Predicting the Effects of Moisture on Wheelpath Rutting in Asphalt Concrete

ROBERT P. LOTTMAN AND DOUGLAS J. FRITH

The approach to predicting moisture sensitivity of asphalt concrete pavements is based on the acceleration of fatigue cracking and wheelpath rutting field distresses. Prediction methods incorporate mechanical properties of the specimen, derived physical property ratios with field time, and environmental effects. In a 1988 TRB paper, methods were discussed that resulted in predicted wet performance lives and laboratory cutoff ratios. Specifically discussed was a University of Idaho method called "Asphalt Concrete Moisture Damage Analysis System" (ACMODAS); ACMODAS2 in reference to fatigue cracking was emphasized. In this paper, ACMODAS3 referenced to wheelpath rutting is emphasized. The parts and procedures are examined along with application of results. The effects of moisture on wheelpath rutting are defined here as being the changes of permanent deformation in the asphalt concrete due to plastic flow. A physical property ratio called Wheelpath Ratio (*WPR*) is developed using wet and dry modulus and stripping values from laboratory specimens after performing a moisture conditioning test. Seasonal increase of *WPR* is related to summer pan evaporation at the pavement location. In the ACMODAS3 method, 1/10-yr permanent deformation "damage" fractions are summed to yield a relative wet performance life in years. A resilient modulus cutoff ratio is also calculated for laboratory control of the specific asphalt concrete mixture. Application of the ACMODAS3 and ACMODAS2 methods shows that a specific pavement mixture can have significant moisture sensitivity only to wheelpath rutting, whereas another mixture can have significant sensitivity only to fatigue cracking.

Significant mileage of asphalt concrete pavements may be affected by moisture damage that accelerates the development of fatigue cracking and wheelpath rutting field distresses. Moisture damage occurs in the form of loss of adhesion (stripping) or loss of cohesion (apparent viscosity decrease in asphalt mastic and film).

Present methods to control moisture damage are laboratory acceptance-rejection methods that compare wet with dry test results of preconstruction mixture specimens. The methods incorporate the visual effects of stripping and wet-retained mechanical properties, such as indirect tensile strength and resilient modulus in the form of ratios. High stripping and low ratios indicate a high potential of field moisture damage. When this occurs, the asphalt concrete mixture is rejected. Remedies are either to redesign the mixture with fewer moisture-susceptible components or to include antistripping additives.

Moisture damage prediction methods translate laboratory test ratios and visual stripping of mixtures into practical terms related to field performance to achieve a more precise evaluation and application of remedies. Predicted are wet pavement performance life and laboratory cutoff ratios, which are location- and mixture-specific.

A prediction method was described by White (*1*) and later presented in the authors' TRB paper, "Methods to Predict and Control Moisture Damage in Asphalt Concrete" (*2*). This method is called ACMODAS2, and it relates moisture susceptibility to fatigue cracking in asphalt concrete. Except for the character of the physical property ratio, the methodology of ACMODAS2 is similar to that of the later-developed method for wheelpath rutting called ACMODAS3, described by Frith (*3*). In this paper the main parts of ACMODAS3 are explained along with examples of results from test data.

Asphalt Concrete Moisture Damage Analysis System 3 (ACMODAS3) is programmed to run on a microcomputer and is intended to be used by laboratory personnel involved with the evaluation of asphalt concrete mixture design and with the development and analysis of additives and/or modifiers for control of moisture damage. It predicts the wet life on a relative basis and the modulus cutoff ratio to achieve acceptable wheelpath permanent deformation distress caused by moisture. This distress is defined as rutting caused by plastic flow or creep in the asphalt concrete surfacing. Densification rutting from the reduction of voids in the wheelpath is not included.

LITERATURE SEARCH

Research has been and is currently in progress on how rutting can be reduced or predicted in dry asphalt concrete pavements on an absolute basis. At the present time research is focusing on determining which methods are most accurate and practical (*4–8*). There has been research on how moisture affects pavements in general and specifically on fatigue cracking of asphalt concrete (*2*, *9–12*). Nothing was found that directly related to the application of wet and dry test results for predicting the effects of moisture on the permanent deformation characteristics of asphalt concrete in the field. Therefore it seems that ACMODAS3 is a first attempt to simulate and quantify this relationship.

DATA REQUIRED

There are three types of input information required in ACMODAS3: laboratory test data for dry- and moisture-

R. P. Lottman, Department of Civil Engineering, University of Idaho, Moscow, Idaho 83843. D. J. Frith, ARE, Inc., 828 Jones Street, Reno, Nev. 89503.

conditioned specimens, environmental data, and pavement performance levels. The laboratory data needed are the wet and dry resilient modulus values and the overall percent stripping in the wet specimens. Environmental information necessary is the annual average summer pan evaporation and the annual number of freeze-thaw cycles and cool-warm cycles. Pavement performance levels are independently selected.

Resilient Modulus

ASTM D4123-82 is used to determine the resilient modulus (*Mr*) of wet and dry test specimens. However, total horizontal deformation under the repeated load application is used for "resilient modulus" in ACMODAS3. It is practically equal to the resilient deformation if measurement is made per individual load application. The wet test specimens are understood to be accelerated, conditioned by water and temperature, using, for example AASHTO T-283-85.

