Methods of Predicting and Controlling Moisture Damage in Asphalt Concrete

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The basis for using mechanical property ratios to predict moisture sensitivity in asphalt concrete is discussed. Also discussed are (a) physical property ratios, which depict specific types of pavement distress such as fatigue cracking and are calculated from the wet accelerated conditioned and dry mechanical properties, and (b) mathematical models to predict field-developed wet performance life, which are based on relative life computational methods and incorporate the physical property ratios. Initial test data from the moisture damage test sections of NCHRP Projects 4-8(3)/1 and 4-8(4) are used in two relative life mechanistic models developed at the University of Idaho to predict wet performance lives. Periodic core properties obtained during a 10-year period are used to evaluate in situ wet lives of the test sections. Comparisons indicate that predicted lives and in situ lives are similar. Implications are that additional built-in complexity in moisture damage models may not be needed in the near future. Control of moisture damage is more reliably achieved through the application of both indirect tensile strength and resilient modulus cutoff ratios, which are readily calculated from prediction models. These ratios are dependent on strength and modulus test data, pavement location, and performance requirements. There is reason to think that a high reliability of zero moisture damage can be achieved in the field when cutoff ratios are exceeded.

At least one-half of the state highway agencies in the United States are experiencing moisture damage in asphalt concrete pavements. The agencies have established research projects to evaluate both the extent of the damage and laboratory methods to predict the associated moisture sensitivity of asphalt concrete mixtures before paving. In addition, National Cooperative Highway Program (NCHRP) Project 4-8(4), a 10-year field evaluation of moisture damage in test sections constructed by six U.S. state highway agencies, ended in November 1986 and completed the field study of NCHRP Project 4-8(3)/1, which began after the 1971 laboratory phase [Project 4-8(3)] (*1–4*). Therefore it is timely to relate the highlights of this and current research to the technical process required for a solution to the moisture damage problem.

Technological applications based on laboratory tests and field observations are needed to eliminate life-robbing distress in pavements caused by moisture damage. The intention is to provide a focus for these applications. Moisture sensitivity ratios (i.e., moisture damage ratios) for asphalt concrete mixtures are defined and discussed. These ratios are calculated from indirect tensile strength and resilient modulus laboratory tests and form the basis of all methods currently used to evaluate moisture damage. The authors' opinion is that mathematically based field models, which predict pavement wet performance life and determine laboratory cutoff ratios, will be routinely used to control moisture damage. Because this is a new technology, the physical concepts of current models are discussed. Pavement wet life predictions and evaluation based on periodic core tests of the NCHRP projects are presented to demonstrate results from two field models.

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RATIOS

Definitions of ratios and a summary of their applications are presented in this section.

Minimum Ratios

A given asphalt concrete mixture is represented by test specimens that possess realistic dry pavement characteristics. Specimens that match initial pavement cores are fabricated according to properly simulated field aging and compaction methods. When the specimens are subjected to accelerated moisture conditions (wet) in the laboratory, they should ideally have one wet/dry ratio corresponding to each mechanical property required. This ratio is desirably a minimum ratio, one that is descriptive of the basic, realistic "maximum" moisture sensitivity of a particular asphalt-aggregate combination, aged and compacted for the average field condition. This is to say that the minimum ratio is location independent, and thus it is a specific mixture characteristic. The practicality of this is that only one, or possibly two, laboratory accelerated conditioning method needs to be employed. This will eliminate the need to solve, at the local level, the difficult laboratory testing problem of finding a moisture conditioning scheme that matches the magnitude of the ratio to the climate and other characteristics of the pavement location.

Use of the minimum ratio in a pavement wet life mathematical model will solve the location-specific problem. The correct sensitivity of the model to climatic and other location-specific conditions is easier to develop and adjust than are laboratory accelerated conditioning methods. For example, minimum ratios obtained from the laboratory accelerated conditioning method are not always reached in the field in mild climates. An acceptable model should also demonstrate this.

Moisture Sensitivity

The mechanical property ratio (or physical property ratio), wet/dry, is inversely proportional to the moisture sensitivity of a mixture. The lower the ratio, the higher the sensitivity. This is a comparative approach. Many daily decisions are based on the comparative approach, so the ratio for a given mixture has valid application.

However, difficulty arises when the performance of two mixtures, each having a different ratio and a different dry mechanical property, needs to be compared. The source of difficulty is the current inability to know the difference in predicted field performance of the mixtures as reflected by their dry mechanical properties. The range of dry indirect tensile strength (dry ITS) of all asphalt paving mixtures in the United States is at least 40 to 180 psi at 55°F, yet each mixture meets some agency's minimum stability requirements and is deemed satisfactory. Relating pavement life to dry ITS (and other dry mechanical properties) is a pavement design problem that involves the interaction of mixture properties. It requires an absolute solution rather than a comparative one. When this problem is solved, moisture sensitivity (i.e., ratio) will be performance documented, and the need for complete comparison of different mixtures will be satisfied as well.

An illustration of the comparative approach using ratios follows. Suppose two mixtures are being compared; one is a control (or reference) mixture and the other is an additive- or modifier-treated mixture. Assume their ITS values are

- Control: dry ITS = 100, wet ITS = 60
- Treated: dry ITS = 85, wet ITS = 75

The indirect tensile strength ratios (TSRs), wet/dry, are control TSR = 0.60 and treated TSR = 0.88.

Clearly the treated mixture's moisture sensitivity is less than that of the control mixture because its TSR is greater. If there exists no definite evidence that the control mixture's dry field life, based on its dry ITS of 100, is better than that of the treated mixture, based on its dry ITS of 85, then the treated mix is a much better choice.

However, if evidence does exist that field life is proportional to dry ITS, then the ratio must be reflective of the control dry ITS. In this case, a combined TSR is calculated and it is equal to (Treated wet ITS/Control dry ITS) = 75/100 = 0.75 or, in a basic form, (Treated dry ITS/Control dry ITS) × (Treated wet ITS/Treated dry ITS) = 85/100 × 75/85 = 0.75. In the basic form, the first term is the "modifier effect" ratio and the second term is the "moisture sensitivity" ratio. The combined TSR of 0.75 is greater than the control mixture's TSR of 0.60, but it is less than the treated mixture TSR of 0.88. Thus this treated mixture has less overall performance advantage when described by the combined TSR of 0.75 instead of the individual TSR of 0.88.

