CONCLUSIONS

The experimental results are indicative of the complexity inherent in this combination stabilization strategy. An improved understanding of the effect of emulsion type on the engineering and physical properties of the lime-treated clay is needed. Potential physical interactions involving clay surface chemistry and emulsion chemistry require investigation, since they may influence the ability of the bituminous emulsion to be satisfactorily dispersed during mixing. Other test data are needed to define tensile properties, stress-deformation characteristics, and the response of the material to moisture penetration.

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Laboratory Test Method for Predicting Moisture-Induced Damage to Asphalt Concrete

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A laboratory test method is described for the prediction of moisture damage in dense-graded asphalt concrete mixtures. The method consists of obtaining diametral (or indirect) tensile-strength and modulus ratios of compacted specimens subjected to vacuum saturation with water and to freeze-plus-warm-water-soak accelerated moisture conditioning. Test results for dry specimens are used to form the ratio bases. The ratios are used to predict short-term and long-term field damage. Fatigue curves for two mixtures exposed to the dry, vacuum-saturation, and accelerated moisture conditioning of the test method are presented to show effects of moisture on fatigue life. A tentative relationship shows a correlation between tensile-strength ratios obtained by the test method and pavement fatigue-life ratios. An example of the practical use of the correlation is shown. Results are presented from a five-year field evaluation study conducted by seven highway agencies on eight pavement test sections to determine whether the test method's predictive ratios and stripping tendencies correlate with field results. Short-term ratios from laboratory vacuum saturation were reached at four years of pavement age or before. Long-term ratios from laboratory accelerated moisture conditioning ranged from 0 to 0.80; they were reached at five years for some pavements and probably will be reached in a few more years for the other pavements. This ratio is considered one of maximum moisture damage to minimum moisture damage. Visual stripping in the field cores appears similar to the predicted laboratory stripping. Agency-determined layer coefficients decreased due to the loss of moisture cohesion from the associated stripping observed in the field.

The destructive influence of moisture in dense-graded asphalt concrete has been recognized for decades. Laboratory tests have been developed to predict potential moisture damage. The purpose of the tests is to assess the redesign of asphalt mixtures (changes of aggregate type, asphalt, and compaction and addition of antistripping treatments) prior to paving in order to minimize the damage.

Immersion-compression and Marshall-type tests on asphalt concrete mixtures evaluate the effect of water on the asphalt concrete mixture in a compacted state in order to find the interaction of all the mixture constituents. The evaluation methods relate the wet strength to the dry strength either as a ratio or as a percentage of retained strength. Highway agencies have developed specifications for the ratios or retained percentages; low values imply high moisture damage and the necessity to redesign or alter the asphalt concrete mixture being evaluated.

Moisture mechanisms that cause damage have been the objective of studies by many investigators. Simulation of the mechanisms to produce closer field-related moisture-damage conditioning in the laboratory should give more realistic predictive damage ratios. The following are some of the major moisture-damage mechanisms that cause stripping or mixture softening or both:

1. Pore pressure of water in the mixture voids due to wheel-loading repetitions; thermal expansion-contraction differences produced by ice formation, temperature cycling above freezing, freeze-thaw, and thermal shock; or a combination of these factors;
2. Asphalt removal by water in the mixture at moderate to higher temperatures;
3. Water-vapor interaction with the asphalt-filler mastic and larger aggregate interfaces; and
4. Water interaction with clay minerals in the aggregate fines.

Added to the importance of simulating the proper moisture-damage mechanism in laboratory tests is the selection of methods to measure damage. Loss of bond due to stripping seems to be measured more directly by tensile-type tests. Also, moisture-damaged asphalt concrete loses cohesion and the pavements crack and deteriorate, especially when severe stripping is observed. Cracking and some of the deterioration result from repeated tensile stress (or strain) in the field due to wheel loads. Thus, measurement by tensile-mode laboratory tests appears to show the field-associated moisture-damage effect in a realistic manner. Likewise, the stress (or strain) value obtained from these tests has the advantage of being directly used in the current mechanistic approaches of pavement fatigue-life prediction. Here, the indirect-tension (diametral-tension) test is useful; modulus or strength values or both can be used to evaluate effects of moisture. In addition, there is an advantage to using the indirect-tension test under repeated loads as a fatigue test. The relationship of fatigue life to indirect tensile-strength ratios from laboratory moisture-damage simulation may also become practical for pavement life assessment and should provide a closer end-result examination of mixture design and treatment alternatives.

The objectives of this paper are as follows:

1. To describe the laboratory moisture-damage predictive test method that was developed under NCHRP Research Project 4-8(3) for dense-graded asphalt concrete (1),
2. To show the practical implications of how moisture-damage ratios might be related to the change of asphalt mixture fatigue life as a result of the effects of moisture conditioning applied in the test method, and
3. To determine the correlation of the predicted moisture-damage ratios and stripping (determined by the test method) with the damage ratios and stripping found in the asphalt concrete pavements selected for study.