Stripping

Percent stripping is estimated by splitting the wet specimens in half and estimating on the interior faces the percentage of coarse aggregate stripped using a magnifying glass. The percentage of fine aggregate stripped is estimated using a 15-power stereozoom microscope. The overall percent stripping is calculated as 0.40 times the percent coarse aggregate stripped plus 0.60 times the percent fine aggregate stripped. The assumption is that, of the asphalt binder that coats surfaces, 40 percent of the surface area is coarse aggregate and 60 percent is fine aggregate. Remaining fine aggregate are particles small enough to be immersed in the asphalt (i.e., as a mastic) and therefore by definition are not coated by asphalt film for practical stripping observation.

Environmental

The partial drying out in the asphalt concrete surfacing during the summer causes a temporary recovery to a lower moisture damage. This is related to summer pan evaporation, which is the average annual evaporation (Class A) multiplied by the mean May–October evaporation in percent of annual. This information should be available at the local weather station, or it can be obtained by an estimated procedure (*3*).

The number of annual 24-hr freeze-thaw cycles and cool-warm cycles determine the field rate to achieve maximum moisture damage from moisture ingress and its effectiveness. A freeze-thaw cycle is defined as a temperature change from below freezing to above freezing within a 24-hr period. A cool-warm cycle is defined as a temperature increase of at least 35°F in a 24-hr period with a low temperature of 33–40°F.

Pavement Performance Levels

The dry performance life of the asphalt concrete surfacing in years to terminal (failure) rut depth is required; this is the reference life. It is obtained by thickness design methods using dry asphalt concrete properties or by *estimation*, which is suitable for most moisture sensitivity objectives.

Percent allowable reduction (*PAR*) of dry performance life is stipulated as the maximum allowable reduction of dry life due to moisture damage in the field. Thus, wet lives to terminal rut depths that correspond to percentage dry life losses greater than *PAR* are not acceptable, and the mixture is rejected. (Mixture redesign is performed or additives are incorporated, or both.)

WHEELPATH RATIO

The wheelpath ratio (*WPR*) is a wet-to-dry physical property ratio that relates the moisture resistance to rutting; it is defined as the allowable repetitions to permanent deformation failure when the mixture is wet compared with when it is dry. The allowable repetitions to failure are those that cause a permanent deformation (or rut depth) equal to an unacceptable amount (e.g., 0.50 in.). *WPR* incorporates a relationship between repetitions to failure (an unacceptable rut depth) and permanent deformation. The development of the relationship for *WPR* follows.

Basic Relationships

Where N is the allowable number of 18-kip single-axle loads (repetitions) to an unacceptable rut depth (failure), and the subscripts w and d stand for wet and dry conditions, respectively, $WPR = N_w/N_d$. Thus, *WPR* is defined for use in a relative performance life model similar to current usage philosophy for mechanical property ratios.

N is inversely proportional to the cumulative permanent strain (εtp) in the pavement that corresponds to the critical rut depth, and $\varepsilon tpd = \varepsilon tpw$. N is assumed to be equal to εtp divided by the permanent strain per load cycle (εpc), so that $N_w/N_d = \varepsilon pcd/\varepsilon pcw$. εpc is determined from the total shear strain (εt) and from the viscous loss component (J'') of the complex compliance in the frequency domain as related to the cycle of repeated loading in the resilient modulus test.

The Chevron 5L elastic layer program was used to find εt in a typical pavement corresponding to asphalt concrete resilient moduli (*Mr*). The following equation was derived from the relationship:

$$\varepsilon t = 2.59 * Mr^{-0.713} \text{ for } 1 \times 10^5 \leq Mr \leq 1 \times 10^6 \text{ psi} \quad (1)$$

The complex compliance (J^*) is equal to the inverse of the complex modulus, $J^* = 1/E^*$, and consists of J', which is the elastic storage component, and J'', which is the viscous loss component $J^* = J' - iJ''$). The expression εpc is proportional to the viscous loss component, J''. To solve for J'', J^* must be determined. This is done by substituting the complex modulus expression $E^* = E' + iE''$ into $J^* = 1/E^*$ and multiplying by the conjugate, which gives $J^* = E'/(E'^2 + E''^2) - iE''/(E'^2 + E''^2)$. Defining $|E^*|$ to be the magnitude of E^*, and recognizing that $|E^*|$ is the hypotenuse of a right triangle where E' and E'' are the legs, then $|E^*|^2 = E'^2 + E''^2$. Thus $J^* = E'/|E^*|^2 - i\,E''/|E^*|^2$ and $J'' = E''/|E^*|^2$. Because $E'' =$

$|E^*| \sin \theta$, where θ is the lag angle ($\theta = \tan^{-1}E''/E'$), then $J'' = \sin\theta/|E^*|$.

Because $WPR = \varepsilon pcd/\varepsilon pcw$ and εpc is considered to be proportional to J'', then $WPR = J''d/J''w = (|Ew^*|/|Ed^*|) \sin\theta d/\sin\theta w$. The proportionality constants are considered canceled.

Setting $|E^*| = \sigma o/\varepsilon t$, where σo is the repeated stress magnitude, and using Equation 1, the basic relationship for *WPR* becomes

$$WPR = MrR^{0.713} \sin\theta d/\sin\theta w \quad (2)$$

where *MrR* is the wet-to-dry resilient modulus ratio.

A measurement of lag angles θd and θw for dry and wet test specimens requires additional electronic equipment beyond the resilient modulus equipment routinely available to many highway agencies. Therefore an approximation of the sine θ ratio in Equation 2 was developed through the measurement of stripping as follows.