Suppose the mixture is treated differently and, as a consequence, develops higher ITS values (e.g., dry ITS = 120 and wet ITS = 106). This mixture's TSR is 0.88, the same as that of the previous treated mixture. However, its combined TSR is 106/100 = 1.06, which is much better than the previous combined TSR of 0.75. A conclusion to be drawn from the combined TSR comparison is that this treated mixture's predicted wet performance is not only superior to that of the dry control mixture, it is also better than that of the previous treated mixture with the lower dry ITS.

Thus the comparative basis from which a ratio is calculated and used should be accompanied by knowledge of the difference in field performance of mixtures with different dry mechanical properties: does the increase of a mechanical property really improve toughness or durability?

The lack of specific answers to this question does not necessarily rule out using the dry properties of the control mixture as a reference. The combined TSR or combined resilient modulus ratio (MrR), or both, may be adequate for comparison of moisture sensitivity of two mixtures.

In addition, the use and philosophy of ratios can be built on to develop comparative (i.e., relative) wet-to-dry performance life prediction models. An interim step is the development of physical property ratios.

Physical Property Ratios

Physical property ratios, as defined here, characterize an asphalt concrete's working stress-strain moisture resistance to a specific field distress such as fatigue cracking or wheelpath rutting. These ratios are calculated from combinations of basic mechanical properties and are required in models that predict field performance life.

Currently it is practical to use ITS and resilient modulus (Mr) as basic mechanical properties and to determine moisture sensitivity from their ratios (TSR and MrR, respectively). It is expected that the moisture sensitivity depicted by the physical property ratios will not be equal to TSR or MrR for a given asphalt concrete mixture. However, it will be shown later that the mechanical properties ITS and Mr and their ratios remain basic mixture properties required for the control of moisture damage.

Physical property ratios can be used as individual ratios or as combined ratios. The physical property combined ratio appears to be more valid than the mechanical property combined ratio. Examples of physical property ratios follow.

Fatigue Life Ratio

Fatigue life ratio (FLR) is related to asphalt concrete cohesive life evidenced by the onset of wheel load–associated cracking in the asphalt concrete pavement layer. It is proportional to resistance to fatigue cracking and is developed from the mechanics of materials relationship for the relative position of the wet and dry strain fatigue strength lines, the wet and dry pavement layer strains, and their intersections. The relative positions of the two lines are predicted using the correlations of dry reference strain [defined as (2 dry ITS)/(Dry Mr)] and of strain-shifted toughness ratio (defined as TSR^2/MrR^2) at repetitions equal to 100,000 (5), and by functions of wet and dry Mr. The relationships were developed at the University of Idaho from laboratory tests that produced data on fatigue strength, ITS, and Mr for wet and dry conditions. The FLR equation is

$$FLR = [(2 \text{ dry } ITS/\text{dry } Mr)]^{-\text{wet } k + \text{dry } k} \times (TSR^2/MrR^2)^{-\text{wet } k} \times (\text{wet } \varepsilon^{-\text{wet } k})/(\text{dry } \varepsilon^{-\text{dry } k})$$

where k = the inverse of the slope of log strain (ε) vs log repetitions fatigue strength line, and is predicted by $k = -1.4 \times 10^{-3}\ Mr^{0.573}$, and ε = the tensile bending strain due to wheel loads and is predicted for average condition by $\varepsilon = 1.53 \times 10^{-3}\ Mr^{-0.187}$.

Dry and wet values of Mr are substituted in the equations to calculate the corresponding dry and wet values of k and ε.

A numerical example of FLR for the control mixture using 55°F test data follows:

dry ITS = 100, wet ITS = 60, TSR = 0.60 and
dry Mr = 757,600, wet Mr = 426,370, MrR = 0.56.

Thus,

dry $k = -3.391$, wet $k = -2.439$ and
dry $\varepsilon = 122 \times 10^{-6}$, wet $\varepsilon = 136 \times 10^{-6}$.

Substituting into the FLR equation,

$$FLR = 0.50$$

The control mixture's FLR can be greater or less than its TSR and MrR, depending on the ITS-Mr relationship. In this case, FLR is less, indicating that somewhat more moisture sensitivity exists by reference to fatigue life than by reference to either tensile strength or resilient modulus.

Examination of the FLR equation shows that FLR is maximized for a given TSR provided that MrR remains less than TSR.

Toughness Ratio

Toughness ratio (TR) relates asphalt concrete resistance to crack propagation in the pavement layer after the end of its cohesive life (i.e., fatigue life). When wet asphalt concrete has a lower crack propagation resistance than does dry asphalt concrete, time to terminal serviceability in the field will decrease.

Mathematically TR is a ratio between the proportionality of the wet to the dry areas under the failure stress-strain lines. It is approximated by the equation

$$TR = TSR^2/MrR$$

The control mixture's example values of TSR = 0.60 and MrR = 0.56 give TR = 0.64. It should be noted that this physical property ratio is somewhat greater than either TSR or MrR when TSR is greater than MrR. This indicates that the crack propagation process reflected by TR is usually less moisture sensitive than indicated by either TSR or MrR.

Wheelpath Ratio

Wheelpath ratio (WPR) relates the asphalt concrete's resistance to wheelpath rutting (permanent deformation) and in general is proportional to MrR. Although the WPR is not precisely defined at the present time, it will consist of wet and dry modulus-related values that will properly define the moisture sensitivity of permanent deformation. For example, WPR might consist of the characteristics of permanent deformation related both to adhesive loss (stripping) and to cohesion loss (asphalt binder softening), the effects of which on wheelpath rutting can be unequal. Percentage of stripping as well as wet and dry Mr are required to calculate adhesion and cohesion change (*5*). These values, in turn, would be incorporated into the WPR.

The mathematical field model for predicting wheelpath deformation with WPR will be a different model than the one that uses FLR and TR for fatigue cracking, although it might share some common computational methods.

