

NATIONAL COOPERATIVE
HIGHWAY RESEARCH PROGRAM REPORT

274

**USE OF ANTISTRIPPING ADDITIVES
IN ASPHALTIC CONCRETE MIXTURES
LABORATORY PHASE**

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
REPORT

274

USE OF ANTISTRIPPING ADDITIVES IN ASPHALTIC CONCRETE MIXTURES LABORATORY PHASE

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ASSOCIATION OF STATE HIGHWAY AND
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AREAS OF INTEREST:

PAVEMENT DESIGN AND PERFORMANCE
BITUMINOUS MATERIALS AND MIXES
(HIGHWAY TRANSPORTATION)
(AIR TRANSPORTATION)

TRANSPORTATION RESEARCH BOARD
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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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The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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The members of the technical committee selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and, while they have been accepted as appropriate by the technical committee, they are not necessarily those of the Transportation Research Board, the National Research Council, the American Association of State Highway and Transportation officials, or the Federal Highway Administration, U.S. Department of Transportation.

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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 asphaltic concrete pavements. It reviews the current use of antistripping additives in asphaltic concrete mixtures and contains guidelines for incorporation of the additives into the paving mixtures in the field. A laboratory procedure is described in detail for predicting antistripping additive effectiveness for a specific asphalt-aggregate paving mixture. On the basis of this and previous research and experience, it is recommended that the prediction procedure be used on a trial basis to estimate the effectiveness of various antistripping additives with different asphalt-aggregate mixtures.

Moisture is often the major factor associated with the deterioration of asphaltic concrete pavements. The most serious consequence of the adverse action of moisture is the loss of adhesion between the aggregate and asphalt cement, commonly called "stripping," resulting in substantial reduction in the tensile strength of the asphaltic concrete paving material. Because the asphalt-aggregate adhesion properties of mixtures are very complex, many tests that have been used to evaluate these properties have involved visual inspection of mixtures in the presence of water. NCHRP Reports 192 and 246 describe the development and verification of an empirical test procedure for predicting the performance of pavements built with specific asphalt-aggregate mixtures. The next needs, and the objectives of the research described in this report, are (1) the further development of procedures for predicting the effectiveness of antistripping additives used in asphaltic concrete paving mixtures and (2) the preparation of guidelines for incorporating antistripping additives in asphaltic concrete paving mixtures during construction.

To accomplish the objectives, the research team of David G. Tunnicliff, Consulting Engineer, Chicago Testing Laboratory, Inc., and Richard E. Root, Vice President, first conducted a survey of state highway and other agencies to determine the extent of asphalt stripping problems, current use and experience with antistripping additives, and practices with regard to testing of asphalt-aggregate to determine the need for and effectiveness of antistripping additives. Stripping problems were found to be widespread and influenced by a large number of factors. Antistripping additives are being used extensively even though no generally accepted procedure appears to be available to evaluate or predict their effectiveness. In response to this need, the laboratory test procedure described in NCHRP Reports 192 and 246 was modified for use as an empirical procedure for evaluating the effectiveness of antistripping additives and used in an experimental program to provide limited verification. The test procedure is suitable for use on a trial basis for evaluating specific antistripping additive-aggregate asphalt combinations.

A field evaluation phase of the research was begun in 1984 and is due to be completed in 1987. Test sections with and without antistripping additives will be included in regular asphaltic concrete paving projects in six states. Laboratory tests using the procedure described in this report will be conducted using the actual aggregates, asphalts, and additives from the construction projects to predict pavement performance; the pavements will be tested over a 2-year period to compare actual performance with the predictions. It is anticipated that further observations of the test sections will be made following completion of the field study phase of the project.

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ACKNOWLEDGMENTS

The research reported herein was performed under NCHRP Project 10-17, by David G. Tunnichliff, Consulting Engineer, and Chicago Testing Laboratory, Inc. David G. Tunnichliff was the contractor for this study. The work performed by Chicago Testing Laboratory was under a subcontract with David G. Tunnichliff.

Dr. Tunnichliff was principal investigator and author of this report. The co-principal investigator and co-author of this report was Richard E. Root, Vice President, Chicago Testing Laboratory. The work was done under the general supervision of Dr. Tunnichliff. The work at Chicago Testing Laboratory was done under the supervision of Mr. Root.

Chert aggregates for use in this study and advice on chert mixture designs were furnished by Buford D. Stroud, Testing Engineer, Mississippi State Highway Department. Materials used for correlation with NCHRP Report 246 were furnished by state highway agencies from Georgia, Virginia, Arizona, Colorado, Montana, and Idaho, and the Federal Highway Administration.

Sources of asphalt cement and antistripping additives used in this study are confidential. The suppliers are acknowledged anonymously with thanks for their willing assistance.

Some of the experimental data appearing in Table C-5 was developed in a concurrent study sponsored by the National Asphalt Pavement Association and is published herein with the permission of Richard W. Smith, Director of Research and Development.

USE OF ANTISTRIPPING ADDITIVES IN ASPHALTIC CONCRETE MIXTURES LABORATORY PHASE

SUMMARY

There is an increasing awareness of asphaltic concrete pavement failures caused by stripping of asphalt cements from the aggregates. Consequently, more highway agencies are requiring the use of antistripping additives. If an additive is used when it is not needed, the added cost is an economic waste. If an additive is used ineffectively, the pavement may require early and costly maintenance and/or rehabilitation. Highway agencies need information on the selection, effectiveness, and use of antistripping additives.

Accordingly, the overall objective of the research conducted under NCHRP Project 10-17 is to provide information on the selection and use of antistripping additives (materials used to improve the asphalt-aggregate adhesion in asphaltic concretes). The specific objective of the research was to develop guidelines for the incorporation of antistripping additives in asphaltic concrete paving mixtures considering the influence of such factors as (1) storage and handling of the additives, and (2) stability and effectiveness of additives during mixing and storage of asphaltic concrete.

This report provides information on the state of the art of the use of antistripping additives in asphaltic concrete, and the development and evaluation of a testing procedure for determining antistripping additive effectiveness. The state of the art was determined by means of a questionnaire sent to state highway and other interested agencies. Responses reveal that stripping has been related to many factors including various aggregate types, asphalt cement grade and source, and numerous aspects of mixture design, construction, and climate. These variables are coupled with a very large number of testing procedures and modifications. Experimental procedures that are not part of the art were also investigated. None of the existing or experimental procedures was judged to be entirely satisfactory for purposes of testing antistripping additive effectiveness. A procedure was developed which controls the degree of saturation of compacted specimens and subjects them to moisture under conditions not likely to create damage other than stripping. The procedure is simple and rapid enough to be practical for use in field laboratories. This new procedure was used to evaluate the effects of storage and handling on antistripping additives and indicates that normal construction practices and testing conditions are not detrimental to chemically stable additives, but they make unstable additives ineffective. The procedure was also found to correlate satisfactorily with observed moisture damage experience in the field. From this, guidelines for using antistripping additives were developed including a procedure for judging additive effectiveness.

The material in the following pages of this report presents the details of the research. Chapter One briefly sets forth the background that led to the research and describes the research approach. Chapter Two discusses the findings and centers on the state of the art, the effects of storage and handling on antistripping additive performance, the experimental procedures and techniques for evaluating and applying antistripping additives, and correlating and evaluating the test method. Chapter Three presents the guidelines for using antistripping additives. Chapter Four summarizes the conclusions emanating from the research and includes recommendations for further research. The appendixes contain supporting materials.

INTRODUCTION AND RESEARCH APPROACH

Antistripping additives have been used in asphaltic concrete paving mixtures for many years, and in recent years their use has increased significantly. At the same time, pavement failures associated with moisture damage, stripping or otherwise, are becoming more prevalent. Antistripping additives may be able to prevent or minimize stripping damage, but at the present time, a satisfactory means of evaluating their effectiveness is not available.

This report provides information on current practices for using antistripping additives, methods that are being used to evaluate the effectiveness of antistripping additives, the development of a practical testing procedure for that purpose, the influence on additive effectiveness of variables that may be encountered during construction, guidelines for the use of antistripping additives, and recommendations for further research to develop criteria for the selection and use of antistripping additives.

BACKGROUND

Stripping in asphalt pavements is defined as the displacement of asphalt cement films from aggregate surfaces by water. Once initiated, stripping usually progresses rapidly and leads to premature failure of the pavement. Stripping problems were recognized as early as 1932 when they were considered to be adhesion problems (1). Since then, major efforts have been undertaken to determine the nature of the stripping problem and means of measuring it (2, 3, 4, 5, 6, 7).

Soon after stripping was recognized, interest in additives to improve adhesion between asphalt and aggregate developed (8, 9, 10). Since then, a number of antistripping additives have been developed and used. In 1947 approximately 150 chemical compounds were recognized as potential antistripping additives (11). Most of these were never used because of practical considerations. Today, most antistripping additives are proprietary chemical compounds, but common substances such as hydrated lime are also used.

Proprietary chemical antistripping additives are soluble in asphalt cement and designed to migrate to aggregate surfaces where they are adsorbed, probably selectively, rendering the aggregate surface more easily wetted by asphalt. Such chemicals are often known as surface active agents, or surfactants. Strictly speaking, typical surfactants are compounds such as soaps which, when dissolved, lower the surface tension of the solvent making it better able to wet solid surfaces. In the case of antistripping additives, there may be no effect on the surface tension of the asphalt cement, but the result is the same, a more easily wetted solid.

Wetting alone does not necessarily produce better adhesion. Therefore, an antistripping additive to be effective must promote

the development of an improved bond at the asphalt-aggregate interface. In an idealized setting, chemical antistripping additives can do this, for example, by using basic chemicals in the additive which alter the surface of an acidic aggregate, such as granite, to provide better adhesion with acidic asphalts. This example is probably the typical situation, but the opposite is also possible—that is, acidic chemicals in the additive which alter the surface of a basic aggregate, such as limestone, to provide better adhesion with basic asphalts.

Materials such as hydrated lime function in part like inert mineral filler but can also help to neutralize acidic surfaces and thereby provide better adhesion with asphalt. The function of such materials is not fully understood, but it is clearly beneficial at times (12, 13).

In spite of a long history of use, only a few studies of antistripping additives and their effectiveness are reported in the literature (14, 15, 16, 17, 18, 19, 20). Some of these studies deal with the use of additives in cold mixtures containing cutback asphalts and are not entirely applicable to hot-mixed asphaltic concrete. Most are laboratory studies including little, if any, correlation with field conditions. Still, these studies show that different additives act differently with different aggregates and different asphalt cements. Because of certain test procedures and other limitations, none of these studies is entirely conclusive. Information and test procedures which reliably indicate additive effectiveness under field conditions of construction and service are lacking.

Reliable information and test procedures concerning additive effectiveness are needed in order to ensure that the use of an additive is economic. Neither the use of an additive when none is needed, the use of an ineffective additive, nor the absence of an additive when one is needed, is economical use of funds. Yet, without reliable information and test procedures, any of these can occur.

Because of the economic consequences of additive misuse, the lack of information and test procedures dealing with additive effectiveness, and the presence of stripping in pavements, NCHRP developed Project 10-17 to provide information on the selection and use of antistripping additives.

RESEARCH APPROACH

The immediate objective of NCHRP Project 10-17 was to develop guidelines for the incorporation of antistripping additives into asphaltic concrete mixtures considering the influence of such factors as storage and handling of additives, and stability and effectiveness of additives during mixing and storage of asphaltic concrete.

To accomplish this objective, the first step was to determine the state of the art of procedures used to determine the need

for and dosage of an antistripping additive, and to control incorporation of additives into asphalt cement or paving mixtures. The state of the art was studied by sending a questionnaire to state and other agencies who may use antistripping additives, trade associations who may have an interest in additives, asphalt cement producers, and additives manufacturers. Experimental procedures and techniques for studying and using additives that have not been reduced to practice were also investigated separately.

Information obtained from the questionnaire, the technical literature, and other sources was analyzed in order to select procedures which appear to be capable of determining the need, selection, and dosage of additives, and the effects of storage,

handling, and pavement construction. The selected procedures were expected to be laboratory procedures using readily available equipment. No existing procedure or group of procedures was found to be entirely satisfactory for these purposes, and a procedure was developed as a modification of the method described in NCHRP Report 246, Appendix A, for predicting moisture damage to asphaltic concrete.

The new procedure was evaluated and correlated with moisture damage experience, and used to study effects of storage, handling, and pavement construction on additive effectiveness.

From this background, guidelines for using antistripping additives were developed.

CHAPTER TWO

FINDINGS

STATE OF THE ART

The state of the art of the use of antistripping additives in asphaltic concrete was determined by a questionnaire sent to state and provincial highway agencies and other interested parties. Stripping was found to be a problem in more than half of the states, and all states recognized the problem of using antistripping additives, either liquid additives added to the asphalt cement or powders such as hydrated lime.

Responses to the questionnaire show that stripping has been related to many factors. Various types of coarse aggregate are cited most frequently, followed by several types of fine aggregate, aggregate gradation, and source and grade of asphalt cement. Aggregates, such as gravel and natural sand, which are supposed to strip, are listed among those that strip in some areas and among those that do not strip in other areas. Limestone coarse and fine aggregates, which are not supposed to strip, are listed among those that do not strip in some areas and among those that do strip in other areas. Similar contradictions are found throughout, leading to the conclusion that no aggregate type always strips and no aggregate type never strips. Asphalt cement has not been studied as thoroughly as aggregates, but where it has been studied it is known that some asphalts strip more than others. Asphalt cement is a complicating factor because of the possibility of continually changing composition caused by changing crude oil sources, that may or may not influence additive effectiveness. Against this background, there are more than 100 known additives, most differing from each other in some unknown way. Materials alone present thousands of variables that may influence stripping and additive effectiveness.

The questionnaire revealed that there are 14 testing procedures used with additives. Of these, only three are AASHTO or ASTM standards. There are numerous variations of procedures to the extent that the number of test variables may ap-

proach the number of materials variables. Tests are used to determine additive need, dosage, presence, heat stability, and effectiveness when used in the field. Most testing is applied to determine the need for an additive and is performed on complete mixtures. Because all known additives are affected by the surface area and chemistry of aggregates and the chemical nature and viscosity of asphalt cement, testing complete mixtures is necessary in order to determine additive dose and effectiveness.

No testing procedure currently in use is entirely satisfactory for purposes of evaluating additives. Many require too much time, while others employ techniques that may create either moisture damage or other physical damage which is not stripping. To overcome these deficiencies, a procedure was developed as a modification of the method described in NCHRP Report 246, Appendix A, for predicting moisture damage to asphalt concrete. The new procedure requires 2 to 3 days, which is less than most existing procedures. It is unlikely that this time can be reduced because preferential wetting is not an instantaneous phenomenon and the procedure must allow enough time for stripping to occur. Equipment and techniques are neither unusual nor difficult. Field laboratories equipped to run Marshall stability and Rice specific gravity can run this procedure also. The only new aspect of the procedure is that it requires control of the degree of saturation of compacted specimens so that the specimen contains enough water to cause stripping, but avoids supersaturation which probably can only be accomplished by causing physical damage that is not stripping.

Briefly, the procedure employs specimens of a job mix formula compacted to about 7 percent air voids. The compacted specimens are saturated with water by applying a partial vacuum to submerged specimens so that the volume of water permeating the specimen is between 55 and 80 percent of the volume of air voids. Saturated specimens are conditioned under water at 140 F for 24 hours and tested for tensile strength in accord with ASTM

Method D 4123. Companion specimens are tested dry, and the wet-to-dry ratio is used to judge moisture damage. The procedure was evaluated and found to be sensitive to water damage, additive dose, different additives, and asphalt cements from different sources.

The procedure was used in a laboratory experiment designed to study the effects of storage and handling on additive performance. Results, applicable only to the materials tested, indicate that long times and high temperatures are not detrimental to the effectiveness of good, heat stable additives, but that normal times and temperatures are detrimental to the effectiveness of other additives.

Other procedures for testing additives, which are largely experimental and not part of the art, were also studied. All of those procedures provide information that may be useful in evaluating additives, but none is able to evaluate complete mixtures. Therefore, the experimental procedures are useful mostly in providing data to supplement procedures which test complete mixtures.

Based on the previous work, guidelines for using antistripping additives were developed. The guidelines address the large number of variables that affect stripping and additives, and the testing procedure developed in this project is recommended for routine use because it is believed to be the most practical means of dealing with the large number of variables. Other procedures that may provide useful supplementary information are recognized. A procedure for judging additive effectiveness is also developed and recommended for use with the new testing procedure.

EFFECTS OF STORAGE AND HANDLING ON ANTISTRIPPING ADDITIVE PERFORMANCE

Conditions likely to be encountered by antistripping additives in the field were investigated in laboratory experiments. The experiments were designed to determine whether or not additives remain chemically stable when subjected to high temperatures or long time periods in the presence of asphalt cement, and whether or not additives are effective under less rigorous conditions.

Experimental Design

Materials

Most of the experimental data was obtained using a Chert-B mixture with AC-20-1 (as described in Appendix B). Altogether 7 additives including 6 cationic surfactants and hydrated lime were tested. The additives are identified in Table 1 along with an indication of expected performance. Additives 1 and 2 are those which were used in the laboratory experiment (App. B). Additives 4 and 11 were not designed for use in hot mix. There is no record of the use of hydrated lime with this chert; therefore, the performance to be expected is unknown.

A limited amount of data was also collected from two other mixtures. One was the Chert-B mixture with AC-20-2 from Appendix B. The other was a limestone mixture with no history of moisture damage which was used with additive 2, an additive designed to improve limestone mixtures.

Table 1. Antistripping additives.

Additive	Expected Performance	
	with Chert	Heat Stability
1	good	good
2	poor	good
4	good	poor
5	good	good
6	good	good
11	good	poor
Hydrated Lime	unknown	good

Procedure

The testing procedure was essentially that appearing in Appendix B. Temperature and time requirements listed in the procedure had to be violated in order to determine their effects. Compaction was standardized at 15 Marshall blows per face. Because of variable temperatures and times, void content of the specimens could not be controlled, and all specimens did not have approximately 7 percent air voids required by the procedure. Saturation was achieved by partial vacuum which was adjusted, as necessary, to try to achieve the minimum degree of saturation of 55 percent required by the procedure. Even so, for a number of practical reasons involving conditions in the experiment that are not present in the normal laboratory or field test, all specimens were not saturated to the minimum of 55 percent before moisture conditioning.

Factorial Experiment. To study the effects of high temperatures and long times, a factorial experiment involving six temperature and time factors each at two levels was designed. The factors and levels are presented in Table 2. All normal levels in Table 2 comply with the procedure in Appendix B. Details of the factorial experiment appear in Appendix D.

Additional Experiment. Other additives at various dosages, another asphalt cement, and another aggregate were tested under normal conditions.

Experimental Results

Factorial Experiment

Complete data from the factorial experiment are included in Appendix D. Analysis of replicate cells, air voids, degree of saturation, and difference in tensile strength of duplicate specimens (App. D) shows that precision of the factorial experiment is satisfactory.

Tensile strength, rather than tensile strength ratio, was de-

Table 2. Factorial experiment.

Factor	Level	Approximates
Agent holding time in asphalt	Normal-15 minutes	In-line blending at asphalt plant
	Long-5 days	Adding additive in bulk at terminal
Agent holding temperature in asphalt	Normal-300F for AC-20	Typical plant operation
	High-350F	Maximum allowed by many specifications
Mixing time after adding treated asphalt	Normal-30 seconds	Typical plant operation
	Long-120 seconds	Unusually long for batch plant, may approximate drum mix plant
Mixing temperature	Normal-300F for AC-20	Typical plant operation
	High-325F	Maximum allowed by many specifications
Mixture holding time	Normal-2 hours	Typical paving operation
	Long-5 hours	Unusually long but possible with silo and long haul
Mixture holding temperature	Normal-275F for AC-20	Typical paving operation
	High-325F	Maximum allowed by many specifications

terminated because the ratio would have required twice as many samples, too many to be practical. The average tensile strength of conditioned specimens for the 64 cells was 148.2 psi. The range was 84.1 psi to 207.5 psi. Cell 1, using normal conditions, resulted in 117.3 psi. The same mixture in Appendix B tested under the same normal conditions had an unconditioned tensile strength of 112.1 psi without additive and a conditioned tensile strength of 94.3 psi with additive.

The conclusion is that none of the factors resulted in a significant loss of strength and there was no moisture damage. Either the additive was effective throughout or the factors created circumstances of some other nature that prevented moisture damage.

Because tensile strength was not reduced at all, and in fact increased, asphalt cement was recovered from specimens representing four cells and tested to determine whether or not the increase in tensile strength was caused, at least in part, by increased viscosity of the asphalt cement. The results are given in Table 3. Asphalt recovered from cell 1 is within ranges to be expected for normal hot mix operations. The remaining cells reflect results indicative of the effects of time and temperature with the more severe conditions resulting in higher viscosities. Although the data show that some of the increased tensile strength can be attributed to increased viscosity of asphalt cement, cells 4 and 62, representing the lowest and highest tensile strengths respectively, have nearly identical viscosities showing that factors other than viscosity are influencing results.

The additive used in this work was supposed to be a good, heat stable additive. Whether or not all observed effects should be attributed to the additive, none of the conditions investigated resulted in significant moisture damage. Long times and high temperatures do not impair the effectiveness of this particular additive.

Effects of Additive Dose

High temperatures and long times could provide conditions that would promote excess additive migration toward aggregate

Table 3. Characteristics of recovered asphalt cement.

Cell	Description	Viscosity		Penetration
		#140F, p	#275F, cSt	
1	Normal	6,949	640	32
4	Lowest tensile strength	61,000	1,458	16
47	Average tensile strength	9,630	717	29
62	Highest tensile strength	64,000	1,404	17

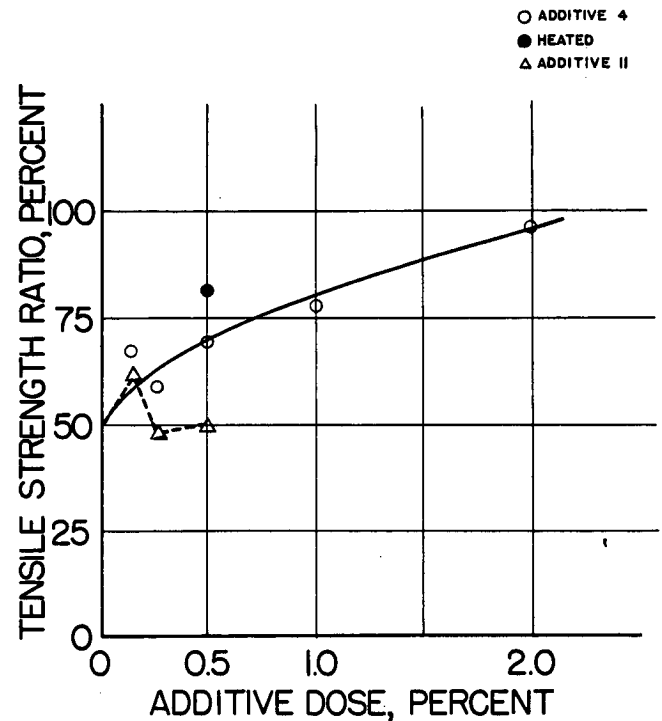


Figure 1. Unstable additives.

surfaces resulting in a weak layer of asphalt cement susceptible to cohesive failure. To investigate this the factors for cell 62, which had produced the highest tensile strength, were used with five different additive dosages. Results in Table D-6 show that regardless of additive dose, tensile strength ratio was always more than 90 percent showing negligible moisture damage.

Without additive, tensile strength ratio was 90 percent, suggesting that cell 62 factors produce mixtures that resist moisture damage whether or not an additive is used. Therefore, it cannot be concluded that the additive is always effective.

Because high temperatures and long times had not revealed poor additive performance, it appeared as if normal conditions would have to be used for testing, and additives which are not heat stable would be detected. With two exceptions, long times and high temperatures were not used in subsequent experiments.

Unstable Additives

Additives 4 and 11 were not intended for use in hot mix and could be expected to be ineffective at normal temperatures. The data in Figure 1 show that these additives are generally less

effective than additive 1 in Figure B-2 in Appendix B. Analysis in Appendix D shows that the different doses of both additives produce significantly different results, and that the effect of different doses is much greater than the effect of variability in testing.

An anomaly appears in the data for both additives 4 and 11 where a sharp increase in tensile strength ratio occurs at 0.125 percent followed by a sharp decrease at 0.25 percent. An explanation for this behavior has not been developed.

Although additives 4 and 11 appear to be less effective than additive 1, there remains a question as to whether or not they are effective enough to be useful. In Appendix A, the survey reveals that in most cases when a mechanical property of a mixture is measured, a lower limit of strength index or ratio is used to determine whether an additive is needed, and when an additive is used, whether or not it is effective enough. To use such a limit in this study, it would be necessary to establish an arbitrary limit. For example, Figure B-3 suggests that a tensile strength ratio less than 60 percent reveals severe moisture damage in chert mixtures. Because the tensile strength ratio of Chert-B without additive is 50 percent, the need for an additive seems to be well established. If it were decided that the additive should increase the ratio to 60 percent or more, then additive 4 would be judged effective enough at any dosage of 0.125 percent or more, and additive 11 would be judged effective enough at 0.125 percent and ineffective at higher dosages. These judgments must be questioned because these additives are not supposed to be heat stable and should not be effective in hot mix at the lower dosages. Furthermore, the limit of 60 percent may be applicable for chert mixtures but not other mixtures.

A different approach has been used in Appendix B. Instead of arbitrary ratio limits, a probability of 20:1 has been used to determine whether or not observed differences are real differences. The probability of 20:1 can be defended easily based on statistical considerations and is used frequently in many processes. The question of whether or not an additive is effective enough, however, is not necessarily addressed simply by showing that the probability that observed improvement in tensile strength ratio is real is 20:1. To be absolutely certain that an additive is effective enough to be useful, a higher probability can be selected and used with confidence. A high probability for this purpose would be 100:1.

When compared to the mixture without additive, additive 11 is found to be not significantly different regardless of dose. Additive 4 is significantly different from no additive at a dose of 0.5 percent where the probability that the treatments are different is more than 100:1. For purposes of comparison, additive 1 at 0.125 percent is better than no additive with a probability of more than 1000:1.