The approximation is based on the premise that if moisture diffusion into the asphalt mastic and film occurs, then it may cause an apparent decrease of binder viscosity and, accordingly, a cohesion decrease. The ratio of permanent shear strain to total shear strain will increase. For a given total strain, the magnitude of the permanent strain per cycle will increase as the cohesion decreases. Thus the change of cohesion is related to the $\sin\theta$ ratio.

Assuming that the increase in permanent strain relative to total strain is linear when there is a cohesion loss, then $\sin\theta w = \sin\theta d\,(1 - (CCP/Mrd))$. *CCP/Mrd* is known as the cohesion change and is equal to $CCP/Mrd = MrR + S - 1$, where *S* is the fraction of stripping in the wet aggregate (*13*). [The mechanics of cohesion and adhesion changes was developed in a 1984 AAPT paper (*13*).] This work indicates that quantification of the changes requires the measurement of debonding (stripping) as well as wet and dry mechanical properties.) In the case of cohesion gain, the cohesion term is damped by letting $CCP/Mrd = A + Be^{(-D(CCP/Mrd))}$, where *A*, *B*, and *D* are constants. The constants were solved using boundary conditions (*3*). The following expression results: $\sin\theta w = \sin\theta d \{1 - [0.5 - 0.5e^{(-1.1\,CCP/Mrd)}]\}$. Substituting the preceding equation into the previous *WPR* equation for $\sin\theta w$ gives the approximate relationship for *WPR*:

$$WPR = (MrR)^{0.713}(1.0/\{1 - [0.5 - 0.5e^{(-1.1\,CCP/Mrd)}]\}) \quad (3)$$

WPR Trends

As calculated by Equation 2 or 3, *WPR* becomes the long-term field ratio representing the maximum moisture sensitivity of the mixture (specimens) to permanent deformation.

When cohesion losses occur in addition to stripping (i.e., moisture causes the viscosity of the asphalt binder to decrease), then *WPR* will decrease more than only by the drop of *MrR* alone. A cohesion loss is considered here to be a detrimental factor when permanent deformation is considered. A drop in cohesion causes the permanent strain per cycle to increase with respect to the total strain per cycle ($\sin\theta$ ratio decreases below 1.0). *WPR* can never exceed 1.0 if there is a cohesion loss in the mixture.

WPR can sometimes be greater than 1.0 if the wet *Mr* is greater than the dry *Mr*. A *WPR* greater than 1.0 means that the pavement is less susceptible to wheelpath permanent deformation in the wet condition as compared with the dry condition, and it is due to a cohesion gain. This can happen if water diffusion in the asphalt or mastic causes a stiffening effect, if there is stiffening due to reaction by water with additives, or if an antirutting modifier is used and the cohesional gain is referenced to an untreated dry control mixture.

There can be cases where the *WPR* is less than 1.0 (primarily due to adhesion loss) but the mixture still exhibits a cohesion gain. Here, the permanent strain increase is not as high as it would be if there were no cohesion gain at all.

Change of *WPR* with Field Time

How *WPR* changes from an initial dry-to-dry ratio to the long-term ratio in the field depends on climatic factors: the annual freeze-thaw and cool-warm cycles and the amount of drying occurring during the summer months. For damage, the freeze-thaw and cool-warm cycles increase the rate at which the *WPR* decreases to the long-term ratio because the differential thermal expansion forces are greater. If a pavement location has a high number of freeze-thaw and cool-warm cycles, then *WPR* will reach the long-term ratio sooner than at a location with very few temperature cycles.

An exponential time function is used in ACMODAS3 to simulate these changes in *WPR*, the basis of which comes from field tests. For example, in the field study conducted under NCHRP Project 4-8(3) pavement cores were evaluated using the laboratory test methods previously described (*14*). The tests revealed that the indirect tensile strength ratio and the resilient modulus ratio generally decrease in an exponential manner when moisture damage builds up. The function was determined to be of the form e^{-KT}, where *K* is a field moisture rate constant and *T* is the time. At paving, *WPR* is equal to the dry-to-dry ratio, then decreases with time, asymptotically reaching the long-term *WPR* calculated from the laboratory test data of moisture-conditioned specimens. *WPR* as a function of time (*T*) is expressed by the following equation:

$$WPR(T) = WPR + (DDR - WPR)e^{-KT}$$

where

$WPR(T)$ = the wheelpath ratio at a given time,
DDR = the initial dry-to-dry ratio (equal to 1.0 unless comparison is to different, control mixture),
WPR = the long-term wheelpath ratio, and
K = the moisture rate constant.

K is estimated from annual freeze-thaw and cool-warm cycles in the field and from the saturation level, which is simulated in specimens when water-temperature conditioning is performed in the laboratory moisture damage test. *K* ranges from 0.20 (mild climate) to 1.50 (severe climate) under moderate saturation.

Highway agencies have reported increases in mechanical property ratios during the late summer and early fall when the pavement is drier. Schmidt and Graf showed reversibility of *MrR* as moisture increased and then decreased in an asphalt concrete pavement (*15*). Therefore, a seasonal variation in the form of a sine wave simulates the summer increase in *WPR*.

The amplitude of the sine wave varies and is dependent on the amount of moisture that may evaporate from the pavement. It is defined as the summer increase of *WPR* and is determined by predicting the amount of increase of adhesion and cohesion based on the evaporation. The percent change in the adhesion and cohesion of the wet mixture used in ACMODAS3 is 100 percent when the summer pan evaporation is 95 in. (assumed U.S. maximum) and 0 percent when the pan is 10 in. (assumed U.S. minimum). An equation for the allowable recovery was developed by Frith (*3*).