Minimum Moisture Damage and Cutoff Ratios

Ratios such as TSR and MrR are presently calculated from mean ITS and Mr test values, but the probability that the ratios are lower than those calculated is proportional to the standard deviations of their test values. Tunnicliff and Root (*6*) applied mean and standard deviation test values to determine if mean values of additive-treated mixtures are statistically different, hence better, than those of corresponding untreated mixtures. This implies that ratios such as TSR will require statistical definition to better describe and control moisture sensitivity. Large standard deviations will require larger TSR when TSR is calculated from mean values. In the future, the direct or equivalent use of standard deviation (as well as mean values) associated with ITS and Mr will be used with field wet life prediction models to assess and provide the specified reliability needed to achieve minimum or zero moisture damage.

The physical property ratios (e.g., FLR and TR) are equal to 1 when the mechanical property ratios (e.g., TSR and MrR) are equal to 1. This indicates that zero moisture damage will result when both TSR and MrR are known and are verified to be equal to 1. In addition, the reliability of not exceeding a minimum, specified level of moisture damage using TSR and MrR together as cutoff ratios appears to be greater than that of using either TSR or MrR as a cutoff ratio. Therefore it appears that the control of properties for minimum or zero moisture damage requires application of both TSR and MrR. TSR and MrR need not be equal to 1 to achieve a specific minimum moisture damage, but they should be high values.

It is customary to allow mixtures to be used for paving when their mechanical property ratios are less than 1 but greater than a minimum ratio, for example 0.70. The 0.70 ratio is then called the cutoff ratio. The reason cutoff ratios are less than 1 appears to be that, at average reliability, the field conditions and variables associated with reaching the TSR cutoff in time account for a probable minimum loss of pavement life.

When physical property ratios developed from mechanical properties are used instead of the mechanical property ratios, intuitions are supplemented by explicit requirements to take advantage of the apparently improved predictability. One such requirement is to limit the extent of moisture damage in the field or, in other words, to specify the maximum percentage loss of pavement performance life as a result of moisture damage. This appears to average 10 percent currently (*4*). This figure is used with the field prediction model to calculate the cutoff ratio or ratios in terms of the mechanical property ratios of TSR and MrR. The calculated cutoff ratios are not always the same number (e.g., 0.70); instead they can be as high as 0.95 and sometimes below 0.70 because of differences in the maximum specified loss of pavement life, in the mechanical properties of asphalt concrete mixtures, and in pavement location factors (*7*).

High FLR and TR are required for good fatigue cracking wet life and are best achieved when the TSR cutoff is greater than the MrR cutoff (e.g., TSR cutoff = 0.75 and MrR cutoff = 0.70). TSR and MrR cutoffs are predicted for the six test sections of NCHRP Projects 4-8(3)/1 and 4-8(4) using a prediction model that incorporates physical property ratios of FLR and TR. They are discussed in a later section of the paper.

PREDICTION OF WET PERFORMANCE LIFE OF PAVEMENT

The translation of the laboratory minimum ratio or ratios to wet performance life is best visualized and accomplished by use of mathematical models. Basic concepts of the mechanics of the model should be understood and the correlation equations for constants should be reevaluated periodically using valid field or laboratory data as they become available.

All wet life prediction models consist of at least the following parts:

1. Field time change (e.g., reduction) of the physical property ratio or ratios from 1 at time equals zero (i.e., all dry) to the minimum ratio or ratios years later when wetness and thermal cycles maximize;
2. Application of a technically based method that relates predicted field ratio or ratios from Item 1 to the asphalt concrete pavement layer's wet performance life in repetitions of traffic loads; and
3. Translation of the ratio-life repetitions from Item 2 to obtain the wet performance life of the pavement layer in years.

Wet life is compared with the assumed reference or standard-designed all-dry life to determine if the proposed mixture will provide the required life when it becomes wet in the field. Reference to this information will minimize the additional life-cycle cost associated with this loss of life. Wet life prediction models can be readily used for calculating cutoff ratios. The cutoff ratios are referred to in the laboratory during mixture design analysis. Thus wet life prediction models are well suited for mixture evaluation before construction.

Unacceptably low wet life or corresponding low laboratory ratios (i.e., below cutoff ratios) require a change of mixture constituents; reduction of voids, if possible; or treatment by inclusion of additives that retain adhesion and cohesion in the mixture. Wet life prediction models should be realistically sensitive to changes in mixture variables and to additive treatments. The physical property ratios show this sensitivity because they depend on the magnitude of the ITS and Mr values or their ratios that, in turn, are sensitive to mixture variables and additives.

Brief descriptions of wet life prediction models follow:

1. Absolute life: Existing pavement design equations may be used. The equations, developed for "all dry life," are used with the appropriate wet damaged asphalt concrete property. The magnitude of wet life is an absolute value that is independent of dry life. Its accuracy is dependent on the design method and the moisture sensitivity characterization used in the method.
2. Relative life: Wet life is calculated and its magnitude is dependent on an assumed or precalculated dry life. The change of life relationship that is developed for the method is readily based on working stress-strain mechanics such as the relative (wet/dry) relationships of fatigue strength, stress, and strain in the pavement layer. The mechanics approach appears to have acceptable prediction accuracy when applied to the relative life method instead of the absolute life method. The stipulated condition of relative life methods is that wet life is related to dry life and only to the specific asphalt concrete pavement layer. Comparative decisions are based on this condition.

Absolute Life

The application of the AASHTO asphalt concrete pavement design life equation is an example of calculating absolute life. The AASHTO structural number's layer coefficient for the asphalt concrete due to moisture sensitivity is calculated by use of a ratio. A brief description of models that use TSR follows:

Time Reduction of Ratio

A method described in 1982 (*7*) incorporates two steps (or moisture stages) of the TSR. Figure 1 shows the two stages. The first stage is represented as dry with the ratio of the pavement layer equal to 1, and the second stage, which begins when the field ratio has decreased halfway to the laboratory minimum ratio, is represented by the minimum TSR associated with laboratory accelerated conditioning. Dry stage time can be adjusted to specific locations.

A more detailed method developed by Nesichi and Ishai at Technion University (*8*) incorporates three moisture stages: dry, saturated, and accelerated conditioned, which are represented by corresponding laboratory TSR-values. The TSR-values are predicted to decrease with time through the moisture stages using a rate constant established by experience or by correlation with the serviceability loss relationship in the AASHTO equation. The rate constant appears to be adjustable to represent different locations.