MOISTURE-DAMAGE TEST METHOD

Background

The destructive mechanism of water pressure in the voids of dense-graded asphalt concrete was employed in the development of a laboratory test method for the Idaho Department of Highways in 1971 (2). The test method consisted of saturating compacted mixtures and subjecting them to thermal cycling. Moisture damage was measured by the indirect-tensile test, and the tensile-strength ratio was used as the measure of moisture sensitivity (damage). During the following years, a similar test method was developed under the National Cooperative Highway Research Program (NCHRP) Research Project 4-8(3) (1) with modifications that included the addition of the resilient-modulus ratio and the substitution of the accelerated moisture conditioning variant of a freeze-plus-warm-water soak in place of thermal cycling. In this project a number of cores were obtained and tested from 3- to 12-year-old moisture-damaged pavements in the United States. These results were compared with the damage resulting from several modifications of accelerated moisture conditioning by using laboratory-compacted specimens with aggregate and asphalt types incorporated in the pavements. A close field match was observed with the freeze-plus-warm-water-soak conditioning procedure (3). It was observed that this accelerated conditioning was responsible for the majority of moisture-damage mechanisms.

The moisture conditioning and the testing procedure use routine laboratory equipment. The saturation and testing portion of the test method can also be used to monitor pavement damage by testing cores drilled from the asphalt concrete layer under investigation. The evaluation of the effectiveness of antistripping additives and treatments is also a potential application of the test method.

Test Method

Details of the test method are in the final report of NCHRP Research Project 4-8(3)/1 (1). A summary of the test method is as follows:

1. Nine specimens 4 in in diameter by 2.5 in thick are made from mixtures of aggregate and asphalt materials to be used in the pavement and compacted to the field-estimated permeable voids (based on volume of water absorbed by vacuum saturation into the initially dry specimen).
2. After one or two days of room-temperature curing, the specimens are divided into three sets of three specimens each. One set is selected for the dry test, the second set for the vacuum-saturation test, and the third set for the accelerated-conditioning test (vacuum saturation followed by freeze-plus-warm-water soak). (Permeable voids are calculated during the vacuum-saturation procedure for the second and third sets.) Vacuum saturation consists of immersing the specimens in jars filled with distilled water, pulling a 26-in Hg vacuum for 30 min, and keeping the submerged specimens in the jars for an additional 30 min at atmospheric pressure.
3. The first (dry) and second (vacuum-saturation) sets are submerged in a water bath at the mechanical test temperature for 3 h. Dry specimens are maintained dry, e.g., placed in watertight jars in the bath. If the resilient modulus is desired, then it should be measured first at 55°F (or at room temperature) by using the Schmidt or Chevron procedure (4). By using the same specimens, their indirect tensile strength is measured at 55°F by using a vertical deformation rate of 0.65 in/min (3). Average values for each set are calculated. Visual stripping is also recorded for the two interior faces of each split specimen.
4. Before application of the accelerated conditioning, each wet, vacuum-saturated specimen of the third set is tightly wrapped in thin plastic wrap. Each wrapped specimen is placed in a heavy-duty plastic bag with about 3 mil of distilled water, sealed, and immediately placed in a 0-10°F freezer for 15 h. The wrapped, frozen specimens are then quickly submerged in a 140°F water bath for 3 min. The thawed wrappings are rapidly removed and the specimens are immediately replaced in the 140°F bath for 24 h. The specimens are then submerged in a cooler water bath (set at the desired mechanical test temperature) for 3-5 h prior to testing according to step 3 above.
5. Two resilient-modulus ratios and two indirect-tensile-strength ratios are calculated from the average test values. The ratio of vacuum-saturated specimens to dry specimens is considered to be a short-term ratio that simulates moisture in the asphalt concrete at the moisture peak or saturation in the field. The ratio of accelerated-conditioning specimens to dry specimens is considered to be an ultimate, long-term moisture-damage measurement, which occurs in the asphalt concrete (after the saturation effects) due to the forces of environment and traffic. This ratio is almost always less than the vacuum-saturation ratio, and severe stripping is almost always associated with very low ratios.

MOISTURE-DAMAGE AND FATIGUE-LIFE RATIOS

Field moisture damage, e.g., stripping, can destroy most of the cohesion of the asphalt concrete, and the pavement layer does not withstand bending stress to the degree exhibited initially after paving. Severe cases deteriorate the asphalt concrete to a virtually cohesionless base material. This will lead to early cracking and premature pavement distress. Therefore, low indirect-tensile-strength and resilient-modulus ratios should be related to low asphalt concrete fatigue life. Since the fatigue-

Figure 1. BK 142 mix: fatigue relationships at 70°F for moisture conditioning.