The actual timepath that *WPR* follows in the field due to moisture effects (WPR_f) is predicted by combining the exponential function and the summer sine wave of the form $WPR_f = WPR(T) +$ Sine Wave. This is shown in Figure 1.

WET PERFORMANCE LIFE, CUTOFF RATIO, AND BENEFIT-TO-COST RATIO CALCULATIONS

Wet Performance Life

WPRf is used to predict the cumulative, relative increase in permanent strain to rutting failure. In ACMODAS3, Miner's cumulative damage relationship (*16*) is adjusted to field time as equivalent to repetitions and becomes sum [$t/(WPRf \times FADPL)$], where *WPRf* is the wheelpath ratio at a given time, *t* equals 0.1-yr time increment (the developing rutting is summed over 0.1-yr increments), and FADPL is the field all-dry performance life (i.e., dry reference life), in years. When the sum equals 1.0, the predicted wet performance life (to rutting failure) is obtained.

Resilient Modulus Cutoff Ratio

The *Mr* cutoff ratio in ACMODAS3 is dependent on the dry *Mr*, the allowable percent reduction (*PAR*) of the dry reference performance life, the adhesion and cohesion properties of the mixture, and the environmental data for the region. This makes the cutoff ratio unique for each mixture and each location.

The cutoff ratio is obtained by calculating by increments both the wet *Mr* and stripping until a life equal to the required wet performance life is reached. The required wet performance life is the dry reference life reduced by *PAR*. For example, if dry reference life and *PAR* are selected to be 15 yr and 10 percent, respectively, then the required wet life = 15 − 0.10 * 15 = 13.5 yr. The wet *Mr* corresponding to 13.5 yr is divided by the dry *Mr* to get the *Mr* cutoff ratio.

Benefit-to-Cost Ratio

A benefit-to-cost ratio (*B/C*) is used to evaluate the effectiveness of treatments by additives and modifiers. A high *B/C* indicates that the treatment may be cost-effective. *B/C* is defined as the ratio of the treated wet performance life to the untreated wet performance life (the benefit) divided by the ratio of the initial cost of the treated mix to the initial cost of the untreated mix (cost ratio). It is not an incremental procedure. Comparisons are made to a minimum *B/C*, independently obtained.

The minimum *B/C* is the dry performance life divided by the required wet life. Because the required wet life is a function of *PAR*, the minimum *B/C* is also a function of *PAR*. For example, suppose a highway agency specifies a dry reference life of 15 yr and a *PAR* of 10 percent; then the minimum *B/C* is 15/(15 − .10 * 15) = 15/13.5 = 1.11. Therefore,

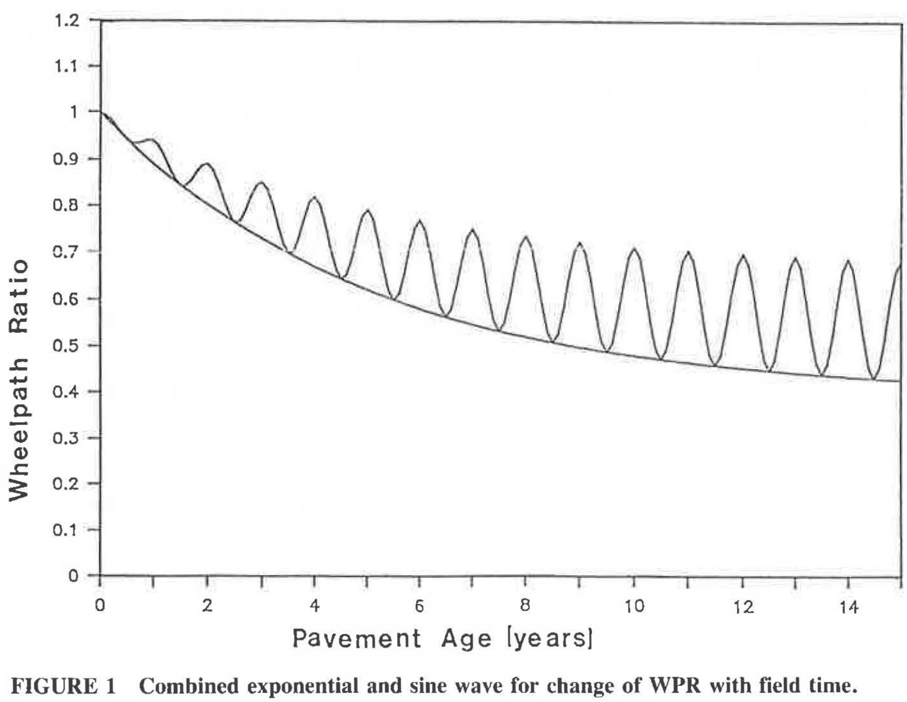

FIGURE 1 Combined exponential and sine wave for change of WPR with field time.

for a treated mixture to be cost beneficial for these data, its *B/C* would have to exceed 1.11.

SENSITIVITY ANALYSIS OF ACMODAS3

A sensitivity analysis was performed on ACMODAS3 to estimate the effects of each input variable and to determine the percent variation in the results of wet performance life and *Mr* cutoff ratio.

The input data varied were the wet and dry resilient modulus values, the percent stripping, the summer pan evaporation, and the field moisture rate constant. Variances were denoted as "tight control" and "general control." Interlaboratory testing may be closer to general control. Table 1 lists the variances.