Relating Ratios to Wet Life Repetitions

Miner's rule (cumulative damage) is applied in the 1982 method (*7*). The AASHTO equation is used to calculate basic dry and wet lives in 18-kip single-axle equivalents for the two moisture stages represented by TSR equal to 1 and by TSR equal to laboratory minimum. The retained cohesion in the asphalt concrete layer during the wet stage is calculated using the minimum TSR. The resulting wet stage layer coefficient is used to calculate a wet stage structural number, from which the basic wet fatigue life is calculated. The specific life in the wet stage is calculated and is added to the life in the dry stage to equal the dry-wet life, or "wet" life. The rate of cumulative damage in the wet stage is greater than in the dry stage when minimum TSR is less than 1; therefore the dry-wet life would be less than the dry life.

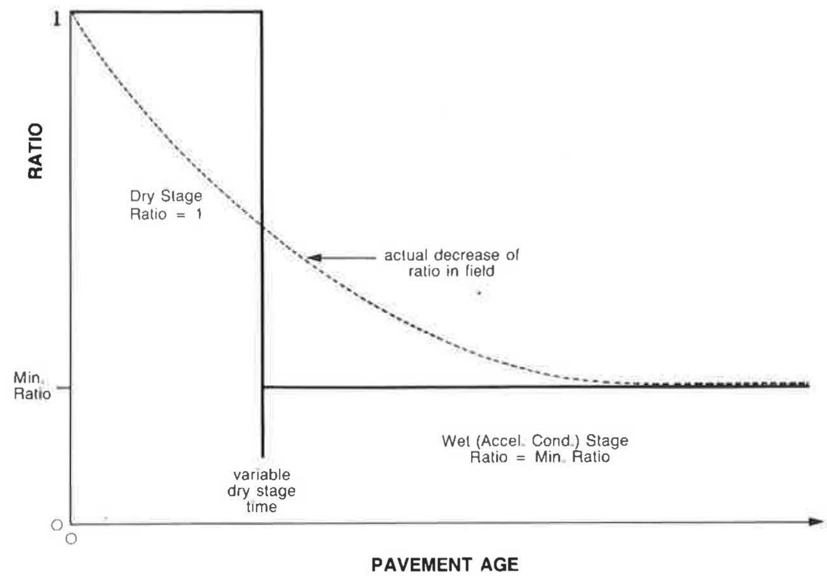

FIGURE 1 Two-stage decrease of ratio in field.

The Technion method (*8*) calls for the calculation of three pavement lives from the AASHTO equation to represent each stage after the length of the dry and saturation stages has been determined. Establishment of the TSR for each stage is readily adjusted to be compatible with the rate constant and loss of serviceability calculated from the AASHTO equation. The asphalt concrete layer coefficients for these stages are calculated using TSRs as measures of retained cohesion. The dry-wet life is the sum of the lives from each stage and can be compared with the dry life using a TSR equal to 1.

Repetitions to Years

Asphalt concrete life is mechanistically associated with repetitions, but life in years is used for decision making. This requires an estimate of the traffic rate. The life in years is usually stipulated as a design constraint to satisfy a planned field performance period at a given reliability. It is interpreted to be a dry life. The required repetitions of dry life are thereby established from the traffic rate constant and the required dry life in years. The traffic rate is the same when the pavement is wet and is undergoing moisture damage. Dry-wet or wet life repetitions calculated from the AASHTO equation are translated to wet life years by using the traffic rate. This approach applies to both absolute life and relative life methods.

Relative Life

Two models developed at the University of Idaho are described briefly to illustrate the relative life method. Both models reflect fatigue cracking distress and use physical property ratios instead of TSR or MrR alone. They are on computer software and predictions are available in minutes.

The Asphalt Concrete Moisture Damage Analysis System (ACMODAS) was developed in 1984 to meet the need to relate laboratory ratios to field wet life and to calculate cutoff ratios. The ACMODAS model was evaluated and applied by Busching et al. in 1985 in a South Carolina study of moisture damage assessment of aggregates and mixtures (*9*). Applications of the model are being evaluated at the materials and research facilities of several state highway agencies and at several additive-modifier companies.

An alternate version (1987) of the model, ACMODAS 2, incorporates the same objectives but has additional parts that reflect refinements in simulating the physical process of moisture damage.

Time Reduction of Ratio

A two-stage reduction of ratio FLR is incorporated in ACMODAS and is shown in Figure 1.

In contrast, a continuous function depicting the exponential decrease of ratios FLR and TR with time by a rate constant is incorporated in the alternate model, ACMODAS 2. It is shown in Figure 2. It has the form: Ratio = min.Ratio + $(1 - \text{min.Ratio})^{-KT}$, where min.Ratio is a physical property ratio (FLR and TR), K is a rate constant, and T is time in the field. In addition, a partial increase (i.e., recovery) of Ratio is specified to represent an annual, warm drying-out period. This is accomplished by superimposing a sine wave on the continuous function. The cyclic recovery is Ratio + 0.15, which corresponds to a sine amplitude of 0.075. A maximum recovery to Ratio = 1 may occur in the first year or so, especially if K is low. The predicted ITS and Mr mechanical properties in the FLR calculated at the time of onset of cracking (i.e., completion of cohesive life) are used to calculate the TR. The TR reduces with time by the same rate constant used with the FLR.

The models are field adjusted to a specific location. In ACMODAS this is done by varying the dry stage time and by using a regional factor, which is a multiplier of the wet strain in the FLR equation. The usual procedure is to set the dry stage time equal to 4 years and vary the regional factor. High regional factors are associated with a large number of annual freeze-thaw cycles. Adjustment in ACMODAS 2 is made by varying the continuous function rate constant. The rate constant is proportional to the number of annual freeze-thaw cycles and

24-hr cool-warm cycles. A high rate constant is associated with the combination of 150 freeze-thaw cycles and 150 cool-warm cycles per year. The effective moisture damage differences between the two types of cycles are recognized in guidelines for estimating the rate constant.