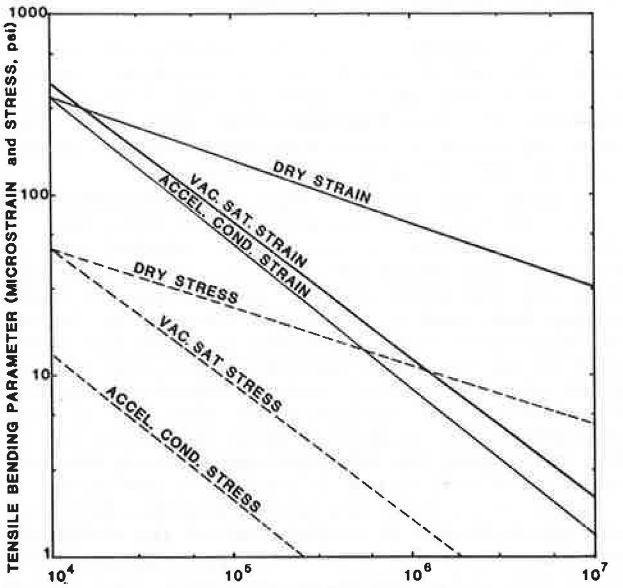
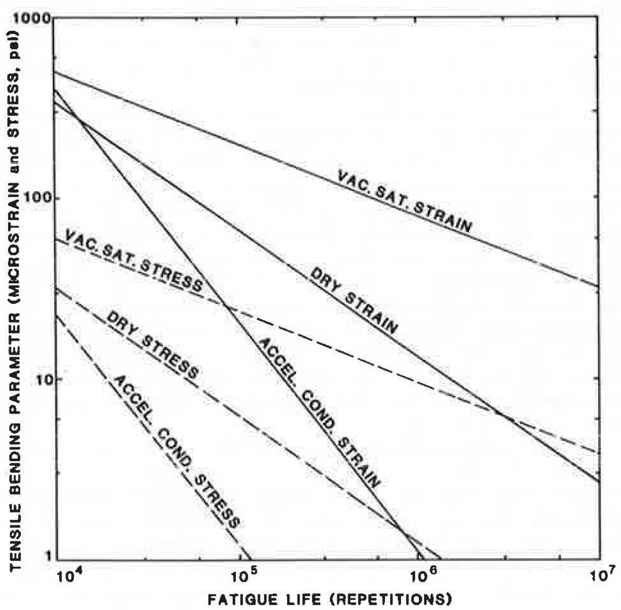


Figure 2. BK 117 mix: fatigue relationships at 70°F for moisture conditioning.



life consideration is an end result, its correlation to moisture-damage ratios should provide a practical basis for the selection of laboratory tensile strength or modulus, which denotes acceptable (or unacceptable) mixtures.

Research has shown that changes of indirect tensile strength and resilient modulus for asphalt concrete affect bending fatigue life and the relationship is somewhat orderly (5). Diametral or indirect tensile fatigue tests also have been performed on a number of asphalt concrete mixtures. The test data were transformed to construct bending fatigue curves (6). As a consequence of these practical developments, constant-stress diametral (indirect) tensile fatigue tests were performed on specimens of two different mixtures subjected to dry, vacuum-saturation, and accelerated moisture conditioning to provide the rudiments of a laboratory correlation between the ratios of indirect tensile strength and fatigue life. These mixtures were made with aggregates that have exhibited differences in moisture sensitivity: Idaho BK 142 aggregate has a history of being associated with severe moisture damage, and Idaho BK 117 aggregate has a history of less moisture damage. A control AC-10 asphalt was used. The mixtures were compacted to 8-9 percent permeable voids in order to emphasize moisture damage or sensitivity differences.

Laboratory-developed fatigue curves for the two mixtures are shown in Figures 1 and 2. The constant-stress diametral (indirect) tensile fatigue data were transformed to uniaxial-type bending fatigue by using the stress difference multiplier of 4.0. Fatigue strains corresponding to transformed fatigue stresses were calculated by dividing the stresses by the appropriate modulus (dry, vacuum saturation, or accelerated conditioning) and then multiplying by the following term: 3 times Poisson's ratio + 1. Poisson's ratio was assumed equal to 0.33.

Indirect tensile strength, modulus, and maximum repeated stress for a fatigue life of 100 000 cycles are listed in Table 1 with their ratios. For these data, tensile-strength and modulus ratios are close to each other for a given mixture and type of moisture conditioning. However, the ratios for the two mixtures are different and this difference is also apparent in and related to the positioning of the fatigue curves. The fatigue curves are roughly proportional to the changes of tensile strength and modulus brought about by the moisture conditioning. This is observed by the tensile-stress ratio corresponding to a fatigue life of 100 000 cycles. Tensile-strength (or modulus) ratios less than 1.0 reflect steeper and lower fatigue curves--a decreased fatigue life for the moderate stress and strain range encountered in pavements.

Mechanistic-theory fatigue-life ratios were calculated for computed stresses and strains in the bottom of the asphalt concrete for two simulated pavements subjected to the 18-kip equivalent single-axle load (ESAL). Resilient-modulus values that represent each type of moisture conditioning for each mixture were used in the computation. The fatigue-life curves (Figures 1 and 2) were entered at the computed stress and strain values for the pavements, and the corresponding lives for each type of moisture conditioning were found. Fatigue-life ratios were then calculated based on the fatigue life in the dry condition. The stress and strain values and the resulting fatigue-life ratios are listed in Table 2.

It should be noted that the decrease of modulus produces a decrease of stress but an increase of strain in the asphalt concrete. Therefore, the decrease of modulus due to moisture damage will affect strain fatigue more adversely than stress fatigue. The resulting strain increase due to moisture damage results in a fatigue-life decrease that is somewhat greater than that apparent in Figures 1 and 2.