One additional experiment was performed by storing additive 4 in asphalt cement at 350 F for 24 hours. The resulting specimens developed both tensile strength and tensile strength ratio greater than comparable specimens subjected to normal conditions, and the difference in ratio is shown to be significant with a probability more than 100:1. This result is consistent with the results in the factorial experiment where high temperatures did not result in increased moisture damage.

Because of the performance of additives 4 and 11, it is concluded that normal temperature and time conditions in the testing procedure will distinguish between stable and unstable additives.

Stable Additives

Additives 5 and 6, along with additive 1, are designed for use in hot mix and should be chemically stable in asphalt cement. The results shown in Figure 2 show that the three additives perform differently from each other, but compared to Figure 1, the stable additives develop a different pattern from the unstable additives. The analysis in Appendix D shows that the different doses of additive 6 produce different results, and that the effect of different doses is much more significant than variability in testing. Different doses of additive 5 are shown to produce little differences in results, not significantly greater than differences caused by variability in testing. In other words, additive 6 is shown to be sensitive to dosage, and additive 5 is shown not to be sensitive to dosage. Additive 1 was found to be sensitive to dose in Appendix B.

Turning to the question of whether the improvement over zero dose is significant, the probability that additive 5 is better than no additive is more than 100:1 at a dosage of 0.125 percent and all higher dosages. The probability that additive 6 is better than no additive is more than 100:1 at a dosage of 0.5 percent and less than 100:1 at any lower dosage.

Additive for Limestone

Additive 2 was not intended to be used with chert, and was found to be less effective than additive 1 in Appendix B. However, it was noted that the most effective dose of additive 2 may not have been used. The effect of varying the dosage of additive 2 is shown in Figure 3. The analysis in Appendix D shows that different doses produce significantly different results, and that the effect of different doses is much greater than the effect of variability in testing. When the dosage of additive 2 is 1.0 percent or more, the probability that the treatment is better than no additive is more than 100:1.

Additives 4 and 11 produced unexplained behavior wherein a dose of 0.125 percent appeared to be more effective than 0.25 percent. The same behavior also appears with additive 2 in the chert mixture. Even though these three additives could be expected to have their effectiveness impaired for different reasons, all performed abnormally well at the lowest dosage tested.

Data from Appendix B at a dosage of 0.5 percent are also plotted in Figure 3. Normal testing conditions were used for the data, but a mixture holding temperature of 325 F was used when additive dosages were varied. The analysis in Appendix D shows that the tensile strength ratios at 0.5 percent additive are not different, and the probability that the effect of variability in testing is significantly greater than the difference caused by holding temperature is less than 5:1. This confirms the findings from the factorial experiment which show that high temperatures do not result in more moisture damage with heat stable additives.

Additive 2, which was designed to be used with limestone, was also used in a limestone mixture at a dosage of 0.5 percent. Tensile strength ratio was 61.1 percent without additive and 78.8 percent with additive. The probability that the additive produced a significant improvement is more than 100:1, and the effect of the additive is much more significant than the effect of variability in testing. Compared to its effectiveness with chert, additive 2 is shown to be more effective when used for what it was designed to do.

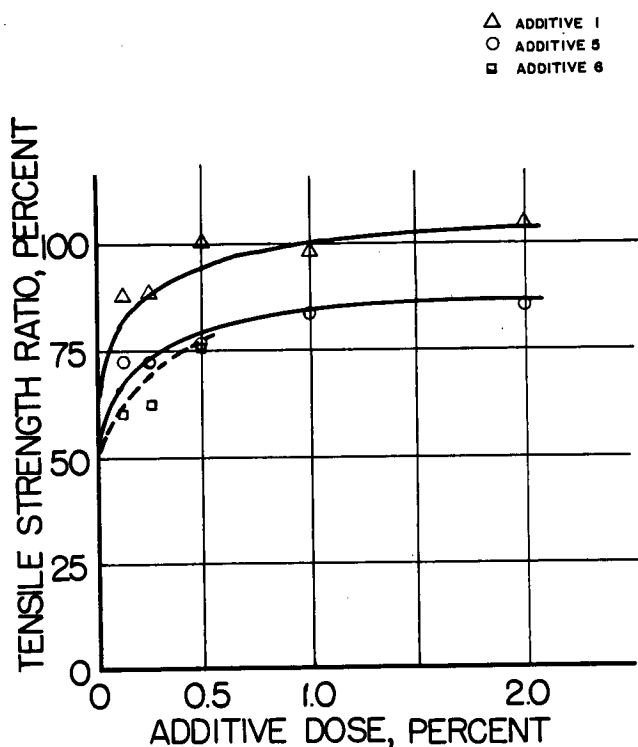


Figure 2. Stable additives.

Different Asphalt Cements

In Appendix B, additives 1 and 2 were used with AC-20-1 and AC-20-2 to verify that the procedure is sensitive to the effects of different asphalt cements. To make the results more conclusive, the data base was expanded by testing additional specimens containing AC-20-2 with and without additive 2. Analysis of the results from Tables C-5 and D-7 are given in Table 4.

Without additive the tensile strength ratio was 50.0 for AC-20-1 and 47.5 for AC-20-2. The analysis shows that the two asphalts are not different and that the probability that variability in testing is significantly greater than the effect of the different asphalt cements is less than 5:1.

The original data for AC-20-2 in Table B-8 shows that the treatments are different, and that the effect of different treatments is much more significant than the effect of variability in testing. Results for AC-20-2 in Table 4 confirm this. However, contrary to Table B-8, the comparison of means in Table 4 shows conclusively that the three means are different at a probability of more than 20:1. The question of whether or not an additive is effective enough at a probability of 100:1 or more can also be addressed. Table 4 shows that additive 1 is effective enough in AC-20-2, and that additive 2 is not.

Comparing the two asphalt cements, the original data in Table B-9 show that the treatments are different, and that the effect of treatments is much more significant than the effect of variability in testing. Table 4 confirms this. Again, contrary to the original data, the comparison of means in Table 4 shows conclusively that the two asphalt cements perform differently with either additive.

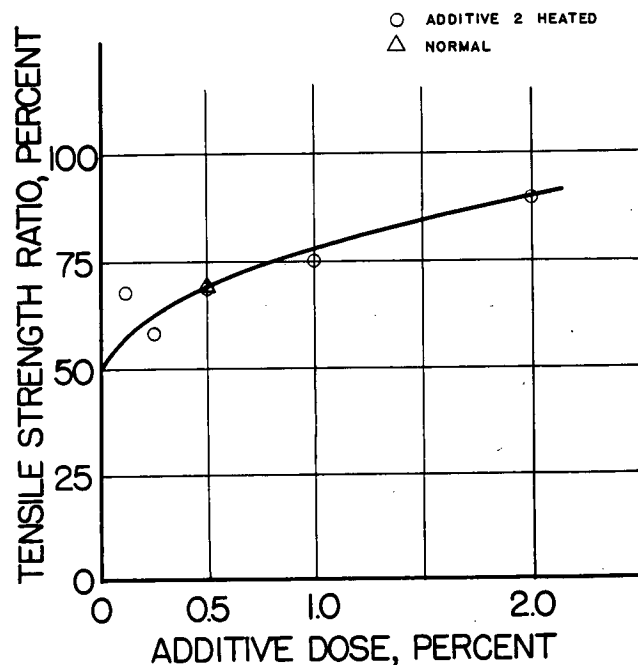


Figure 3. Additive for limestone.

Table 4. Comparison of asphalt cements.

Asphalt Cement	Tensile Strength Ratio, Percent					
	Without Additive	AC-20-1		Without Additive	AC-20-2	
Treatment		0.5% Add. 1	0.5% Add. 2		0.5% Add. 1	0.5% Add. 2
n	17	6	8	6	6	6
\bar{X}	50.0	99.9	68.1	47.5	79.9	54.6
S	8.4	7.4	13.6	6.1	8.0	3.1
Range	39.9 - 71.6	90.6 - 110.8	50.7 - 83.1	37.2 - 53.8	72.8 - 95.2	50.9 - 59.3

Analysis of Variance

Without additive the two asphalt cements do not result in mixtures of different moisture susceptibility. The probability that variability in testing is significantly greater than the difference caused by the asphalt cements is less than 5:1.

With the additives the probability that the treatments are different is more than 100:1.

With the additives in AC-20-2 the probability that the treatments are different is more than 1000:1.

Comparison of Means

Without additive the probability that the two asphalt cements are different is less than 5:1.

With Additive 1 the probability that the two asphalt cements are different is more than 1000:1.

With Additive 2 the probability that the two asphalt cements are different is more than 20:1.

In AC-20-2 the probability that Additive 1 results in a different asphalt cement is more than 1000:1.

In AC-20-2 the probability that Additive 2 results in a different asphalt cement is more than 20:1.

In AC-20-2 the probability that Additive 1 results in a different asphalt cement than Additive 2 does is more than 1000:1.

Data showing conclusively that the two asphalt cements perform differently with different additives even though the two asphalts are not different without additive is important in this study. It demonstrates that the experimental data are valid only for the mixtures that were actually tested. It also demonstrates that to determine additive effectiveness, actual mixtures must be tested. Finally, the data were obtained at normal testing conditions of time and temperature showing that long times and high temperatures are not needed to reflect differences among asphalt cements, additives, and combinations.

Hydrated Lime

Hydrated lime was incorporated dry into the Chert-B mixture with AC-20-1 in two dosages, 0.5 percent and 1.0 percent of the weight of aggregate. The data and analysis in Appendix D show conclusively that it was ineffective. A complete study of the effects of storing and handling hydrated lime might include other methods of incorporating the additive including adding the hydrated lime to the aggregate in slurry at various times before heating and drying, adding the hydrated lime to the asphalt cement, and adjusting the mixture design. Because hydrated lime was so ineffective in this mixture, these options were not pursued.

Comparing Additives

It has already been noted that data developed in this study are valid only for the mixtures tested. It would be incorrect to conclude that one particular additive is always either more or less effective than another. However, some comparisons can be made which provide insight into the observed effects.

Additive 1. Additive 1 produced the largest improvement in tensile strength ratio. In fact, at 0.125 percent its ratio exceeds that of all other additives at any dosage except 2.0 percent of additive 4. Additive 1 was designed to be effective with siliceous aggregates and to be chemically stable in asphalt. If it is possible to relieve stripping in this chert mixture with a cationic surfactant, an additive like additive 1 should be able to do it.

Additives 5 and 6. The other stable additives were designed to be all-purpose additives capable of improving adhesion of asphalt cement to basic as well as acidic surfaces. Because certain components of these additives were incapable of enhancing adhesion to chert, their lower tensile strength ratios compared to additive 1 should be expected. Perhaps higher ratios could be expected at the higher dosages, but the components intended to improve adhesion to basic surfaces may have lowered the cohesion of the asphalt cement. As dose increased, any improvement in adhesion would be offset by reduced cohesion.

Additive 2. Additive 2 was not intended to be an all-purpose additive but had to have similar chemical characteristics. It produced a pattern of tensile strength ratios very similar to those produced by additives 5 and 6, and the same explanation applies.

Additives 4 and 11. These additives were not chemically stable in asphalt cement but could have contained components which improve adhesion to acidic surfaces. The relationship between the dosage of additive 4 and the tensile strength ratio

indicates that additive 4 contained components that reacted chemically with certain constituents of the asphalt cement, but as dosage increased all of these components did not react because the reactive asphalt constituents had been exhausted, and the additive components became available to improve adhesion. Additive 11 may have reacted with the same constituents or others and failed to improve adhesion because the reactive constituents were not exhausted at the additive dosages investigated.

On this basis, the observed relationships among cationic surfactants appear to be reasonable and understandable. Furthermore, the most useful relationships were observed at normal times and temperatures.

Conclusions

Conclusions to this study of the effects of storage and handling on antistripping additive performance are applicable only to the materials actually tested. If other materials are under consideration, they should be tested rather than assumed to be applicable to this experiment.

High temperatures are not needed to determine antistripping additive effectiveness and may be misleading. Both stable and unstable additives were investigated at high temperatures without increasing moisture damage. The effect of high temperature may be to obscure the true effectiveness of the additive so that an ineffective additive may appear to be effective. For testing, the indication is that the lowest practical temperatures should be used to subject additives to the most severe conditions. With respect to storage and handling of additives in actual construction, none of the high temperature conditions investigated caused moisture damage suggesting that additive effectiveness is not likely to be impaired by construction practices. Rather than high temperatures, normal temperatures appear capable of impairing performance of chemically unstable additives.

Long time periods with an additive in the presence of asphalt cement result in almost the same conclusions as high temperatures for the same reasons. Therefore, for testing, the shortest practical times should be used to subject additives to the most severe conditions. In construction, time periods detrimental to additive effectiveness are not likely to be found provided that the additive is properly and uniformly distributed throughout the asphalt cement.

EXPERIMENTAL PROCEDURES AND TECHNIQUES FOR EVALUATING AND APPLYING ANTISTRIPPING ADDITIVES

There are a number of test methods and practices applying to antistripping additives that are not included in Appendix A because they are experimental in nature and were not a part of the art at the time the state-of-the-art survey was made. The purpose of this section is to describe and evaluate these procedures, and suggest how they might be applied in practice.

Additive Effects on Asphalt Cement

Asphalt Composition and Physical Characteristics

The effects of antistripping additives on asphalt cement have been studied by Anderson (32). Experimental data show that

additives may result in changes in composition and physical characteristics of an asphalt cement sufficient to result in non-compliance with standard specifications. The data also show that each additive produces unique effects on different asphalts. These effects are significant, but no guidance which distinguishes between desirable and undesirable effects is offered. It seems unlikely that changes in composition and physical characteristics of an asphalt cement caused by an additive can indicate whether or not stripping should be expected in a complete mixture, but such data may be helpful if used to supplement results of other tests.

Chromatography

High performance gel permeation chromatography has been used by Jennings to determine the effect of antistripping additives on the molecular size distribution of asphalt cement (33). Gel permeation chromatography employs a solid with pores of known size through which the asphalt, dissolved in a suitable solvent, is passed. Larger molecules are unable to enter the pores and elute first followed by molecules of successively smaller sizes (34). The method has been used to determine molecular weight, but in a complex material, such as asphalt, results may be misleading because molecules of the same size may differ greatly in weight (35, 36). In spite of difficulties, gel permeation chromatography is regarded as a useful tool for studying asphalt composition (35, 36).

Jennings' technique uses treated asphalt cement extracted from mixtures so that the effect of the additive is determined in the presence of both asphalt and aggregate. By comparing the resulting chromatogram with the chromatogram of a known satisfactory asphalt cement, it is possible to judge whether or not the effect of the additive is undesirable. Available data are insufficient to be conclusive but indicate that gel permeation chromatography may prove to be useful in studying additives. However, it is not clear that anything more than the effect of the additive on the molecular size distribution is revealed. Whether or not stripping potential is measured is not known.

Other chromatographic techniques have been used for many years to study asphalt composition. Absorption chromatography methods such as ASTM Method D 4124 employ selective adsorption of asphalt fractions and permit qualitative and quantitative determinations of those fractions (37, 38). Inverse gas-liquid chromatography employs asphalt in liquid form in the chromatographic column through which selected chemicals in gaseous state are passed (39, 40, 41). Evidence that these techniques have been used to study the effect of antistripping additives on asphalt composition has not been found, but their use for that purpose appears possible. It is not clear, however, that the resulting data would be any more useful than data from gel permeation chromatography.

Additive Compatibility Test

The asphaltene settling test developed by Plancher and others at the Laramie Energy Technology Center and Johns Manville Corporation is intended to indicate the compatibility of asphalt components which is regarded as an important property contributing to durability (42). In the test, 2 grams of asphalt are

digested in 50 ml of n-hexane under continuous agitation for 24 hours. The resulting solution is placed in a graduated cylinder, and the height of the meniscus at the top of the asphaltene phase is observed and recorded at 5-min intervals. The test result is the time required to settle a predetermined amount with longer settling times indicative of better asphalts.

If applied to additives, the test could detect potential poor performance in systems that are known to be satisfactory otherwise. For example, other tests might show that an additive is present at the correct dosage and that the additive does adhere to the aggregate. Poor performance, perhaps not stripping, could still occur because of poor compatibility of asphalt components caused by the effect of the additive.

At the present time, the asphaltene settling test is experimental, and the significance of test results is not fully understood. With respect to antistripping additives, it offers the potential of a useful supplement to other procedures that test complete mixtures.

Additive Indicator Tests

Two indicator tests, the bottle test and the color indicator test, as identified in Appendix A, are qualitative only and only show that an additive either is or is not present. Two additive manufacturers have developed indicator tests that are quantitative and intended for use in field laboratories. In addition, there is a chromatographic indicator procedure.

Color Indicator Tests

A procedure based on ASTM Method D 2074 has been simplified to apply only to amines in asphalt cement. In the procedure, about 20 grams of asphalt are dissolved in isopropyl alcohol at 160 to 180 F and agitated thoroughly. The mixture is allowed to cool undisturbed to room temperature, and the liquid is decanted through a filter into a flask. The alcohol extraction is repeated twice, and the filtrates are combined. Titration follows at 150 F using a 0.2 N solution of hydrochloric acid in isopropanol containing 0.2 percent bromophenol blue as the indicating reagent. The end point of the titration is a blue to yellow color in the filtrate. The percentage of antistripping additive is calculated by the following relationship:

$$A_a = \frac{T \times N \times C_n}{W_a}$$

where A_a = percentage of antistripping additive in the asphalt; T = volume of reagent at end of titration, mm; N = normality of HCl; C_n = combining weight of additive; and W_a = weight of asphalt cement, grams.

To use the procedure, the additive manufacturer must furnish the combining weight of the additive. The combining weight is the ratio of the weight of the additive which combines with hydrochloric acid to the weight of hydrochloric acid. Additive manufacturers usually know the combining weight of their additives, and furnishing the combining weight should pose no difficulties.

This procedure appears to be reasonably simple and rapid and probably can be used in field laboratories as intended. When

used with an additive of known composition and known dosage, detection of a smaller dosage would indicate a chemical reaction between the additive and the asphalt cement suggesting that the two should not be used together. Usually additive composition is not known, and even if dosage is known, which would be the case only if introduction of additive into asphalt cement is monitored, detection of a dosage smaller than prescribed shows that something is amiss but fails to pinpoint the source of the problem. Although the procedure offers the advantage of a quantitative determination, like the indicator procedures in Appendix A, it cannot determine that stripping either will or will not occur. Probably its most useful application would be to supplement other tests that examine complete mixtures. For example, a mixture failing the procedure described in Appendix B is judged to be susceptible to stripping, but why it is, is not known. If supplemented with this procedure, it is possible to develop additional information such as wrong additive for the asphalt, wrong dosage, or wrong additive for the aggregate.

Another procedure that has been developed is applicable to any polyamine antistripping additive. In the procedure, 10 grams of asphalt cement are placed in a solution of 80 percent naphtha and 20 percent n-butyl alcohol and dissolved with gentle heating and occasional agitation. Forty ml of this solution is mixed with 20 ml of an extraction solution consisting of 10 percent concentrated hydrochloric acid and 90 percent distilled water treated with sodium chloride in a concentration just sufficient to cause precipitation. After vigorous mixing, the container is left undisturbed to allow the layers to separate. Following separation, the bottom (aqueous) layer is placed in a separate container, and asphalt droplets are allowed to rise to the top of the solution. A portion of the asphalt-free aqueous phase is removed by pipet and adjusted to a pH of 11. N-butyl alcohol is added, and the resulting material is mixed and allowed to settle. Following settlement, the pH is adjusted, and 8 drops of a prescribed detector solution is added and mixed for 1 min. The pH is adjusted again as necessary. If a polyamine additive is present, an intense reddish color will appear in the top layer; if it is not present, the color will be light yellow. A portion of the top layer is removed and diluted with n-butyl alcohol. The color of this test solution is compared with previously prepared standards made from the same asphalt with known additive concentrations to determine the concentration of additive in the test solution.

High Performance Liquid Chromatography

An HPLC procedure for detecting amide amine antistripping additives in asphalt has been developed by Gilmore and others (43). Asphalt cement treated with an antistripping additive is dissolved in a solvent and passed through a chromatographic column under high pressure. This technique was developed to overcome resolution problems in other chromatographic methods associated with the accurate detection of small amounts of additives in asphalt. Determinations may be both qualitative and quantitative. This technique should be useful in a manner similar to the two indicator tests described previously with the added disadvantage that chromatography is not likely to be used in field laboratories. Although only amide amines can be detected, the technique can be used in conjunction with the color indicator procedure which only detects polyamines, to work with a wide range of additives.

Mixture Tests

Water Susceptibility Test

The water susceptibility test, developed by Plancher and others at the Laramie Energy Technology Center, is designed to be a simple test which can find practical application (44). A small compacted specimen of prescribed dimensions is placed on a conical pedestal and subjected to 24 hours freezing at -10°C and 24 hours thawing at 60°C . The number of freeze-thaw cycles to failure, either visible cracks or fracture, is the test result. Simplicity is achieved mostly by using a relatively small sample of compacted mixture containing aggregate sized between the No. 20 and No. 35 sieves. By using this aggregate fraction, the resulting specimen is porous and easily permeated by water. Also, this aggregate fraction is intended to improve repeatability by eliminating most of the heterogeneity found in most asphalt paving mixtures. As a result, fewer specimens are needed. Experimental results correlate well with field experience, and the test is sensitive to asphalts, aggregates, and additives (44, 45).

A modified version of the test has been used by Kennedy at the University of Texas (46, 47, 48, 49). Although only a limited number of mixtures have been studied, the results confirm those of the Laramie group showing good correlation with field experience and sensitivity to aggregates and additives. One Texas innovation is to use the test with individual aggregates in order to determine which mixture component is most susceptible to moisture damage.

The water susceptibility test appears to be helpful in studying moisture damage and additive effectiveness, but additional experimental results are needed before its usefulness can be judged. In particular, criteria for distinguishing between good and poor performance is needed. Even if criteria were established, the test would still present two serious problems. First, because the test uses the No. 20 to No. 35 size aggregates, it cannot evaluate additive dosage. By crushing, this fraction can duplicate the mineralogy of most of a complete mixture. It cannot, however, duplicate surface area, and neither the very large surface area nor the mineralogy of the fraction smaller than No. 35 is tested at all. Because of the relationship between aggregate surface area and additive dosage, the method appears to be incapable of evaluating additive dosage. The relative effect of different additives at the same dosage could be determined, but the best dosage of any one additive for a complete mixture could not. It is possible also, again because of aggregate surface area, that certain asphalts would not be properly evaluated.

The second problem is that the test requires 48 hours for one complete freeze-thaw cycle. Test results on moisture-resistant mixtures require weeks of cycling before they are available. A Texas modification uses a 24-hour freeze-thaw cycle based on experimental data showing no difference between the two cycles, but results still may not be available for weeks (46). An added limitation is that it seems unlikely that the equipment and techniques would be found in field laboratories. At the present time, the water susceptibility test appears to be useful as a supplement to other tests that evaluate entire mixtures and produce results rapidly.

Heat of Immersion

Heat of immersion is the energy released when an insoluble

solid is immersed in a liquid and is proportional to the adhesion between the liquid and the solid (50). Because the energy release on immersion is always small, a very sensitive calorimeter is required for its measurement. A satisfactory microcalorimeter for this purpose has been built and used in limited experiments by Ensley at the Laramie Energy Technology Center (50). The test is run on 5 grams of asphalt and 0.5 gram of aggregate that are held at 150 C for 48 hours. Then the aggregate is dropped into the asphalt, and the immersion energy produced is measured for at least 3 hours.

Experimental data show that measurement of heat of immersion reflects effects of different asphalts, aggregates, and additives. In these respects, heat of immersion appears to be a useful tool based on fundamental concepts for investigating moisture damage and effectiveness of antistripping additives; however, much more experimental verification and satisfactory correlation with field experience is needed before the method can be judged to be applicable in practice. There are two other problems. First, the equipment and techniques seem not likely to be found outside central laboratories. Second, aggregate sized between the No. 35 and No. 48 sieves is used. For reasons noted with respect to the water susceptibility test concerning surface area of selected aggregate fractions, heat of immersion appears to be incapable of evaluating additive dosage.

Nitrogen Analysis

Plancher and others at the Laramie Energy Technology Center have concluded that certain nitrogen containing molecules occurring in asphalt may help to reduce moisture damage in asphalt pavements (51). To investigate this further, the nitrogen analysis procedure was developed. The analysis can be run on aggregates, asphalts, additives, aggregate coated with asphalt with or without additive, and aggregate coated with additives. Only aggregate fractions of the No. 20 to No. 35 sieve size or the No. 60 to No. 80 sieve size prepared by grinding are used. The procedure uses sophisticated, expensive equipment, and very careful techniques are required (45, 51). Briefly, nitrogen is adsorbed on aggregate surfaces, washed with water, and then thermally desorbed by gradual heating to 900 C. Experimental data are recorded on a strip chart to produce a thermogram showing the intensity of nitrogen desorption as a function of temperature. After an opportunity to adsorb nitrogen, little or no desorption indicates an aggregate which does not bond well with asphalt and would be highly susceptible to moisture damage. On the other hand, an intense nitrogen desorption peak at high temperatures indicates a strong asphalt-aggregate bond not readily displaced by water. Experimental results correlate well with field experience, and the procedure is sensitive to different aggregates, asphalts, and additives (45, 51).

Nitrogen analysis is a new approach to moisture damage studies in asphalt paving, and it uses an entirely different approach from other work. No judgment can be made at this time concerning its practical application to moisture damage investigations and additive effectiveness. More experimental results are needed. In the meantime, the method presents the two problems noted earlier with respect to the water susceptibility test and heat of immersion—equipment not suited for field laboratories and selected aggregate size fractions making evaluation of additive dosage impossible. In these respects, nitrogen analysis appears to offer potential as a useful supplement in

central laboratories to other procedures that test complete mixtures and can be used in the field. It may prove to be, however, a more useful supplement than other supplemental procedures because of its potential in simplifying the testing of additives. Compared to the procedure in Appendix B or other procedures that test complete mixtures, nitrogen analysis uses very small samples and may produce definitive results with very few tests. For example, some aggregates have been tested which adsorb nitrogen but allow it to be washed off with water easily. Such aggregates will not be improved by using cationic surfactants. With the usual procedures, one might be faced with testing a long list of additives in a certain mixture. With the help of nitrogen analysis using only pyridine, the decision could be made not to run the conventional tests at all because none of the additives would be effective.