Figure 3 shows the influence of rate constants on predicted wet life using the ACMODAS 2 model. The lowest rate constant (.20) corresponds to a mild climate; the highest constant (.85) corresponds to a severe thermal cycle climate (e.g., 150 freeze-thaw and 150 24-hr cool-warm cycles per year).

Relating Ratios to Wet Life Predictions

Both models use life in years directly in their computational methods. Traffic rate can be applied to obtain a dry design life beforehand, and this dry life in years becomes the reference with which corresponding wet life is compared.

ACMODAS employs the cumulative damage method for each of the two moisture stages. The relative wet life is calculated assuming that the cumulative damage equals 100 percent for the sum of the two stages. A similar cumulative damage calculation is used in the absolute life method with the AASHTO equation (7).

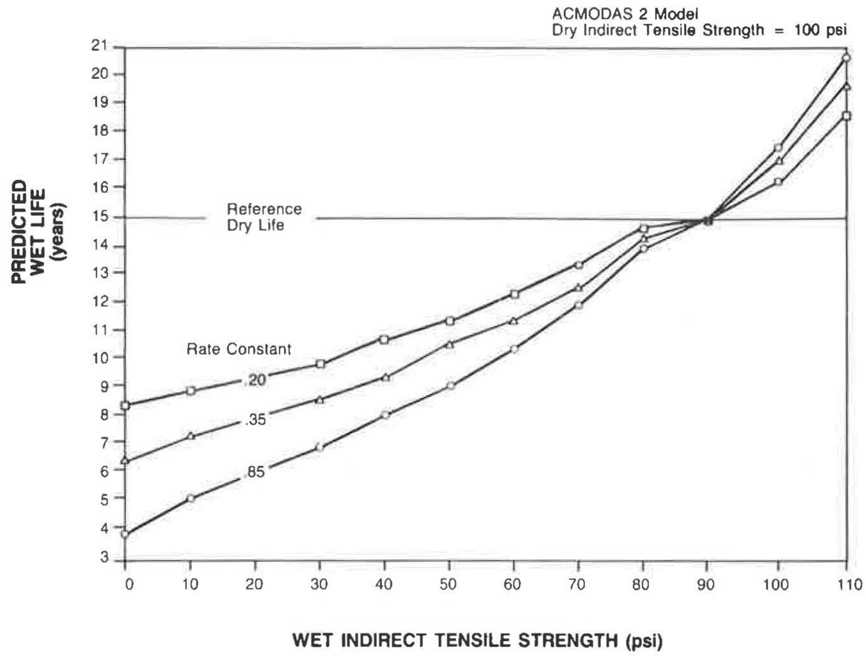

FIGURE 2 Continuous decrease of ratio in field with annual partial recovery.

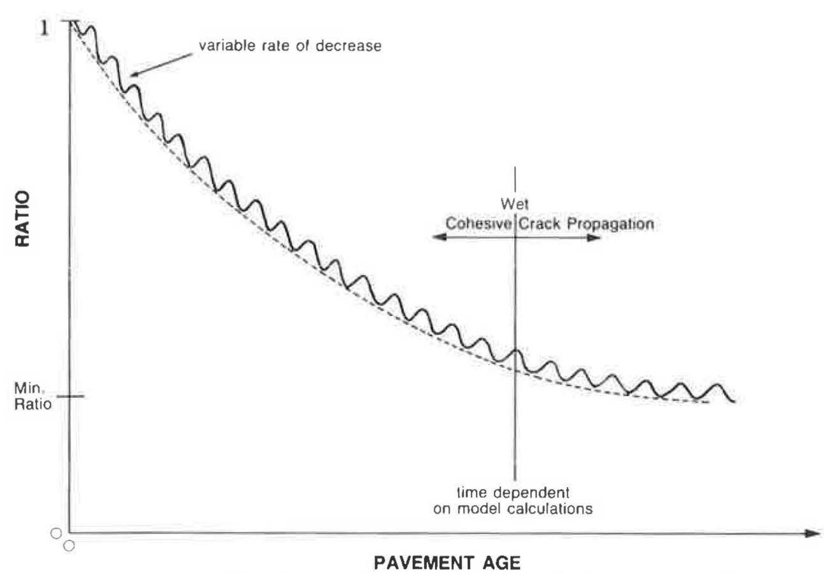

FIGURE 3 Effect of rate constant for ratio decrease in field on predicted wet life.

ACMODAS 2 employs the cumulative damage method for fatigue life (or cohesive life) and for crack propagation life using FLR and TR, respectively, on a continuing time basis. Time increments of damage are summed until no fatigue life remains. This is called wet cohesive life. Thereafter a similar incremental procedure is performed for crack propagation life. Predicted relative wet life therefore equals cohesive life plus crack propagation life.

The use of basic dry fatigue lives in the cumulative damage method of ACMODAS 2 is more complex. The basic dry fatigue lives are based on the present serviceability index (PSI) versus time (T) curve, which has the form PSI = initial PSI − AT^B. A and B are constants and are calculated to fit the PSI curve conditions of the reference dry life (e.g., 15 years), initial serviceability (e.g., 4.6), terminal serviceability (e.g., 2.5), and the specified percentage drop of PSI at the end of the dry cohesive life before crack propagation (e.g., 25 percent). The basic dry cohesive life used in cumulative damage calculations remains constant at two-thirds of the reference dry life. However, the basic dry crack propagation lives used for their respective time increments are not constant but decrease with increasing crack propagation time; they are calculated through slopes obtained from the equation of the PSI versus T curve in the crack propagation region. In Figure 4 predicted wet life relative to dry life is illustrated by the PSI versus T curve.

Comparison of Wet Life Predictions

It can be seen from the preceding discussion that the ACMODAS 2 model is more complex than the ACMODAS model. Also, the wet lives calculated from the same ITS and Mr data are not the same. Nevertheless, in many instances it appears that the wet lives are usually close enough for purposes of general agreement. For example, if the previously applied numerical ITS and Mr data for the control mixture are used (e.g., TSR = 0.60), the wet life from ACMODAS is 10.5 years and from ACMODAS 2 it is 10.8 years, when a 15-year reference dry life and average location (climatic) conditions are considered.