Tensile-strength ratios are plotted versus corresponding mechanistic-theory strain fatigue-life ratios for the two Idaho aggregate mixtures in Figure 3. The semi-log graph of Figure 3 shows great sensitivity between the two. The tensile-strength ratio calculated from the moisture-damage test is based on a simple arithmetic scale, and the fatigue-life ratio is calculated from a log-log relationship. Field performance could also behave with similar sensitivity. For instance, a tensile-strength ratio of 0.80 could mean that the fatigue-life ratio is no better than 0.15 to 0.40, which

Table 1. Tensile-strength, modulus, and stress fatigue-life ratios for two permeable asphalt concrete mixtures.

Mixture	Moisture Condition	Tensile Strength[a] Psi	Tensile Strength[a] Ratio	Resilient Modulus[b] 10^5 psi	Resilient Modulus[b] Ratio	Maximum Repeated Tensile Stress at 100 000-Cycle Fatigue Life[c] Psi	Maximum Repeated Tensile Stress at 100 000-Cycle Fatigue Life[c] Ratio
BK 142 aggregate with AC-10 asphalt; voids, 9.0 percent	Dry	46	1	3.10	1	24	1
	Vacuum saturation	41	0.89	2.34	0.75	9	0.38
	Accelerated conditioning (Severe stripping observed)	14	0.30	0.69	0.22	2	0.08
BK 117 aggregate with AC-10 asphalt; voids, 8.6 percent	Dry	39	1	1.74	1	7	1
	Vacuum saturation	47	1.21	2.64	1.52	24	3.43
	Accelerated conditioning (Slight stripping observed)	34	0.87	1.25	0.72	1	0.14

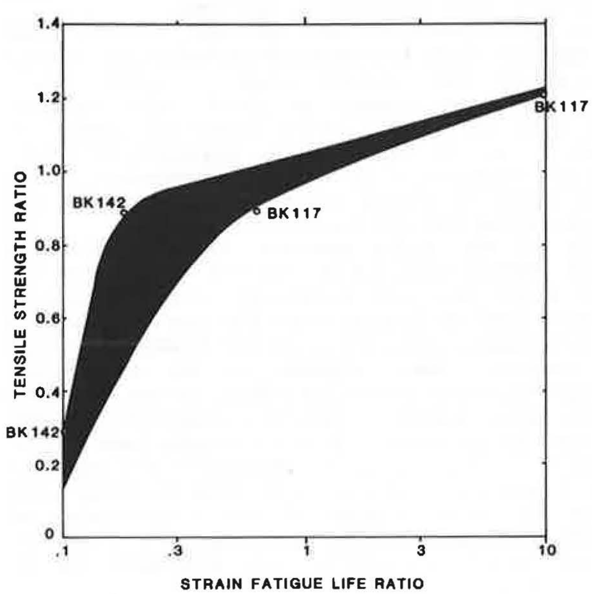
[a]Test performed at alternate temperature of 70° F (0.10 in/min) to coincide with fatigue-test temperature.
[b]Test performed at 70° F (0.10-s load-pulse-duration time) to coincide with fatigue-test temperature.
[c]Calculated from fatigue lives for each moisture condition (see Figures 1 and 2) at 1 x 10^5 repetitions.

Table 2. Mechanistic-theory tensile stress and strain fatigue-life ratios for two permeable asphalt concrete mixtures.

Mixture	Moisture Condition	Asphalt Concrete Pavement Bending Parameters: Tensile Stress[a] (psi)	Asphalt Concrete Pavement Bending Parameters: Tensile Microstrain[b]	Fatigue-Life Ratios[c]: Tensile Stress	Fatigue-Life Ratios[c]: Tensile Strain
BK 142 aggregate with AC-10 asphalt; voids, 9.0 percent	Dry	153	117	1	1
	Vacuum saturation	139	136	7.0	0.18
	Accelerated conditioning (Severe stripping observed)	58	238	4.0	0.07
BK 117 aggregate with AC-10 asphalt; voids, 8.6 percent	Dry	119	158	1	1
	Vacuum saturation	145	128	0.71	10.0
	Accelerated conditioning (Slight stripping observed)	100	185	2.1	0.63

[a]Thin pavement: 3.6-in asphalt concrete with 9.6-in untreated base.
[b]Thick pavement: 9.6-in asphalt concrete with 3.6-in untreated base.
[c]Calculated from fatigue lives for each type of moisture conditioning (see Figures 1 and 2) by using asphalt concrete bending parameters.

Figure 3. Tensile-strength ratio versus mechanistic-theory strain fatigue-life ratio.



results in a much greater drop in field performance than that indicated by a tensile-strength ratio. A region of large fatigue-life change occurs at tensile-strength ratios between 0.95 and 1.00. Ratios above this range imply much better fatigue life and ratios below this range imply much worse fatigue life as compared with ratios for dry mixtures.