Applying Additives

In conventional practice, three methods of applying additives are used:

1. Cationic surfactants designed to be soluble in asphalt are added to the asphalt cement at some point before the asphalt is injected into the mixture.
2. Pulverulent solids, including hydrated lime, portland cement, and fly ash, are added in dry form to the aggregate.
3. A slurry of approximately 35 percent hydrated lime and 65 percent water is used to pretreat the aggregate before it enters the dryer.

The first two methods are reasonably simple and convenient and frequently are used for those reasons. Pretreatment of aggregate with lime slurry is used in some cases because it is believed to impart better resistance to moisture damage even though it is not so simple and convenient.

At least two manufacturers of cationic surfactants advocate aggregate pretreatment with cationic surfactants. The most promising system would use a cationic surfactant that is soluble in water instead of asphalt. The concentration of additive could be as low as 0.1 percent. This solution would be applied directly to the aggregate prior to drying, and if the additive were heat stable, it would be at the aggregate surface where it can maximize its effectiveness when asphalt cement is added. It is estimated that pretreatment would require about 10 percent of the amount of additive that treatment of the asphalt requires. The advantages of pretreatment with cationic surfactants would be a significant reduction in materials costs perhaps accompanied by improved additive effectiveness.

Aggregate pretreatment is not new. Lime slurry has been used for many years. Silane, which so far as is known has never been used in practice as an antistripping additive, has been investigated and found to be an effective pretreatment chemical (51). Pyridine pretreatment of aggregates, which were then dried at 464 F (240 C) has been found to be more effective than conventional cationic surfactants added to the asphalt (44).

Aggregate pretreatment with cationic surfactants cannot be recommended at this time. Research is needed to show that the system is satisfactory under field conditions of application and service. Means of determining the most effective pretreatment additive dosage and the most effective application procedure

also need to be studied. The potential benefits appear to justify the research.

Application procedures for pulverulent solid additives are also a suitable subject for research. With respect to hydrated lime, questions include: whether to apply dry or slurry; what is the best dosage either way; what, if any, adjustments should be made in the mixture design; if slurry, what, if any, curing or drainage time is needed; and if dry, should lime be applied before or after drying. The same questions apply to fly ash, and all but curing or drainage time for slurry would be applicable to portland cement. While aggregate pretreatment with cationic surfactants offers potentially large materials savings, it does not seem to offer similar savings with solids, another point needing more research.

Conclusions

Investigation of experimental procedures that might be used to evaluate antistripping additive effectiveness has failed to find a procedure that satisfies all of the considerations in Appendix B. None of the experimental procedures is capable of evaluating complete asphaltic concrete mixtures. Each does provide information that may be useful in moisture damage and additive effectiveness studies. In particular, the procedure in Appendix B might show that an additive is ineffective, but it will not show why. One or more of the experimental techniques could then be used to determine why. Only two of the experimental procedures, the color indicator tests described earlier, are intended and considered suitable for use in field laboratories. All procedures, including these two, can be used in central laboratories and provide information useful in supplementing test results from procedures which evaluate complete mixtures.

Procedures for applying antistripping additives that may result in improved additive effectiveness and cost effectiveness have been proposed by additive manufacturers. Questions are raised concerning application of both cationic surfactants and pulverulent solids. Answers to these questions are not available and are beyond the scope of the present research. They are recommended as suitable topics for future research.

CORRELATING AND EVALUATING THE TEST METHOD

The testing procedure in Appendix B was developed because no existing procedure was believed to be entirely satisfactory for evaluating antistripping additives. The procedures described in the previous section are not entirely satisfactory either, although most appear to be useful supplements. The procedure in Appendix B appears to be the most suitable for application to practice, but it still lacks correlation with field experience and its precision is unknown.

Correlating with Field Experience

The chert mixtures used in previous experiments have a history of moisture damage. Experimental data in Appendix B show that the procedure in Appendix B agrees with this experience. The data also show that the testing procedure from *NCHRP Report 192* agrees with this experience (7). Data in

Table C-6 show that the two testing procedures agree with each other on limestone and glacial gravel mixtures, but these mixtures do not have the moisture damage history indicated by the two testing procedures. An explanation for the disagreement between the testing procedures and the moisture damage history of these two mixtures has not been developed. However, there are indications that moisture damage has occurred in these mixtures but has not been interpreted as such in the field.

To obtain better agreement between the procedure in Appendix B and moisture damage experience in the field, it was desirable to use more mixtures that had been studied with respect to moisture damage. Mixtures and pavements reported by Lottman in *NCHRP Report 246* presented an opportunity to correlate the procedure in Appendix B with documented field experience (53).

Laboratory Experiment

Materials. The pavements studied by Lottman were built between October 1975 and March 1977 (53). Six to 8 years later, materials used in the original construction would not be available, but it was believed that materials from the same or comparable sources could be obtained. When contacted, all 7 agencies which had cooperated in the Lottman study agreed to supply materials as close as possible to those used in the original construction and data on the job mix formulas so that the original mixtures could be duplicated as closely as possible. Comparable asphalt cements were perhaps the most difficult because of refinery modifications and closings, and changes in crude oil sources. Even so, Georgia and Virginia supplied samples of the original asphalt, and Georgia supplied a sample of the original additive.

The original Idaho mixture contained 1 percent hydrated lime. The Laramie Energy Center had tested the Idaho materials without lime (45). Therefore, it was decided to include the Idaho materials both with and without lime.

In addition to the mixtures already studied in this project, the Chert-B mixture with additive 1 had not been tested by the procedure from *NCHRP Report 192*. By including this mixture and procedure in the correlation study, a total of 10 mixtures would be investigated.

Test Methods. The test method in Appendix B was used with the mixtures from *NCHRP Report 246*. The test method from *NCHRP Report 192* is the same as the method in *NCHRP Report 246* and was used on Chert-B with additive. The boiling water test, ASTM Method D 3625, was run on six of the mixtures.

Results. Experimental results are tabulated in Appendix E, Table E-1, and summarized in Table E-2. A comparison with results from *NCHRP Report 246* appears in Table 5. Of the eight sets of materials, two do not rank the same at all, and one is questionable.

The FHWA materials ranked second best in Lottman's laboratory predictions and best in the field study (53), but seventh best using the procedure in Appendix B. This discrepancy is attributed to the materials available 8 years after the original construction. The source of the original asphalt cement no longer makes asphalt, and the best that could be done now was to use asphalt from another source thought to be comparable. Lack of the original asphalt may be the principal reason for poor

Table 5. Correlation of test methods.

Material	NCHRP Report 246 (53)		Appendix B		Boiling Water
	TSR	Rank**	TSR, %	Rank**	
ID w/lime	.82	1	81	2	*
FHWA	.63	2	41	7	very slight
MT	.62	3	81	2	very slight
VA	.35	4	81	2	moderate to severe
CO	.22	5	64	5	moderate
AZ	.21	6	45	6	slight
GA	0	7	37	8	severe
GA w/add.	0	7	83	1	*

*not run because of insufficient material.

**in order of increasing moisture damage.

correlation in this case. The Laramie Energy Center found the FHWA asphalt to be the best of those used in the Lottman study with respect to resistance to moisture damage (44, 51). The original aggregates came from a county stockpile, and there is some uncertainty now concerning what the source of aggregate in the stockpile was then. It is also difficult to be certain that the correct job mix formula was used now.

Swell of the FHWA mixture tested here is over 3 percent, by far the largest swell observed throughout this project. All other mixtures that swelled more than 1 percent were found to be seriously damaged by water. The swell of the FHWA mixture is believed to be an indication of a mixture design susceptible to moisture damage and confirmation of the test results.

Georgia materials with additive ranked last in all phases of Lottman's work, but was first using the procedure from Appendix B. In contrast to the FHWA materials, the Georgia materials were from the original sources, and the asphalt cement and additive were samples of the original materials. These same materials were studied by the Laramie Energy Center (45, 51). When all of the data from Lottman and Laramie is studied, there is about as much evidence that the additive was effective as that it was ineffective. Some of the Laramie work shows a very definite, positive effect caused by 0.25 percent additive when the job mix called for 0.50 percent (51). There is a possibility that the dosage used in Lottman's work was incorrect. The reason for the discrepancy with this mixture between the two testing procedures is not known and probably cannot be determined 6 years after the fact. However, there are enough questions in the original data that this discrepancy does not warrant the conclusion that correlation is unsatisfactory.

While FHWA and Georgia with additive materials are completely out of place, the Virginia materials appear to be somewhat higher than they should be when tested by the procedure in Appendix B. The reason for this may be lack of original asphalts from Idaho and Montana which could have produced higher ratios for these two mixtures resulting in the Virginia materials falling into the same ranking as the original Lottman ranking. Also, the field evaluation of the Virginia materials is the most questionable of all in Lottman's study. Virginia's visual evaluations reported severe stripping of the coarse aggregate

only, which is the same stripping observed on these materials in this project, but all others reported stripping ranging from very slight to very severe on entire mixtures. It is difficult to rank Virginia on this basis. Evidence that the Virginia materials were better than indicated by Lottman is also found in the final set of field cores which were the most moisture resistant of all. Considering all evidence, it is concluded that the Virginia results based on Appendix B are not out of line.

The Idaho materials without lime were evaluated by the Laramie Energy Center where it was concluded that this mixture would fall between Montana and Virginia (45, 51). The ratio of 66 using the procedure from Appendix B places it between Virginia and Colorado. For reasons noted in the previous paragraph concerning the Virginia materials, this agreement is considered to be satisfactory.

Using the procedure from *NCHRP Report 192* on the Chert-B mixture with 0.5 percent additive 1 results in a ratio of 71.9 percent. The same procedure and mixture without additive had a ratio of 42.4 percent. When tested by the procedure in Appendix B, the same mixture developed ratios of 99.9 and 50.0 for with and without additive respectively. This is considered to be satisfactory agreement, and it is consistent with all but one of the comparisons between the two procedures which show that the procedure from *NCHRP Report 192* develops the lower ratios.

The boiling water tests do not correlate very well with Lottman's results or with results from the procedure in Appendix B. Results in Table 5 are given in nomenclature comparable to that used by Lottman (53). If rated in accordance with ASTM Method D 3125, FHWA and Montana retained over 95 percent coating, and all others less than 95 percent. Compared to Lottman's ranking, Montana and Arizona rate too high by boiling water. Compared to rankings based on the procedure from Appendix B, FHWA and Arizona rate too high and Virginia too low. All in all, boiling water tests are not very helpful, but they do not negate the apparent correlation between Lottman's field study and the procedure in Appendix B.

Although agreement between Lottman's field study and results using the procedure in Appendix B is not perfect, it is believed that the agreement is about as good as can be expected considering differences in materials after 6 or 8 years, and other factors already noted.

Calculating Degree of Saturation

In the development of the procedure in Appendix B, it was concluded that it is necessary to control the degree of saturation in specimens subjected to moisture conditioning. Originally, degree of saturation was calculated by expressing the volume of water in a saturated specimen as a percentage of the volume of voids in the air dry specimen. This was the basis for calculating degree of saturation in Table C-1. After gaining experience with this procedure, it was observed that most specimens, even at above 7 percent voids, gained only about 1 or 2 grams of water in the saturated surface dry state during the air voids determination. It was concluded that for most practical purposes this water was mostly adsorbed on the surface of the specimen instead of permeating the air voids, and that it should not be included with saturation water. Therefore, the volume of water in a saturated specimen was calculated based on the difference

in weight between the saturated specimen and the saturated surface dry specimen from the air voids determination. This resulted in a revised method for calculating degree of saturation of specimens. The revised method was used in calculating the degree of saturation in Table C-2 and all subsequent work until the correlation data for Table E-1 were prepared.

The mixtures used for correlation absorbed an average of 5 to 6 grams of water in the saturated surface dry state during the air voids determination. It is obvious that most of this water had permeated the air voids rather than simply being adsorbed on the surface of the specimen, and this water should be included with saturation water. The amount of water gained in the saturated surface dry state appears to be a characteristic of each mixture and can vary greatly among different mixtures. Although considering the water gained at the saturated surface dry state as saturation water may tend to overstate the degree of saturation slightly, this error is insignificant compared to the opposite error when significant amounts of water have permeated the air voids at the saturated surface dry state.

For these reasons, the method of calculation of degree of saturation was changed back to correspond to the original calculation, and the saturation data in Table E-1 were recalculated on that basis. In some cases the degree of saturation after saturating, as shown in Table E-1, exceeds the 80 percent limit in the procedure. This is the result of using the revised method of calculation which understated the degree of saturation when the laboratory work was done, and then using the original method for recalculating the values for Table E-1. It is believed that the data reported in Table E-1 are the best representation of the actual condition of the specimens.

To control the degree of saturation, the procedure in Appendix B requires that after saturating by partial vacuum, the degree of saturation must be between 55 and 80 percent. No reason to change these limits has been found as a result of the studies on the method for calculation of degree of saturation. The original method of calculation makes it easier to saturate specimens, meaning that 55 percent saturation can be reached with a lower partial vacuum. Then, the probability of supersaturation is reduced. The revised calculation actually lessens the possibility of creating damage which is not stripping.

Evaluating the Test Method

The test method in Appendix B has been evaluated with respect to its sensitivity to water, different additives, additive dosages, and different asphalt cements. An evaluation of the test method itself is still needed. Such an evaluation attempts to examine the sensitivity of the method to variables within the method to determine the degree of control that should be specified. A complete evaluation could include dimensional tolerances or other details of apparatus, nearly all steps in specimen preparation, and nearly all steps in the procedure. An evaluation of this extent was not considered necessary in this case because much of the method utilizes apparatus and techniques that have already been standardized for use in other methods. Also, there are too many variables that may interact in this type of an evaluation involving moisture damage and additives to be studied within practical limitations of time and cost. A limited evaluation of the method was, therefore, conducted involving the following factors:

1. Compaction method.
2. Time lapse between compaction and saturation.
3. Saturation temperature.
4. Ranges in air voids and degree of saturation.

Additives were not included in the investigation of the first three factors because no influence on additive effectiveness caused by any of these factors, within the ranges studied, was expected or even believed possible.

Compaction Method

The test method allows the use of any one of four methods of compacting specimens. The same four methods are permitted in ASTM Method D 4123, and Lottman used two of them, Marshall hammer and kneading compactor, in his moisture damage studies and concluded that method of compaction did not influence results (53). Although the precedent is there, evidence that the methods of compaction have been compared with each other under conditions free of interlaboratory variability and actually testing the same materials for moisture damage has not been found.

To study compaction method, specimens of Chert-B and limestone mixtures were fabricated using the static load procedure from ASTM Method D 1074 with load adjusted as necessary to yield the desired specimen, and test results from these specimens were compared to results on the same mixtures compacted with Marshall hammer. Experimental data appear in Table E-3 and are summarized in Table E-7. Compared to Marshall compacted specimens, the Chert-B mixture compacted by static load resulted in tensile strength of dry specimens somewhat higher, tensile strength of wet specimens somewhat lower, and lower tensile strength ratio. In these respects the results are not the same; however, the probability that the difference between wet and dry specimens compacted by static load is real is more than 20:1. Specimens compacted by Marshall hammer resulted in the same probability. The conclusion is the same regardless of the method of compaction. The limestone mixture yielded similar results, different tensile strengths and tensile strength ratio, but the same probability that the difference between wet and dry specimens is real, more than 20:1, regardless of the method of compaction.

This investigation of compaction methods is inconclusive because only two methods were studied. The test method was developed based on the thought that test specimens should have certain desirable characteristics. This limited investigation indicates that two different compaction methods produce the required specimens.

Time Lapse Between Compaction and Saturation

When originally drafted, the test method allowed a curing time at room temperature of at least overnight but not more than 24 hours. Overnight was thought necessary to be sure that specimen temperature was reasonably uniform throughout, and 24 hours was simply a practical maximum beyond which no useful purpose would be served. That time lapses this long are needed was questionable, and a shorter time was desirable. To investigate the effect of the time lapse, the opposite extreme was

studied. Compacted specimens had been cooled at room temperature before being extracted from the holds. To cool faster, a stream of room temperature air was blown past the specimens with a fan. When the specimens reached room temperature, they were extracted from the molds and saturated immediately instead of waiting overnight. The total time lapse between compaction and saturation was 1 to 2 hours instead of 16 to 24 hours.

Experimental data in Tables E-4 and E-7 show differences associated with time to cool and saturate in tensile strengths and tensile strength ratios for both mixtures, but in all cases the conclusion that dry and wet specimens are different at a probability of more than 20:1 is the same regardless of the time lapse. Because of this conclusion, the test method was revised to permit rapid cooling and saturation as well as the original time.

Saturation Temperature

The test method allows saturation at room temperature, and places no limits on what this temperature might be. The method is intended to be used in field laboratories and other installations where various room temperatures may be encountered. In addition, when mixtures are difficult to saturate up to the required minimum of 55 percent because of equipment limitations or for any other reason, it was believed that the degree of saturation could be increased by increasing the temperature of the water. Whether or not an elevated water temperature would influence tensile strength if the maximum saturation of 80 percent was not exceeded was not known. To investigate the effects of room temperature variations, a set of specimens was saturated at 65 F and another set was saturated at 100 F. Both sets were then conditioned and tested as usual. To investigate elevated temperatures a third set was saturated at 140 F, and then conditioned and tested as usual.

Experimental data in Tables E-5 and E-8 show that there is no difference between specimens of the same mixture saturated at 65 F and those saturated at 100 F. This temperature range probably includes most room temperatures that might be encountered, and there is no need for additional control in the method. Specimens saturated at 140 F were saturated too much, which shows that the elevated temperature does make mixtures easier to saturate. There is no evidence of damage other than that caused by supersaturation. Therefore, the method was revised to permit water temperatures up to 140 F for saturation.

Voids and Saturation

The test method recommends compacting specimens to approximately 7 percent air voids and suggests that the average air voids for a mixture should be between 6 and 8 percent. It is not clear, however, that specimens compacted to 6 percent voids are comparable to specimens compacted to 8 percent voids. The contention on which the method is based is that such specimens are comparable provided that all specimens regardless of void content are saturated to between 55 and 80 percent. The saturation range was determined experimentally, but the void content range and the possibility of an interaction between void content and degree of saturation has not been studied.

To investigate these factors, a set of specimens of the same

mixture was compacted to about 6 percent air voids, and another set was compacted to about 8 percent air voids. A subset of each set was saturated to about 55 percent, and another subset was saturated to about 80 percent. Moisture conditioning and tensile strength determination followed as usual. A third subset of each set was tested dry. Four different mixtures were tested resulting in the data in Table E-6.

Tensile strengths of dry and wet specimens of like void content of each mixture are compared in Table E-9. Previous data show that the tensile strength of wet and dry specimens of three of the mixtures, Chert-B, limestone, and glacial gravel, is different, and a probability of more than 20:1 that the difference is real was used to conclude that moisture damage was severe. The same conclusion is reached with these three mixtures based on the data in Table E-9 regardless of void content and degree of saturation. The mixture of Chert-B with additive 1 had been found to sustain little moisture damage and produced a probability of less than 10:1 that the strength of dry and wet specimens is different. The same probability is found for three of the comparisons in Table E-9. In the remaining case, Chert-B with additive 1 at low voids and high saturation, the difference in strength between dry and wet specimens is significant at a probability of more than 20:1. In one case out of 16, studying voids and saturation leads to a conclusion contrary to conclusions based on other data.

The influence of voids and saturation on tensile strength ratios is also of interest. Experimental results are in Table E-10. Analysis of variance reveals that the different void and saturation treatments resulted in significantly different ratios for Chert-B and no significant differences for Chert-B with additive, limestone, and glacial gravel. Comparing the effects of individual treatments reveals that in the Chert-B mixture the effects of high and low saturation at high voids are not significantly different, but that all other combinations of treatments produce significant differences. In Chert-B with additive the effects of low and high saturation at low voids are significantly different, and the effects of low voids and low saturation are significantly different from the effects of high voids and high saturation. All other combinations of treatments result in ratios that are not significantly different. With limestone and glacial gravel mixtures, no combination of void and saturation treatments resulted in significant differences in tensile strength ratios.

The improvement in tensile strength ratio resulting from an additive should also be considered. In Chapter Two, a probability of 100:1 was used to show that the improvement in tensile strength ratio caused by an additive is enough to judge the additive effective enough. Data in Table E-11, representing the Chert-B mixture with and without additive, show that two void and saturation conditions lead to the conclusion that the additive is not effective enough, and the remaining six combinations indicate that the additive is effective enough.

The important consideration is whether or not the void and saturation variables affect test results enough to lead to erroneous conclusions. Only two decisions are addressed with all of these data: the severity of moisture damage and the effectiveness of an additive. The effect of voids and saturation on tensile strength ratio in Table E-10 does not bear directly on either of these decisions, but if the data showed no differences in ratios, there would be no reason to expect different decisions because of voids and saturation. The differences among ratios for the Chert-B mixture are enough so that different conclusions could certainly be expected.

In spite of Chert-B, only one conclusion concerning the severity of moisture damage in Table E-9 is questionable. Chert-B with additive at low voids and high saturation indicates severe moisture damage in spite of the additive. That this is caused by voids and saturation is not clear. The mixture had a tensile strength ratio over 90. Rather than conclude that voids and saturation ranges need to be revised, the indication is that the test method and the statistical criteria for judging results still leave room for engineering judgment, which in this case would lead to the conclusion that moisture damage is not too severe and the additive is effective enough.

Two conclusions involving additive effectiveness in Table E-11 are questionable also. The Chert-B mixture without additive at low voids and saturation is involved in both cases. This mixture developed a tensile strength ratio more than 50 percent greater than previous data. That the improved ratio is the result of voids and saturation cannot be determined with a high degree of certainty. However, assuming that the data are correct, the conclusions would not be questionable if this mixture compacted to low void content had been saturated to a high degree. To guard against possible erroneous decisions, a note is being added to the test method advising that specimens of average void

content closer to 6 percent than to 7 percent should be saturated to a level above 70 percent.

Summary

Evaluating the test method shows that large differences in tensile strength and tensile strength ratio may be encountered especially when the evaluation data are compared with previous data. Even so, decision criteria used for various purposes throughout the study show that it is possible to arrive at the same conclusions concerning moisture damage and additive effectiveness within the limits of the variables evaluated. No reason for a major revision of the test method has been found.

Because this evaluation was limited, further evaluation is desirable. Additional compaction methods, kneading compactor and gyratory, need to be studied, and these two along with the two methods studied here should be subjected to more different mixtures. Void and saturation ranges involving different mixtures, and especially mixtures with different additives, warrant more study, and different compaction methods should be included. The other factors studied here, time lapse to saturate and saturating temperature, seem to be conclusive enough and need no further investigation.

CHAPTER THREE

GUIDELINES FOR USING ANTISTRIPPING ADDITIVES

The project statement required the development of guidelines for using antistripping additives in asphaltic concrete paving mixtures based on the results of the previous chapter. Chapter Three presents these guidelines.

VARIABLES IN STRIPPING

Results of the state-of-the-art questionnaire in Appendix A reveal a large number of variables in stripping, antistripping additives, and using additives. Guidelines for using antistripping additives must address these variables. The variables identified in Appendix A are repeated briefly here to place them in the context of guidelines.

Aggregates

Thirty-two agencies relate stripping to one or more of 12 different types of coarse aggregate, and 29 agencies relate stripping to one or more of 11 different types of fine aggregate. It is noted in Appendix A that some of these types should be expected to strip and others should not, but that other agencies do not relate stripping to any of these types. It was concluded that no aggregate type always strips and no aggregate type never

strips. It is also noted in Appendix A that crushing may change the stripping characteristics of some aggregates, and stripping characteristics of any aggregate may change within a single source when operations move from one strata or pocket to another.

Asphalt Cements

Seven agencies relate stripping to low viscosity asphalts, and 12 agencies relate stripping to the source of asphalt cement. In Appendix A it is noted that these relationships are predictable. It is also noted that asphalts seem not to have been studied as extensively as aggregates and probably deserve more attention. In Chapter Two and in Appendix B, the experimental data show that the source of asphalt cement is indeed a significant variable.

Antistripping Additives

Eighteen agencies identified 27 manufacturers of liquid cationic surfactants with 116 approved additives. Four other agencies use none of these but do use one of three pulverulent solids. All of the surfactants are proprietary chemicals and exact com-

position is not known. New surfactants are continually appearing on the market, and old ones are frequently being removed so that the 116 additives identified by agencies may be an incorrect number, but the number of additives is always large. A number of problems in using additives in asphaltic concrete are recognized, and there seems to be no such thing as a foolproof antistripping additive.

Asphaltic Concrete Mixtures

In the total picture, aggregates alone present thousands of variables involving chemical composition, surface area, and crushing history, and asphalt cements offer at least hundreds of grade and source variables. Fortunately, most of these variables are not present when a specified mixture is produced for a given purpose. Even so, neither aggregate source nor asphalt source can be assumed to be constant and always maintain the same stripping potential; therefore, there are aggregate and asphalt variables for each mixture. When one out of a hundred or so additives is added, it is far from certain that that one is best for this mixture, or if it is, that it will continue to be. Experimental data in Chapter Two and Appendix B show conclusively that different additives yield different test results in the same mixture.

Testing

Forty-four agencies reported that one or more of 14 different testing procedures are used for one or more of 5 different purposes involving moisture damage and antistripping additives. Most of the 14 procedures are used by more than one agency, and there are numerous variations in the procedures. With so many procedures and variations in procedures, the number of testing variables may approach the number of materials variables. Furthermore, it seems unlikely that the various procedures can produce the same answer.

A number of additional testing procedures are described in Chapter Two. It is noted that none of these can evaluate additives in complete mixtures. For that reason, their usefulness is limited to furnishing data that may be helpful in supplementing results of other tests.

GUIDELINES FOR USING ADDITIVES

Aggregate Guidelines

When additives are being considered for use, aggregates should be tested with additives in a condition as close as possible to the condition that is expected during actual field application. Gradation is particularly important because of its effect on aggregate surface area, and the relationship between surface area and additive dose. Crushing history is also important because of the change in moisture damage potential which occurs in some aggregates in very short time periods. Often, when job mix formulas are developed, the aggregate's age after crushing is much greater than can be expected during actual pavement construction; consequently, decisions regarding additives made when the job mix formula is developed should be considered to be tentative. Subsequent testing, including during construction,

should be considered to be conclusive only if aggregates are tested within complete mixtures.

