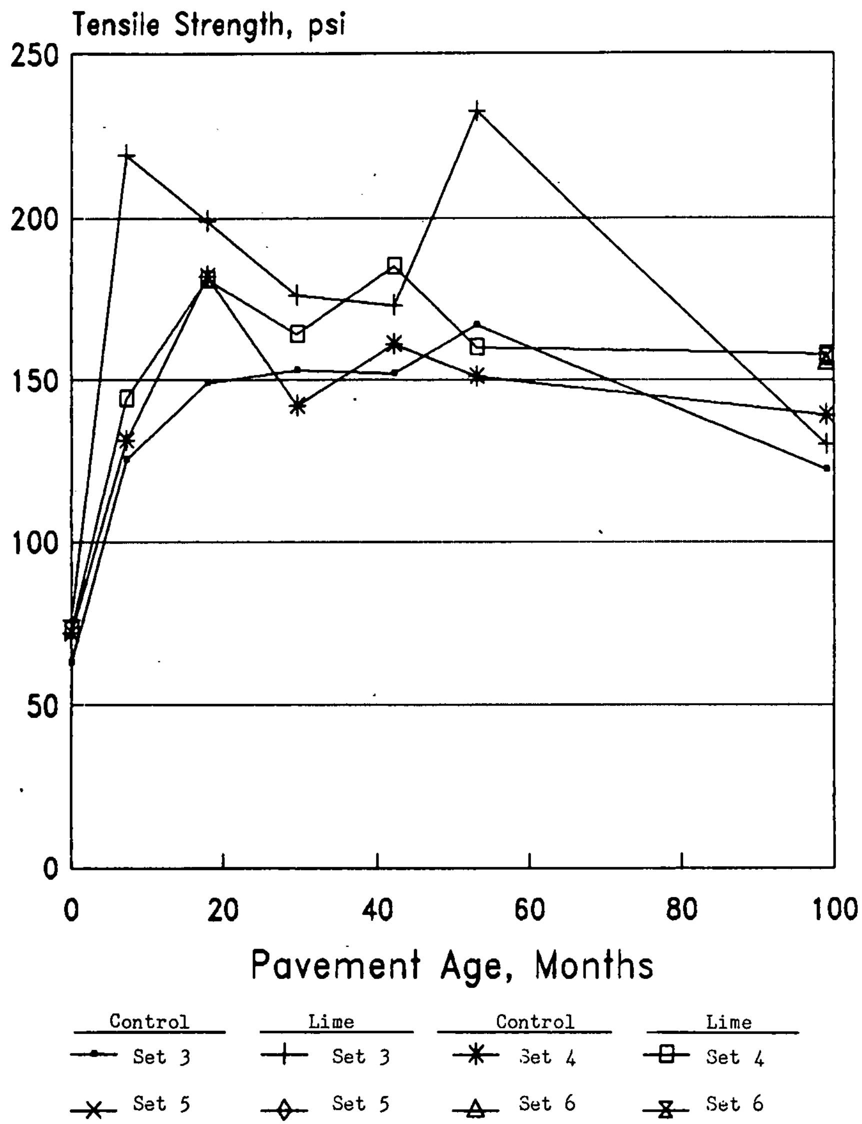

Figure D-1. Georgia Cores

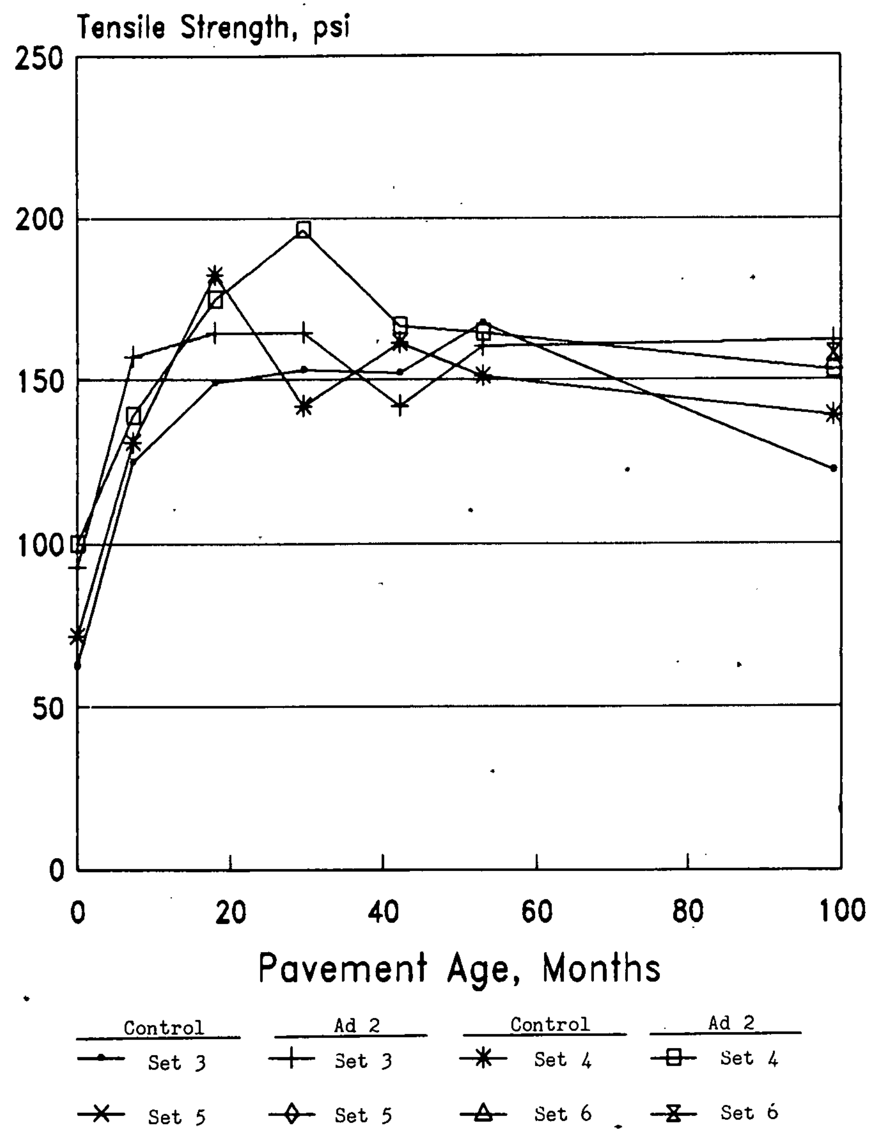

Figure D-2. Georgia Cores

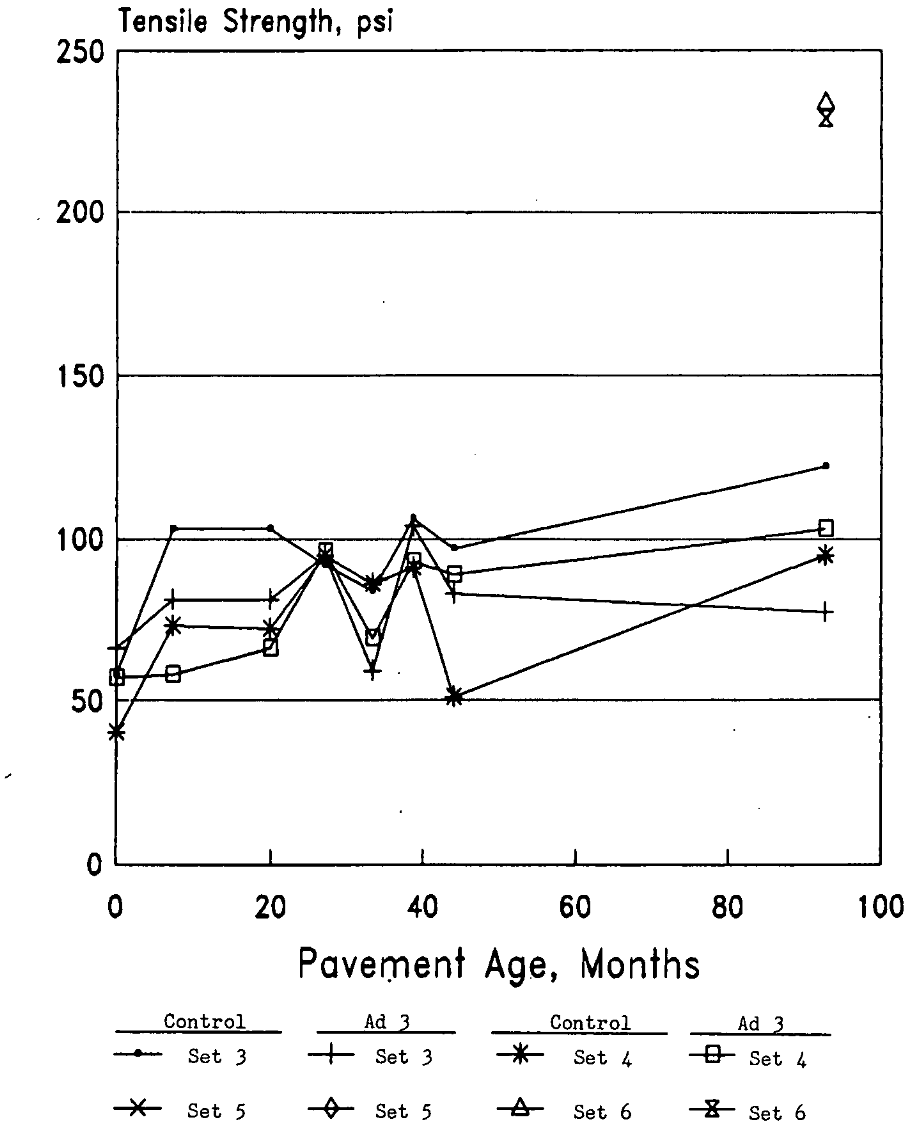

Figure D-3. Virginia Cores

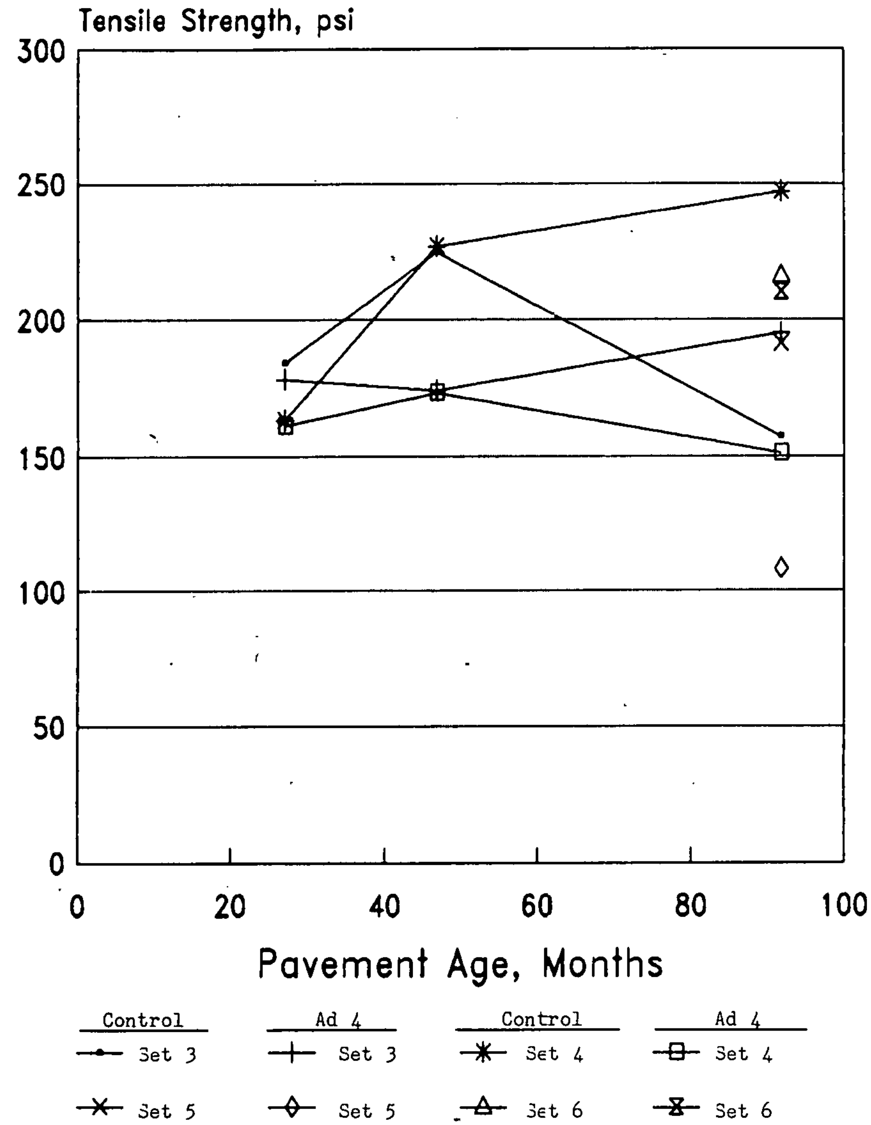

Figure D-4. Arkansas Cores

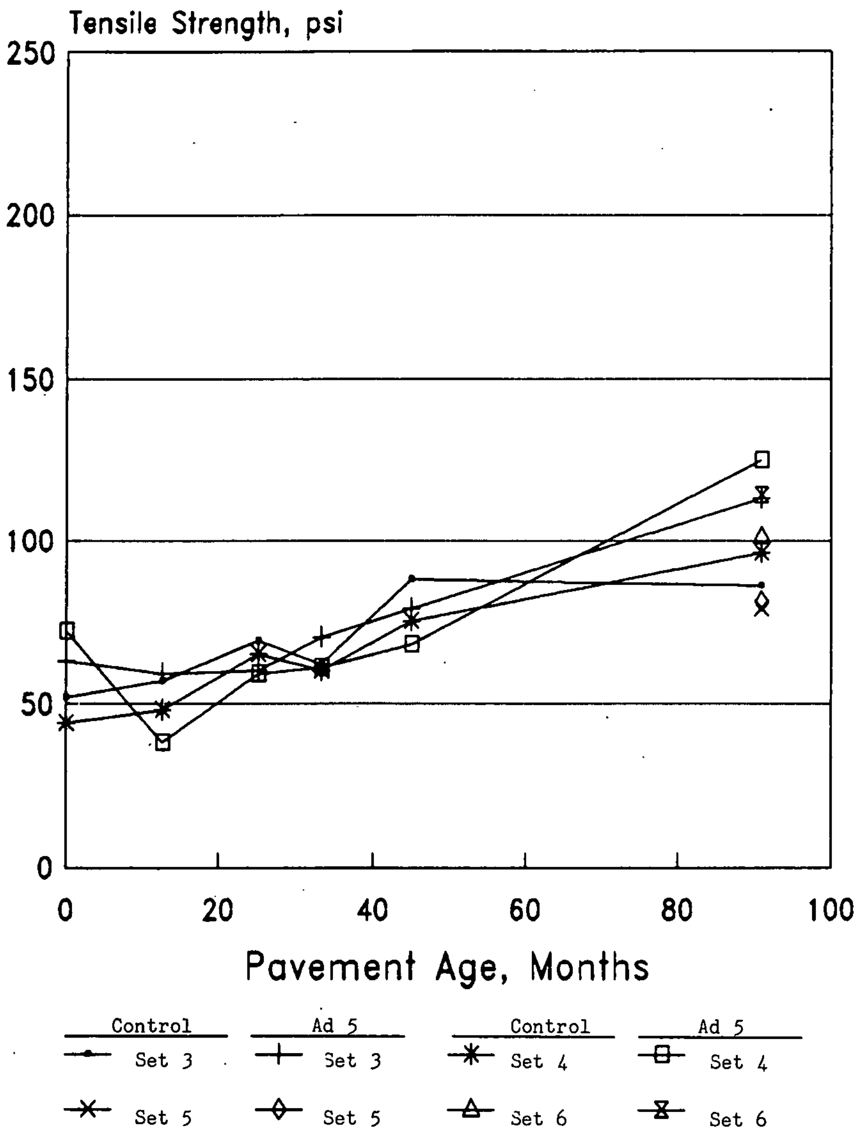

Figure D-5. Maine Cores

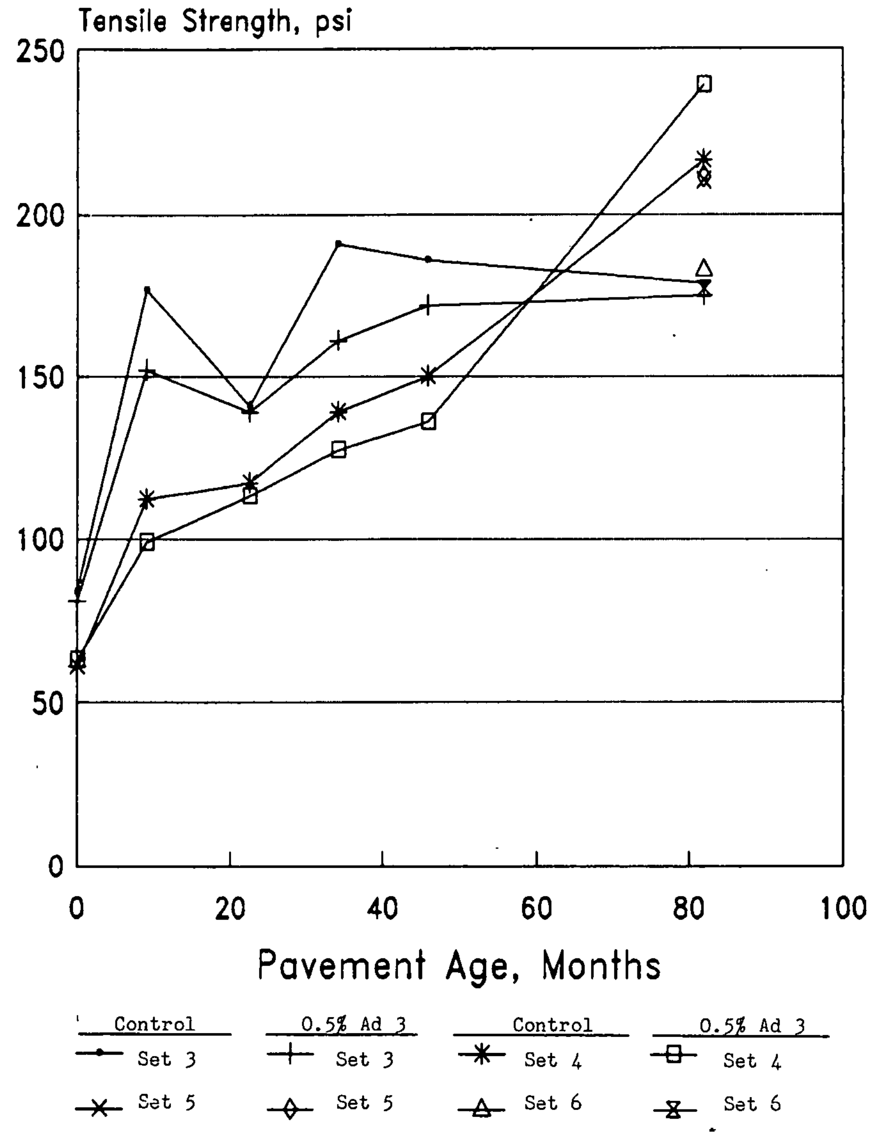

Figure D-6. Illinois Cores

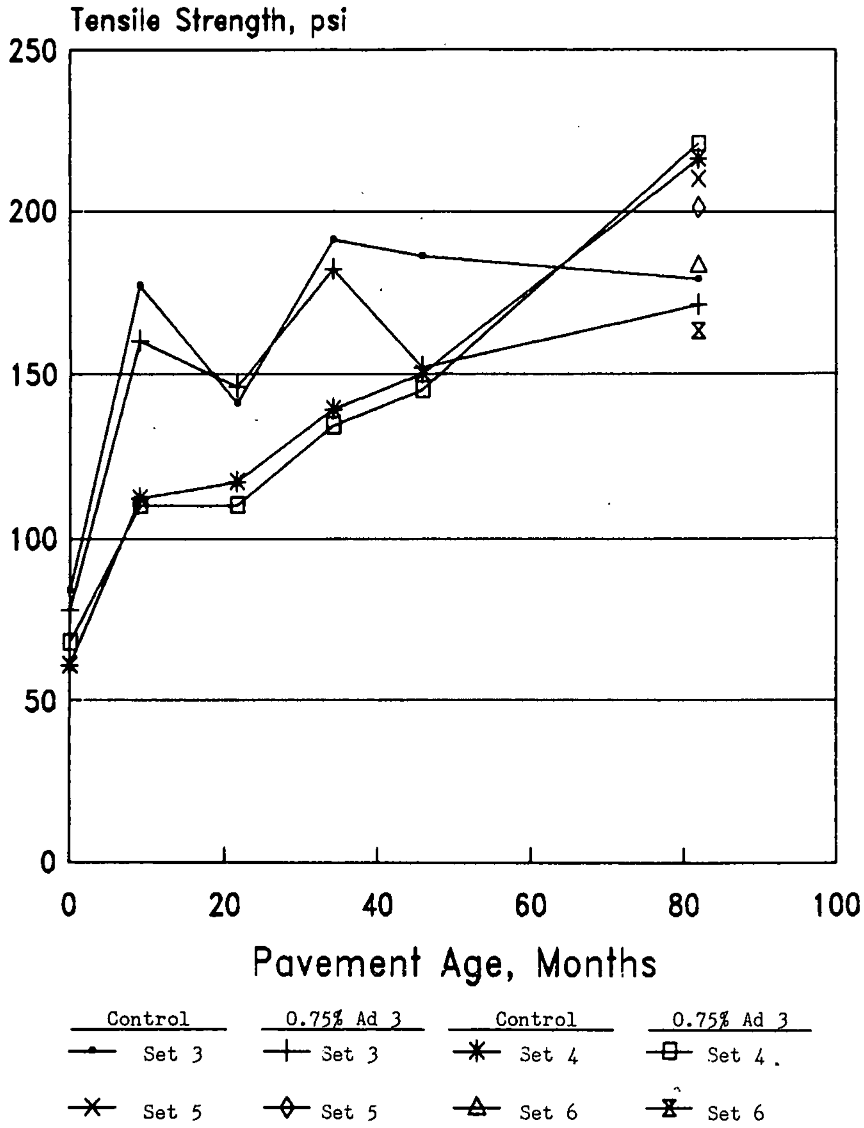

Figure D-7. Illinois Cores

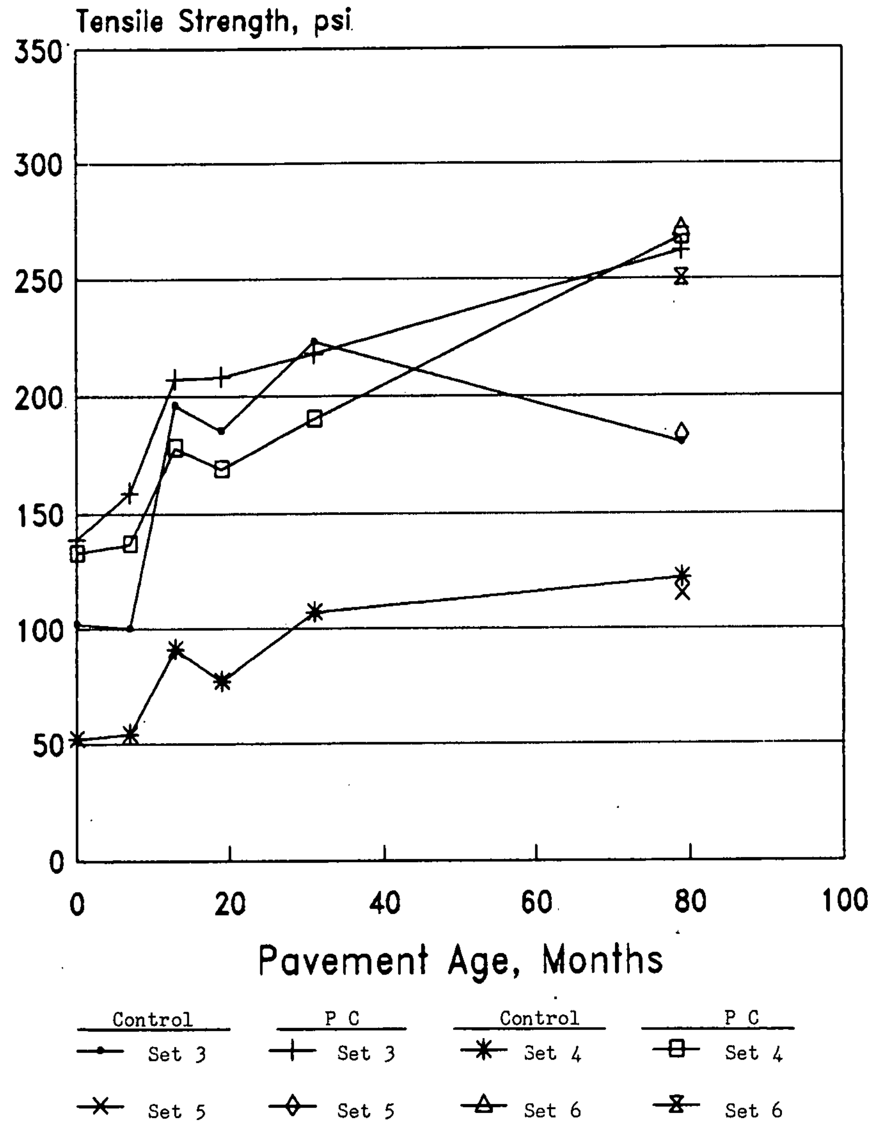

