Procedure for Predicting Laboratory Retained Strength Cut-Off and Additive Benefit-Cost Ratios of Moisture-Damaged Asphalt Concrete

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There is a need to evaluate and use retained strength ratios obtained from laboratory moisture damage tests on asphalt concrete mixes to predict field performance based on highway agency acceptance criteria. Two calculation procedures are described and discussed: (a) retained strength cut-off ratio required for an untreated mix and (b) pavement life benefit-initial cost ratio when antistripping additives are used. Data supplied by six state highway agencies are used for calculating these performance ratios to illustrate typical ranges. Performance ratio procedures make use of pavement thickness design methods and retained strength ratios from laboratory tests as well as the thickness, soil support, regional factor, and terminal serviceability for a specific pavement or overlay to be constructed. Retained strength ratios are related quantitatively to the reduced structural layer coefficients of asphalt concrete. Pavement life is prorated in a simplified version of the moisture damage by stages using Miner's cumulative fatigue damage rule. The calculations show that retained strength cut-off ratios range from 0.59 to 0.95. A range at least this large is expected when considering the differences in thickness design methods and pavement parameters. However, a specific ratio is associated only with a given set of pavement conditions. Calculations of benefit-cost ratios show a range from 1.0 to 2.0. The larger ratios are desirable. The benefit-cost ratios for three of the highway agencies were low enough to question the effectiveness of an additive for the untreated-to-treated retained strength range used. The calculation methods can be a helpful aid for decision makers when they are evaluating the results of laboratory moisture damage tests.

Highway agencies are observing stripping and other forms of moisture damage in asphalt concrete pavements, and they recognize that shortened pavement life results from this damage. There is a need to evaluate and use retained strength ratios obtained from laboratory moisture damage tests to make quantitative predictions of the related pavement damage in the field and of the improvement in performance due to additive treatment.

This can be accomplished by predicting the reduction of cohesion-adhesion of asphalt concrete in the field by calculating the reduction of structural layer coefficients (or substitution ratios). Corresponding reduced structural numbers (or gravel equivalencies) are then calculated and the associated future reduction of pavement life is found by using the agency's pavement design relationship of traffic-volume life versus structural number.

The procedures summarized in this paper describe the calculation of two performance-related ratios that are important for decision making before paving. These performance ratios are as follows:

1. Retained strength cut-off ratio. This is the minimum ratio of retained strength (wet strength/dry strength) for acceptance of an asphalt concrete mix without inclusion of an antistripping additive.
2. Benefit-cost ratio. This ratio is equal to the increase of pavement life ratio using an additive divided by the initial cost ratio associated with purchase, handling, and inspection of the additive at the asphalt plant.

Both performance ratios use the retained strength ratio determined by an accepted laboratory moisture-damage susceptibility test. The NCHRP 4-8(3) test method uses a freeze plus warm water soak conditioning after vacuum saturation. The test ratio is determined by performing the tensile splitting strength test (tensile strength ratio) (1,2). Variants of this method are also being evaluated. The immersion compression method incorporates a warm water soak, and the test ratio is determined by performing a compressive strength test. A variant of this method includes vacuum saturation before the warm water soak. The main objective of the tests is to make accurate predictions of the moisture damage susceptibility of an asphalt concrete and, hence, its expected long-range field condition. Low test ratios indicate severe long-range field damage that necessitates the use of antistripping additives or mix design changes or both. Additional test ratios are then obtained to assess the effectiveness of the additive type, dosage, or mix design change. These test ratios should reflect a greater retained cohesion-adhesion equivalency in the asphalt-treated layers through their increased structural layer coefficients or structural numbers.

The procedure can be divided into the following four steps:

1. Calculate the retained strength cut-off ratio for the asphalt concrete mix for the specific pavement and location.
2. Determine the retained strength ratio of the untreated mix and compare it with the calculated cut-off ratio. If the retained strength ratio is equal to or greater than the cut-off ratio, the mix is approved for the specific pavement. If the retained strength ratio is less than the cut-off value, too much moisture damage will occur in the field. Additive treatment or mix redesign will be necessary.
3. For the additive treatment option, determine the retained strength ratio of the treated mix and compare it with the calculated cut-off ratio. Ideally, the retained strength ratio should be at least equal to the cut-off ratio. Different additive types and dosages can be used to achieve high ratios.
4. Calculate the benefit-cost ratio using the pavement life ratio calculated by using the untreated and treated mixes and the additive cost ratio. When several additive types and dosages are being evaluated, choose the combination that gives the highest benefit-cost ratio, if the cost is affordable and if documented experience supports the benefit predicted.

In some instances a highway agency obtains a high retained strength ratio for an additive treated mix but questions the strength of the additive treated mix compared with the untreated mix. In these instances the retained strength ratio of the treated mix can be defined as being equal to the wet strength of the treated mix divided by the dry strength of the untreated mix. The untreated mix ratio, however, remains conventional; i.e., its wet strength is divided by its dry strength.