Given in Table 1 are the predicted relative wet lives for the six test sections evaluated in NCHRP Projects 4-8(3)/1 and 4-8(4). Wet life predictions for the Idaho (ID) and Montana (MT) asphalt concrete in the test sections are close to or greater than the 15-year reference dry life. This is primarily due to the high TSR and favorable ITS-Mr relationship used in the physical property ratios. General agreement of the models on predicted wet life ranking can be observed for the test sections.

There appears to exist a threshold of model complexity which it is not practical to exceed. There are two apparent reasons for this:

- The overall functionality between laboratory ratios and pavement life may be self-limiting in spite of the modeling of moisture damage to more sophisticated and complex levels and
- The accuracy of verifying predicted relative wet life in the field may not be sufficient to finely tune more complex models to idealistic levels.

In Situ Wet Life Predictions

Cores taken periodically from existing pavements can be tested in dry and saturated conditions. Accelerated conditioning is not used. Field moisture damage will be manifested in the saturated condition, and wet/dry periodic ratios are calculated. Relating these ratios to a computational method used in the models will provide a prediction of wet performance life for an existing pavement. For instance, the periodic core test data of the six state highway agency test sections in NCHRP Projects 4-8(3)/1 and 4-8(4) were applied in this manner to the ACMODAS and ACMODAS 2 computational methods. The wet lives of the test sections are given in Table 2. These lives are the probable in

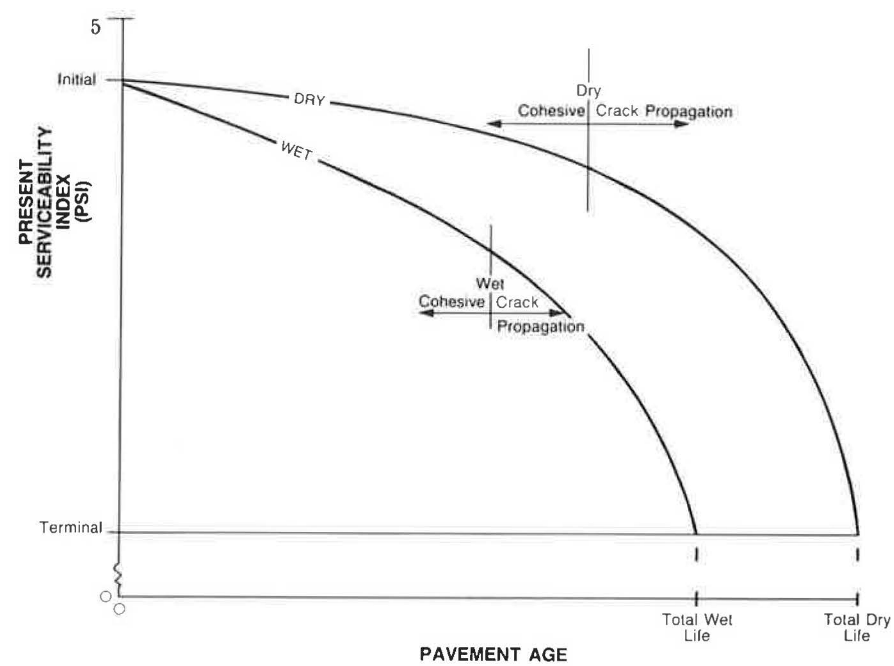

FIGURE 4 A predicted wet life serviceability curve relative to a dry life curve.

TABLE 1 COMPARISON OF PREDICTED WET LIVES FOR ASPHALT CONCRETE BY ACMODAS MODELS

Test Section Designation (state highway agency)	Initial ITS Data at 55°F			Wet Life Prediction in Years (dry life = 15 yr)					
					ACMODAS 2				
	Dry	Wet	TSR	ACMODAS	Cohesive	+	Crack Propagation	=	Total
ID	52	47	0.90	16.2	10.3		5.0		15.3
MT	47	40	0.85	15.7	10.0		4.9		14.9
VA	47	24	0.51	11.3	8.0		3.6		11.6
CO	36	16	0.44	11.3	8.1		3.4		11.5
AZ	97	39	0.40	7.7	6.2		3.2		9.4
GA	104	0	0	4.0	4.7		1.6		6.3

situ wet performance lives for the lower asphalt concrete layer in the pavement and appear to be reasonable on the basis of the 10-year pavement evaluation by the highway agencies. Comparison of the lives indicates that the results from the two models are again in general agreement. Another comparison indicates, however, that the three longer-lived test sections as predicted and listed in Table 1 are now in different order in Table 2 based on the periodic core evaluations. Certainly, one of the reasons for this difference is not being able to predict all incidental changes that occur in the field from the practical application of a single laboratory test. For instance, the "asphalt-fines" in the lower layer of asphalt concrete in the Idaho section appeared to be partly eroded after 5 years, giving rise to a TSR that is lower than the predicted minimum TSR developed from the accelerated conditioning of freeze plus 24-hr 140°F water soak. Maybe the application of several freeze plus warm water soak cycles would have produced the lower TSR by causing this erosion.

TABLE 2 COMPARISON OF PROBABLE IN SITU WET LIVES FOR ASPHALT CONCRETE USING PERIODIC CORE PROPERTIES

Test Section Designation (state highway agency)	Wet Life Prediction in Years (dry life = 15 yr)					
		ACMODAS 2				
	ACMODAS	Cohesive	+	Crack Propagation	=	Total
MT	16.9	10.8		4.9		15.7
VA	12.7	9.9		3.9		13.8
ID	11.5	8.5		4.1		12.6
CO	11.0	7.9		3.6		11.5
AZ	8.5	5.8		3.2		9.0
GA	7.6	5.7		3.1		8.8

Constructing a graph is a helpful method for comparing probable in situ moisture damage using the relative approach. On the graph, mechanical and physical property (periodic) ratios are plotted relative to reference dry life damage as a function of time. To accomplish this, the percentage remaining life versus time line is drawn to depict the probable load-associated life reduction of the dry asphalt concrete. It is a reference dry life line. Then ratios from cores are calculated, multiplied by the asphalt concrete's percentage remaining dry life, and plotted at the time corresponding to the core drilling. This is repeated periodically and wet life lines are drawn through the plotted points. A wet life line below the reference dry life line reflects moisture damage.