Figure D-8. Arizona Cores

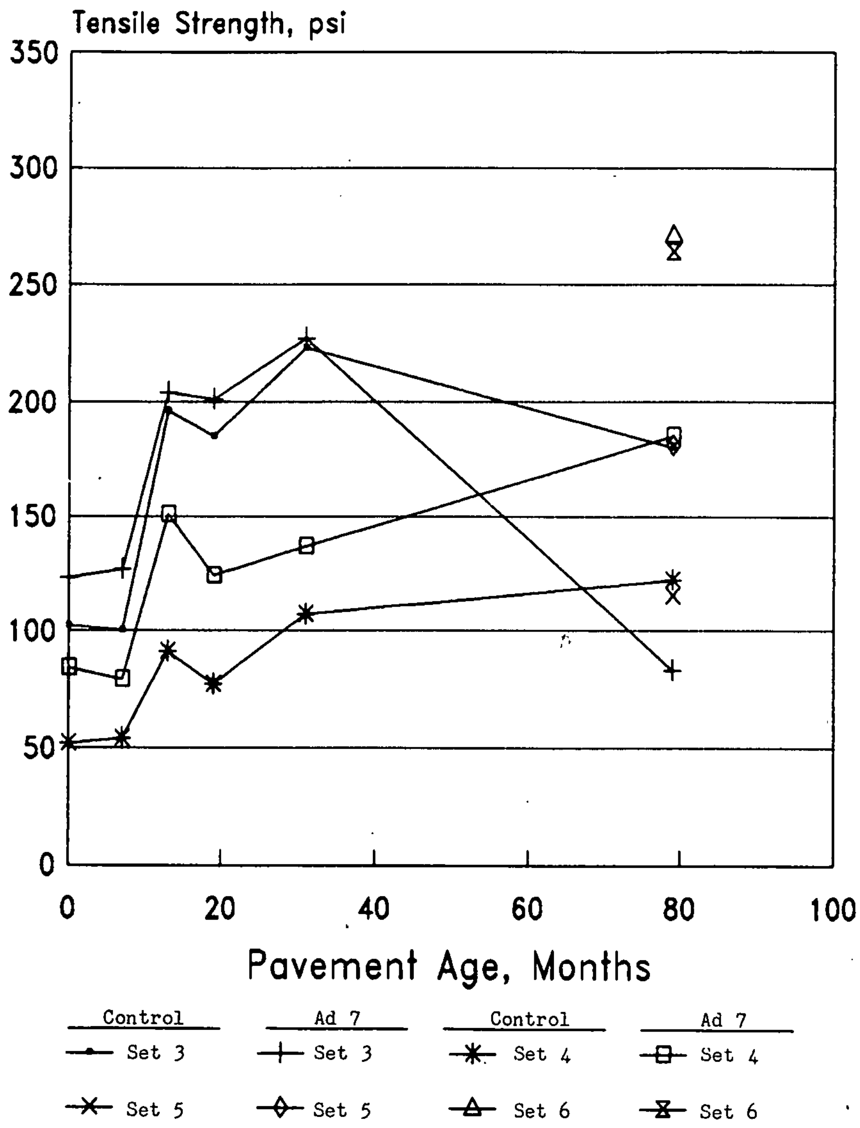

Figure D-9. Arizona Cores

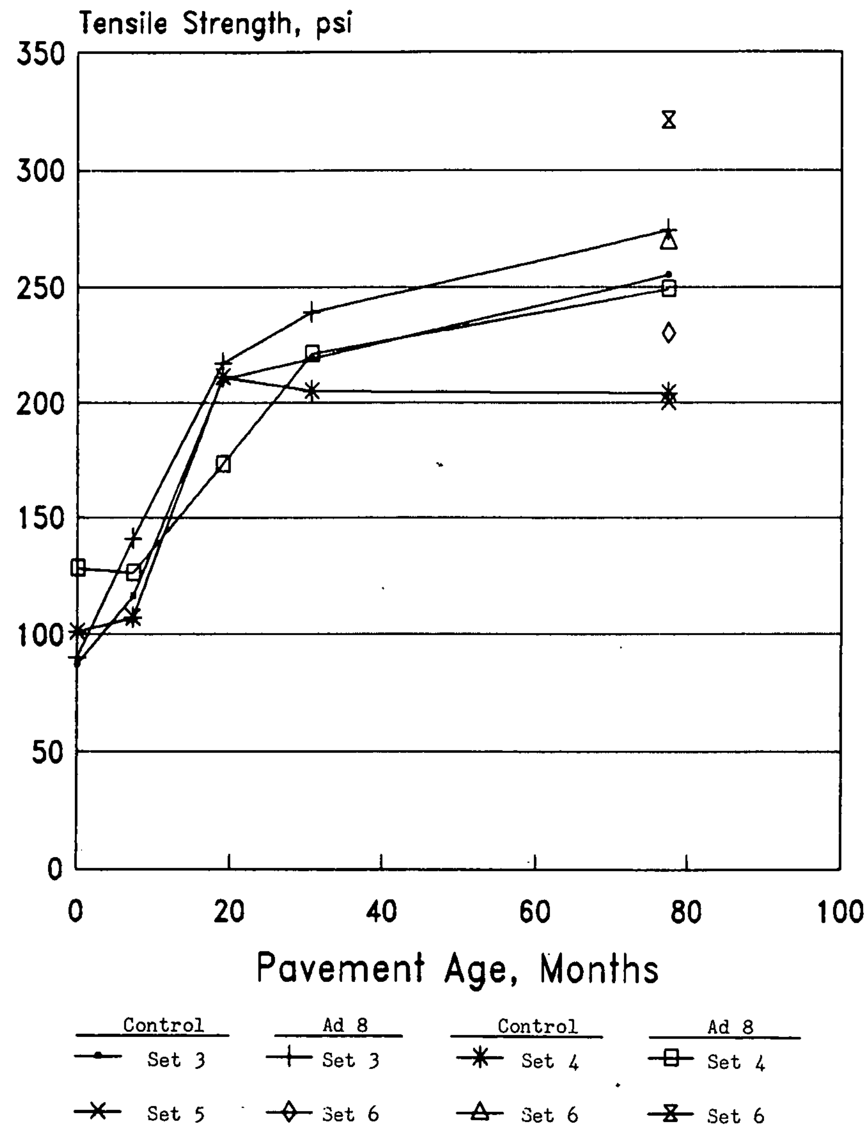

Figure D-10. Alabama Cores

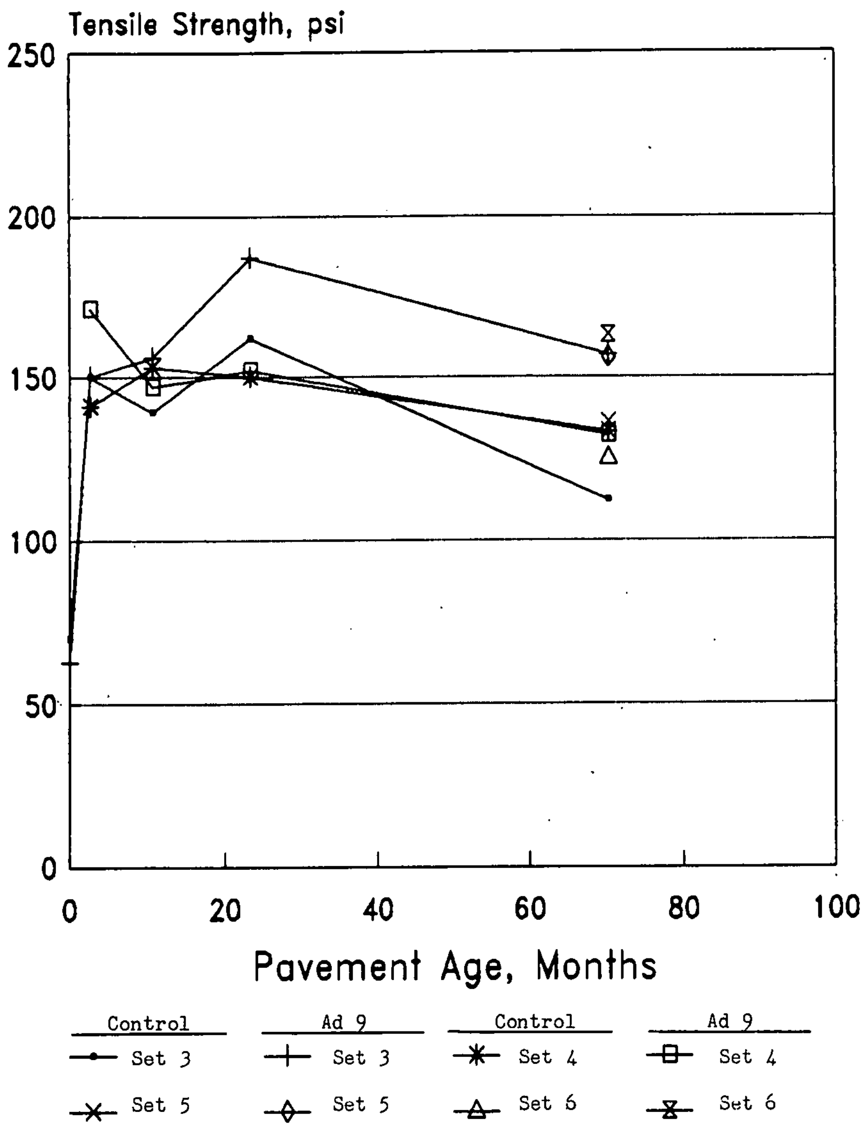

Figure D-11. Texas Cores

Table D-11

GEORGIA CONDITION SURVEY DATA

	Section	Severity	Section	Severity	Section	Severity
	Control		Lime		Ad 2	
Date	1988		1988		1988	
Cracking, 1 ft/sta Longitudinal	100	low	50	low	50	low
Transverse	10	low	4	low	4	low
Average Rut Depth, in	.06		.03		.03	
Raveling, sq ft/sta	72	low	24	low	24	low