Asphalt Cement Guidelines

Like aggregates, asphalt cement should be tested with additives under conditions as close to field conditions as possible. The asphalt grade and source that are expected to be used should be tested at expected field application temperatures. Although grade and temperature may be unlikely to change during construction, source is subject to change for two reasons. First, source is usually a terminal which is serviced by one or more refineries that may not have constant sources of crude oils. Second, contractors may have access to more than one terminal. Consequently, decisions involving additives made at the time the job mix formula is developed should be considered to be tentative. Subsequent testing, including during construction, should not be considered to be entirely conclusive unless asphalt cements are tested within complete mixtures.

Antistripping Additive Guidelines

Testing

For reasons already stated with respect to aggregates and asphalt cement, decisions regarding additives made when the job mix formula is developed should be considered to be tentative, and subsequent testing, including during construction, should be considered to be conclusive only if the additive is tested within complete mixtures.

Prior Approval

The practice of maintaining a list of approved additives appears to be an ineffective means of ensuring additive effectiveness. Prior approval is necessarily based on standard materials (aggregates and/or asphalts) or other factors, including time, that are too far removed from actual construction to be able to account for the actual variables. Also, there are more than 100 additives on the market, and some products are dropped and others added continually. The number of additives and the changes present an overwhelming testing program of dubious actual value.

Storage and Handling

Normal construction practices used by most agencies do not appear to damage good, heat stable additives, but do render unstable additives ineffective. No basis for choosing the best time or point to introduce additives into asphalt cement or asphaltic concrete mixtures has been found. Most agencies use testing conditions that approximate normal construction practices, and these testing conditions appear to be correct.

Testing Guidelines

While agencies have little control over materials variables,

they can control testing variables. One of the most effective means of ensuring additive effectiveness is to use one testing procedure. The procedure in Appendix B was developed in order to be able to accommodate the large number of variables in a timely fashion, and this procedure is recommended for use whenever additives are involved.

No Testing

In Appendix A, it is noted that some agencies decide to use additives with certain aggregates based solely on experience. It is recognized that experience may be a suitable basis for this decision, and experience may also dictate what additive and at what dosage. If, however, what additive and at what dosage are not known, or a new additive is being considered, testing appears to be required. Subsequently, the decision concerning whether or not the additive is effective in the field also requires testing unless a known additive was used, it is known that it was used, and the dosage is known. Therefore, if experience is used, often it should be supplemented with the procedure in Appendix B.

Aggregate Tests

Four testing procedures are identified as "aggregate tests" in Appendix A. These procedures cannot fulfill the requirements of testing when antistripping additives are used for reasons stated in Appendix B, but they can be useful. Their most useful application appears to be in monitoring stripping characteristics of aggregates where the aggregate production allows enough time prior to asphaltic concrete production so that the test result can be used. Monitoring would serve as an early warning that a change is occurring and should trigger a more intense subsequent testing program using the procedure in Appendix B.

Indicator Tests

Two additive indicator testing procedures are given in Appendix A, and three additional indicator tests are described in Chapter Two. Two of the procedures in Chapter Two are quantitative, but otherwise no basis has been found for preferring one procedure over the others. An indicator test may be useful in central laboratory work by screening asphalts and additives for chemical reactions. If an indicator test cannot detect an additive in asphalt cement, perhaps after a prolonged period of storage together at elevated temperatures, further testing by a much more difficult and expensive procedure such as that in Appendix B may serve no useful purpose. Only asphalt and additive combinations which pass the indicator test should be tested further. During construction, changes in asphalt cement which may make a previously effective additive or changes in the additive itself could be detected by indicator procedures. Although the reason for the change will not be revealed by indicator procedures, when changes are indicated, the treated asphalt cement should be rejected until other tests show that mixtures containing it resist moisture damage satisfactorily or that an effective additive can be used.

Boiling Water Test

The boiling water test listed under mixture tests in Appendix A is an ASTM Standard and is intended to be a rapid field test. It can be useful for this purpose by providing early information, either good or bad. Unsatisfactory results of the boiling water test should lead to more intense inspection of aggregates, asphalts, and additives, and more intense testing of mixtures.

Long-Term Effects

Although the procedure in Appendix B is recommended for use whenever additives are involved, at the present time it only serves to indicate short-term performance of additives in the field. There is no known procedure that reliably predicts long-term performance of additives in pavements.

Judging Additive Effectiveness

In Appendix A it is noted that when compacted mixtures are tested by a mechanical test, a variety of limiting indices are used to judge the extent of moisture damage and the effectiveness of additives. In Chapter Two and Appendix B, such indices are not used, and decisions are based on analysis of variance and Student's "t" test. The statistical treatment of data used in Chapter Two and Appendix B is preferred because it takes into account all of the data, the variability in testing, and the individual nature of each mixture. For practical purposes of routine laboratory and field tests, the "t" test is simple and rapid, and can be used. The following decisions must be made:

1. Central Laboratory—whether or not moisture damage is severe enough to consider an additive.
2. Central Laboratory—whether or not a particular dose of an additive is effective enough.
3. Field Laboratory—whether or not the additive in field mixtures is effective enough.

Decision 1

The first decision is reached by comparing tensile strength of dry specimens to tensile strength of wet specimens. In Appendix B a probability of 20:1 or more that the difference between wet and dry specimens is real was used to indicate that an additive should be considered.

Decision 2

The second decision requires two steps. First, the tensile strength of wet and dry specimens containing additive is compared in the same way that specimens without additive are compared for the first decision. Regardless of whether or not the probability exceeds 20:1, the second step still follows. In this step, tensile strength ratios of untreated and treated specimens are compared. Tensile strength ratio needs to be used for this because the data in Chapter Two and Appendix B show that tensile strength may be dependent on the additive. In Chap-

CHAPTER FOUR

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

CONCLUSIONS

The research conducted in this project leads to the following conclusions:

1. Stripping is recognized as a problem in asphaltic concrete pavements throughout much of the United States, and antistripping additives are used widely in an effort to solve the problem.

2. There are a large number of variables involved in stripping and antistripping additives making the problem and its solution very complex.

3. A testing procedure for evaluating antistripping additive effectiveness is needed, and a procedure for that purpose has been developed. Within the constraints of the limited number of materials and conditions that could be investigated, the new procedure:

- a. Has been shown to be sensitive to the effects of water, different additives, additive dosages, and different asphalt cements.
- b. Was used to study the effects of storage and handling on antistripping additive performance and showed that normal construction practices and testing conditions do not impair the effectiveness of heat stable additives but do render unstable additives ineffective.
- c. Correlates satisfactorily with field observations of pavement performance.

SUGGESTED RESEARCH

1. There is no known testing procedure for evaluating long-term performance of antistripping additives. A field study of pavements containing additives is needed to assess their performance and the ability of tests to predict their performance.

2. The testing procedure developed in this project judges moisture damage on the basis of the wet-to-dry strength ratio, similar to practices that have been used with other procedures for 35 or more years. Under this system, a mixture developing a low strength ratio is judged to be susceptible to moisture damage and in need of an additive. Another mixture developing a high strength ratio results in opposite conclusions; yet, the wet strength of the former mixture may be significantly greater than the wet strength of the latter. This raises the question of

which mixture can be expected to perform best. There is a need for research designed to determine the significance of the absolute values of specimen strength and the relationship, if any, between absolute values and wet-to-dry strength ratios.

3. The procedure developed in this project requires specimens compacted to a high void content and control of the degree of saturation. There are other procedures in use which use compacted specimens but both high voids and controlled saturation are not a part of any of them. Although it is believed that one testing procedure should be used by all, it is not realistic to assume that all other procedures will be abandoned. It is believed that all other procedures using compacted specimens would be improved by compacting to high void content and controlling degree of saturation. There is a need for research designed to investigate these two points in other procedures and determine how the resulting modified procedures correlate with the procedure developed in this project.

4. Testing for moisture damage and additive effectiveness requires testing complete mixtures. The procedure developed in this project does this, and it is simpler and more rapid than other procedures which test compacted mixtures. Even so, the NCHRP Project 10-17 procedure is time consuming, somewhat expensive, and may involve testing many specimens. There is a need for other simpler and more rapid tests to supplement the NCHRP Project 10-17 procedure and reduce testing frequency. Aggregate tests, indicator tests, and boiling water tests identified in this project may do this, but at present there are too many of these tests and no way of knowing which are the most useful. Research is needed to determine which tests are the most useful and reliable supplements to the NCHRP Project 10-17 procedure.

5. NCHRP Project 10-17 was assigned to study the use of antistripping additives in asphaltic concrete. Other solutions to stripping problems were not studied. In particular, adjusted mixture designs may be equally as effective as additives in preventing moisture damage. Research is needed to determine how effective adjusting mixture design is compared to additives, and which is the most cost effective.

6. Additives, both liquids and powders, are usually added to mixtures by the most convenient method available. Other, perhaps less convenient methods have been used at times, and still others have been proposed. One proposal, aggregate pretreatment with cationic surfactants, offers the potential of a very effective antistripping treatment which is also unusually cost effective. Research is needed on ways of applying additives.

ter Two a probability of 100:1 or more that the difference between treated and untreated specimens is real was used to show that an additive is effective enough.

Interpretation of the results from the two steps involves the four possibilities listed in Table 6.

In Case 1, comparing the wet and dry specimens containing additive shows that moisture damage is not severe, but comparing the ratios of treated specimens to untreated shows that the additive is not effective enough. This contradiction could be caused by a number of reasons, but the most probable cause is incorrect additive dosage. The indication is that the same mixture should be tested at another dosage.

In Case 2, the wet- and dry-treated specimens again show that moisture damage is not severe, and the comparison of ratios between treated and untreated specimens shows that the additive is effective enough. There is no contradiction here, and the conclusion is that the mixture with additive can be used. Even so, the possibility of an even more effective dosage of the same additive, a different and more effective additive, or a redesigned and more moisture resistant mixture should not be ignored.

In Case 3, the wet and dry specimens indicate severe moisture damage in spite of the additive, and the comparison of ratios between treated and untreated specimens shows that the additive is ineffective. There is no contradiction here, and the conclusion is that this mixture should not be used with this additive at this dosage. The solution here could include all of the possibilities noted in Case 2.

In Case 4, the wet and dry specimens indicate severe moisture damage in spite of the additive, but the comparison of ratios between treated and untreated specimens indicates that the additive is effective. This contradiction is most likely with mixtures having poor resistance to moisture damage without additive. Such mixtures can be improved enough so that the additive appears to be very effective simply because there is so much room for improvement. However, further improvement is desirable and probably necessary. Again, the solution could include all of the possibilities noted in Case 2.

Decision 3

The third decision is reached by comparing the tensile strength of wet and dry specimens of field mixtures. Tensile strength rather than tensile strength ratio must be used because mixtures without additive would not, or at least should not, be produced in the field. Field mixtures without additive can, of course, be tested also. There may be a temptation to compare tensile strength ratio of the field mixture with the ratios of the previously determined treated and untreated laboratory mixtures. These comparisons are not recommended because of materials variables and interlaboratory variability. The question of how much difference should be expected between wet and dry field specimens has not been addressed in previous chapters. In any case, if the additive is effective, there should be little difference. If dry specimens are stronger than wet specimens, a probability of less than 10:1 that the difference is real is suggested for this purpose. If wet specimens are stronger, there is no moisture damage and no need for the calculation.

Appendix F illustrates the use of the "t" test for judging additive effectiveness. A format is used for the calculations, and a graphical solution of "t" probabilities based on standard sta-

Table 6. Judging additive effectiveness—central laboratory.

	Probability that Wet and Dry Specimens Are Different (Step 1)	Probability that Additive Is Effective (Step 2)
Case 1	less than 20:1	less than 100:1
Case 2	less than 20:1	more than 100:1
Case 3	more than 20:1	less than 100:1
Case 4	more than 20:1	more than 100:1

tistical tables is provided (30). The procedure in Appendix F is intended for those not accustomed to statistical calculations. Those familiar with statistics will readily recognize further simplifications that can be used.

Limiting Indices

The alternative to the "t" test for judging additive effectiveness is a limiting index or a ratio comparing wet and dry strengths. Such practices seem to have originated with the index of retained strength in the immersion-compression test in 1947 (23). After 35 years, data in Appendix A show a wide variety of such indexes in use. Limiting indexes range from 40 to 85 for immersion-compression, from 70 to 75 for Marshall stability, and from 60 to 75 for tensile strength. Although some of the differences among limiting indexes may be caused by variations in testing procedures, and some by peculiarities of local materials, it is unlikely that the several indexes will lead to the same decisions concerning moisture damage and additive effectiveness.

An example of how limiting indexes may lead to different decisions and be misleading is the limestone mixture using additive 2. Data in Appendix D show that without additive this mixture has a tensile strength ratio or index of 61.1. If a limiting index of 60 were being used to decide whether or not an additive should be tried, the test result of 61 would lead to the decision that an additive need not be considered. On the other hand, if the limiting index were 65, the opposite decision, that an additive should be tried, would prevail. Both cannot be correct. The statistical approach in Appendix F leaves no doubt that an additive should be tried. Then, when 0.5 percent additive 2 was used in this mixture, data in Appendix D would reveal an index of 78.8. If a limiting index of 80 were used to judge whether or not the additive is effective enough, the decision would be that the additive is ineffective, but if the limiting index were 75, the decision would be that the additive is effective enough. Statistics in both Appendixes D and F show that the additive is effective but that moisture damage will still occur.

Although statistical analysis is preferred over arbitrary limiting indexes, some hazards remain in the statistics. The three probability levels suggested for use with the "t" test are equally as arbitrary as the various limiting indexes used in practice. Also, experimental data collected to date are not comprehensive enough to apply the statistical concept with confidence to all circumstances.

The desirability of using a single testing procedure has been emphasized previously. A single procedure for judging additive effectiveness is equally desirable. The procedure in Appendix F has been developed to provide a rational approach to judging additive effectiveness, and its use is recommended.

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APPENDIX A

STATE OF THE ART

FINDINGS

The questionnaire (Exhibit A-1) used to determine the state of the art of the use of antistripping additives in asphaltic concrete was circulated in April 1981, and it is intended to reflect the situation at that time. It is realized that responses to the questionnaire may have been different if it had been circulated at a later date. No attempt has been made to keep up with running changes. The responses are believed to have been accurate and correct at the time they were made, even though changes may have occurred a few months later.

Response to the questionnaire is considered to be excellent. Questionnaires were sent to all 57 members of AASHTO's Sub-

committee on Materials and 9 other agencies. Replies were received from 56 AASHTO members and 7 others. Eleven of 19 asphalt cement producers who were contacted replied. Initially, 4 additive manufacturers were contacted, and all four responded. Later there were additional contacts with manufacturers. Finally, trade associations were contacted, all at their request, but only one, The Asphalt Institute, responded. Altogether, of the 93 questionnaires that were circulated, there were 81 responses. Most of the following analysis of replies comes from the 63 AASHTO members and other agencies. Perspectives of asphalt producers and additive manufacturers are different from the agency perspective as well as from each other, but are, nevertheless, valuable in their own way.

Exhibit A-1

QUESTIONNAIRE

NCHRP Project 10-17

"Use of Antistripping Additives in Asphalt Concrete Mixtures"

Responding Agency _____

Return to:

Person Name _____

D. G. Tunnickliff

Completing Title _____

9624 Larimore Ave.

Form _____

Omaha, NE 68134

Office Address _____

City _____ State _____ Zip Code _____

Office Telephone _____

1. Have you identified stripping problems in any of your bituminous mixtures in the last five years? Yes _____ No _____.
2. Do you have a test to measure the stripping potential of your bituminous mixtures? Yes _____ No _____.
3. Do you use antistripping additives in your mixtures currently? Yes _____ No _____.

If the answers to the three previous questions were No, it is not necessary to complete the questionnaire. However, if you feel that you have information that will aid in the successful completion of the project, please continue.

If any of the above questions were answered yes, please continue.

4. If you use antistripping additives in any of the following mixtures, what was the approximate production in tons of mixtures in 1980?

	Dense Graded		Open Graded	
	Total 1980 Production, tons	Production, with Additive, tons	Total 1980 Production, tons	Production, with Additive, tons
Base	_____	_____	_____	_____
Binder/Leveling	_____	_____	_____	_____
Surface	_____	_____	_____	_____

5. What has been your experience with antistripping additives?
generally favorable _____ partly favorable _____ generally unfavorable _____ no opinion _____

NCHRP Project 10-17

Questionnaire Page 2

6. If your research, testing, or field performance evaluations have identified stripping problems, have you been able to relate stripping to:

- a. Coarse Aggregate Type? Yes _____ No _____.

If yes, indicate type(s): gravel _____; limestone _____; slag _____; sandstone _____; granite _____; rhyolite _____; traprock _____; other _____

- b. Fine Aggregate Type? Yes _____ No _____.

If yes, indicate type(s): natural sand _____; manufactured sand _____; screenings _____; and if manufactured sand or screenings, indicate origin: gravel _____; limestone _____; slag _____; sandstone _____; granite _____; rhyolite _____; traprock _____; other _____

- c. Aggregate source? Yes _____ No _____.

If yes, list source(s) and type(s): _____

- d. Asphalt Grade? Yes _____ No _____.

If yes, list grade(s): _____

- e. Asphalt Source? Yes _____ No _____.

If yes, list source(s): _____

- f. Aggregate Gradation? Yes _____ No _____.

If yes, please explain: _____

- g. Field Compaction? Yes _____ No _____.

If yes, please explain: _____

- h. Time of Construction? Yes _____ No _____.

If yes, please explain: _____

- i. Other? Yes _____ No _____.

If yes, please explain: _____

7. How do you determine whether or not to use an antistripping additive in dense graded mixtures?

a. Experience? Yes _____ No _____.

If yes, what procedures and criteria are used? _____

b. Laboratory tests on (please check all applicable answers and indicate AASHTO, ASTM, or in-house test method):

Aggregate _____ Method _____

Asphalt _____ Method _____

Asphalt & Coarse Aggregate _____ Method _____

Mixture _____ Method _____

If in-house procedure or modified AASHTO or ASTM method is used, please identify and attach copy of procedure. _____

c. What criteria, such as index of retained strength, and numerical values are used with test results to determine that:

i. there is a stripping problem? _____

ii. an additive should be used? _____

iii. the additive is effective? _____

d. In addition to the above tests and criteria, what other considerations are used? _____

8. How do you determine the dosage of antistripping additive in dense graded mixtures?

a. Manufacturer's recommendation? Yes _____ No _____.

b. Experience? Yes _____ No _____.

c. Test various dosages by method in question 7? Yes _____ No _____.

d. Other? _____

9. Do you have a procedure for determining that the correct dosage of additive is used on field projects? Yes _____ No _____.

If yes, how? Field test _____ (please attach copy of method)

Monitor addition of additive to asphalt _____

Other _____

10. Do you require heat stable antestripping additives? Yes _____ No _____.

a. If yes, how is heat stability determined?

i. Certified by manufacturer _____

ii. AASHTO or ASTM test Method No. _____

iii. In-house method _____ (please attach copy of method)

b. What construction controls are used to insure heat stability and additive effectiveness?

i. Point additive is incorporated into asphalt cement or mixture: _____

ii. Length of time additive may be incorporated into asphalt cement prior to introduction into mixture: _____

iii. Temperature of additive: _____

iv. Temperature of asphalt cement: _____

v. Mixing temperature: _____

vi. Mixing time: _____

vii. Mixture storage temperature: _____

viii. Mixture storage time: _____

ix. Other: _____

x. None (meaning construction controls are the same with or without additives): _____

11. Do you have a procedure for determining the effectiveness of antistripping additives on field projects? Yes _____ No _____.

If yes, please describe: _____

12. Do you maintain a list of approved antistripping additives? Yes _____ No _____.

Approved additive manufacturers? Yes _____ No _____.

Please attach copy of current approved list(s).

On what basis were these additives and/or manufacturers approved? _____

13. If different from the list(s) applicable to question 12, please attach list of brand names and manufacturers of antistripping additives known to have been used in your pavements in recent years.

Pattern of Use

The first three questions in the questionnaire were designed to promote a good return since respondents without stripping problems only needed to answer these three. If the respondent had not identified stripping problems recently, did not test for stripping, and did not use antistripping additives, no further reply was required. Responses to these questions also provided information on where additives are used. Question 4, which asked for approximate tonnage of mixtures containing additives, provided information on the intensity of additive use. Responses to this question were not entirely definitive, and it was necessary to classify intensity into broad categories. Question 4 also identified the use of additives in open-graded mixtures. For purposes of this investigation into the use of additives in asphaltic concrete, agencies using additives only in open-graded mixtures were classified as not using additives.

The geographic distribution of antistripping additive use in asphaltic concrete and the intensity of use in the United States and Canada are depicted in Figure A-1. Intensity of use was classified as follows:

- **Heavy**—Antistripping additive used in all or nearly all asphaltic concrete base, binder, and surface mixtures.
- **Much**—Antistripping additive used in a major proportion of all asphaltic concrete mixtures, or in all mixtures of a certain type, such as all base mixtures.
- **Some**—Antistripping additive used in a relatively small proportion of asphaltic concrete mixtures.
- **Little**—Antistripping additive used in less than 10 percent of all asphaltic concrete mixtures.
- **Rare**—Antistripping additive used only under special circumstances.

Four states classified as antistripping additive users in Figure A-1 use only hydrated lime, fly ash, or portland cement for antistripping additives. All four have identified stripping problems in their pavements and use these additives rather than liquid additives in asphalt cement.

Experience Evaluation

Question 5 asked each agency to evaluate its own experience with antistripping additives. The 32 agencies using additives in asphaltic concrete responded as shown in Table A-1. There appeared to be little, if any, relationship between experience evaluation and intensity of use. For example, two heavy users were generally favorable and two were partly favorable, while three "little" users were generally favorable and four were partly favorable.

Factors Related to Stripping

Question 6 asked agencies to identify factors with which stripping had been related by the agency's research, testing, or field performance evaluations. Altogether, 42 agencies responded to this question. Some of these agencies do not have stripping problems and do not use antistripping additives, but they have related stripping to certain factors which they reported.

Coarse Aggregate

Coarse aggregate is related to stripping by 32 agencies. Coarse aggregate types were identified with the frequency indicated in Table A-2. Each agency identified all aggregate types related to stripping, which in most cases was more than one. In addition to aggregate types, clay coatings on aggregates, rounded aggregates, and lack of fractured faces were cited twice each. All of this applies to gravel, but it relates stripping with gravel only under certain circumstances.

Table A-1 Experience using antistripping additives.

<u>Experience Evaluation</u>	<u>Number of Agencies</u>
Generally Favorable	20
Partly Favorable	10
Generally Unfavorable	1
No Opinion	1

Table A-2 Stripping of coarse aggregate.

<u>Aggregate Type</u>	<u>Number of Agencies</u>
Gravel	25
Limestone	12
Granite	12
Rhyolite	6
Traprock	6
Slag	4
Sandstone	4
Quartzite	3
Novaculite	1
Seyenite	1
Obsidian	1
Gneiss	1

Fine Aggregates

Twenty-seven agencies related stripping to fine aggregate. Aggregate types were identified with the frequency shown in Table A-3. Each agency identified all fine aggregates related to stripping; consequently, totals exceed 27.

Five agencies related stripping to fine aggregate but not coarse aggregate, and 10 agencies related stripping to coarse aggregate

but not fine aggregate. Seventeen agencies related stripping to both coarse and fine aggregate of the same type. For example, one agency related stripping to gravel, limestone, granite, and rhyolite coarse aggregates, and natural sand and manufactured sand made from limestone, granite, and rhyolite.

Aggregate Source

Twenty agencies related stripping to aggregate source. No significance is attached to the fact that the remaining 22 agencies did not because these respondents may have considered aggregate source and type to be the same. Of those who did relate stripping to aggregate source, some offered only general relationships such as nearly all sources used for asphaltic concrete aggregates. Others pointed to specific geologic formations, and a few identified specific quarries or gravel pits. One agency identified certain quarries in a neighboring state which reported stripping problems with its own aggregates. Another agency identified aggregate sources in two neighboring states, neither of which reported stripping problems in their own pavements.

Aggregate Gradation

Aggregate gradation was related to stripping by 10 agencies. Four reported the relationship with coarse-graded mixtures, one with oversanded mixtures, one with excess minus No. 200, one with excess minus 5 microns, and the other three mentioned high voids or open gradings. One agency which related stripping with aggregate gradation (oversanded) did not relate stripping to other aggregate factors: coarse aggregate type, fine aggregate type, and aggregate source.

Asphalt Grade

Low viscosity asphalt cement was related to stripping by 8 agencies. One agency reported that only one grade, AC-20, is used and that there are stripping problems. The latter response deserves some emphasis because replies to this question indicate that low viscosity asphalt cement may be more likely to strip, not that the higher viscosity grades do not strip.

Asphalt Source

Twelve agencies related stripping to the source of asphalt cement. Of these, 8 agencies reported that investigations into asphalt source were either incomplete or inconclusive, but left no doubt that in their opinion a relationship exists. Four agencies were able to point to asphalt cement from specific refineries with stripping characteristics different from other asphalt cements. One agency asked whether or not a constant or uniform source of asphalt cement exists in 1981. Another provided a partial answer by pointing out that the stripping characteristics of asphalt cement from a specific source had changed dramatically recently.

Seven of the 8 respondents who related stripping to low viscosity asphalt cement also related stripping to the source of asphalt cement. One agency relating stripping to both asphalt

Table A-3 Stripping of fine aggregate.

<u>Aggregate Type</u>	<u>Number of Agencies</u>
Natural Sand	20
Manufactured Sand	16
Screenings	3
Natural Sand and Manufactured Sand or Screenings	9
<u>Parent Materials</u>	
Gravel	20
Limestone	7
Granite	7
Rhyolite	4
Slag	3
Sandstone	2
Quartzite	2
Traprock	1
Novaculite	1
Obsidian	1
Gneiss	1

grade and source also related stripping to aggregate gradation but not to type of either coarse or fine aggregate. One also related stripping to fine aggregate type and aggregate gradation but not coarse aggregate type. The remaining 10 agencies relating stripping to asphalt source also relate stripping to type of both coarse and fine aggregate, and three of these also relate stripping to aggregate gradation.