Although a curve similar to that in Figure 3 (or a family of such curves) may exist for dense-graded asphalt concrete, there are not enough data at present to form a reliable correlation. Further testing of other mixtures could produce a wider band of data on tensile-strength ratios and mechanistic fatigue life that would result in an obscure correlation. Tensile-bending strain ratios could be lower or higher than corresponding indirect-tensile-strength ratios, depending on the relative positioning of the dry versus accelerated-conditioning stress fatigue curves (e.g., stress ratio at 100 000 cycles) and of the difference in resilient modulus (e.g., resilient-modulus ratio). As an alternative to mechanistic theory, highway agencies may prefer to use the stress ratio at fatigue life of 100 000 cycles when developing a correlation similar to that of Figure 3. A reliable correlation substantiated by field performance could then be used to predict the reduction of the structural coefficient of the asphalt concrete pavement layer due to loss of cohesion from moisture damage.

Specific fatigue-life analyses by using moisture-damage ratios, e.g., the tensile-strength ratio, and Figure 3 can be made with a knowledge of asphalt concrete design life, the rate of 18-kip ESALs and field time to reach the equivalencies of vacuum saturation and of accelerated conditioning. For example, suppose the anticipated design life for an asphalt concrete in a new pavement is 4 000 000 18-kip ESALs. At an average rate of 250 000 repetitions per year, this gives 16 years of life in a dry condition. Suppose estimates of field times are 4 years to reach vacuum-saturation equivalency and 6.5 years to reach accelerated-conditioning equivalency and that the laboratory-determined tensile-strength ratios are as follows: 0.95 for vacuum saturation and 0.70 for accelerated conditioning (moderate stripping observed). By using the middle of the band in Figure 3, the corresponding fatigue-life ratios are 0.60 for vacuum saturation and 0.20 for accelerated conditioning. The estimated (noncracked) asphalt concrete fatigue life might be calculated in a simplified way, as follows:

(a) Years 1-4, dry: Repetitions = 250 000 x 4 = 1 000 000.
(b) Years 4-6.5, vacuum saturation: Equivalent repetitions = 250 000 x (6.5 - 4) x 0.60 = 375 000.
(c) Years 6.5-16, accelerated conditioning: Equivalent repetitions = 250 000 x (16 - 6.5) x 0.20 = 475 000.

The sum of a + b + c equals 1 850 000 repetitions. At 250 000 repetitions per year, the estimated life is 7.4 years (instead of 16 years). The predicted life would be considered too low. The asphalt concrete mixture should be redesigned or antistripping treatments used in order to achieve higher tensile-strength ratios for longer asphalt concrete fatigue life.

A longer fatigue life will occur in the field if moisture conditions, climate, and traffic produce seasonal cyclic asphalt concrete drying and healing, even if they are only temporary. These conditions will increase the time to reach the ultimate damage predicted by accelerated conditioning. Effects of temporary recovery of moisture damage in the laboratory have been observed (7).

FIELD OCCURRENCE OF PREDICTED MOISTURE-DAMAGE RATIOS

Eight asphalt concrete pavements were evaluated periodically for approximately five years in NCHRP Research Project 4-8(3)/1 (1). These pavements were constructed in 1975 through 1977 by Arizona, Colorado, FHWA Region 10, Idaho, Georgia, Montana, and Virginia highway agencies. A variety of climatic regions and mixtures were represented. Aggregates were generally chosen that had a history of moisture damage when incorporated into asphalt concrete pavement.

Each highway agency selected a 1000-ft evaluation section of the pavements and performed the NCHRP 4-8(3) moisture-damage test method as previously described to obtain moisture-damage predictions. Laboratory specimens incorporated the aggregate and asphalt materials used in the lowest asphalt concrete layer of their respective pavements. In addition, each agency performed the test method on the lowest asphalt concrete layer cores drilled from the pavement sections immediately after paving. Then the predicted tensile-strength and modulus ratios were compared with ratios from the field cores obtained periodically throughout the study. The field ratios were calculated by using vacuum saturation only because, over a period of time, the natural environmental forces will produce an accelerated-conditioning equivalency on their own and thus would be built in with the measurement of the field vacuum-saturation ratio. One half of each set of periodic cores was desiccated in the laboratory in order to obtain the dry base for the field ratios. If the field-core ratios and stripping became close to the predicted laboratory ratios and stripping, then there would be a good indication that the test method (and its ratios) reasonably predicted the occurrence of moisture damage in the pavements. The following is a summary of the comparison.

Figures 4 through 7 show tensile-strength ratio predictions, and the lines represent the lower running periodic field-core ratios for tensile strength. (Resilient-modulus ratios showed similar trends.) These lines are labeled WP (wheelpath) or BWP (between wheelpath), depending on which core location produced the lower field ratio. Arrows in the figures represent ratios of the strength of saturated final drilled cores to the strength of maximum-dry-strength cores that occurred over the pavement age to date. For this ratio calculation, the reduction of dry-core strength due to moisture damage is minimized and should more closely match the physical nonaging conditions of the laboratory test method used for predictions.

Short-term predictive ratios were determined by vacuum saturation and long-term predictive ratios were determined by accelerated conditioning. Each predictive ratio is identified by highway agency abbreviation and a C or an L in parentheses; C denotes initial core prediction and L denotes laboratory-fabricated specimen prediction.

In most cases, predictive ratios determined from initial cores were greater than the ratios predicted by laboratory-fabricated specimens. Current laboratory mixing and compaction methods seem to be at best a fair estimate of the compacted paved field mixture when moisture damage is considered. Therefore, it appears that moisture damage is overestimated by the use of laboratory-fabricated specimens. However, ratios of tested laboratory specimens are practical predictions that are useful to highway agencies.