ACMODAS3 was run using the following sample mean values: dry *Mr* = 757,600 psi, wet *Mr* = 462,000 psi, stripping = 30 percent, summer pan evaporation = 45 in., rate constant = .35, dry field performance life = 15 yr, and *PAR* = 10 percent. Results are a predicted wet performance life equal to 11.8 yr and an *Mr* cutoff ratio equal to 0.80. Application of the sensitivity results in Table 2 shows that the actual wet performance life has a range of 10.9 to 12.7 yr at a probability of about 67 percent for tight control. About 84 percent of the time, the wet life should be at least 10.9 yr. For general control, the range of 67 percent probability is 10.3 to 13.3 yr, and the wet life will be at least 10.3 yr at an approximate probability of 84 percent.

Continuing, the *Mr* cutoff ratio range at 67 percent probability for general control is 0.70 to 0.90, which indicates approximately 13.5 yr of minimum wet life at 84 percent probability if a cutoff of 0.90 rather than 0.80 is employed.

SAMPLE RESULTS

As previously mentioned, a wet performance life, an *Mr* cutoff ratio, and a *B/C* comparison (if chosen) are calculated using the ACMODAS3 model. Other data printed are the wheel-path ratio (*WPR*), the percent adhesion change, the percent cohesion change, the require wet life (based on *PAR*), and the resilient modulus ratio of the mixture. These data are printed in one of two ways: either relative to the dry test mixture (test-to-test) or relative to a dry control mixture (test-to-control). This section contains illustrations of how the results are interpreted and used.

Test-to-Test Comparison

The test-to-test comparison is used mostly for untreated mixtures (i.e., those with no additives or modifiers). This comparison shows the relative change between wet and dry specimens of a given mixture. The two major results of interest are the predicted wet life and the *Mr* cutoff ratio.

For this example typical input data are assumed as follows:

Dry reference performance life = 15 yr;
dry *Mr* = 757,600 psi;
wet *Mr* = 462,000 psi;
stripping = 30 percent;
average summer pan evaporation = 45 in.;
moisture rate constant = 0.35; and
percent allowable reduction (*PAR*) = 10 percent.

Based on these values the mixture's *MrR* is 0.61 and the required wet permanent deformation life using *PAR* is 13.5 yr. Output of ACMODAS3 consists of Figures 2 through 5. Figure 2 shows the change in *WPR* with time. Notice that the initial dry ratio equals 1 and *WPR* decreases exponentially to the long-term *WPR* calculated using the laboratory data. Figure 3 shows the percent adhesion and cohesion changes in the mixture; in this case, both changes were losses. The comparison between the mixture's *MrR* and the *Mr* cutoff ratio is illustrated in Figure 4. Note that the *MrR* is less than the *Mr* cutoff ratio. Figure 5 contains the printouts of the input data and results.

Because the mixture's *MrR* is less than the *Mr* cutoff ratio, the predicted wet life must be less than the required life. This is shown in Figures 2 and 5, where the predicted wet life (to rutting failure) is 11.8 yr and the required wet life (to rutting failure) is 13.5 yr. Thus the mixture is not acceptable and

TABLE 1 TIGHT AND GENERAL CONTROL VARIANCE

VARIABLE	TIGHT CONTROL(%)	GENERAL CONTROL(%)
Dry Mr	12	18
Wet Mr	12	18
Stripping (S)	15	20
Pan Evap. (Ep)	15	25
Rate Const. (K)	20	30

TABLE 2 SENSITIVITY OF RESULTS

CONTROL	WET LIFE VARIANCE(%)	Mr CUTOFF RATIO VARIANCE (%)
Tight	8	5
General	13	12

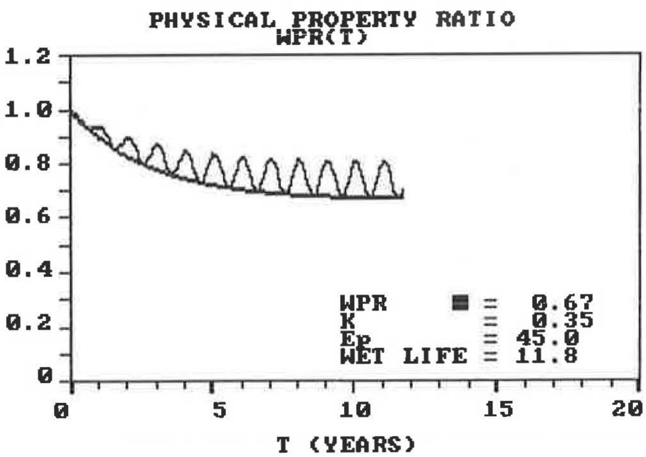

FIGURE 2 Change of WPR with field time for untreated mixture.

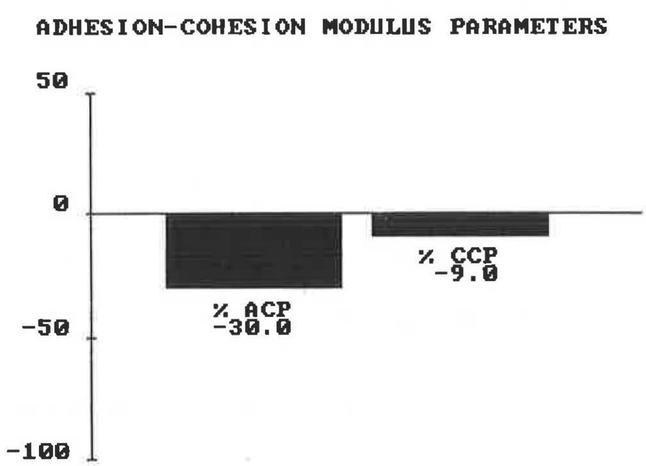

FIGURE 3 Percent change of adhesion and cohesion parameters for untreated mixture.