Date	1992		1992 (After Overlay)		1992	
Cracking, 1 ft/sta Longitudinal	25	low	2	low	5	low
Average Rut Depth, in	0		0		.03	

Table D-12

VIRGINIA CONDITION SURVEY DATA

	Section	Severity	Section	Severity
	Control		Ad 3	
Date	1989		1989	
Cracking, 1 ft/sta Transverse	7	low	5	low
Raveling, sq ft/sta	300	low	10	low
Date	1992		1992	
Cracking, 1 ft/sta Longitudinal	149	low	4	low
Transverse	30	low	12	low
Average Rut Depth, in	.03		.14	
Polishing, sq ft/sta	600	low	600	low
Raveling, sq ft/sta	600	low	600	low

Table D-13

ARKANSAS CONDITION SURVEY DATA

	Section	Severity	Section	Severity
	Control		Ad 4	
Date	1988		1988	
Cracking, 1 ft/sta Transverse	5	low	5	low
Average Rut Depth, in	0		.03	
Raveling, sq ft/sta	300	low	300	low
Date	1992		1992	
Cracking, 1 ft/sta				
Longitudinal	50	low	0	low
Transverse	20	low	20	low
Average Rut Depth, in	.38		.25	
Raveling, sq ft/sta	300	low	300	low

Table D-14

MAINE CONDITION SURVEY DATA

	Section	Severity	Section	Severity
	Control		Ad 5	
Date	1988		1988	
Cracking, 1 ft/sta Transverse	16	mod	15	mod