The field ratios do not really show a moisture-damage bias for WP or BWP locations. For some pavement sections the BWP location contains more severe moisture damage than the WP location does. For others, this situation is reversed.

For the asphalt concrete pavement mixtures that had low long-term (accelerated-conditioning) predictive ratios that denote severe moisture damage (stripping), the decrease of field ratios occurred soon after an initial twoto three-year period of pavement age. At this time the beginning of stripping was observed; later it was accompanied in the worst cases by severe stripping that caused some core disintegration in the field.

Six of the eight pavement sections developed ratios greater than 1.0 during the initial period, which meant that the saturated cores had greater strength (and stiffness) than the dry cores. This was not always predicted from the laboratory-specimen ratios. There appears to be an initial strengthening and stiffening effect in the field due to the early phases of moisture conditioning; some addition to the fatigue life may result (see Figures 2 and 3). However, field predictions for the initial period may be difficult to make by using laboratory specimens because of the complexities of interaction between early moisture conditioning, asphalt aging mechanisms, and aggregate surface reactions.

Figure 4. Periodic field ratios versus prediction ratios for Arizona and Colorado test sections.

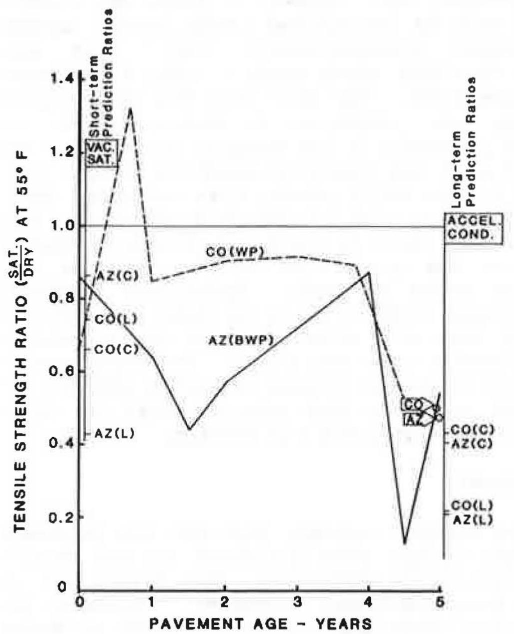


Figure 5. Periodic field ratios versus prediction ratios for FHWA 10 and Georgia-A test sections.

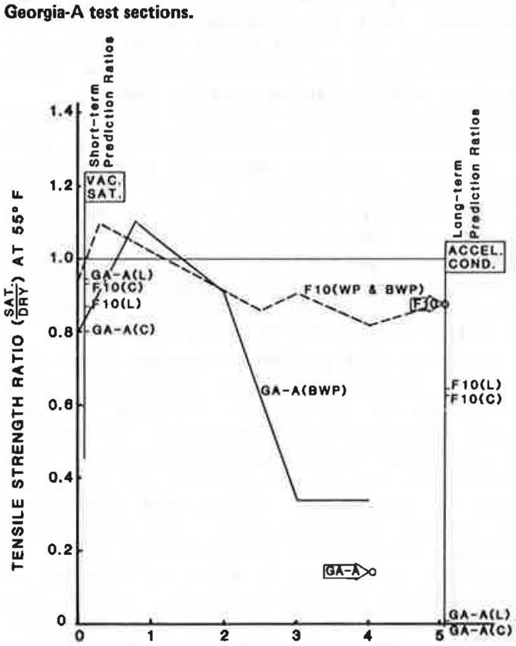


Figure 6. Periodic field ratios versus prediction ratios for Georgia-B and Idaho test sections.

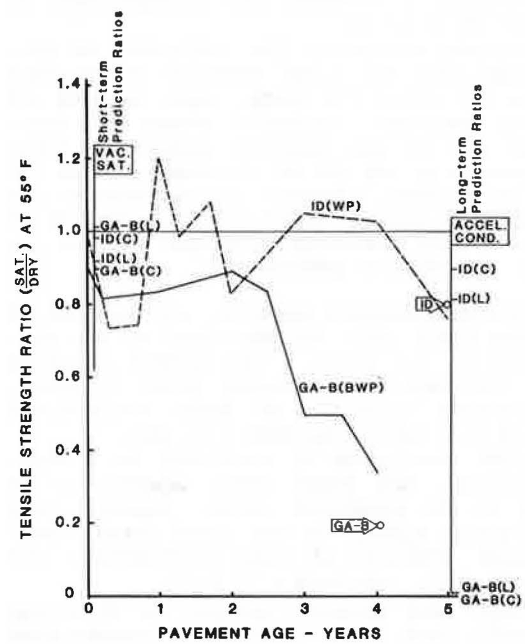
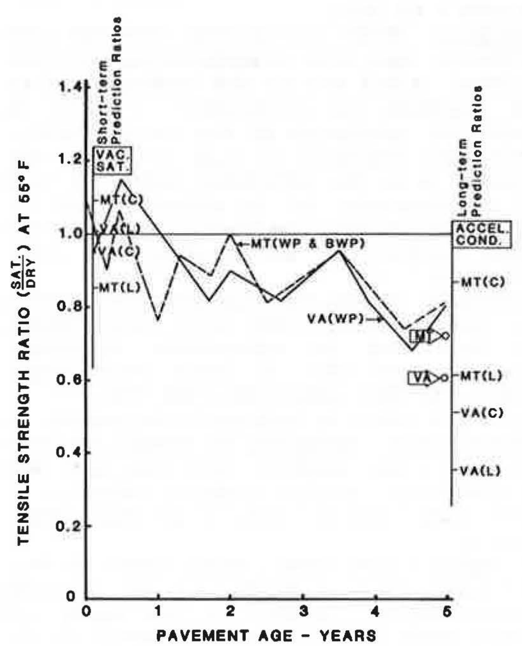