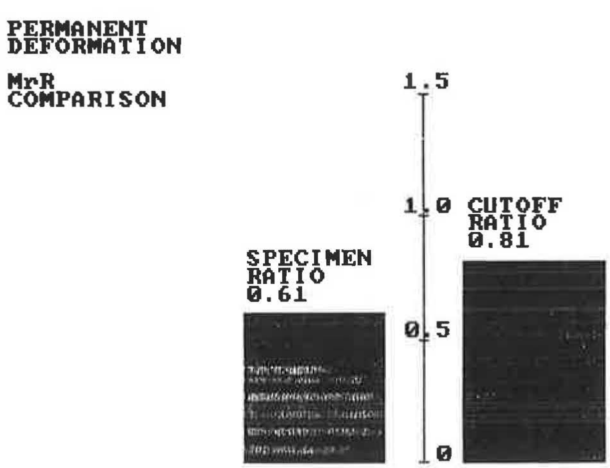

FIGURE 4 Specimen modulus ratio and cutoff requirement for untreated mixture.

needs either to be redesigned or treated with additives or modifiers, or both. Figure 3 is helpful in the decision. Here the major loss of modulus is due to an adhesion loss; therefore an additive that promotes adhesion would be a good choice of treatment. (If it was cohesion loss, a cohesion modifier would be a choice of treatment.)

Test-to-Control Mixture

In continuation of the example, assume that an additive has been incorporated into the mixture; thus the effects of that additive on both the dry properties of the mixture and on its moisture sensitivity are of interest. The test-to-control comparison is used, as well as a benefit-to-cost analysis.

The following are the assumed properties of the treated mixture (all other data are assumed to remain the same as previously shown):

Dry *Mr* = 800,000 psi;

wet *Mr* = 650,000 psi;

stripping = 10 percent.

The control mixture's data are the same as the previous untreated mixture's data. In this treated mixture, the additive increased the dry *Mr* slightly and increased the wet *Mr* substantially, which is encouraging for resistance to permanent deformation. The adhesion promotion is shown by the decrease in the percent stripping. The associated ACMODAS3 printouts are shown in Figures 6 through 9. Notice in Figure 6 that *WPR* does not start at 1.0 but rather at something slightly greater (approximately 1.1); this means that the dry treated mixture has more potential (dry) resistance to permanent deformation than the dry (untreated) control mixture. Figure 7 shows that the additive did increase the adhesion (reduced its loss), although it still could have been more effective by providing an even larger increase. Also notice that the additive did not change the cohesion significantly, which points out that it is an adhesion promoter. Figure 8 shows that *MrR* is greater than the *Mr* cutoff ratio; thus the mixture now has an acceptable wet performance life for rutting distress. This acceptable life is 14.2 yr, as shown in Figures 6 and 9. Figure 9 also shows the result of the *B/C* analysis using a 7 percent increase in the cost of asphalt concrete due to additive inclusion (i.e., *C* = 1.07). The *B/C* is 1.12, just exceeding the minimum *B/C* of 1.11, which indicates that this additive can be acceptable on the basis of effectiveness. Other additives could be tested that might be more effective (i.e., having a *B/C* larger than 1.12).

Example of Wet Performance Lives from NCHRP 9-6(1) and Implications

In this NCHRP study on the development of an asphalt-aggregate mixture analysis system conducted by Brent Rauhut Engineering, mixtures from several pavement sections are being tested for effects of compaction, aging, and prediction of resistance to field distresses. For this example, only moisture sensitivity predictions of pavement sections C and W are

WHEELPATH RUTTING (ACMODAS3)

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INPUT DATA

SPECIMEN IDENTIFICATION AND TEST INFORMATION ....
EXAMPLE PROBLEM USING THEORETICAL DATA

DRY REFERENCE WHEELPATH DEFORMATION PERFORMANCE LIFE (years)	15
PERCENT ALLOWABLE REDUCTION IN FIELD PERFORMANCE LIFE	10
FIELD MOISTURE RATE CONSTANT (K)	.35
AVERAGE SUMMER PAN EVAPORATION (Ep), (inches)	45
RESILIENT MODULUS OF DRY TEST SPECIMEN (psi)	757600
RESILIENT MODULUS OF WET TEST SPECIMEN (psi)	462000
PERCENT STRIPPING OF WET TEST SPECIMEN	30

RESULTS

RESULTS ARE OF A WET TEST MIXTURE RELATIVE TO A DRY TEST MIXTURE

WHEELPATH DEFORMATION RATIO (WPR)	0.67
PERCENT ADHESION CHANGE (%ACP)	-30.0
PERCENT COHESION CHANGE (%CCP)	-9.0
PREDICTED WET WHEELPATH DEFORMATION LIFE (years)	11.8
REQUIRED WET WHEELPATH DEFORMATION LIFE (years)	13.5
SPECIMEN RESILIENT MODULUS RATIO (MrR)	0.61
RESILIENT MODULUS CUTOFF RATIO	0.81

FIGURE 5 Data and results for untreated mixture.