The following are procedures for calculating retained strength cut-off ratio (Part A) and benefit-cost ratio (Part B). Ratios are calculated from a summary investigation using the state highway agency data to illustrate the range that might be expected around the country.

It should be noted that most agencies use a prescribed design period for their thickness-life methods, e.g., 20 yr. Although the following procedures for cut-off ratio and for benefit-cost ratio are based on a prescribed design period, the actual pavement life can be less or more than the design period without affecting the calculated ratios. The use of the prescribed design period makes it possible to prorate fatigue life proportionally between dry and wet field stages and the associated traffic volume. Therefore, it is believed that the loss of asphalt concrete cohesion due to moisture damage will not be affected.

PART A: RETAINED STRENGTH CUT-OFF RATIO

Calculation of Retained Strength Cut-Off Ratio

The calculation procedure is written using AASHTO thickness design terminology, e.g., structural number, layer coefficient, 18-kip single axle load equivalents, and 20-yr design period.

Step 1. The pertinent pavement thickness method and the related data for the specific pavement are obtained; i.e., layer thickness, the customarily used coefficients, the coefficient for 100 percent stripped asphalt concrete (usually equal to the coefficient of untreated crushed stone base), soil support value, regional factor, and terminal serviceability.

Step 2. The maximum percentage of pavement life reduction allowable without using additives is determined by an independent life-cost acceptance criterion. Usually this falls between 5 and 25 percent. Let this percentage = PR; then calculate the related maximum allowable dry/dry-wet ratio

$$1/[1 - (PR/100)]$$

For example, if PR = 15 percent, maximum dry/dry-wet ratio = 1.176.

Step 3. Assuming 20 yr of life in the dry stage, the required life in the dry-wet stage is

$$20 \text{ yr}/(\text{dry/dry-wet ratio}) = Y_{DW}, \text{ years.}$$

For example, Y_{DW} = 20 yr/1.176 = 17 yr.

Step 4. The field moisture stage is assumed to consist of an initial dry stage followed by a wet stage. Actually it consists of three or more stages, but for simplicity only two stages will be considered here: 4 years in the dry condition followed by the remaining years in the wet condition simulated by the accelerated conditioning of the laboratory tests specimens.

This approach was developed from the field data obtained by the highway agencies in NCHRP Project 4-8(3)/1 (1,2). The tensile strength ratios of field cores for the six participating state highway agencies are illustrated by black solid dots in Figure 1. The long-term laboratory ratios predicted from accelerated conditioning are shown to the right of the black dots and are assumed to be reached sometime after 4 or 5 years. These ratios, although lower, are proportional to the 4 or 5 year field ratios. Then tensile strength ratios obtained from the simplified two-step moisture stage are superimposed on the ratio trends of Figure 1 and the results are shown in Figure 2 for three of the state highway agencies.

Although the time to reach the long-term predicted ratio is estimated, it appears that the dry ratio (1.0) should be used for several years before applying the long-term ratio obtained from the accelerated conditioning of laboratory specimens using the test method of the NCHRP study. Four years at the dry ratio (1.0) followed by the long-term accelerated conditioning ratio may not be unreasonable as a simplified method for indicating the field moisture damage stages. (An intermediate step using the ratio from vacuum saturation of laboratory specimens may also be incorporated if more precision is required.) The two-stage simplified method is also assumed to be applicable to other laboratory moisture damage tests for predicting retained strength ratios, e.g., immersion compression.

For the simplified two-step method, the required wet life (Y_W) is

$$Y_{DW} - 4 \text{ yr dry} = Y_W, \text{ years.}$$

For example, Y_W = 17 yr - 4 yr = 13 yr.

Step 5. The unweighted structural number of the pavement is calculated by using the regional factor and the in-place future pavement thickness as well as the pavement thickness design procedure, the customarily used layer coefficients, and the specific pavement parameters. [For new pavements, the customarily used layer coefficients are new material coefficients for all untreated and treated layers. However, if an overlay is being evaluated for an existing pavement, the coefficients of the existing layers (perhaps reduced) and the customarily used

Figure 1. Field ratios and predicted ratios from NCHRP Project 4-8(3)/1.