Figure 7. Periodic field ratios versus prediction ratios for Montana and Virginia test sections.



If there are fatigue-life and other benefits derived from the field-conditioning effect, they are overcome by stripping brought on gradually by the environmental moisture forces during the later stages. For those pavement sections for which stripping was predicted by the accelerated conditioning of laboratory specimens, the ratios decreased below 1.0. Stripping was first observed when the field ratios decreased to 0.80 and became more severe as the ratios decreased further. Minimum field ratios (denoted by arrows) provided a good correlation to the stripping severity observed at the end of the field measurement. They show that the moisture-damage ranking of pavements is essentially the same as the predicted ranking by using the test method's long-term ratios. However, for most of the test sections, the field ratios remain greater than the predicted long-term ratios.

The field-conditioning effect and partial rehealing due to moisture and environmental changes appear to be more responsible than test variability for the zig-zag ratio patterns shown. (Coefficients of variation for tensile-strength and modulus tests of the field cores averaged 15 percent.) For those mixtures for which stripping was predicted, the rate of overall decrease of the field ratios appears proportional to the heavy traffic volume on the pavements. A correlation of the moisture-damage rate to temperature extremes and precipitation is not apparent at this time.

The following summarizes the comparison of predicted damage with the field moisture damage that occurred at the end of the study. Also included are the highway agencies' estimated change of layer coefficient due to the moisture damage in their asphalt concrete at the end of the study and for the long-term estimation. Numbers in parentheses are the corresponding minimum field ratios at the end of the study and the predicted long-term ratios, respectively, expressed as percentages.

AZ: Although temporary rehealing was apparent at 5 years, the field ratio had decreased to the predicted ratio at 4.5 years. Some severe stripping and core disintegration occurred after 4 years. Percent cohesive retention of layer coefficient: end of study = 42 (48); long-term = 21 (22).

CO: After four years of remaining in a high-ratio condition, the field ratio appears to be decreasing to the predicted ratio. However, only slight stripping appears in the field cores. Percent cohesive retention of layer coefficient: end of study = 87 (50); long-term = 73 (22).

F10: This FHWA pavement section is in Crater Lake National Park. It is used by recreational vehicles when it is open during the warmer visitor's season; 18-kip ESALs are negligible. The field ratio remains above the predicted ratio at five years with very slight stripping. Percent cohesive retention of layer coefficient: end of study = 100 (90); long-term = 43 (65).

GA-A and GA-B: These two pavement sections show severe stripping; some core disintegration occurred after two years. Field testing was terminated after four years (pavement was constructed in 1977) to coincide with the conclusion of the overall study. Field ratios have decreased to 0.20 or less. The predicted ratio is 0; the additional length of time to reach 0 is uncertain, but in effect it will be reached in a year or two. Percent cohesive retention of layer coefficient: end of study = 50 (19); long-term = 20 (0).

ID: Predictive ratios for this pavement section were high. The five-year field ratio also remains relatively high with no appreciable stripping. Percent cohesive retention of layer coefficient: end of study = 100 (80); long-term = 100 (82).

MT: The field ratio is apparently decreasing to the predictive ratio; stripping is considered moderate to light so far, slightly less than what was ultimately predicted. Percent cohesive retention of layer coefficient: end of study = 64 (72); long-term = 21 (60).

VA: Stripping became severe after three to four years. The field ratio is about 0.60 and is above the predictive ratio. Traffic is not heavy and there are definitely rehealing cycles present in the field, but the field ratio zigzig pattern appears to be downward, probably to reach the predictive ratio at about eight years of pavement age. Percent cohesive retention of layer coefficient: end of study = 62 (62); long-term = 62 (36).

The retention of the layer coefficient, based on the asphalt concrete as a cohesive material versus an untreated gravel, shows a general relationship to the ratios but leans more toward the values due to the stripping observed in the final pavement cores. Considering the possibility of fatigue-life decrease, the estimated decrease of layer coefficients might not be enough for about half of the test sections.

In summary, short-term ratios and stripping, predicted by vacuum saturation, can occur up to four years of pavement age. Long-term ratios and stripping, predicted by accelerated conditioning, appear to be maximum moisture-damage levels that are achievable to field times greater than five years for most pavements. The test method's accelerated conditioning was correlated to damage in 3- to 12-year-old pavements in the earlier study (2). It is expected that the predicted moisture damage will be reached in the field within this variable time. For those pavements with heavier traffic volume, the associated field times to reach the long-term damage should be on the lower side of the pavement age range (eight years or less). Associated pavement surface distress brought about by loss of cohesion and fatigue life will also occur in the moisture-damaged pavements in a few years. The time cannot be accurately predicted because of cyclic changes of moisture and rehealing that interact with the different pavement thicknesses and traffic.