Figures 5 and 6 show examples of the wet life lines obtained from the periodic core ratios of the Virginia and Colorado test sections. Lines are shown for the ratios of TSR, MrR, FLR, and TR. Both test sections have moisture damage after 5 years. Notice that moisture damage characterized by MrR tends to be the highest and that characterized by FLR and TR tends to be the lowest.

If equal weighting is assigned to each of the four ratios, the broad band of wet life lines for the ratios of the Virginia test section in Figure 5 implies large variance and less certainty about the exact extent of moisture damage. The average retained life appears to be 20 percent at 10 years. The predicted wet life information from Tables 1 and 2 as well as the observation of 35 percent stripping in the 10-year cores also indicate the occurrence of moisture damage in the Virginia test section.

In contrast, it can be observed in Figure 6 that a much narrower band of wet life lines exists for the ratios of the Colorado test section; this implies a lower variability for the occurrence of in situ moisture damage after 5 years. Here, retained life of 20 percent at 10 years is more reliable. The 10-year cores from the Colorado test section show "severe" stripping (about 50 percent), and the predicted wet life information from Tables 1 and 2 verifies the occurrence of higher moisture damage (e.g., Table 2 gives an in situ life of around 11 years, about 2 years less than the Virginia in situ life).

PREDICTING CUTOFF RATIOS

Both absolute life and relative life prediction models can be used to calculate cutoff ratios that are applied during the design and analysis of a mixture in the laboratory. Cutoff ratios for TSR are calculated from the AASHTO equation and the two-moisture stage model and were presented previously by Lottman (7). The results indicate that the TSR cutoff is not a constant; it is dependent on pavement location, percentage of allowable reduction of life, and dry mechanical properties. Severe climatic conditions (e.g., many freeze-thaw cycles) and low percentage of allowable reduction of life (e.g., 5 percent) will increase the cutoff ratio. Similar results are indicated for relative life models.

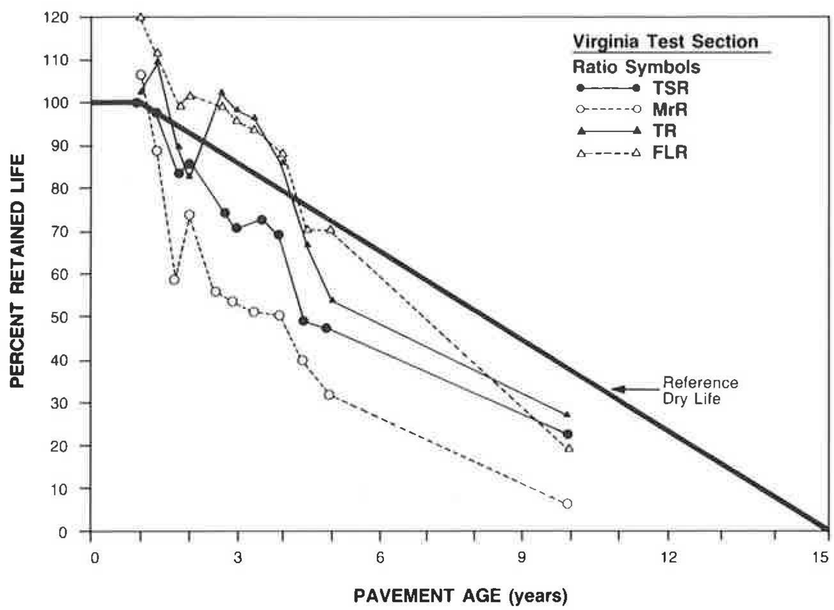

FIGURE 5 Relative wet life lines of four ratios for the Virginia moisture damage test section.

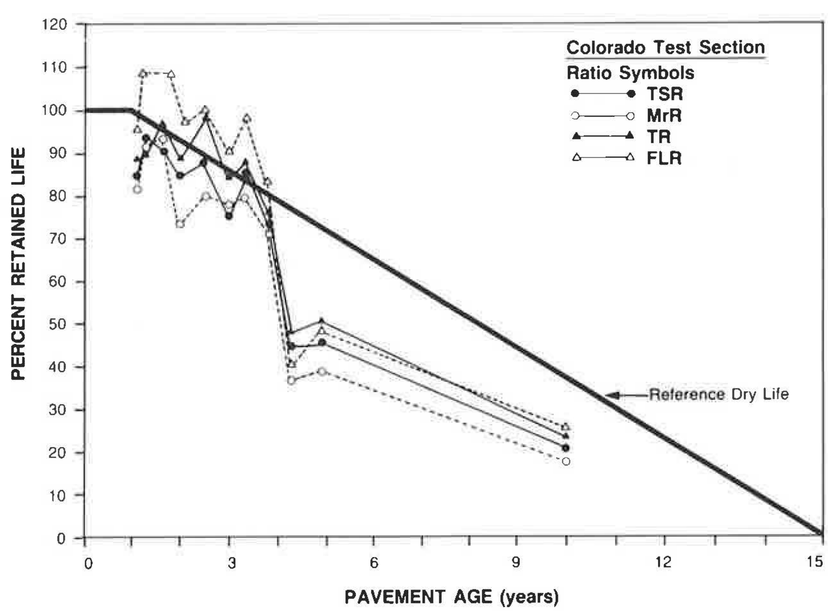

FIGURE 6 Relative wet life lines of four ratios for the Colorado moisture damage test section.

When the relative life models of ACMODAS and ACMODAS 2 are used with the previously applied numerical examples of the control mixture's ITS and Mr data, the respective TSR cutoffs are calculated to be 0.75 and 0.78. [These ratios are for average pavement location (i.e., climatic conditions) and for a 10 percent allowable reduction of life.] Because the control mixture's TSR of 0.60 is less than the TSR cutoff, the mixture is unsatisfactory (i.e., too much moisture sensitivity) and the mixture must be redesigned or an effective additive must be used. The TSR of the reconstituted or treated "new" mixture must be compared with the TSR cutoff to ensure that it is at least equal to the cutoff ratio. The TSR cutoff required for the new mixture might be different from the previous cutoff ratio if the treated mixture's dry mechanical properties are different.