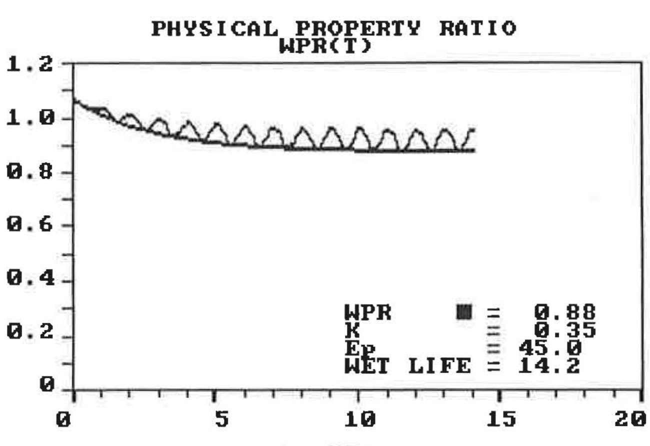

FIGURE 6 Change of WPR with field time for additive treated mixture.

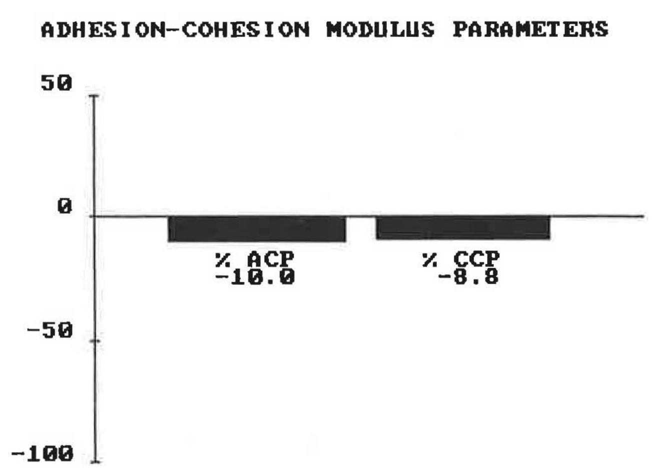

FIGURE 7 Percent change of adhesion and cohesion parameters for additive treated mixture.

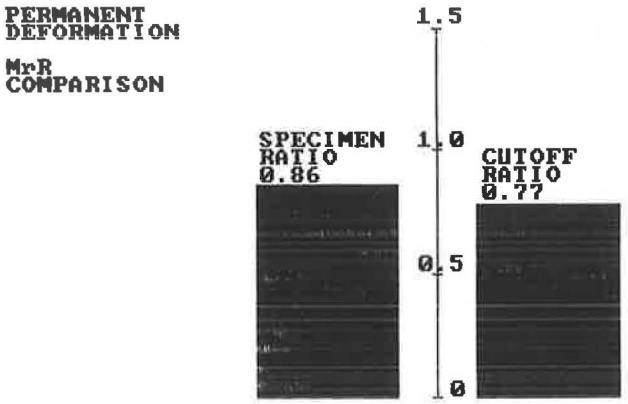

FIGURE 8 Specimen modulus ratio and cutoff requirement for additive treated mixture.

included to demonstrate that pavements can have unique sensitivity to wheelpath rutting distress and to fatigue cracking distress.

Specimens representing the section mixtures were fabricated by Texas A&M University under two different compaction methods: Marshall and Texas gyratory. Antistripping additives, which were incorporated into some of the sections, were purposely omitted in the gyratory specimens.

A representative number of compacted specimens was sent to the University of Idaho for moisture damage tests. The mechanical properties were input into ACMODAS3 to predict relative wet performance lives for the C and W pavement sections. Input data (assumed) were a dry field performance life of 15 yr, a summer pan evaporation of 45 in., a moisture rate constant of 0.35 for the NCHRP 4-8(3) test and 0.61 for the AASHTO T283 test (because of differences in satuation),

WHEELPATH RUTTING (ACMODAS3)
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INPUT DATA

SPECIMEN IDENTIFICATION AND TEST INFORMATION ....
EXAMPLE PROBLEM USING THEORETICAL DATA

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PERCENT ALLOWABLE REDUCTION IN FIELD PERFORMANCE LIFE	10
FIELD MOISTURE RATE CONSTANT (K)	.35
AVERAGE SUMMER PAN EVAPORATION (Ep), (inches)	45
RESILIENT MODULUS OF DRY CONTROL SPECIMEN (psi)	757600
RESILIENT MODULUS OF DRY TEST SPECIMEN (psi)	800000
RESILIENT MODULUS OF WET TEST SPECIMEN (psi)	650000
PERCENT STRIPPING OF WET TEST SPECIMEN	10
COST RATIO OF TREATED-TO-UNTREATED MIXTURE	1.07
WET DEFORMATION PERFORMANCE LIFE OF UNTREATED MIXTURE (years)	11.8

RESULTS

RESULTS ARE OF A WET TEST MIXTURE RELATIVE TO A DRY CONTROL MIXTURE

WHEELPATH DEFORMATION RATIO (WPR)	0.88
PERCENT ADHESION CHANGE (%ACP)	-10.0
PERCENT COHESION CHANGE (%CCP)	-8.8
PREDICTED WET WHEELPATH DEFORMATION LIFE (years)	14.2
REQUIRED WET WHEELPATH DEFORMATION LIFE (years)	13.5
SPECIMEN RESILIENT MODULUS RATIO (MrR)	0.86
RESILIENT MODULUS CUTOFF RATIO	0.77
BENEFIT-TO-COST RATIO OF TREATED-TO-UNTREATED MIXTURE	1.12
REQUIRED MINIMUM BENEFIT-TO-COST RATIO	1.11