RECOMMENDATIONS

Dense-graded asphalt concrete that has low moisture damage (high ratios) when subjected to the accelerated conditioning withstands the rigors of a reasonable moisture-damage mechanism. Evidence so far shows that these mixtures should have no worse damage or stripping in the field and provide long-term service in the presence of moisture. Conversely, if low ratios and severe stripping are predicted, then they will also occur in the field and these mixtures will not provide long-term field service. Ratios of the field cores from moisture-damaged pavements could be used to determine layer coefficients for rehabilitative overlay design.

The effects of particular climatic and environmental differences on the rate of field damage were uncertain. However, highway agencies may want to use an accelerated conditioning of cold-water-plus-warm-water soak for mild climates if it is warranted by their field and laboratory experience. In the meantime, the freeze portion is recommended for all locations because of the wide range of asphalt concrete materials variables encountered throughout the country and in situations of heavy traffic.

Highway agencies will probably develop their own acceptable ratio limits and visual stripping limits for specifications as acceptance criteria for mix design and for antistripping treatments. If fatigue life is as sensitive to moisture conditioning (and tensile-strength ratio) as it appears to be, then the selection of acceptable ratios and specifications should be done conservatively. It is possible that a developed correlative relationship, shown in a preliminary way in Figure 3, will be helpful in selecting acceptable tensile-strength ratios for dense-graded asphalt concrete. Data for two mixtures show that the mechanistic-theory tensile-strength ratios should not be much less than 1.0 in order to maintain the better dry-condition strain fatigue life in the pavement. (It could be a difficult assignment to improve these mixtures to that level.) The upgrading of asphalt concrete mixtures by the use of additives should be assessed by their ability to increase fatigue life when the additive-incorporated mixtures have been subjected to accelerated conditioning and referenced to the untreated control mixture's fatigue life. This seems to be a practical supplement to the use of tensile-strength ratios by themselves.

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The opinions and findings expressed or implied in this paper are mine. They are not necessarily those of the Transportation Research Board, the National Academy of Sciences, the Federal Highway Administration, the American Association of State Highway and Transportation Officials, or the individual states participating in the National Cooperative Highway Research Program.

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Chemistry of Asphalt-Aggregate Interaction: Relationship with Pavement Moisture-Damage Prediction Test

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Relationships were found between fundamental chemical and physical properties of the asphalt-aggregate bond and moisture-induced damage in asphalt pavement mixtures subjected to the Lottman conditioning procedure in National Cooperative Highway Research Program (NCHRP) Field Evaluation Project 4-8(3)/1. The relative tendency of different chemical functional types in asphalts to be strongly adsorbed on aggregate surfaces and their relative displacement from aggregate surfaces by water were determined. The affinity of the aggregates for pyridine-type nitrogen was also determined. For most asphalt-aggregate mixtures of the Lottman-NCHRP study, resistance to moisture-induced damage appeared to be controlled by a number of interrelated variables. These variables must be considered in concert to rationalize pavement moisture damage. The sensitivity of pavement mixtures to moisture-induced damage was explained by considering fundamental physiochemical properties of the asphalt-aggregate bond.

Premature pavement failure attributed to moisture-induced damage has long been recognized, but solutions to the problem have been far from satisfactory. This type of damage, generally believed related to rupture of the adhesive bond at the asphalt-aggregate interface, is a complex phenomenon involving physical and chemical properties of both the asphalt and the aggregate. Moisture damage is also strongly influenced by pavement-mixture morphology and external environmental factors.

A laboratory test method for predicting moisture-induced damage in asphaltic pavements was developed by Lottman (1) during work sponsored by the National Cooperative Highway Research Program (NCHRP). Phase 2 of this program involved a field evaluation to determine test-method predictability. The field evaluation commenced in 1974 under Lottman's direction with participation by seven state and federal agencies (2, 3) and was completed in 1981.

Our study reported in this paper was conducted by using materials identical to those used in the field-evaluation pavements. Objectives of our study were (a) to determine physiochemical properties of the asphalt-aggregate interaction as related to pavement moisture damage, (b) to correlate these findings with the predictive results of the Lottman test obtained by the participating agencies, and (c) to evaluate potential moisture-damage test methods developed in our own laboratory. The correlation of Lottman test-method results with actual field performance, which requires consideration of construction and environmental factors, is germane to the NCHRP study but is not considered in this paper.

In our study we have used methods developed in our laboratory for qualitatively and quantitatively determining a number of chemical functional group types in asphalts (4,5), their relative tendency to be adsorbed on mineral aggregate surfaces (6-8), and their relative displacement from aggregate surfaces by water (8). The methods are based on selective solvent desorption of asphalt components from aggregate surfaces followed by functional group characterization of the components by using differential infrared spectrometry and selective chemical reactions. These methods provided fundamental data on the chemistry of the asphalt-aggregate interaction by using microcalorimetry (9) and characterization