Raveling, sq ft/sta	400	low	400	low
Date	1993		1993	
Alligator Crack sq ft/sta	0		8	mod
Block Cracking, sq ft/sta	11	mod	23	mod
Cracking, 1 ft/sta				
Edge	5	mod	5	mod
Longitudinal	40	mod	30	mod
Polishing, sq ft/sta	1200	low	1200	low
Raveling, sq ft/sta	1200	low	1200	low

Table D-15

ILLINOIS CONDITION SURVEY DATA

	Section	Severity	Section	Severity	Section	Severity
	Control		0.5% Ad 3		0.75% Ad 3	
Date	1988		1988		1988	
Cracking, 1 ft/sta Reflection	12	low	12	low	12	low
Average Rut Depth, in	.06		.06		0	
Raveling, sq ft/sta	100	low	100	low	100	low
Date	1992		1992		1992	
Cracking, 1 ft/sta						
Longitudinal	0		5	low	0	
Reflection	12	mod	12	mod	12	mod
Raveling, sq ft/sta	400	low	400	low	400	low

Table D-16

ARIZONA CONDITION SURVEY DATA

	Section	Severity	Section	Severity	Section	Severity
	Control		P C		Ad 7	
Date	1988		1988		1988	
Cracking, 1 ft/sta Transverse	9	low	5	low	9	low
Average Rut Depth, in	.06		.06		.06	
Date	1992		1992		1992	
Cracking, ft/sta						
Longitudinal	15	low	0		15	low
Transverse	9	hi	5		9	hi