FIGURE 9 Data and results for additive treated mixture.

and a PAR of 10 percent. Table 3 is a comparison between the Marshall specimen and the gyratory specimen results using the NCHRP 4-8(3) test method (high saturation). Table 4 is the same type of comparison as Table 3 except that the data are from the AASHTO T283 test method (moderate saturation). Note that both pavement sections had some stripping as denoted by the percent adhesion loss. The lack of additives in the gyratory specimens is indicated by the greater adhesion losses and lower predicted lives in the more highly saturated specimens of the NCHRP 4-8(3) test method. The relative predicted wet rutting life is significantly lower for C compared with W; in fact, no practical decrease of rutting life was predicted for W. Therefore, the C test section is expected to develop moisture-sensitive rutting, with a relative loss of life from 3 to 5 yr, based on a 15-yr dry rutting life.

The results of the ACMODAS2 moisture sensitivity program for fatigue cracking for the C and W sections were opposite those concluded from Tables 3 and 4 for rutting. For fatigue cracking, W was predicted to develop significant moisture-sensitive cracking, with a loss of life from 3 to 5 yr, as based on a 15-yr dry fatigue cracking life. C was predicted not to have a loss of fatigue cracking life.

Therefore, the effects of moisture in asphalt concrete on the field distresses of wheelpath rutting and fatigue cracking can be different and might now be predicted by using methods developed for each distress. In ACMODAS2 (fatigue cracking), the resistance to moisture is achieved by maintaining asphalt concrete toughness, such as high wet indirect tensile strength relative to wet resilient modulus. Opposite that, however, is the decrease by moisture of modulus more than of strength so that the mixture plasticizes. Although mixture resistance to fatigue cracking increases, the mixture will become less resistant to rutting. This is indicated by a decrease of *WPR* in ACMODAS3 because *WPR* is related to the modulus ratio, not the strength ratio.

SUMMARY

ACMODAS3 is a prediction method that predicts the wet performance rutting life of asphalt concrete in pavements. It deals specifically with the permanent deformation (rutting) occurring in the asphalt that is known as creep or plastic flow.

Laboratory-determined resilient modulus mechanical properties of wet and dry asphalt concrete specimens are translated into a physical property ratio, termed the wheelpath ratio (*WPR*), depicting the resistance to moisture on the permanent deformation. *WPR* is derived from two perspectives: theoretical and practical. In the theoretical method *WPR* is a product of the permanent shear strain ratio (related to modulus ratio) and the lag angle ratio of the two complex compliance components. The practical method approximates the theoretical approach by relating the lag angle ratio to the cohesion change of the mixture, which, in turn, is related to percent stripping.

WPR continuously changes with field time in an exponential manner and reaches a laboratory-determined, long-term ratio. Environmental factors cause *WPR* to change from the initial

TABLE 3 RESULTS COMPARISON USING NCHRP 4-8(3) MOISTURE DAMAGE TEST METHOD

PAVEMENT LOCATION	COMPACTION METHOD[a]	ADHESION CHANGE (Mr,%)	COHESION CHANGE (Mr,%)	PREDICTED LIFE (YRS)[b]	MrR CUTOFF
C	Marshall	-12	-15	12.4	.87
C	Gyratory	-36	-28	9.5	.83
W	Marshall	-15	16	15.8	.72
W	Gyratory	-34	5	13.1	.75

Notes: a. Mixtures for gyratory compaction did not contain additives.
b. Results are for a dry reference life of 15 years.

TABLE 4 RESULTS COMPARISON USING AASHTO T283 MOISTURE DAMAGE TEST METHOD

PAVEMENT LOCATION	COMPACTION METHOD[a]	ADHESION (Mr,%)	COHESION (Mr,%)	PREDICTED LIFE (YRS)[b]	MrR CUTOFF
C	Marshall	-9	-34	10.1	.89
C	Gyratory	-11	-32	10.3	.88
W	Marshall	-12	4	14.5	.72
W	Gyratory	-19	14	15.4	.54

Notes: a. Mixtures for gyratory compaction did not contain additives.
b. Results are for a dry reference life of 15 years.

dry-to-dry ratio to the long-term, wet-to-dry, accelerated conditioned ratio. The effectiveness of temperature cycles on the ingress of moisture over time is partially retarded by the seasonal recovery during the summer months.

In conjunction with Miner's cumulative damage theory, *WPR* is used to estimate the time at which a pavement is said to fail—that is, the time when the magnitude of the permanent deformation rutting is unacceptable.

The predicted resilient modulus cutoff ratio is based in part on the input percent allowable reduction in life and can be used as a specification in asphalt concrete mix design to control the loss of permanent deformation life.

Results can be relative either to a dry test mixture or to a different dry control mixture, and they can be used in several different ways. Is the mixture moisture susceptible? What is causing the moisture damage, adhesion loss, or cohesion loss? How does a wet treated mixture compare with a dry untreated mixture? Is an additive treatment "cost-effective"?

ACMODAS3 results are sensitive to changes in resilient modulus values and percent stripping, yet large variations in life are not caused by small variations in input data. Results will vary by 13 percent under the state-of-the-art general variances for input variables.

An application was the prediction of the permanent deformation wet lives of test sections from NCHRP Research Project 9-6(1). It is implied that moisture sensitivity in different test sections can be distress specific. For example, it is predicted that one section is rutting-prone and that another is fatigue-cracking-prone to moisture in a significant way.

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