Field Compaction

Sixteen agencies relate stripping to the degree of compaction achieved in the field during construction, and four others suspect a relationship. In all cases, high levels of voids in the field are considered to promote stripping, but information on what level of voids is needed to prevent stripping was not obtained. All agencies relating stripping to field compaction, also relate stripping to at least one other factor.

Time of Construction

Construction in late fall is related to stripping by 13 agencies, and a relationship is suspected by two others. Damp aggregates, cool weather, and damp weather which can be present in late

fall as well as other times of the year were also noted. Only two respondents related late fall construction with high voids. Two respondents noted that an adequate traffic seal which might prevent the entry of water does not develop with late fall construction. All respondents relating stripping with time of construction also relate stripping to at least one other factor.

Other Factors

A number of items mentioned by respondents under this category have been reclassified into the categories already listed above. Four items remain: asphaltic concrete overlays on old portland cement concrete pavements, moisture vapor in arid climates, the use of a drum dryer-mixer plant, and an antistripping additive which was incompatible with the asphalt cement. In all cases, these responses are understood to mean that the same mixture would not be expected to strip under any other circumstances. All respondents noting items under this category also relate stripping to at least one other factor.

Testing for Moisture Damage and Additive Effectiveness

Responses to Questions 7 through 11 revealed that several testing procedures are used to measure moisture damage and additive effectiveness. All of these tests are described briefly in this section, and specific applications are identified later.

Aggregate Tests

These procedures are used mostly for testing stripping tendencies of coarse aggregate. There are four procedures in this group.

Static Immersion. The static immersion test is AASHTO Method T 182, ASTM D 1664, or a modification. The $\frac{3}{8}$ in. to No. 4 fraction of coarse aggregate is mixed with 5.5 percent asphalt cement at 275 F to 300 F and immersed in distilled water for 16 to 18 hours. The asphalt coating is observed visually and estimated to be either above or below 95 percent. This is the only procedure in this group which has been standardized by a national organization. Modifications include the size of the aggregate tested, the use of a curing period before immersion, and the temperature and time of immersion.

Criteria used to evaluate coating includes 95 percent by 5 agencies, 90 percent by 2 agencies, and 70 percent by 1 agency.

Dynamic Immersion. These procedures are similar to static immersion procedures through the soaking period in distilled water. Then the specimen is agitated violently. Agitation is provided in various ways including rotation, paint shaker, or malted milk mixer. Time of agitation ranges from 5 to 30 min. Following agitation, the specimen is usually washed to remove loose coatings, and the retained coating is estimated visually as in static immersion. In one case coating is measured by weight loss.

Criteria used to evaluate coating includes 95 percent, 90 percent, and 65 percent by one agency each.

Boiling Water. Boiling water tests are applied to coarse aggregate fractions such as are used in static immersion. In some cases, mixtures are prepared, allowed to cure at room temperature, and then immersed in water which is brought to a boil and held for a short period of time such as one minute. Coating is estimated as in static immersion. In other cases, mixtures are prepared and while still hot are immersed in water that is already boiling, where they are held for a relatively long period of time, such as 10 min. Variations in evaluating coating include pouring the water off, rinsing the specimen, and placing the specimen on a paper towel for evaluation.

Two agencies require 100 percent coating and one compares coating to two reference aggregates, one representing good coating and the other stripping.

Tracer Salt. In the tracer salt method (21), a coarse aggregate fraction is impregnated with the tracer salt, coated with asphalt, and soaked in distilled water for 16 to 18 hours. After soaking, the concentration of tracer salt in the water is determined by flame photometry, and stripping is estimated by comparison with the concentration found in a blank sample using uncoated aggregate.

Additive Indicator Tests

The aggregate tests listed above can be used to indicate the presence of an antistripping additive in asphalt cement. Two other procedures are also used for this purpose and are as follows.

Bottle Test. In the bottle test, the asphalt cement is cut back by blending with naphtha or a similar diluent. Ottawa sand is placed in a container and covered with distilled water. The cutback asphalt is added and the container is shaken vigorously for several seconds. The contents are poured out and examined visually. If an effective antistripping additive is present, the sand and asphalt will be uniformly mixed. If the additive is not present, the wet sand and asphalt will not mix.

Color Indicator. In the color indicator test, a sample of asphalt cement is placed in isopropyl alcohol. Bromophenol blue indicator is added in a quantity sufficient to bring pure isopropyl alcohol to a yellow color, at which point the test sample should be green or dark blue if an antistripping additive is present.

Mixture Tests

Complete mixtures are tested by one procedure using loose mixture and by 7 procedures, with numerous variations, using compacted specimens.

Boiling Water. This procedure is ASTM Method D 3625 applied to specimens of loose mixture, or modifications similar to those used for testing aggregates. A coating of 95 percent is required to be acceptable.

Swell and Absorption. Two swell tests on compacted mixtures are used. One determines swell on the basis of changes in specimen height occurring during moisture conditioning, and the other uses volume change during moisture conditioning. Absorption is determined on the basis of weight change during moisture conditioning.

Swell and absorption tests are used to supplement other tests. Specific criteria based on swell or absorption to determine whether or not an additive is needed or effective are not used. Instead, what is considered to be excessive values of either is cause for further examination by other means.

Abrasion Tests. Compacted specimens are moisture conditioned by one of two procedures. One uses soaking in distilled water at 120 F for 6 days, and the other uses soaking at room temperature for 20 hours followed by 5 hours at 100 F. Conditioned specimens are subjected to violent abrasion under water for specified times at specified temperatures, in one case ice water. Water damage is evaluated by determining weight loss caused by abrasion.

Immersion-Compression. This procedure is the only one using compacted specimens which has been standardized, AASHTO Method T 165 or ASTM Method D 1075. Specimens, usually 4 in. in diameter and height, are prepared according to prescribed procedures and compacted using the double plunger technique. Specimens are sorted into two groups of approximately equal bulk specific gravity. One group is moisture conditioned by soaking in distilled water at 120 F for 4 days. An alternate procedure in the standard method uses soaking in distilled water at 140 F for one day. Both groups of specimens are tested in unconfined compression at a low rate of strain, 0.05 in./min/in. of height. Moisture damage is estimated by calculating the ratio of the strength of the moisture conditioned group to the strength of the unconditioned group and expressing the ratio as a percentage called the index of retained strength.

Modifications of this procedure include compaction by kneading compactor and vacuum saturation before moisture conditioning by soaking at 140 F for one day.

Criteria for acceptable indices range from 40 to 85 percent.

Other procedures in this group are similar in that all compare a mechanical property of moisture-conditioned specimens to unconditioned specimens. Variations include methods of preparing, saturating, and moisture conditioning specimens, and the mechanical property that is measured.

Marshall Immersion. The usual procedure uses standard Marshall specimens, 4 in. in diameter by 2.5 in. in height, compacted by Marshall hammer. Moisture conditioning is by soaking in distilled water at 140 F for one day. Marshall stability of conditioned and unconditioned specimens is determined, and moisture damage is estimated on the basis of the ratio of the two.

There are numerous modifications. One is compaction by double plunger using the immersion-compression procedure. Another is vacuum saturation of specimens before moisture conditioning with vacuum applied after immersion in some cases and before immersion in others. A pressure of 30 mm Hg or less is usually used for one hour. Another modification is random grouping of conditioned and unconditioned specimens instead of grouping based on specific gravity. A final modification is testing unconditioned Marshall specimens at 140 F obtained in an air bath instead of a water bath.

An acceptable index of 75 percent is required by 4 agencies and 70 percent by 4 agencies.

Tensile Splitting. Indirect tensile strength is used in two distinctly different procedures. The procedure developed by Jimenez (6) employs specimens 4 in. in diameter by 2.5 in. in height compacted by kneading compactor. Specimens are vacuum saturated with a vacuum of 20 in. Hg for 5 min to assure

the development of pore water pressure. Saturated specimens are moisture conditioned further by soaking at 122 F and applying a pressure pulse to the water varying from 5 to 30 psi 580 times per minute for an unspecified period of time. Tensile strength at 77 F is determined by a double punch system applied to the horizontal faces at 1.0 in./min.

The Lottman (7) procedure uses specimens 4 in. in diameter by 2.5 in. in height compacted by a kneading compactor to approximate the void content expected in the field. Specimens are vacuum saturated with a vacuum of about 26 in. Hg for 30 min. Moisture conditioning is by either a thermal cycle from 0 F to 120 F to 0 F on an 8-hour cycle for 6 days, or freezing at 0 F for 15 hours followed by soaking at 140 F for 24 hours. Indirect tensile strength is determined at either 55 F or 73 F by applying diametral loads at 0.065 in./min or 0.150 in./min respectively. Moisture damage is estimated by calculating the ratio of the tensile strength of conditioned specimens to that of unconditioned specimens.

Modifications are used in all parts of the procedure. Specimens are compacted by Marshall hammer with effort adjusted to yield field levels of voids. Vacuum-saturated specimens are moisture conditioned by soaking at 140 F for 24 hours. Testing uses a strain rate of 0.2 in./min at 77 F in one case, 2.0 in./min at 77 F in another, and 2.0 in./min at 140 F in a third.

Four agencies require a tensile strength ratio of 0.70, one requires 0.75, and one requires 0.60.

Resilient Modulus. This procedure was also developed by Lottman and through moisture conditioning uses the same procedure as tensile splitting (7). Resilient modulus is determined by using the Schmidt apparatus and procedure (22). Moisture damage is expressed as the ratio of the resilient modulus of conditioned to unconditioned specimens.

Hveem Stability. Compacted specimens prepared by kneading compactor for Hveem stability testing are moisture conditioned by water vapor generated in an oven at 140 F for 75 hours. Hveem stability of the conditioned specimens is determined, and moisture damage is judged by comparison with Hveem stability of unconditioned specimens.

Application of Testing Procedures

The testing procedures described above are used for the purposes given in Table A-4. The data show that most testing is performed to determine the need for an additive, and complete mixtures are most often tested.

Determination of Additive Need

Question 7 asked how the need for an antistripping additive was determined. There were 43 responses to this question including some agencies who do not use antistripping additives but do have procedures that would determine the need for an additive if one were needed.

Experience. Twenty agencies reported that experience is used to a certain extent to determine whether or not an antistripping additive is used. Of these, 8 agencies noted experience with

Table A-4 Application of test procedures.

Procedure	Number of Agencies Using Procedure to Determine Additive				
	Need	Dose	Pres-ence	Heat Sta-bility	Effec-tive-ness
Aggregate Tests					
Static Immersion	9	1	-	3	-
Dynamic Immersion	7	-	-	-	-
Boiling Water	3	-	-	5	3
Tracer Salt	1	-	-	-	-
Total	20	1	0	8	3
Additive Indicator Tests					
Bottle Test	-	1	1	3	2
Color Indicator	-	1	1	-	1
Total	0	2	2	3	3
Mixture Tests					
Immersion-Compression	16	9	2	-	5
Marshall Immersion	10	7	2	2	2
Tensile Splitting	8	4	-	-	3
Abrasion	3	1	-	-	-
Hveem Stability	1	1	-	-	-
Resilient Modulus	1	-	-	-	-
Swell and Absorption	3	-	-	-	-
Boiling Water	2	2	3	2	2
Total	44	24	7	4	12

certain aggregates or mixtures, and 7 agencies related experience with interpretation of test results. Five use antistripping additives in certain mixtures as a matter of policy because experience has shown that the additives are needed. Subsequent testing is used to assess potential moisture damage in mixtures containing additives but not to determine whether or not an additive will be used.

Aggregate Tests. Aggregates are tested by 18 agencies to determine the need for antistripping additives. Six use no other test. The tests are given in Table A-4. Two agencies use two of these tests.

Mixture Tests. Thirty-six agencies test asphaltic concrete mixtures to determine whether or not additives are needed. Of these, 24 use no other test. The procedures are given in Table A-4. Three agencies use both immersion-compression and tensile splitting, and one also uses resilient modulus. Another uses both surface abrasion and Hveem stability.

Determination of Additive Dosage

Question 8 asked how the dosage of antistripping additive was determined. Thirty-five replies indicated that 4 agencies rely on experience only, 3 agencies rely on manufacturer's recommendation, and 3 agencies rely on both. The remaining 25 agencies use the testing procedures given in Table A-4. Two agencies which use tests also rely on experience, two also rely on manufacturer's recommendation, and four also rely on both.

Checking Additive Dosage in the Field

In response to Question 9, 18 agencies reported that procedures are used to determine that the correct dosage of additive is used on actual projects. Ten agencies monitor the addition of the additive to the asphalt cement, and one requires certification of additive dosage from the asphalt cement producer.

Nine agencies use the testing procedures given in Table A-4. Two agencies monitor and also use one other procedure.

The monitoring reported was the use of in-line blenders equipped with calibrated additive dispensers that can be checked regularly by inspectors.

Of 43 agencies reporting procedures for determining whether or not an additive is needed, 25 agencies reported no procedure for determining that the correct dosage is actually used.

Determination of Heat Stability

Responses to Question 10 revealed that 25 agencies require heat stable antistripping additives. Of these, 12 agencies require the additive manufacturer to certify heat stability, and 15 agencies use the tests given in Table A-4. One agency uses 3 test procedures, and another uses 2. Two agencies require heat stable additives but do not use a testing procedure or require certification.

Where tests are used, most agencies require tests on asphalt cement or mixture samples from actual projects so that heat stability of additives is checked under actual job conditions whatever those conditions might be. Others specify time and temperature of the asphalt cement after the additive has been incorporated. These requirements range from 48 hours at 280 F to 4 weeks at 350 F.

Six agencies who do not check additive dosage do test for heat stability using field samples. In effect, the test determines both dose and heat stability because if either were incorrect, the test would fail. Therefore, 24 agencies actually check dosage and 19 agencies do not.

Construction procedures or controls to ensure heat stability and additive effectiveness were reported by 14 agencies. Six agencies require in-line blending of antistripping additive and asphalt cement at the asphalt plant as close to the mixer as possible. Two agencies require addition of additive to asphalt cement at the asphalt plant during transfer of asphalt cement from transports to storage tank followed by circulation of the storage tank. Three agencies restrict the time that the additive can be in the asphalt cement before being incorporated into the mixture. One agency allows a maximum time of 24 hours, and the other two 96 hours. Three agencies indicated the use of a test to check either the asphalt cement or the mixture with no special construction procedure.

Determination of Additive Effectiveness on Field Projects

Eleven agencies reported that additive effectiveness is tested on field samples. Similar responses were received with respect to additive dosage and heat stability. Since tests on field samples are equally effective regardless of intent, a total of 17 agencies reported using the tests given in Table A-4. One agency uses two tests.

Question 11 was intended to ask, if it is known that the additive is heat stable, present in the required dosage, and effective in mixture design or other laboratory procedure, then how do you know that it is effective when it is actually used? The responses suggest that about the most anyone can say is that the additive was equally effective when the pavement was built as when it was studied earlier in the laboratory.

Approved Antistripping Additives

Questions 12 and 13 requested information on antistripping additives that are used or approved for use by the agencies. Eighteen agencies replied that additives are approved in advance and furnished lists of approved products. These lists revealed 27 antistripping additive manufacturers with 116 approved products.

Asphalt Cement Producers

Asphalt cement producers advised that their interest in antistripping additives is mostly confined to adding additives to asphalt cement at refineries or terminals at customer's request. Type of additive and dosage would be as specified. In one case, this practice has been discontinued because of safety considerations.

Trade Associations

Of four trade associations contacted, only The Asphalt Institute replied. Its reply is similar to replies from state and other agencies, and it is included in data already reported.

Additive Manufacturers

Replies from 11 additive manufacturers indicate that all known antistripping additives are proprietary chemicals, and because of that, detailed information concerning additives is not available and was not sought. All additives are amines or chemical compounds containing amines, which are strongly basic compounds derived from ammonia. Most are cationic, designed to promote adhesion between acidic aggregate surfaces and acidic asphalt cement. Some contain both cationic compounds and anionic compounds and may improve adhesion with all aggregates and asphalt cements. A few are anionic designed to promote adhesion to basic aggregate surfaces.

Some antistripping additives are said to be 100 percent active, which is understood to mean 100 percent surfactant. Such materials may contain an amine and some other product such as tall oil or a fatty acid. Other additives are not 100 percent active and may contain diluents such as fuel oil and aromatic oils. A wide variety of additive characteristics such as flash point, pour point, viscosity, and specific gravity are reported.

Additive manufacturers recommend dosages ranging from several hundred parts per million (less than 0.1 percent) to 3.0 percent by weight of asphalt cement. Some warn that if the dose is excessive, the additive will cause rather than prevent stripping because the aggregate surface can adsorb only a limited amount of surfactant. The remaining surfactant stays dissolved in the asphalt cement where it is an ineffective cohesive material. The result of an excessive dose is weak cohesion near but not at the aggregate surface.

Heat stability at usual working temperatures is said to be characteristic of all antistripping additives. To be heat stable, the additive must not contain compounds that react with some component of the asphalt cement and therefore become ineffective as a surfactant. The rate of reaction in such cases increases rapidly with increasing temperature, which accounts for

the term heat stable. What is needed is chemical stability in the presence of asphalt cement, and all manufacturers claim that their products are stable.

All manufacturers stress the importance of thorough blending of the additive into the asphalt cement. All additives are believed to be soluble in asphalt cement, and it is necessary to achieve a uniform distribution so that the additive will be available to all aggregate surfaces.

Even in the absence of a chemical reaction and with satisfactory distribution of additive in the asphalt cement, the additive still may not be able to get to the aggregate surface, where it must be in order to function, for two reasons. First, the additive may interact with certain compounds in the asphalt cement which interferes with the additive's ability to migrate to the aggregate surface. Such an interaction is not a reaction and is distinct from chemical stability in the presence of heat. In the case of reaction, the additive is destroyed and is no longer present. With interaction, the additive is present but cannot function, and the effect is the same. The additive is ineffective. Second, the viscosity of the asphalt cement must be low enough for a long enough period of time to allow the additive to migrate to the aggregate surface. Except in cases of prolonged storage, this time period for asphaltic concrete would be a few hours at most. A short haul combined with conditions causing rapid cooling at laydown could result in less than an hour when viscosity is low enough for migration.

Agencies responding to the questionnaire identified 116 different antistripping additives. Additive manufacturers advised that some of these are no longer being made, but that some new additives are. It appears that the number of additives is constantly changing, but the number is always large. In spite of a large number of additives, each differing from one another in some unknown respect because all are proprietary, the additive manufacturers still recognize a number of problems in the use of their additives. There seems to be no foolproof antistripping additive.

ANALYSIS AND INTERPRETATION

This section presents an analysis and interpretation of the findings reported earlier in this appendix with the objective of developing test procedures for measuring antistripping additive effectiveness and guidelines for antistripping additive use.

Pattern of Use

The pattern of antistripping additive use in Figure A-1 is different from the pattern reported in 1958 (16). Twelve states using additives in 1981 also used them in 1958. Eighteen states using additives in 1981 were not using them in 1958. On the other hand, 7 states not using additives in 1981 were using them in 1958. Exactly why the pattern of use has changed from 1958 to 1981 is not known. The 1958 pattern includes antistripping additives used in both hot-mixed asphaltic concrete and in cold mixtures made with cutback asphalts. The latter are excluded from the 1981 pattern, but that alone does not account for the different patterns. Regardless of why, the changing pattern is significant because it shows that stripping and additive use are variables.

Another aspect of Figure A-1 should be noted. Returns from the questionnaire show that there are isolated areas without stripping problems, and other isolated areas with stripping problems. For example, the District of Columbia and North Carolina do not report stripping problems or additive use, but they are surrounded by states which both have problems and use additives. Conversely, Ontario is the only Canadian Province reporting stripping problems and additive use. These isolated cases are delineated by political boundaries. It seems unlikely that materials characteristics, or effects of climate, or other factors contributing to stripping would be completely different just because of such a boundary. These patterns suggest that stripping problems and their solutions are complex and not likely to be susceptible to simple solutions.

Factors Related to Stripping

Every factor listed in the questionnaire which might be related to stripping is related to stripping by at least one respondent, and several additional factors have been identified. Some factors are cited more frequently than others, but this is not considered to mean that factors cited less frequently are unimportant.

Aggregates

In some respects responses were expected, but there are contradictions throughout. For example, gravel and natural sand are the aggregates most frequently related to stripping. This is consistent with stripping theory which considers silica to be acidic and not a favorable surface to which acidic asphalt cements adhere well. Yet, the northern half of the country stretching from the eastern seaboard to the foothills of the Rocky Mountains experiences few stripping problems and rarely uses antistripping additives. Gravel and natural sand abound throughout this area and are used regularly in asphaltic concrete. Granite coarse aggregate and manufactured sand are related to stripping frequently and are a similar example. The surface of granite should be expected to strip, but areas where granite is used in asphaltic concrete regularly report no stripping problems.

Limestone provides the opposite example. Limestone coarse aggregate and manufactured sand are among the aggregates frequently related to stripping, but limestone aggregates are not supposed to strip because of their basic surface. Many areas where limestone is used in asphaltic concrete do not relate stripping to limestone. Slag is a similar example.

Other aggregate types related to stripping by the questionnaire are types that can be expected to strip because of the chemistry of their surfaces. However, as with gravel, stripping is not always related to these materials. In short, the questionnaire reveals that no aggregate type always strips, and no aggregate type never strips.

It has been pointed out in the literature that aggregate types may not perform as expected (9). Over a period of geologic time, a gravel deposit may adsorb compounds that prevent stripping, but when the same gravel is crushed, the fractured faces may have the chemistry of the original deposit and therefore strip. Limestone can be expected to prevent stripping but may, after being quarried, adsorb compounds or even react mildly so that

surfaces that can strip are created in very short time periods. Adsorbed layers of various gases or liquids that can inhibit good adhesion with asphalt, can form on many aggregate surfaces. Such layers will not necessarily be removed by heating at normal hot-mix construction temperatures.

Although aggregate type may appear to be an unreliable indicator of stripping, responses to the questionnaire do not suggest that aggregate source or gradation is, in general, better. Aggregates present hundreds of variables that may be important one way or another with respect to stripping. It appears that each aggregate or combination of aggregates should be evaluated on its own merits.

Asphalt Cements

The questionnaire indicated a relationship between low viscosity asphalt cement and stripping at least in some cases. This relationship should exist because it should be more difficult to peel a stiff (high viscosity) film from a surface than a more fluid film. That this relationship was not noted more frequently is not surprising because often only one grade is used. Also, the grade of asphalt cement should affect only the degree of stripping, which may be imperceptible.

Asphalt source was also related to stripping, but the responses suggest that asphalt sources have not been studied with respect to stripping as much as aggregates have. That asphalt source is significant has been known for many years (14,16). Also, additive manufacturers emphasize the importance of different asphalts affecting additives in different ways. Asphalt source may deserve more attention than it has received, especially considering one response that suggested that today sources of crude oil continually change. It is possible that asphalt sources present hundreds of additional variables that may be important with respect to stripping, and, as with aggregates, each asphalt source should be evaluated on its own merits.

Construction

All responses concerning construction relate stripping to construction practices only if construction is conducted in a way that admits water into the pavement. The indication from the questionnaire is that stripping problems are not going to be solved by construction practices as long as known good practices are followed.

Other Factors

Three of the other factors involve certain circumstances that allow water into the pavement, or that tend to trap water within the pavement once it enters. These situations are believed to be important because they involve materials and construction practices that do not result in stripping under other circumstances. This emphasizes the complexity of the causes of stripping. The final other factor, an antistripping additive incompatible with the asphalt cement, also emphasizes the complexity of the causes of stripping. In this case, it is a large number of additives used with asphalt cements that may or may not change constantly and significantly because of crude oil sources.

Testing for Moisture Damage and Additive Effectiveness

The questionnaire reveals that no testing procedure has gained universal acceptance. Table A-4 shows that 43 agencies use a total of 14 test procedures for 5 different purposes. Most of the procedures have at least a few variations, and often more than one procedure is used by the same agency for one purpose. When procedure variations and test combinations are considered, the number of testing variables becomes very large. The reason for so many procedures, variations, and combinations is that each agency has developed moisture damage testing programs which address its own problems. Each procedure offers certain advantages, disadvantages, and limitations. The purpose of this section is to try to develop an objective appraisal of the procedures that are being used.

Aggregate Tests

The four procedures in this category, static immersion, dynamic immersion, boiling water, and tracer salt, have certain common features, and therefore common advantages and disadvantages, most of which have been recognized for many years (23).

1. All test a coarse aggregate function, and the effect of fine aggregate and filler is ignored completely.
2. All evaluate stripping in terms of aggregate surface exposed by moisture which is not a measure of adhesion.
3. Three procedures rely on a visual estimate of coating. Only one variation of dynamic immersion and the tracer salt method use an objective, quantitative measurement.
4. None provides an indication of the effect of stripping on the structural quality of the pavement.

All procedures are reasonably rapid and simple, and only the tracer salt method requires sophisticated equipment. Three procedures require approximately one day, and certain variations of the boiling water test are complete in less than an hour.

Static Immersion. The standard test, AASHTO Method T 182, in essentially its present form was proposed in 1947 as a modification of an earlier method (23). It was considered to be a satisfactory method for rapid evaluation of coarse aggregate. Static methods have been criticized for not being severe enough. However, the overabundance of water creates a highly unlikely degree of saturation, certainly severe conditioning in its own way. If preferential wetting by distilled water can occur, it should be revealed by this procedure.

Dynamic Immersion. Dynamic immersion procedures seem to have originated with Dow's wash test in 1936 (8). The objective was to develop a severe procedure that would predict water damage not detected by static immersion procedures. It is not clear that violent agitation in the presence of water actually causes more stripping than static immersion. Instead, agitation appears capable of removing films that have already stripped, perhaps making the visual detection of stripped areas easier.

Boiling Water. Boiling water procedures have been used since before 1936 (9,10). At that time there were questions, which have not been answered yet, concerning the action of

boiling water compared to water at a much lower temperature and at a temperature where water is not changing state. The effect of test temperature, even if water were not boiling, is also questionable and could have opposite effects with different mixtures. In one case, high temperature and low asphalt viscosity could promote easier migration of antistripping additives to aggregate surfaces and could indicate more additive effectiveness than is actually present. On the other hand, the same conditions result in a film that is easier to peel, and could indicate more stripping than is actually present.