TSR cutoffs are calculated from the ACMODAS 2 prediction model with average climatic conditions (rate constant = 0.35) for the six NCHRP 4-8(3) and 4-8(4) test sections. Initial field TSRs are listed next to the calculated TSR cutoffs in Table 3. The four lowest ranked sections (VA, CO, AZ, and GA) have initial TSRs less than the TSR cutoff and would have required mixture redesign or use of additives, or both. These moisture sensitive mixtures were purposely paved without redesign or treatment to satisfy the objective of moisture damage research in the NCHRP project.

TABLE 3 INDIRECT TENSILE STRENGTH AND RESILIENT MODULUS CUTOFF RATIOS FOR 10 PERCENT ALLOWABLE LIFE REDUCTION BY ACMODAS 2 MODEL

Test Section Designation (state highway agency)	Initial TSR	TSR Cutoff	Initial MrR	MrR Cutoff
ID	0.90	0.70	0.84	0.66
MT	0.85	0.68	0.80	0.64
VA	0.51	0.68	0.48	0.64
CO	0.44	0.67	0.41	0.63
AZ	0.40	0.76	0.38	0.71
GA	0	0.76	0	0.71

A TSR cutoff of 0.70 appears to be a current national average used in routine mixture testing. It is interesting to note that 0.70 appears to be about a model-predicted average for the NCHRP test sections (Table 3).

An advantage of prediction models is that MrR cutoff as well as TSR cutoff can be predicted readily. MrR cutoffs from the ACMODAS 2 model are listed in Table 3 for the NCHRP test sections. The four lowest ranked test sections have initial MrRs that are less than the MrR cutoff, which is a problem here because their TSRs are less than the TSR cutoff. For these specific mixtures, it appears that remedies to increase TSR to TSR cutoff would also increase MrR at the same time. However, performance goals might not be reached if MrR increased more rapidly than TSR when using some treatments. Therefore it is important to make sure not only that both TSR and MrR meet the respective cutoff ratios, but also that TSR remains greater than MrR.

DEVELOPING SUPERIOR PERFORMANCE

Current procedures deal with moisture sensitivity as a disadvantage; that is, there is moisture damage because of decrease in mixture adhesion and cohesion. Thus the effort is to keep the loss of pavement performance life to a minimum.

On the other hand, there appears to be an optimistic side to moisture sensitivity. The possibility exists for achieving improved mechanical properties in the wet stage. All asphalt concrete will contain moisture; therefore it will be advantageous to purposely make use of moisture to gain equivalent performance life by altering the wet ITS-Mr relationship through the use of chemical modification of asphalt or aggregate. The specific advantages of the improvement would be to increase the reliability of developing zero moisture damage in the field by increasing the wet life beyond dry life at average reliability. If 90 percent reliability of a specific reference dry life is stipulated, the achievement of an equal reliability of zero moisture damage may also be required.

Blends of several generic antistripping additives with modest concentrations of some polymeric modifiers can develop a combined FLR as high as 2.0, which should provide a high reliability of zero moisture damage. There are also blends that are not effective, giving combined FLR of less than 1.0. The high FLR requires adhesion loss to be negligible and cohesion gain to be greater for ITS than for Mr after accelerated conditioning.

The required TSR and MrR cutoffs corresponding to the high FLR (and TR) will also be higher ratios. The 90 percent reliability of zero moisture damage was evaluated on a limited basis in the ACMODAS 2 model using an average standard deviation of 10 percent and mean values of wet and dry ITS and Mr for treated moisture sensitive mixtures. What appears to be required is a TSR in the range of from 1.15 to 1.20 with an MrR of about 85 percent of the TSR for ratios calculated from mean values.

The predictability and cost-effectiveness of chemical compounds and blends that develop the proper gains of mechanical properties for a specific reliability of zero moisture damage are topics of future research on chemical modification and statistical application.

SUMMARY

Identification and application of moisture damage ratios currently are based on mechanical properties calculated from the indirect tensile strength (ITS) and resilient modulus (Mr) tests. These tests are becoming commonplace and will be used in laboratory procedures for the analysis of asphalt concrete mixtures.

Laboratory moisture conditioning (accelerated conditioning) that produces minimum mechanical property ratios for a specific mixture is recommended. The use of a prediction model corrected for the specific field environment (e.g., climate) is suggested for technical efficiency.

Physical property ratios are made up of ITS- and Mr-values and reflect a mixture's working resistance to a specific type of field damage. They are used in mathematical prediction models. In turn, the models are used to predict the wet performance life and laboratory cutoff ratios for ITS (TSR) and for Mr (MrR). Two physical property ratios currently used in the University of Idaho models are fatigue life ratio (FLR) for the onset of fatigue cracking and toughness ratio (TR) for crack propagation.

Absolute life and relative life models have a different basis of computations and comparisons. Relative life models appear suitable for incorporating mechanistic methods because the models use comparative calculations to a known reference performance. All models employ a field time decrease of ratio, from 1 at zero time to a laboratory minimum ratio at a later time when environmental conditions produce the moisture damage corresponding to the accelerated conditioning. The rate of decrease of ratio is changed according to climatic conditions, resulting in a significant change in the number of years for ratio decrease and for wet performance life.

Applications of ratios and prediction models to NCHRP field data indicate that there are advantages to using physical property ratios and models. Although the level of model complexity may be limited by current practical applications and verification skills, implications are that the ratios required for achieving the necessary reliability of obtaining zero moisture damage are best determined through the calculation of statistically equivalent wet life increases from prediction models.

It is advantageous to know and use the cutoff ratios calculated from a prediction model because the ratios are dependent on the specific mixture's ITS and Mr test values as well as pavement location data. TSR cutoff ratios of about 0.70 on average are used currently in the United States to limit field moisture damage. Prediction models indicate that 0.70 is, in general, associated with not more than 10 percent loss of dry performance life at average reliability. A TSR about equal to 1 and an MrR slightly less than the TSR appear to be required for a higher reliability of zero moisture damage. Even higher reliabilities (e.g., 94 percent) of zero moisture damage require the TSR of treated mixtures to be greater than 1 (with corresponding MrR less than TSR). This superior performance might be achievable with specific blends of antistripping additives and polymeric modifiers that not only stop adhesion loss but also promote cohesion gain through the correct buildup of mechanical property ratios.

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