Patching, sq ft/sta	0		0		8	low
Average Rut Depth, in	.11		.07		.14	
Date in addition to 1992	1993		1993		1993	
Block Cracking, sq ft/sta	0		0		4	low
Raveling, sq ft/sta	0		0		200	mod

Table D-17

ALABAMA CONDITION SURVEY DATA

	Section Control	Severity	Section Ad 8	Severity
Date	1988		1988	
Cracking, l ft/sta Transverse	25	low	10	low
Average Rut Depth, in	.12		.08	
Raveling, sq ft/sta	100	low	100	low
Date	1992		1992	
Cracking, l ft/sta Longitudinal	10	low	4	low
Transverse	10	low	4	low
Average Rut Depth, in	.16		.11	
Raveling, sq ft/sta	300	low	300	low

Table D-18

TEXAS CONDITION SURVEY DATA

	Section Control	Severity	Section Ad 9	Severity
Date	1989		1989	
Cracking, l ft/sta Edge	100	low	0	
Average Rut Depth, in	.03		.02	
Raveling, sq ft/sta	100	low	100	low
Date	1992		1992	
Cracking, l ft/sta Edge	100	mod	100	mod
Average Rut Depth, in	.06		0	

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Transportation Research Board
National Research Council
2101 Constitution Avenue, N.W.
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