Tracer Salt. Except for the measurement of stripping, tracer salt procedures are the same as static immersion. It is not clear that the measurement is enough of an improvement to justify the equipment.

Appraisal. None of these procedures, by itself, appears capable of predicting moisture damage in actual asphaltic concrete pavements or measuring antistripping additive effectiveness in pavements. All can indicate moisture damage and additive effectiveness at least qualitatively, and when used with other tests and experience, they can be part of a reasonably effective deterrent to moisture damage. Nevertheless, more effective procedures that test complete mixtures and result in quantitative measurements are desirable.

Additive Indicator Tests

The two tests in this category, bottle test and color indicator, are qualitative and only determine whether or not an additive is present. They cannot determine that the correct dosage of additive either is or is not present. Both of these tests are limited to applications after the additive has been added to the asphalt cement. Both are simple and rapid and can be used immediately before mixture production. The color indicator is also used with extracted asphalt cement.

Bottle Test. The bottle test uses asphalt cement that is cut back for purposes of the test resulting in an asphalt that allows easier additive migration to aggregate surfaces. This may result in the detection of additives that are ineffective in actual mixtures. The test also uses Ottawa sand, and therefore does not test additive effectiveness with actual aggregates.

Color Indicator. The color indicator is designed to detect amines and would not detect other antistripping additives. The test may also detect an additive that cannot migrate to the aggregate surface.

Appraisal. Neither positive nor negative results from these tests appear to be completely reliable. A positive result means that the test detects an additive, not that stripping will not occur. A negative result means that the test cannot detect an additive, not that stripping will occur. The most useful application of these tests appears to be to supplement other tests and practices that determine additive need and effectiveness with job materials.

Mixture Tests

All mixture tests avoid one limitation of the other tests because the entire mixture is tested and the effects of fine aggregate

and filler as well as coarse aggregate, asphalt cement, and additive are evaluated together. Also, some mixture tests measure adhesion rather than aggregate surface exposure, provide quantitative measurements, and offer at least the potential of indicating the effect of stripping on the structural quality of the pavement. However, compared to other tests, most mixture test procedures are complicated and time consuming.

Boiling Water. Aside from testing the complete mixture, the boiling water test is subject to the same limitations as the boiling water test used with coarse aggregate. In addition, the mixture is tested in a loose condition, not representative of exposure conditions of pavements. At the same time, the test also enjoys the advantages of other boiling water tests, in particular it is simple and rapid.

Abrasion. Abrasion tests have been used regularly for more than 20 years (25, 26), and appear to be reasonable laboratory approximations of moisture damage occurring at the surface of a wet pavement under traffic. It is not clear, however, that stripping occurring in lower layers of a pavement would be identified by these tests, and one agency using an abrasion test also uses a mechanical test with specimens saturated by moisture vapor to detect moisture damage in lower layers.

The major disadvantage in these procedures is the 6-day saturation period used in some cases. Some unusual equipment is used, but it is neither complex nor expensive. Highly specialized techniques are not required.

Excepting hydrated lime, abrasion tests have been used very little for purposes of evaluating antistripping additive effectiveness. Agencies using abrasion tests report no moisture problems with mixtures that satisfy their criteria, a strong indication that the tests could be used to evaluate additives.

Swell and Absorption. Swell is usually considered to be an indication of stripping or an indication of expansive clays, or both. An entirely separate form of water damage may be possible also. If stripping occurs and there is a volume change, dilation or swell appears to be the only possible volume change. If stripping does not occur, it is not clear how expansive clay or anything else in the mixture can become wet and swell, but swell seems to be the only possible volume change.

The swell and absorption tests actually in use are extremely simple and rapid because compacted specimens intended for mechanical tests are used. These procedures are much more simple and rapid than procedures appearing in text books, handbooks, and Asphalt Institute manuals (27). The fact that the procedures are so simple and the data useful seems to be reason enough to include swell and absorption in any mechanical testing program used to measure damage or additive effectiveness.

If a specimen swells, whatever mechanical property is measured will be low whether or not stripping occurs. If a specimen does not swell and the mechanical property is low, serious moisture damage, probably stripping, is indicated. If there is little or no absorption, the test probably is not measuring moisture damage. If the volume of absorbed water exceeds the volume of air voids, swell is confirmed and poor mechanical properties should be expected.

Preparing Mechanical Test Specimens. Methods of preparing specimens for mechanical tests identified by the questionnaire include double plunger, Marshall hammer, and kneading compactor. No respondent mentioned using either the Texas gyratory compactor or the Corps of Engineers gyratory compactor.

There is no known reason why gyratory compaction cannot be used in moisture damage testing, and it is included in the following considerations.

Double plunger compaction is used more than any other single method, and it offers certain advantages. Void content resulting from double plunger compaction is usually higher than void content from other standard procedures. Mixtures at optimum asphalt content often have void contents of 6 percent or more when double plunger compaction is used. This level of voids is needed in order to allow entry of water, and it is realistic compared to voids obtained during construction. Also, double plunger compaction does not squeeze asphalt cement out around the periphery of the specimens creating a seal which may prevent entry of water. Other methods of compaction can create such a seal. The combination of high enough void content without a peripheral seal which permits saturation is believed to be an essential feature of specimens used to study moisture damage. A final advantage of double plunger compaction is that it may not fracture aggregates as other methods do. This also appears to be an important feature because a fracture can admit water which could cause unique moisture damage.

Marshall compaction can be modified by reducing the number of blows, the compaction temperature, or both. Kneading compaction can be modified by reducing foot pressure, number of tamps, leveling load, or a combination of all three. Gyratory compaction can be modified by reducing the number of revolutions. All can result in specimens of desirable voids without a peripheral seal or fractured aggregate which should be equally as satisfactory for moisture damage determination as specimens prepared by double plunger compaction.

It appears as if the standard double compaction used with the immersion-compression test produces specimens with very desirable characteristics for studying moisture damage and additive effectiveness. All other methods of compaction can be modified to produce comparable specimens. The reason for using another method is that double plunger compaction is criticized because of somewhat cumbersome equipment and techniques. Rather than a standard method of compaction, what is important is specimens with the right characteristics. Such specimens can be made in various ways and should be used.

Saturating Mechanical Test Specimens. Some procedures simply expose specimens to moisture that may or may not result in saturation. Other procedures attempt to provide a high level of saturation before exposure to further moisture conditioning. Both vacuum and pressure saturation techniques are used (6, 7, 12, 29).

Vacuum saturation was investigated 35 years ago, and although it was concluded that no swell or loss in strength occurred because of vacuum saturation alone, the procedure was rejected because of poor correlation with field experience (23). Vacuum-saturated specimens do not lose strength in some cases, but suffer significant loss in other cases (7, 12). Limited studies of antistripping additives show that no additive prevented loss of strength caused by vacuum saturation, but all additives studied resulted in no further loss in strength of soaked specimens after the initial loss due to vacuum saturation (12). Swell of vacuum-saturated specimens has been reported (6), and there are unpublished data which show swell, strength loss, and poor correlation with field experience. One pressure saturation technique produces no known ill effects (28). Unpublished data on

another pressure technique show that swell and damage may occur. If either vacuum or pressure saturation results in rupture of asphalt films, the damage is not stripping and the saturation technique is of questionable value for purposes of evaluating antistripping additives. However, rupture may be necessary for purposes of accelerated testing.

Moisture Conditioning Mechanical Test Specimens.

Moisture conditioning of compacted specimens has been accomplished most frequently using the standard techniques of the immersion-compression test, soaking in distilled water at 120 F for 4 days or 140 F for 1 day. These procedures have been shown to be reliable and useful for evaluating additive effectiveness (23, 28), and it is not surprising that they are used often. They are simple and require no special or expensive equipment. The major disadvantage is the 4-day soaking period, which is considered to be somewhat more reliable than 1 day, but creates a prolonged procedure.

Other moisture conditioning procedures may create moisture damage which is not stripping. Freezing and thawing may result in loss in strength but is only remotely related to preferential wetting, if at all. Temperature cycling resulting in loss of strength may be moisture damage and would encourage stripping at higher temperatures, but not at low temperatures where ruptured films seem more likely. Pulsating pressure, which creates pore pressure in the specimen, would not seem to be capable of causing preferential wetting, but could weaken or rupture films.

These moisture conditioning procedures create moisture damage under realistic conditions. A saturated pavement may be subjected to freezing and thawing, temperature cycling, pulsating pressures, or all three. All attempt to create moisture damage in a short enough time to be practical for laboratory purposes. The question is whether or not the physical damage actually accelerates stripping. On the other hand, static soaking at either 120 F or 140 F is a condition a saturated pavement probably never encounters, and certainly not for an entire day, not to mention 4 days. However, these are conditions under which preferential wetting can occur without other physical damage. With respect to antistripping additives, the problem of other physical damage is that additives would be shown to be ineffective in some cases where they are actually effective.

Any procedure for saturating and moisture conditioning specimens which accelerates stripping without other physical damage should be satisfactory. Stripping is not considered to be an instantaneous phenomenon, and the procedure must allow enough time for stripping to occur. Static soaking procedures from the immersion-compression test provide the necessary conditions but may not reach a high enough degree of saturation.

Mechanical Testing. All of the mechanical tests that are being used in moisture damage procedures are dependent at least to some degree on adhesion, and in that respect there is little basis for choosing one over another. Also, most have been shown to

be reasonably reliable (6, 7, 12, 23, 29). If specimens are made and moisture conditioned properly, it seems highly probable that any of these tests could be satisfactory. However, the tensile tests of Jimenez (6) and Lottman (7), or Schmidt's resilient modulus (12), appear to be more dependent on adhesion than are unconfined compression, Marshall stability, or Hveem stability. Resilient modulus may be particularly advantageous for evaluating the effects of additives on the structural quality of the pavement.

Equipment requirements for these methods are not difficult, although resilient modulus equipment is somewhat unusual. Neither unusual nor difficult techniques are required. Unconfined compression, Marshall stability, and Hveem stability are AASHTO and ASTM standards and are widely used at least for routine purposes, if not for moisture damage tests. The tensile tests use testing temperatures and strain rates that are different from those used with other tests. However, the Lottman procedure has been modified to use standard Marshall apparatus, and undoubtedly could be modified for use with other standard equipment and procedures. Similarly, the Jimenez procedure can be modified to use convenient strain rates and test temperatures.

Appraisal. Limitations on the applicability of boiling water and abrasion tests to mixtures have already been noted. Both can be expected to be a part of an effective testing program to determine moisture damage and additive effectiveness, but in both cases other information appears to be needed or at least desirable.

The mechanical test procedures on compacted mixtures avoid, or at least offer the possibility of avoiding, most of the limitations of other procedures. Mechanical test procedures may not always have been used in the most advantageous way, but satisfactory techniques can be identified and used in the future. Specimens for moisture damage and additive effectiveness studies should be compacted without fracturing the aggregate to a density that allows moisture to enter. Specimens must be saturated enough so that moisture damage can occur, but not so much that mechanical damage, in the form of ruptured asphalt films that expose impermeable voids and uncoated aggregate, is incurred. Swell and absorption tests can be very useful in determining that the degree of saturation is satisfactory. Moisture conditioning and saturation may occur simultaneously, or a separate conditioning procedure may be used. For evaluating stripping and additive effectiveness, the moisture conditioning procedure must allow enough time for stripping to occur, but the procedure must also be an accelerated procedure. Satisfactory conditioning procedures should avoid, or at least minimize, mechanical damage such as ruptured films. Static soaking at elevated temperatures is an accelerated moisture conditioning procedure which should encourage stripping without mechanical damage. The best mechanical test should be one that relies heavily on adhesion. Tensile and resilient modulus tests appear to satisfy this requirement.

APPENDIX B

DEVELOPMENT OF PROCEDURE AND METHOD FOR TESTING ANTISTRIPPING ADDITIVE EFFECTIVENESS

BASIS FOR DEVELOPMENT

Consideration of the information obtained from the Questionnaire, the technical literature, and other sources described in Appendix A restricts the development of a testing procedure, if the procedure is to be reliable, to the following conditions:

1. Whether or not moisture damage should be expected must be determined.
2. The most effective dose of the additive under consideration must be determined along with whether or not that dose is effective enough.
3. Whether or not the additive is effective when used in the field.

Testing to determine additive presence and heat stability are not included. Testing for additive presence can, at most, only determine additive presence which is not additive effectiveness. Testing for additive heat stability can be incorporated into the above conditions and does not require special consideration.

Testing to determine whether or not moisture damage should be expected can be accomplished by most of the testing procedures identified previously. In fact, as already noted, some agencies expect moisture damage with certain materials without testing at all. With respect to additive effectiveness, however, the procedure for detecting moisture damage should be one which allows comparison between materials treated with additive and without additive. Therefore, the moisture damage procedure should be the same as the additive effectiveness procedure.

Testing additive dosage requires that the test be performed on entire mixtures. The correct dosage of a particular additive is a function of the chemical characteristics and surface area of the mineral aggregate and the chemical composition of the asphalt cement. It is essential that either proposed job mix formulas or actual field-produced mixtures be tested. Neither additive dosage nor effectiveness can be measured reliably on anything else. For example, the aggregate tests are usually performed on a coarse aggregate fraction. The test may show that loss of coating is excessive without additive but acceptable with a certain dose of a certain additive. When fine aggregate and filler are added in a complete mixture, that dose will almost certainly be incorrect. The additive treats all of the asphalt cement. If the additive has no affinity for the surface of the fine aggregate and filler, the dose is much greater than it should be. If the additive has even a mild affinity for the surface of the fine aggregate and filler, because of the relatively huge surface area of those fractions, the dose will be much too small for the coarse aggregate fraction which was tested and is supposed to

be treated. This restricts possible testing procedures to those that have been classified as mixture tests in Appendix A.

Testing for effectiveness of additives when used in the field can be done on complete mixtures, and in fact any test attempting to reflect field conditions would seem to mandate the use of a mixture test on field-produced mixtures. The ideal situation would be a mixture test that can be used in central laboratories for determining additive dosage and effectiveness on job mix formulas, and in field laboratories for determining additive effectiveness on actual mixtures. Although this ideal may not be wholly attainable, the importance of a practical field test cannot be overemphasized. As opposed to a laboratory-produced job-mix formula, field-produced mixtures can reflect the effects on additive performance of variability in aggregate character and gradation, asphalt content, asphalt cement character because of crude source changes, and storage and heating history of the additive.

On the basis of the foregoing, the development of a testing procedure for measuring additive effectiveness turns toward selecting or developing a mixture test for that purpose. Although the reasons are not entirely the same, the use of a mixture test for this purpose was advocated more than 25 years ago (23, 29). There is no dispute with the reasoning used then. A major difference between the previous work and the present project is the need today for a more rapid procedure to be used in conjunction with mixture design in a practical time period, and one to be used in the field before thousands of tons of unwanted mixture are produced. Another difference is the desire to use equipment readily available today, which is understood to include equipment already on-hand.

The conclusion that aggregate tests and additive indicator tests are not suitable for purposes of determining additive effectiveness is not intended to mean that these tests are dismissed from further consideration with respect to moisture damage or the use of additives. These tests may be useful supplements to an additive effectiveness test, and they are considered in that respect in the guidelines for incorporating antistriping additives into asphaltic concrete in Chapter Three.

PROCEDURE FOR TESTING ANTISTRIPPING ADDITIVE EFFECTIVENESS

Of the mixture tests listed in Appendix A, the boiling water test is considered to be unsuitable for measuring additive effectiveness. As with aggregate tests and additive indicator tests, the boiling water test on mixtures are considered further under the guidelines in Chapter Three.

The abrasion tests appear to be viable for measuring additive effectiveness even though they seem to have been used only with

pulverulent solid additives. The major problem is prolonged moisture conditioning periods which would be undesirable in at least some circumstances. Also, as noted in Appendix A, the tests appear to be applicable to surface stripping problems but perhaps not internal moisture damage. Most rapid saturation and moisture conditioning probably could be used but have never been investigated. For these reasons, these tests are not pursued here, and it is not clear that they would be helpful supplements.

Of the remaining mixture tests, a preference for modulus of rupture and tensile splitting tests is expressed in Appendix A and reasons for that preference are stated. Based on those reasons, it was decided to proceed with the development of a tensile splitting procedure for testing additive effectiveness. Resilient modulus requires equipment which is not readily available and certainly would not normally be found in field laboratories. Therefore, tensile splitting appears to be the practical procedure at this time. Also, if a tensile splitting procedure is used, it can be identical to resilient modulus except for the mechanical test itself. Ultimately, resilient modulus can be incorporated into the procedure, and its advantages of pulsating load and measurement of structural effects can be exploited.

The test method which ultimately evolved appears later in this appendix. The process of development follows.

Laboratory Experiment

Complete details on the experimental procedures and data are covered in Appendix C.

Materials

Most experimental data were developed from a mixture, designated Chert-B, containing chert gravel, chert sand, blend sand, limestone dust, and grade AC-20 asphalt cement. A similar mixture, Chert-A, was used early in the experiment. This chert gravel and sand mixture has a long history of moisture damage problems and was selected for that reason. The asphalt cement was from two different sources known to use different crude oils. Data were also collected from a quartz mixture with known moisture damage problems.

Three mixtures with no moisture damage history were also used. These included a glacial gravel and sand mixture, and two limestone mixtures using limestone from different quarries.

All mixtures comply with customary mixture design criteria at optimum asphalt content (27). All tests were conducted at optimum asphalt content.

Preparing Test Specimens

Characteristics of test specimens for determining moisture damage and additive effectiveness were identified (App. A). Specimens should be compacted to approximately the void level expected in the field, usually 6 to 8 percent. This level is desirable because it allows saturation, does not allow asphalt cement to form a peripheral seal that prevents saturation, and avoids aggregate fracture. This void level is obtained by adjusting the compactive effort experimentally.

Table B-1 Compacting high void specimens with Marshall hammer.

Mixture	Temperature, F	Number of Blows	Air Voids, Percent*
Chert-A	285	20	4.4
	285	20	4.4
	285	20	4.4
	285	20	4.4
	285	20	4.4
	285	20	4.4
Chert-A	285	20	4.6
	285	10	5.1
	285	5	6.3
	240	20	4.9
	240	10	6.1
Chert-A	240	20	4.9
	240	10	6.1
	285	5	5.8
Chert-A	240	10	6.3
	240	10	6.5
	240	10	6.4
	240	10	6.4
	240	10	6.5
	240	10	6.4
	240	10	6.4
	240	10	6.4

*Average of two specimens.

Specimens with field level voids have been made by kneading compactor and Marshall hammer and used in moisture damage investigations without difficulty. Experimental data developed with Marshall hammer, taken from Appendix C, are given in Table B-1. The data show that by adjusting compaction temperature and number of blows, suitable specimens can be fabricated. It also shows that this particular mixture can be compacted with very little effort. Although this mixture would be satisfactory for a pavement, it was somewhat undesirable for this experiment. As a result, the mixture was redesigned by using another chert sand.

Data from the redesigned mixture in Table B-2 show what is considered to be acceptable variability among specimens made the same day. Variability from one day to another may be undesirable but is believed to be acceptable because in application of the procedure it is expected that a set of specimens would be made on one day and divided into two subsets for testing.

Swell and Absorption

Because of reasons stated in Appendix A, very simple and rapid procedures resulting in useful information, swell and absorption tests are considered to be a necessary part of any procedure using compacted specimens. Both should be measured after saturation and again after moisture conditioning. Application of swell and absorption data obtained experimentally appears in a subsequent section.

Saturating Specimens

It is noted in Appendix A that static soaking seems to provide ideal conditions for stripping to occur while both pressure and vacuum saturation procedures may create damage which is not stripping. For practical purposes, however, static soaking may require too much time. Similarly, the moisture vapor saturation technique creates conditions under which stripping can occur without other damage, but it may require too much time.

To investigate static soaking, specimens of various void contents were soaked at 140 F for 24 hours, and tensile strength was determined. The results are shown in Figure B-1. No specimen was saturated to 50 percent in spite of very high void content. Tensile strength ratios for the points plotted in Figure B-1 range from 78.7 to 108.1 percent with an average of 95.1 percent. Because the chert mixtures are supposed to be susceptible to moisture damage, it was concluded that static soaking was not suitable for saturating and moisture conditioning these mixtures. Rather than requiring too much time, static soaking appears to be incapable of creating a degree of saturation high enough to cause moisture damage at least in the chert mixtures.

The glacial gravel and limestone mixtures were also investigated and for all practical purposes confirmed the foregoing conclusions. Other mixtures found in the literature had been saturated by static soaking at 140 F for 24 hours and resulted in saturation levels for different mixtures ranging from less than 20 percent to almost 70 percent (30). It was concluded that static soaking may provide satisfactory saturation and moisture conditioning for certain mixtures but not for all mixtures. Also, even if a high enough degree of saturation were achieved, saturation may occur gradually throughout the soaking period so that the more inaccessible parts of the specimen are subject to moisture for periods too short to allow stripping to occur.

More positive means of saturation were then investigated. The glacial gravel and limestone mixtures had been subjected to saturation by full vacuum and moisture conditioning by freezing and thawing following the Lottman procedure (7). Twelve out of 14 specimens had saturation levels above 100 percent and tensile strength ratios ranging between 25 and 53 percent. These two mixtures have no history of moisture damage problems, but the two chert mixtures produced similar results, supersaturation

Day-to-day Variability			
Day	n	\bar{X}	Range
1	6*	6.8	6.6 - 6.9
2	6*	7.1	6.8 - 7.3
3	8*	6.7	6.2 - 7.0
4	12	6.6	6.2 - 7.0
5	16	6.5	6.1 - 6.8

*Average of two specimens.

Table B-2 Compacting high void specimens with Marshall hammer (Chert-B mixture, 275 F, 15 blows).

and tensile strength ratios ranging between 35 and 55 percent. It was concluded that the supersaturated condition contributed to the loss of strength, but whether supersaturation resulted from vacuum saturation, moisture conditioning, or both could not be determined.

To determine the effect of vacuum saturation alone, a vacuum of 28.6 in. Hg was applied to specimens for 30 min. Chert-B specimens were 89.3 percent saturated and had a tensile strength ratio of 97.8 percent, showing that there was negligible damage caused by vacuum saturation. It was concluded that this vacuum saturation procedure might be satisfactory for certain mixtures, but there was no way of knowing in advance which mixtures.

Two pressure saturation techniques were studied. The Smith hand pump method (29) produced saturation levels similar to those found in static soaking and was abandoned quickly. A pressure cell employing a 50-psi pulse of compressed air for 1 sec twelve times per minute was also studied. Specimens were submerged in distilled water inside the cell and the pressure pulse was applied to the surface of the water. The level of saturation could be increased with this system by maintaining the pulsating pressure for long time periods and by increasing the temperature. Saturation was found to be much more sensitive to temperature than to time. This pressure saturation technique was judged to be satisfactory, but it was more difficult to perform and control than vacuum saturation. It was concluded that a vacuum saturation technique which did not damage specimens should be developed.

Saturation by partial vacuum for short time periods has been used in moisture damage studies (6). It appeared as if such a technique could be used and controlled by measuring swell and absorption immediately following saturation. If the volume of absorbed water exceeds the volume of voids, the specimen has been damaged and is discarded. A second specimen would then be saturated probably by using a lower vacuum. If the volume of absorbed water is too low, the specimen would be saturated again using a higher vacuum. The low limit still has to be determined.

That supersaturated specimens are damaged and should be discarded is shown by 15 cases in this experiment involving five different mixtures in which specimens were supersaturated. Regardless of how saturation was achieved, tensile strength ratio was always low, ranging between 25 and 55 percent.

Experiments with partial vacuums at room temperature revealed that saturation is very sensitive to the magnitude of the vacuum and practically independent of the duration of the vac-

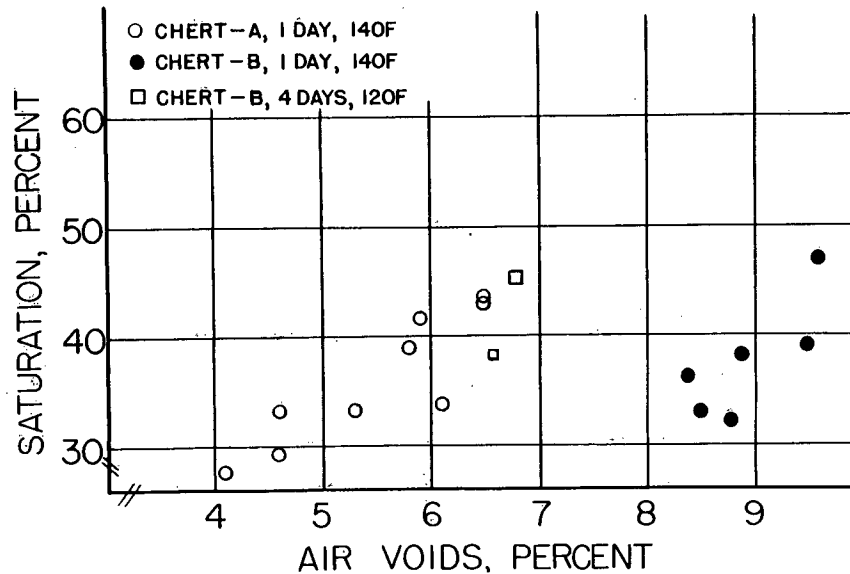


Figure B-1. Saturation by static soaking.

uum. The level of partial vacuum needed to saturate to the required level also appeared to be different for different mixtures.

To determine whether or not specimens could be saturated by partial vacuum without being damaged, specimens of three different mixtures were saturated to at least 55 percent, temperature was stabilized by soaking at 77 F for 30 min, and tensile strength was determined. Results appear in Table B-3. Although criteria for judging what level of tensile strength ratio indicates significant damage has not been established, it was assumed that all ratios in Table B-3 indicate negligible damage. Why the second limestone specimen was saturated to the lowest level, revealed negative swell (shrinkage), and produced the highest ratio is not known, but none of this was interpreted to be evidence of damage. Therefore, it was concluded that vacuum saturation using a partial vacuum could be used to saturate specimens.

Table B-3 Saturation by partial vacuum.

Mixture	Saturation, Percent	Swell, Percent	Tensile Strength Ratio, Percent
Chert-B	67.2	0.0	90.0
	68.4	0.0	98.4
	69.4	0.0	88.9
Glacial Gravel	59.9	0.0	103.7
	55.6	0.2	107.6
Limestone	55.2	0.2	108.6
	36.9	-0.6	121.1

Moisture Conditioning

Static soaking is just as ideal for purposes of moisture conditioning as it is for saturation, but still may require too much time. Specimens partially saturated by partial vacuum could reduce the time required for static soaking to a practical period. The effects of various vacuum saturation techniques in combination with two moisture conditioning procedures are presented in Table B-4. Excepting specimens saturated by partial vacuum of 15 in. Hg, all combinations of saturation procedures and moisture conditioning procedures resulted in tensile strength ratios judged to be unacceptable. The indication is that one moisture conditioning procedure is as effective in creating moisture damage as the other. Because the conditions created by static soaking, which are discussed in Appendix A, are favorable for promoting preferential wetting without causing other damage, static soaking appears to be the preferred procedure for evaluating effectiveness of antistripping additives. Also, static soaking is much simpler and more rapid than freezing and thawing.

Table B-4 also provides further evaluation of saturation techniques. Specimens saturated with a 15-in. vacuum achieved the lowest degree of saturation and the highest strength ratio. This confirms the previous conclusion that saturation must be high enough to result in moisture damage. The degree of saturation in these specimens could easily have been increased by saturating them again with a slightly higher vacuum for a few minutes. The degree of saturation of all specimens increased during static soaking showing that water was able to permeate voids that were not reached by the saturation procedure. All specimens saturated with a 28.6-in. vacuum became supersaturated by the end of the moisture conditioning regardless of the moisture conditioning procedure. Whether or not this is evidence of damage other than stripping, especially in specimens conditioned by soaking, is not known, but the data show that supersaturation after moisture conditioning can be avoided by saturating with a partial vacuum, which eliminates the question.

Table B-4 Saturation and moisture conditioning effects.

Saturation Procedure		Saturation, Percent	Swell, Percent	Moisture Conditioning Procedure	Saturation, Percent	Swell, Percent	Tensile Str. Ratio, Percent
Vacuum, In. Hg	Time, Min.						
20.0	15			soak 24 hr @ 140F	94.2	0.9	44.3
20.0	15			soak 24 hr @ 140F	82.9	0.5	57.2
20.0	30			soak 24 hr @ 140F	86.4	0.7	47.6
20.0	30			soak 24 hr @ 140F	72.7	0.4	50.5
15.0	15			soak 24 hr @ 140F	68.9	1.1	65.3
15.0	15			soak 24 hr @ 140F	68.2	0.4	66.7
20.0	15	59.0	0.0	soak 24 hr @ 140F	84.8	0.7	54.9
20.0	15	61.3	0.2	soak 24 hr @ 140F	88.0	0.9	52.9
20.0	15	64.0	0.5	soak 24 hr @ 140F	85.3	1.1	46.2
28.6*	30*	93.2	0.4	soak 24 hr @ 140F	118.4	1.3	33.4
28.6*	30*	80.5	-0.2	soak 24 hr @ 140F	104.9	0.9	32.6
28.6*	30*	89.1	0.2	soak 24 hr @ 140F	111.4	0.9	35.8
28.6*	30*	81.7	0.4	freeze-thaw*	106.4	1.6	44.7
28.6*	30*	83.1	0.0	freeze-thaw*	107.6	1.1	37.4
28.6*	30*	85.9	0.2	freeze-thaw*	100.2	0.7	47.5

*Procedure from NCHRP Report 192 (7).

Tensile Splitting Test

The diametral tensile splitting test which was selected for testing additive effectiveness is a procedure that is used regularly in research and moisture damage testing. Load is applied at 2 in. per minute at 77 F until the maximum load is reached. The Lottman procedure (7) uses slower loading rates and lower temperatures, both of which make the procedure more difficult, especially for field laboratories. There is no known advantage to these slow rates and low temperatures. Also, the correlation between 2 in. per minute at 77 F and Lottman's conditions has been studied and found to be excellent (19). The strain rate of 2 in. per minute is advantageous because it permits the use of the ubiquitous Marshall stability equipment. The temperature of 77 F is advantageous because, coupled with a strain rate of 2 in. per minute, maximum loads are at desirable levels. Also, 77 F does not require ice or equipment for cooling specimens which may not be available in many field laboratories. Two water baths, one for 77 F and one for 140 F, are desirable, but if necessary the same water bath that is used for the 24 hour soak at 140 F can also be used a few minutes later to stabilize specimen temperature at 77 F.

EVALUATION OF PROCEDURE

To determine that the procedure could be used to measure the effectiveness of antistripping additives, the Chert-B mixture

was used with grade AC-20 asphalt cement from two sources and two antistripping additives. The two sources of asphalt cement, designated AC-20-1 and AC-20-2, are known to use different crude oils, but it was not known that these asphalts would differ with respect to stripping and additives. One of the additives was, according to the manufacturer, designed for use with gravel and natural sand. It should be expected to be very effective in this chert mixture and not very sensitive to dose. This second additive was designed for use with limestone mixtures, and although it could be expected to be helpful in a chert mixture, it should not be as effective as the other additive. The additives are designated: Additive 1—effective, Additive 2—less effective. The manufacturer recommended a dose between 0.3 and 0.5 percent based on the weight of asphalt cement. Except where noted otherwise, a dose of 0.5 percent was used.

Effect of Additive on Tensile Strength

To investigate the effect of an additive, the tensile strength of specimens with and without additive, moisture conditioned and unconditioned, was determined. The tensile strength was used at this point instead of tensile strength ratio because the ratio for unconditioned specimens is always 100, which tends to mask the variability in the testing. Experimental data are given in Table B-5. Considering only average tensile strength, the unavoidable conclusion is that moisture conditioning had a very significant, devastating effect on specimens without additive and practically no effect on specimens with additive. There is,

however, considerable scatter in the data and further analysis was performed.

The analysis of variance compares differences between treatments with differences within treatments and is conclusive in showing that the treatments are different. Throughout this experiment, probabilities of 20:1 or greater are considered to be conclusive. Within treatment variability in this analysis represents the variability in the testing, and the analysis shows that this variability is very small compared to the effects of different treatments.

Average tensile strength of the four treatments was also compared. The comparison between moisture-conditioned specimens with and without additive shows that the treatments are different, which means that the tests show that the additive is effective.

There is also a question concerning whether or not an additive significantly affects the tensile strength of specimens tested dry. In actual practice, this question would not arise because treated and untreated specimens would not be compared. For purposes of evaluating a test procedure the question is important because it influences the number of specimens that must be tested. The analysis shows that the two dry treatments represent different populations, and it was concluded that the tensile strength of mixtures with and without additive should be analyzed separately.

In application, the data in Table B-5 would result in a tensile strength ratio of 49.9 percent for specimens without additive. Although a ratio at which moisture damage becomes excessive with this procedure has not yet been established, this ratio does indicate extensive moisture damage. The tensile strength ratio for specimens with additive is 99.8, indicating a very effective additive.

It was concluded that the procedure can be used to measure moisture damage and the effects of additives.

Effects of Different Additives

Mixtures containing additive 1 and additive 2 were then tested. Results appear in Table B-6. The data show that moisture damage is severe without additive. Additive 1 practically eliminates damage and is very effective. Additive 2, which is not intended for chert, is much less effective but does inhibit moisture damage somewhat. Analysis of variance shows that the treatments are different and that variability caused by treatments is much more significant than variability caused by testing. Comparison of means shows conclusively that mixtures containing additive 2 are different from both mixtures containing additive 1 and mixtures without additive.

For purposes of evaluating a testing procedure, additive 2 is very important. The procedure shows that the additive performs as it should, not highly effective. Also, variability with additive 2 is much greater than with additive 1 or without additive. It is not at all conclusive, but a partially effective additive could be expected to result in variable test results because it might work well one time and not the next. One characteristic of a good additive is that it should be a consistent performer, and a testing procedure should be able to reflect this. The procedure in this case indicates that additive 2 is not very effective and not very consistent.

Table B-5 Effect of additive on tensile strength.

Treatment	Tensile Strength, psi			
	Without Additive		With 0.5% Additive 1	
	Dry	Conditioned	Dry	Conditioned
n	9	10	6	6
\bar{X}	112.1	55.2	94.5	94.3
S	9.5	6.0	14.4	12.6
Range	96.2-118.7	45.7-64.1	77.3-115.3	77.7-110.8

Analysis of Variance

The probability that the effects of the treatments are different is more than 1000:1.

Comparison of Means

Without Additive. The probability that dry specimens represent a different population than conditioned specimens is more than 1000:1.

With Additive. The probability that dry specimens represent a different population than conditioned specimens is less than 10:1.

Dry Specimens. The probability that specimens without additive represent a different population than specimens with additive is more than 50:1.

Conditioned Specimens. The probability that specimens without additive represent a different population than specimens with additive is more than 1000:1.

Table B-6 Effect of different additives.

Treatment	Tensile Strength Ratio, Percent		
	Without Additive	With 0.5% Additive 1	With 0.5% Additive 2
n	11	6	8
\bar{X}	49.0	99.9	68.1
S	5.2	7.4	12.6
Range	40.8 - 57.2	90.6 - 110.8	48.5 - 84.5

Analysis of Variance

The probability that the effects of the treatments are different is more than 1000:1.

Comparison of Means

The probability that specimens treated with Additive 2 represent a different population than either untreated specimens or specimens treated with Additive 1 is more than 1000:1.

Additive Dosage

It has been noted that the most advantageous dose of additive is a function of aggregate surface area and surface chemistry, and the chemical nature of the asphalt cement. Even with the

Table B-7 Effect of additive dosage (additive 1).

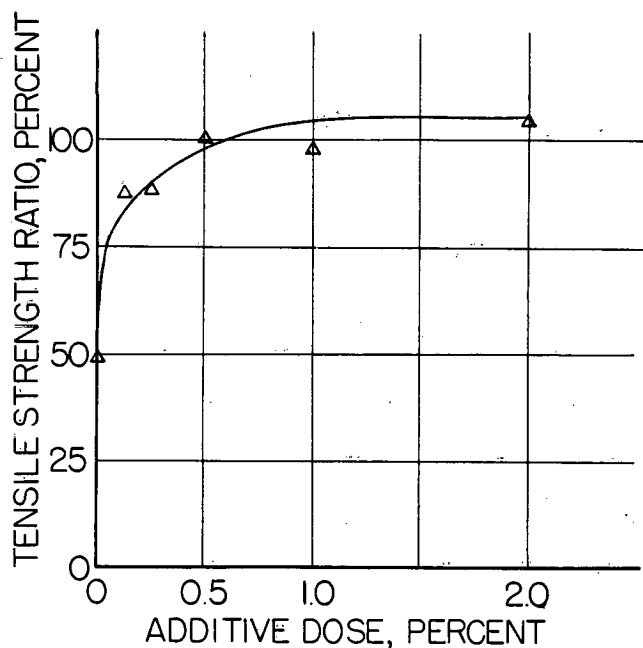
Dose	Tensile Strength Ratio, Percent				
	0.125%	0.25%	0.5%	1.0%	2.0%
n	2	2	6	2	2
\bar{X}	86.6	87.4	99.9	98.7	104.1
S	0.4	3.0	7.4	4.2	1.1

Analysis of Variance

The probability that the effects of the treatments are different is more than 20:1.

Comparison of Means

The probability that specimens treated with 0.25% additive represent a different population than specimens treated with 0.5% additive is more than 100:1. Specimens with smaller differences between means are not significantly different.

*Figure B-2. Effect of additive dosage.*

manufacturer's recommendation, it seems unlikely that the best dose will be used unless it is determined by test. To study dosage, specimens were prepared at various doses and tested, resulting in the data in Table B-7 and Figure B-2.

A very small dose produces a very dramatic effect, but as the dose increases, the effect increases at a decreasing rate. An optimum dose was not found within the ranges studied. The additive manufacturer had advised that in a chert mixture this additive would not be highly sensitive to dosage and might not reveal an optimum dose. In these respects, the procedure revealed what was supposed to be present.

Analysis of variance shows that the effects of the doses are different, and that variability caused by doses is significantly greater than variability caused by testing. Comparison of means shows that $\frac{1}{4}$ percent is different from $\frac{1}{2}$ percent, and that means differing from one another by less than the difference between $\frac{1}{4}$ percent and $\frac{1}{2}$ percent is not significantly different.

This shows that the procedure is sensitive to additive dose. It is expected that other combinations of aggregates, asphalts, and additives could be much more sensitive to dose.

Alternate Source of Asphalt Cement

Additives 1 and 2 were used in mixtures containing asphalt cement AC-20-2, representing the alternate source. Results appear in Table B-8. Compared to the same additives with asphalt cement AC-20-1 in Table B-6, both additives appear to be somewhat less effective with asphalt cement AC-20-2.

Analysis of variance shows that the effects of the treatments in Table B-8 are different and that treatments are responsible for much more variability than testing. At a probability of more than 20:1, this is considered to be conclusive. Comparing means shows that additive 1 is different from without additive with a

Table B-8 Effect of alternate asphalt cement.

Treatment	Tensile Strength Ratio, Percent		
	Without Additive	With 0.5% Additive 1	With 0.5% Additive 2
n	2	2	2
\bar{X}	48.5	88.3	55.5
S	6.2	9.7	5.3

Analysis of Variance

The probability that the effects of the treatments are different is more than 20:1.

Comparison of Means

The probability that specimens treated with Additive 1 represent a different population than specimens without additive is more than 20:1.

The probability that specimens treated with Additive 2 represent a different population than specimens either treated with Additive 1 or without additive is less than 10:1.

probability of more than 20:1 which again is considered to be conclusive. Comparing means between additives and between additive 2 and without additive shows that the means are not different.

Another comparison of the two asphalt cements appears in Table B-9, which contains data taken from Tables B-6 and B-8. Analysis of variance shows that the probability that the effects of the treatments are different is more than 20:1, and that variability caused by different treatments is much more significant than variability caused by testing. This is considered to be conclusive, but comparing means does not show conclusively that either additive is significantly different with either asphalt cement.

For purposes of evaluating a testing procedure, it is considered that the procedure is sensitive to asphalt cement characteristics which influence moisture damage and additive effectiveness. The fact that differences were not significant in all statistical tests does not mean that the procedure is faulty, because there was no way of knowing in advance how much different asphalts would affect test results. Also, additive dose for AC-20-2 was not studied, and it is possible that the most effective dose was not used.

Effect of Saturation

The degree of saturation of specimens appears to be very crucial in detecting moisture damage and measuring additive effectiveness. It has already been noted that static soaking may not provide enough saturation to cause damage, and that certain combinations of saturation methods and moisture conditioning result in supersaturation and low strength which may not be stripping or damage that additives can correct. There remains the question of what level of saturation is required for a valid procedure.

Table B-9 Comparison of asphalt cements.

Asphalt Cement	Tensile Strength Ratio, Percent			
	AC-20-1		AC-20-2	
	With 0.5% Additive 1	With 0.5% Additive 2	With 0.5% Additive 1	With 0.5% Additive 2
n	6	8	2	2
\bar{X}	99.9	68.1	88.3	55.1
S	7.4	13.6	9.7	5.3

Analysis of Variance

The probability that the effects of the treatments are different is more than 1000:1.

Comparison of Means

The probability that the two asphalt cements treated with Additive 1 represent different populations is less than 10:1.

The probability that the two asphalt cements treated with Additive 2 represent different populations is less than 10:1.

The relationship between degree of saturation and tensile strength ratio for the two chert mixtures is shown on Figure B-3. The data include saturation by various partial vacuums held for various times as well as the high vacuum for 30 min used by Lottman (7). Moisture conditioning includes soaking for one day at 140 F and Lottman's freeze-thaw (7). The data suggest that for these mixtures, saturation should exceed 80

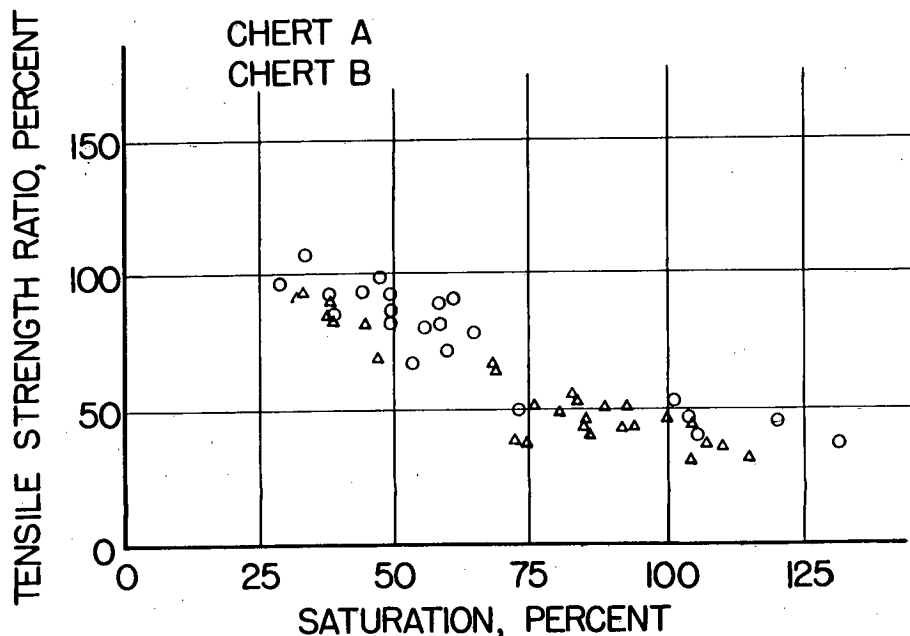


Figure B-3. Effect of degree of saturation.

percent for a valid test. Supersaturation seems to serve no useful purpose and can be avoided, thereby eliminating questions of other damage.

Whether or not 80 percent is a minimum degree of saturation that is applicable to other mixtures is not known. In addition to the chert mixtures in Figure B-3, the glacial gravel and limestone mixtures were saturated by partial vacuum and soaked at 140 F for one day resulting in saturation of 83.9 percent and 72.5 percent, respectively, and tensile strength ratios of 46.9 percent and 78.1 percent, respectively. Previously both of these mixtures had been supersaturated, resulting in strength ratios of less than 50 percent. The data at least suggest that 80 percent saturation may be applicable to the chert mixtures as well as to others.

To achieve 80 percent saturation it is necessary to control the degree of saturation before moisture conditioning. In this study the degree of saturation of all mixtures tested increased during moisture conditioning. In all cases involving untreated mixtures, when the degree of saturation was 55 percent or more before moisture conditioning, it was more than 80 percent after moisture conditioning. Therefore, in the procedure a minimum degree of saturation before moisture conditioning of 55 percent is set. This limit is regarded as tentative, subject to revision when data on more mixtures become available. A maximum saturation at this same point of 80 percent has also been included to avoid supersaturation. The basis for this limit is that 80 percent saturation was achieved only with a vacuum of 28.6 in. Hg, and nearly all specimens saturated by that vacuum were supersaturated at the end of moisture conditioning resulting in very low strength.

All experimental data used to evaluate the procedure did not involve specimens with initial saturation exceeding 55 percent. The limit was derived from the data after the tests were run. Analysis was performed on data excluding specimens saturated to less than 55 percent, and conclusions were found to be the same as when all specimens were included. Therefore, it is believed that the evaluation of the procedure and the limits on degree of saturation are valid.

It was observed that specimens that were not susceptible to moisture damage were more difficult to saturate than specimens that were readily damaged. Usually a partial vacuum of 20 in. Hg held for 5 min resulted in saturation of 55 percent or more. In some cases, the vacuum had to be increased to 22 in. and in others 25 in. following the initial 5 min at 20 in. The same specimens then did not gain saturation during moisture conditioning to the extent that other specimens do. As a result, some specimens were tested at lower degrees of saturation than others. It is believed that within the limits of the available equipment an effort to achieve at least 55 percent initially should be made. If specimens saturated to this level do not gain much additional saturation during moisture conditioning, it is evidence that little moisture damage is occurring. A negligible loss of strength in such specimens is caused by lack of moisture damage, not lack of saturation.

Swell

The procedure in this appendix requires the determination of swell both before and after moisture conditioning. Swell data are included in Appendix C, but swell has not been used to

evaluate the procedure. The reason is that no useful relationship involving swell has been found. It is believed, however, that swell should be determined in order to develop a data base from which useful relationships can be derived. For example, the specimens that were difficult to saturate also did not swell during moisture conditioning as much as other specimens did. This may be evidence of resistance to moisture damage, but there is not enough data to be conclusive. It is suspected that excessive swell may be characteristic of certain mixtures, probably not including those tested here.

Air Voids

A relationship between air voids and tensile strength may exist, but none was found in this experiment. If air voids are significant, however, the effect should be important only with unconditioned specimens. If the procedure is followed properly, air voids of the unconditioned subset will approximate that of the conditioned subset, and there should be no influence caused by air voids. With respect to moisture conditioned specimens, it was found that regardless of air voids, moisture damage was a function of saturation as illustrated in Figure B-4.

SUMMARY

A procedure for testing the effectiveness of antistripping additives has been developed. The procedure uses parts of several existing procedures. The only new concept is that this procedure controls the degree of saturation in compacted specimens to ensure that enough moisture is present to cause stripping but at the same time avoid physical damage that is not stripping.

The procedure is shown to be sensitive to: effects of water, effects of different additives, effects of additive dose, and effects of different asphalt cements.

No attempt has been made to establish a limiting tensile strength ratio for use with this procedure at this time. Such a limit is not needed for the development and evaluation of the procedure, and it should be based on more data than is available now.

The procedure is believed to be suitable for use in studying the effects of storing, handling, and using additives.

METHOD OF TEST FOR DETERMINING THE EFFECT OF MOISTURE AND ANTISTRIPPING ADDITIVES ON ASPHALT CONCRETE PAVING MIXTURES

1. Scope

This method contains procedures for preparing and testing specimens of asphaltic concrete for purposes of measuring the effect of water, or the effectiveness of antistripping additives on the tensile strength of the paving mixture. The method is applicable to dense mixtures such as those appearing in the upper half of Table 3, ASTM Specification D 3515. The method can evaluate the effect of moisture with or without additives, the effect of liquid antistripping additives which are added to the asphalt cement, or pulverulent solids such as hydrated lime or portland cement which are added to the mineral aggregate.

2. Applicable Documents

2.1. ASTM Standards

- D 979 Method for Sampling Bituminous Paving Mixtures
- D 1559 Test for Resistance to Plastic Flow of Bituminous Mixtures by Marshall Apparatus
- D 2041 Test for Theoretical Maximum Specific Gravity of Bituminous Paving Mixtures
- D 2726 Test for Bulk Specific Gravity of Compacted Bituminous Mixtures Using Saturated Surface-Dry Specimens
- D 3203 Test for Percent Air Voids in Compacted Dense and Open Bituminous Paving Mixtures
- D 3515 Specification for Hot-Mixed, Hot-Laid Bituminous Paving Mixtures
- D 3549 Test for Thickness or Height of Compacted Bituminous Paving Mixture Specimens
- D 3665 Practice for Random Sampling of Construction Materials
- D 4123 Method of Indirect Tensile Test for Resilient Modulus of Bituminous Mixtures

3. Significance and Use

This method can be used to test asphaltic concrete mixtures in conjunction with mixture design testing to determine whether or not moisture damage is severe enough so that an additive should be considered, and if it is severe enough, to determine whether or not an antistripping additive is effective and what dose of additive is most effective. It can also be used to test mixtures produced at plants to determine the severity of moisture damage and the effectiveness of additives under conditions imposed by construction in the field. Finally, it can be used to test cores from completed pavements of any age to determine the severity of moisture damage and the effectiveness of additives under conditions of exposure and service in the field.

4. Summary of Method

4.1. To determine the severity of moisture damage and decide whether or not an additive should be considered, a set of laboratory-compacted specimens conforming to the job-mix formula without additive is prepared. The specimens are compacted to a void content corresponding to void levels expected in the field, usually in the 6 to 8 percent range. The set is divided into two subsets of approximately equal void content, and one subset is maintained dry, while the other subset is saturated with water and moisture conditioned. The tensile strength of each subset is determined by the tensile splitting test. The severity of moisture damage is indicated by the ratio of the tensile strength of the wet subset to that of the dry subset.

4.2. To determine the effectiveness of an antistripping additive a set of specimens containing additive but otherwise the same as the set in Section 4.1 is prepared and tested, and the severity of the moisture damage is determined in the manner described in Section 4.1. The effectiveness of the additive is indicated by the improvement in the wet-to-dry ratio of the set containing additive compared to the set without additive. The effect of

additive dosage may be estimated by repeating the set with different additive dosages.

4.3. To determine the severity of moisture damage or the effectiveness of an additive in mixture produced in an asphalt plant in the field, specimens are laboratory compacted to field level void content, divided into wet and dry subsets, and the severity of moisture damage or the effectiveness of the additive is determined as in Section 4.2.

4.4. To determine the severity of moisture damage or the effectiveness of an additive in specimens cored from a pavement, cores are maintained at in-place moisture content until tensile strength is measured. This strength may be compared to the tensile strength determined previously before moisture damage occurred.

5. Apparatus

5.1. Equipment for preparing and compacting specimens from Method D 4123.

5.2. Vacuum pump or water aspirator, manometer or vacuum gauge, and container, preferably Type D, from Method D 2041.

5.3. Balance and water bath from Method D 2726.

5.4. Water bath or oven capable of maintaining a temperature of 140 F for 24 hours.

5.5. Loading jack and ring dynamometer from Method D 1559, or a mechanical or hydraulic testing machine capable of maintaining the required strain rate and measuring load with suitable precision.

5.6. Loading strips from Method D 4123.

6. Preparation of Laboratory Test Specimens

6.1. At least six specimens shall be made for each test, three to be tested dry and three to be tested after saturation and moisture conditioning.

6.2. Specimens 4 in. in diameter and 2.5 in. thick are usually used. Specimens of other dimensions may be used if desired and should be used if aggregate larger than 1 in. is present.

6.3. When 4-in. \times 2.5-in. specimens are used, mixtures shall be prepared in batches large enough to make at least 3 specimens. When larger specimens are used, batches may be prepared for each specimen. If theoretical maximum specific gravity is to be determined, the batch should be large enough to provide the specimen for that purpose also.

6.4. When a liquid antistripping additive is used, the asphalt cement in sufficient quantity for one batch shall be heated to 300 F in a closed one quart can in an oven. The required quantity of additive shall be added. Immediately lower a mechanical stirrer to within 1 in. of the bottom of the container, and mix the contents for 2 min. Maintain the treated asphalt cement at 300 F in the closed can until it is used. If the treated asphalt cement is not used on the same day in which it is prepared, or if it is allowed to cool so that it would require reheating, it shall be discarded.

6.5. When a pulverulent solid antistripping additive is used, the batch of mineral aggregate shall be dried, composited, and heated to 300 F. The required quantity of additive shall be added to the aggregate, and the entire mass shall be thoroughly mixed until a uniform distribution of additive has been achieved. Care

shall be taken to minimize loss of additive to the atmosphere in the form of dust. After mixing, maintain the treated aggregate at the temperature required for mixing until it is used.

6.6. Proportion, mix, and compact specimens in accordance with Method D 4123 and Sections 6.6.1 and 6.6.2.

6.6.1. After mixing, stabilize mixture temperature at the required compaction temperature in a closed container in an oven for from 1 to 2 hours.

6.6.2. Compact specimens to 7 ± 1 percent air voids, or a void level expected in the field. This level of voids can be obtained by adjusting the static load in double plunger compaction; the number of blows in Marshall hammer compaction; the foot pressure, number of tamps, leveling load, or some combination in kneading compaction; or the number of revolutions in gyratory compaction. The exact procedure must be determined by trial for each mixture.

6.6.3. Cool specimens to room temperature as rapidly as possible in a stream of moving air, extract from molds, and proceed with Section 9 immediately if possible, but within 24 hours at most.

7. Preparation of Field Specimens

7.1. Select a truck to be sampled in accordance with Practice D 3665.

7.2. Secure a sample from the truck at the plant in accordance with Method D 979.

7.3. Stabilize mixture temperature to approximately the temperature found in the field when rolling begins. Maintain this temperature in a closed container, in an oven if necessary, for approximately the time lapse between mixing and the start of actual rolling.

7.4. Compact specimens in accordance with Section 6.6.2, and cool and extract from molds in accordance with Section 6.6.3.

7.5. If specimens are not to be compacted in the field laboratory, place the samples in a sealed container, transport to the laboratory, and reheat to the temperature required in Section 7.3. Then proceed with Section 7.4.

8. Preparation of Core Test Specimens.

8.1. Select locations to be sampled on the completed pavement or pavement layer in accordance with Practice D 3665.

8.2. Core at the selected locations in accordance with Method D 979. A wet coring process should be used, and the periphery of the core should be blotted dry immediately after it is taken. Wrap the core in plastic wrap or otherwise protect it to maintain field moisture content until the test layer of the core is separated.

8.3. Separate core layers as necessary by sawing or other suitable means. A wet sawing process is preferred, and the periphery of the test layer of the core should be blotted dry immediately after it is sawn. Wrap the test layer in plastic wrap or otherwise protect it to maintain field moisture content until it is tested.

9. Procedure

9.1. Determine the theoretical maximum specific gravity by Method D 2041.

9.2. Determine specimen thickness by Method D 3549.

9.3. Determine the bulk specific gravity by Method D 2726, and express the volume of the specimen in cubic centimeters. The term (B-C) in Method D 2726 is the volume of the specimen in cubic centimeters.

9.4. Calculate air voids by Method 3203, and express the volume of air in cubic centimeters. The volume of air is the volume of the specimen from Section 9.3 multiplied by the percentage air voids.

9.5. Sort specimens into two subsets so that average air voids of the two subsets are approximately equal. Store the subset to be tested dry at room temperature.

9.6. Saturate the subset to be moisture conditioned with distilled water at room temperature. If it is difficult to reach the minimum degree of saturation of 55 percent required in Section 9.6.3, the water used to saturate may be heated up to 140 F.

9.6.1. Saturate by applying a partial vacuum such as 20 in. Hg for a short time such as 5 min.

Note 1: Experiments with partial vacuum at room temperature indicate that degree of saturation is very sensitive to the magnitude of the vacuum and practically independent of the duration. The level of vacuum needed appears to be different for different mixtures.

9.6.2. Determine bulk specific gravity by Method D 2726. Determine the volume of absorbed water by subtracting the air dry weight of the specimen found in Section 9.3 from the saturated surface dry weight of the saturated specimen found in Section 9.6.2.

9.6.3. Determine the degree of saturation by dividing the volume of absorbed water found in Section 9.6.2 by the volume of air voids found in Section 9.4 and expressing the result as a percentage. If the volume of water is between 55 and 80 percent of the volume of air, proceed to Section 9.7. If the volume of water is less than 55 percent, repeat the procedure beginning with Section 9.6.1 using a slightly higher partial vacuum. If the volume of water is more than 80 percent, the specimen has been damaged and is discarded.

Note 2: If the average air voids of the saturated subset is less than 6.5 percent, saturation of at least 70 percent is recommended.

9.7. Moisture-condition the saturated specimens by soaking in distilled water at 140 F for 24 hours.

9.8. Adjust the temperature of the moisture-conditioned subset by soaking in a water bath for 1 hour at 77 F.

9.9. On moisture-conditioned subset, measure thickness by Method D 3549, and determine bulk specific gravity by Method D 2726.

9.9.1. Determine water absorption and degree of saturation in accordance with Section 9.6.2 and Section 9.6.3. Saturation exceeding 80 percent is acceptable in this step.

9.9.2. Determine swell of saturated specimens by dividing the change in specimen volumes found in Sections 9.6.2 and 9.3 by the specimen volume found in Section 9.3. Determine swell of conditioned specimens by dividing the change in specimen volumes found in Sections 9.9 and 9.3 by the specimen volume found in Section 9.3.

9.10. Adjust temperature of dry subset by soaking in a water bath for 20 min at 77 F.

9.11. Determine tensile strength at 77 F of both subsets.

9.11.1. Apply diametral load in accordance with Method D 4123 at 2.0 in. per minute until the maximum load is reached, and record the maximum load.

9.11.2. Continue loading until specimen fractures. Break open and estimate and record stripping, if any.

9.11.3. Inspect all surfaces, including the failed faces, for evidence of cracked or broken aggregate, and record observations.

10. Calculations

10.1. Tensile Strength

$$S_t = 2P/\pi tD$$

where:

S_t = tensile strength, psi;

P = maximum load, lb;

t = specimen thickness immediately before tensile test, in.;
and

D = specimen diameter, in.

10.2. Tensile Strength Ratio

$$TSR = (S_{tm}/S_{td})100$$

where:

TSR = tensile strength ratio, percent;

S_{tm} = average tensile strength of moisture-conditioned subset, psi; and

S_{td} = average tensile strength of dry subset, psi.

11. Report

11.1. Average room temperature at which any measurements are made.

11.2. Number of specimens in each subset.

11.3. Average degree of saturation after saturating and after moisture conditioning.

11.4. Average swell after saturating and after moisture conditioning.

11.5. Tensile strength of each specimen in each subset.

11.6. Tensile strength ratio.

11.7. Results of estimated stripping observed when specimen fractures.

11.8. Results of observations of fractured or crushed aggregate.

12. Precision

12.1. Precision of the method is under study.

12.2. Tests on one moisture-conditioned mixture containing additive in one laboratory indicate that the difference in tensile strength between duplicate specimens should not exceed 25.2 psi.

APPENDIXES C, D, AND E

Appendixes C, D, and E contained in the report submitted by the research agency are not published herein but are bound under separate cover in a supplement to NCHRP Report 274. They are listed here for convenience of researchers in the subject area, who may obtain copies of the *Supplement* on loan or for purchase upon request to the Director, Cooperative Research Programs. The contents of these appendixes, in brief, are as follows:

- Appendix C—This appendix contains details of the labo-

ratory experiment and experimental data which support the conclusions and findings pertaining to the development of the procedure for testing antistripping additive effectiveness.

- Appendix D—This appendix contains details of the laboratory experiments and experimental data pertaining to the effects of storage and handling on antistripping additive performance.

- Appendix E—This appendix contains 11 tables of correlation and evaluation data pertaining to the test method.

APPENDIX F

EXAMPLE PROCEDURE FOR JUDGING ADDITIVE EFFECTIVENESS

INTRODUCTION

In Chapter Three a statistical method of judging additive effectiveness is recommended. This appendix contains an example of the use of this method using data from the previous appendixes.

STATISTICAL METHODS

Two means may be compared by application of Student's "t" distribution which is a statistical technique particularly suitable for use with small amounts of data. Calculations are easily performed on an electronic calculator.

Figure F-1 is a format for calculating "t." Figure F-2 is used to assign probabilities to the calculated values of "t." The three probabilities in Figure F-2 are those suggested in Chapter Three: more than 20:1 to determine that moisture damage is severe enough so that an additive should be considered, more than 100:1 to show that an additive is effective enough in the laboratory, and less than 10:1 to show that an additive is effective enough in the field.

CALCULATION FOR "t" TEST

Line	Column 1 Data*	Column 2 Squared	Column 3 Data*	Column 4 Squared
1 Data*				
2 Data*				
3 Data*				
4 Data*				
5 Totals				
6 Totals Squared				
7 Number of Specimens	n_1		n_2	
8 (Line 6)/(Line 7)				

Variance = $s^2 = \frac{(\text{Column 2} - \text{Column 1} + \text{Column 4} - \text{Column 3}) / (n_1 + n_2 - 2)}{2} = \frac{(\quad - \quad + \quad - \quad) / (\quad + \quad - 2)}{2}$

Standard Deviation = $s = \sqrt{s^2} = \sqrt{\quad} = \quad$

Mean = $\bar{x}_1 = \frac{(\text{Column 1, Line 5})}{n_1} = \frac{\quad}{\quad} = \quad$
 $\bar{x}_2 = \frac{(\text{Column 3, Line 5})}{n_2} = \frac{\quad}{\quad} = \quad$

If \bar{x}_2 is greater than \bar{x}_1 , the calculation need not be completed because (1) no moisture damage is indicated without additive, (2) the additive is ineffective in the laboratory test, or (3) the additive is shown to be effective in the field test.

$t = \frac{\bar{x}_1 - \bar{x}_2}{s} \sqrt{\frac{n_1 \times n_2}{n_1 + n_2}} = \frac{\quad - \quad}{\quad} \sqrt{\frac{\quad \times \quad}{\quad + \quad}} = \quad$

Degrees of Freedom = $n_1 + n_2 - 2 = \quad + \quad - 2 = \quad$

* Enter data as follows: (1) to determine additive need, tensile strength of dry specimens in Column 1 and of wet specimens in Column 3, (2) to determine additive effectiveness in the laboratory, (a) tensile strength of treated dry specimens in Column 1 and of treated wet specimens in Column 3, and (b) tensile strength ratio of treated specimens in Column 1 and untreated specimens in Column 3, or (3) to determine additive effectiveness in the field, tensile strength of dry specimens in Column 1 and wet specimens in Column 3.

Figure F-1. Format for calculating Student's "t".

EXAMPLE CALCULATIONS

Determining Additive Need

Figure F-3 is an example of the use of the format in a central laboratory. The data are from Table D-7 for additive 2 in the limestone mixture. The calculated value of "t" for comparing wet and dry specimens without additive plots above the 20:1 curve in Figure F-2, and the conclusion is that moisture damage will occur and an additive should be tried.

Determining Additive Effectiveness—Central Laboratory

In Figure F-4, tensile strength of dry and wet specimens of the same limestone mixture containing additive are compared.

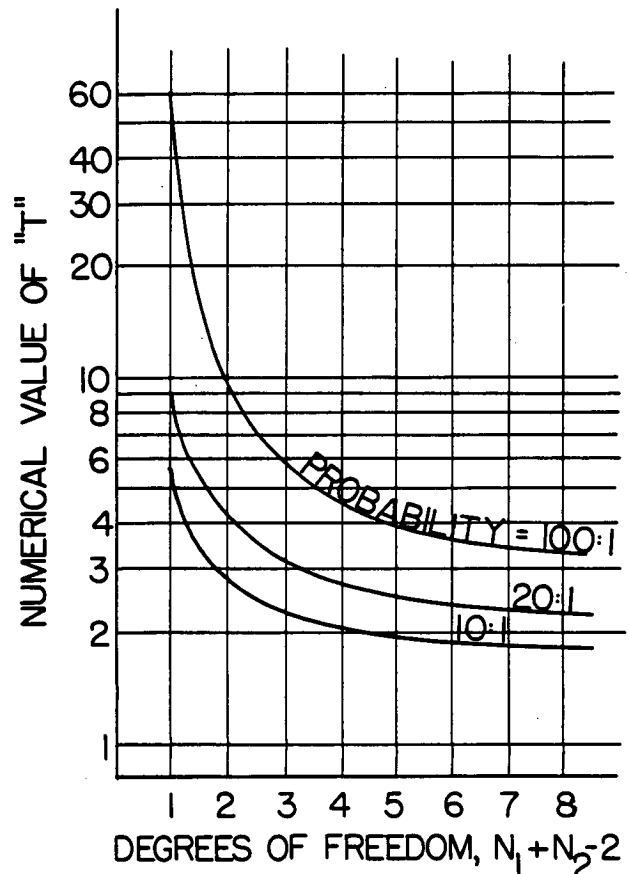


Figure F-2. Probabilities of the "t" distribution.

The calculated value of "t" plots above the 20:1 curve in Figure F-2, and the conclusion is that moisture damage is likely even with the additive.

The next step is shown in Figure F-5 where tensile strength ratios are compared for specimens of the same limestone mixture with and without additive. Ratios in the example were calculated from data for individual wet specimens divided by the average strength of comparable dry specimens. The calculated value of "t" plots above the 100:1 curve in Figure F-2, and the conclusion is that the additive is effective enough to be helpful.

The example in Figures F-4 and F-5 illustrate the Case 4 situation discussed in Chapter Three. Although the additive helps, moisture damage is still indicated, and more improvement in the mixture should be studied.

Determining Additive Effectiveness—Field Mixture

Figures F-6 and F-7 illustrate the use of the format with two examples of the field decision. No field data were collected in this study, and the two examples use laboratory data as if it were field data.

The example in Figure F-6 uses the data from Table D-7 for additive 4 when heated in asphalt cement at 350 F for 24 hours. The calculated value of "t" plots above the 10:1 curve in Figure F-2, and the conclusion is that the additive is not effective enough.

The second example uses data from Table D-7 for additive 2 at a dosage of 2 percent in the chert mixture. The calculated value of "t" plots below the 10:1 curve in Figure F-2, and the conclusion is that the additive is effective enough at that dosage.

CALCULATION FOR "t" TEST

Line	Column 1 Data*	Column 2 Squared	Column 3 Data*	Column 4 Squared
1 Data*	134.5	18090	80.5	6480
2 Data*	132.7	17609	85.1	7242
3 Data*	123.7	15302	72.8	5300
4 Data*	126.7	16053	77.7	6037
5 Totals	517.6	67054	316.1	25059
6 Totals Squared	267910		99919	
7 Number of Specimens	n ₁ = 4		n ₂ = 4	
8 (Line 6)/(Line 7)	66978		24980	

$$\text{Variance} = s^2 = (\text{Column 2} - \text{Column 1} + \text{Column 4} - \text{Column 3}) / (n_1 + n_2 - 2) \\ = (67054 - 66978 + 25059 - 24980) / (4 + 4 - 2) \\ = 155 / 6 = 25.8$$

$$\text{Standard Deviation} = s = \sqrt{s^2} = \sqrt{25.8} = 5.1$$

$$\text{Mean} = \bar{x}_1 = (\text{Column 1, Line 5}) / n_1 = 517.6 / 4 = 129.4$$

$$\bar{x}_2 = (\text{Column 3, Line 5}) / n_2 = 316.1 / 4 = 79.0$$

If \bar{x}_2 is greater than \bar{x}_1 , the calculation need not be completed because (1) no moisture damage is indicated without additive, (2) the additive is ineffective in the laboratory test, or (3) the additive is shown to be effective in the field test.

$$t = \frac{\bar{x}_1 - \bar{x}_2}{s} \sqrt{\frac{n_1 \times n_2}{n_1 + n_2}} = \frac{129.4 - 79.0}{5.1} \sqrt{\frac{4 \times 4}{4 + 4}} = 14.0$$

$$\text{Degrees of Freedom} = n_1 + n_2 - 2 = 4 + 4 - 2 = 6$$

* Enter data as follows: (1) to determine additive need, tensile strength of dry specimens in Column 1 and of wet specimens in Column 3, (2) to determine additive effectiveness in the laboratory, (a) tensile strength of treated dry specimens in Column 1 and of treated wet specimens in Column 3, and (b) tensile strength ratio of treated specimens in Column 1 and untreated specimens in Column 3, or (3) to determine additive effectiveness in the field, tensile strength of dry specimens in Column 1 and wet specimens in Column 3.

Figure F-3. Calculating "t" to determine additive need.

CALCULATION FOR "t" TEST

Line	Column 1 Data*	Column 2 Squared	Column 3 Data*	Column 4 Squared
1 Data*	142.9	20420	107.7	11599
2 Data*	136.5	18632	100.9	10181
3 Data*	123.7	15302	102.7	10547
4 Data*	129.7	16822	108.1	11686
5 Totals	532.8	71176	419.4	44013
6 Totals Squared	283876		175896	
7 Number of Specimens	n ₁ = 4		n ₂ = 4	
8 (Line 6)/(Line 7)	70969		43974	

$$\text{Variance} = s^2 = (\text{Column 2} - \text{Column 1} + \text{Column 4} - \text{Column 3}) / (n_1 + n_2 - 2) \\ = (71176 - 70969 + 44013 - 43974) / (4 + 4 - 2) \\ = 246 / 6 = 41$$

$$\text{Standard Deviation} = s = \sqrt{s^2} = \sqrt{41} = 6.4$$

$$\text{Mean} = \bar{x}_1 = (\text{Column 1, Line 5}) / n_1 = 532.8 / 4 = 132.2$$

$$\bar{x}_2 = (\text{Column 3, Line 5}) / n_2 = 419.4 / 4 = 104.9$$

If \bar{x}_2 is greater than \bar{x}_1 , the calculation need not be completed because (1) no moisture damage is indicated without additive, (2) the additive is ineffective in the laboratory test, or (3) the additive is shown to be effective in the field test.

$$t = \frac{\bar{x}_1 - \bar{x}_2}{s} \sqrt{\frac{n_1 \times n_2}{n_1 + n_2}} = \frac{132.2 - 104.9}{6.4} \sqrt{\frac{4 \times 4}{4 + 4}} = 6.0$$

$$\text{Degrees of Freedom} = n_1 + n_2 - 2 = 4 + 4 - 2 = 6$$

* Enter data as follows: (1) to determine additive need, tensile strength of dry specimens in Column 1 and of wet specimens in Column 3, (2) to determine additive effectiveness in the laboratory, (a) tensile strength of treated dry specimens in Column 1 and of treated wet specimens in Column 3, and (b) tensile strength ratio of treated specimens in Column 1 and untreated specimens in Column 3, or (3) to determine additive effectiveness in the field, tensile strength of dry specimens in Column 1 and wet specimens in Column 3.

Figure F-4. Calculating "t" to determine additive effectiveness—central laboratory, step 1.

CALCULATION FOR "t" TEST

Line	Column 1 Data*	Column 2 Squared	Column 3 Data*	Column 4 Squared
1 Data*	80.9	6545	62.2	3869
2 Data*	75.8	5746	65.8	4330
3 Data*	77.1	5944	56.3	3170
4 Data*	81.2	6593	60.0	3600
5 Totals	315.0	24828	244.3	14968
6 Totals Squared	99225		59682	
7 Number of Specimens	n ₁ = 4		n ₂ = 4	
8 (Line 6)/(Line 7)	24806		14921	

$$\text{Variance} = s^2 = (\text{Column 2} - \text{Column 1} + \text{Column 4} - \text{Column 3}) / (n_1 + n_2 - 2) \\ = (24828 - 24806 + 14968 - 14921) / (4 + 4 - 2) \\ = 69 / 6 = 11.5$$

$$\text{Standard Deviation} = s = \sqrt{s^2} = \sqrt{11.5} = 3.4$$

$$\text{Mean} = \bar{x}_1 = (\text{Column 1, Line 5}) / n_1 = 315.0 / 4 = 78.8$$

$$\bar{x}_2 = (\text{Column 3, Line 5}) / n_2 = 244.3 / 4 = 61.1$$

If \bar{x}_2 is greater than \bar{x}_1 , the calculation need not be completed because (1) no moisture damage is indicated without additive, (2) the additive is ineffective in the laboratory test, or (3) the additive is shown to be effective in the field test.

$$t = \frac{\bar{x}_1 - \bar{x}_2}{s} \sqrt{\frac{n_1 \times n_2}{n_1 + n_2}} = \frac{78.8 - 61.1}{3.4} \sqrt{\frac{4 \times 4}{4 + 4}} = 7.4$$

$$\text{Degrees of Freedom} = n_1 + n_2 - 2 = 4 + 4 - 2 = 6$$

* Enter data as follows: (1) to determine additive need, tensile strength of dry specimens in Column 1 and of wet specimens in Column 3, (2) to determine additive effectiveness in the laboratory, (a) tensile strength of treated dry specimens in Column 1 and of treated wet specimens in Column 3, and (b) tensile strength ratio of treated specimens in Column 1 and untreated specimens in Column 3, or (3) to determine additive effectiveness in the field, tensile strength of dry specimens in Column 1 and wet specimens in Column 3.

Figure F-5. Calculating "t" to determine additive effectiveness—central laboratory, step 2.

CALCULATION FOR "t" TEST

Line	Column 1 Data*	Column 2 Squared	Column 3 Data*	Column 4 Squared
1 Data*	128.5	16512	108.7	11816
2 Data*	127.3	16205	106.1	11257
3 Data*	130.9	17135	104.9	11004
4 Data*	125.5	15750	102.4	10486
5 Totals	512.2	65602	422.1	44563
6 Totals Squared	262349		178168	
7 Number of Specimens	n ₁ = 4		n ₂ = 4	
8 (Line 6)/(Line 7)	65587		44542	

$$\text{Variance} = s^2 = (\text{Column 2} - \text{Column 1} + \text{Column 4} - \text{Column 3}) / (n_1 + n_2 - 2)$$

$$= (65602 - 65587 + 44563 - 44542) / (4 + 4 - 2)$$

$$= \frac{36}{6} = 6.0$$

$$\text{Standard Deviation} = s = \sqrt{s^2} = \sqrt{6.0} = 2.4$$

$$\text{Mean} = \bar{x}_1 = (\text{Column 1, Line 5}) / n_1 = 512.2 / 4 = 128.1$$

$$\bar{x}_2 = (\text{Column 3, Line 5}) / n_2 = 422.1 / 4 = 105.5$$

If \bar{x}_2 is greater than \bar{x}_1 , the calculation need not be completed because (1) no moisture damage is indicated without additive, (2) the additive is ineffective in the laboratory test, or (3) the additive is shown to be effective in the field test.

$$t = \frac{\bar{x}_1 - \bar{x}_2}{s} \sqrt{\frac{n_1 \times n_2}{n_1 + n_2}} = \frac{128.1 - 105.5}{2.4} \sqrt{\frac{4 \times 4}{4 + 4}} = 13.3$$

$$\text{Degrees of Freedom} = n_1 + n_2 - 2 = 4 + 4 - 2 = 6$$

* Enter data as follows: (1) to determine additive need, tensile strength of dry specimens in Column 1 and of wet specimens in Column 3, (2) to determine additive effectiveness in the laboratory, (a) tensile strength of treated dry specimens in Column 1 and of treated wet specimens in Column 3, and (b) tensile strength ratio of treated specimens in Column 1 and untreated specimens in Column 3, or (3) to determine additive effectiveness in the field, tensile strength of dry specimens in Column 1 and wet specimens in Column 3.

Figure F-6. Calculating "t" to determine additive effectiveness—field mixture, data for additive 4.

CALCULATION FOR "t" TEST

Line	Column 1 Data*	Column 2 Squared	Column 3 Data*	Column 4 Squared
1 Data*	118.9	14137	111.4	12410
2 Data*	120.7	14568	99.7	9940
3 Data*				
4 Data*				
5 Totals	239.6	28705	211.1	22350
6 Totals Squared	57408		44563	
7 Number of Specimens	n ₁ = 2		n ₂ = 2	
8 (Line 6)/(Line 7)	28704		22282	

$$\text{Variance} = s^2 = (\text{Column 2} - \text{Column 1} + \text{Column 4} - \text{Column 3}) / (n_1 + n_2 - 2)$$

$$= (28705 - 28704 + 22350 - 22282) / (2 + 2 - 2)$$

$$= \frac{69}{2} = 34.5$$

$$\text{Standard Deviation} = s = \sqrt{s^2} = \sqrt{34.5} = 5.9$$

$$\text{Mean} = \bar{x}_1 = (\text{Column 1, Line 5}) / n_1 = 239.6 / 2 = 119.8$$

$$\bar{x}_2 = (\text{Column 3, Line 5}) / n_2 = 211.1 / 2 = 105.6$$

If \bar{x}_2 is greater than \bar{x}_1 , the calculation need not be completed because (1) no moisture damage is indicated without additive, (2) the additive is ineffective in the laboratory test, or (3) the additive is shown to be effective in the field test.

$$t = \frac{\bar{x}_1 - \bar{x}_2}{s} \sqrt{\frac{n_1 \times n_2}{n_1 + n_2}} = \frac{119.8 - 105.6}{5.9} \sqrt{\frac{2 \times 2}{2 + 2}} = 2.4$$

$$\text{Degrees of Freedom} = n_1 + n_2 - 2 = 2 + 2 - 2 = 2$$

* Enter data as follows: (1) to determine additive need, tensile strength of dry specimens in Column 1 and of wet specimens in Column 3, (2) to determine additive effectiveness in the laboratory, (a) tensile strength of treated dry specimens in Column 1 and of treated wet specimens in Column 3, and (b) tensile strength ratio of treated specimens in Column 1 and untreated specimens in Column 3, or (3) to determine additive effectiveness in the field, tensile strength of dry specimens in Column 1 and wet specimens in Column 3.

Figure F-7. Calculating "t" to determine additive effectiveness—field mixture, data for additive 2.

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