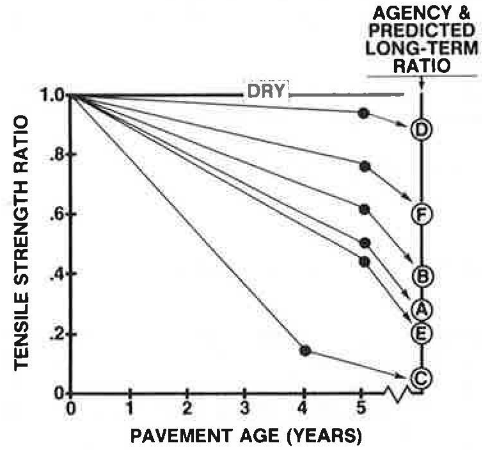

Figure 2. Simulated two-step moisture stage comparison to field ratios

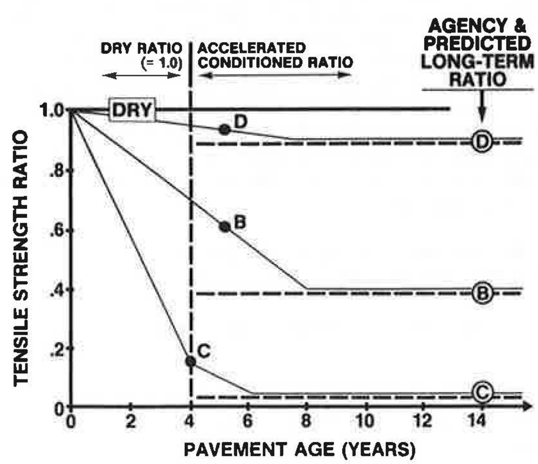

Table 1. Retained strength cut-off data and ratios.

Agency	Maximum Allowable Reduction of Pavement Life Without Inclusion of Additive (PR) (%)	Maximum Allowable Dry/Dry-Wet Ratio	Retained Strength Cut-Off Ratio for Untreated Mix (COR) Thin Pavement	Thick Pavement
A	5	1.053	0.90	0.79
B	5	1.053	0.92	0.95
C	15	1.176	0.88	0.78
D	15	1.176	0.83	0.83
E	25	1.333	0.59	0.87
F	25	1.333	0.74	0.69

new layer coefficient are used for the asphalt concrete overlay.] The corresponding basic 18-kip single axle load equivalents per year $(Equivs/yr)_b$ are found for the 20-yr design period.

Using Miner's cumulative fatigue damage rule, the basic wet life for the pavement is calculated using the following relationship

$$[4\ yr \times (Equivs/yr)_b/20\ yr \times (Equivs/yr)_b] + [Y_W \times (Equivs/yr)_b/Y_{WB} \times (Equivs/yr)_b] = 1$$

Where Y_{WB} = basic wet life of the pavement.

For example, suppose the pavement thickness procedure gives 150,000 single axle load Equivs/yr for the 20-year design period. Then

$$[4\ yr\ dry \times (150{,}000/yr)/20\ yr \times (150{,}000/yr)] + [13\ yr\ wet \times (150{,}000/yr)/Y_{WB} \times (150{,}000/yr)] = 1.$$

Thus, Y_{WB} = 16.3 years.

Step 6. The reduced traffic equivalents/yr (minimum acceptable) is calculated using

$$Y_{WB}/20\ yr \times (Equivs/yr)_b = (Equivs/yr)_{Red}.$$

For example,

$$(Equivs/yr)_{Red} = (16.3\ yr/20\ yr) \times (150{,}000/yr) = 122{,}250/yr.$$

Using $(Equivs/yr)_{Red}$, the corresponding unweighted structural number is found; then, it is weighted using the regional factor. This is the minimum (required) in-place structural number that will be necessary in the wet condition.

Step 7. The required layer coefficient for the asphalt concrete in the wet condition is calculated using the wet condition weighted structural number from Step 6 with the coefficients of the other layers that are unaffected by moisture and all the layer thicknesses. Let this coefficient be A_{1W}.

Step 8. Using 100 percent stripped asphalt concrete A_1 coefficient, the required layer coefficient (A_{1W}) calculated from Step 7, and the asphalt concrete coefficient normally used in pavement design (A_1), the minimum required percentage of retained cohesion-adhesion for the asphalt concrete in the wet condition is

$$[(A_{1W} - 100\ \text{percent stripped}\ A_1)/(A_1\ \text{normal} - 100\ \text{percent stripped}\ A_1)] \times 100 = C$$

where C is the minimum percentage required cohesion-adhesion.

For example, suppose A_{1W} = 0.37, A_1 normal = 0.44, and 100 percent stripped A_1 = 0.18, then C = 73 percent.

Step 9. The required retained strength cut-off ratio is

$$C/100 = COR$$

where COR = the cut-off ratio.

For this example, COR = 73/100 = 0.73.

This calculated retained strength cut-off ratio can be used as a ballpark ratio for a specific pavement and PR value. There may be instances where an adjustment will be necessary based on practical experience.

Results and Discussion of Calculated Cut-Off Ratios

Each highway agency uses slightly different pavement thickness models, as well as different coefficients, soil support, and regional factor values. Thus one can expect different cut-off ratios (CORs) for the same pavement thickness. In addition, there are pavement variables within each state or jurisdiction as well as different pavement thicknesses. Therefore, a larger range of CORs can be expected. Until a predictive COR model is developed for each agency the COR for a specific pavement should be calculated independently. Finally there will be a difference among agencies when determining the maximum percentage of pavement life reduction without additive (PR). Generally, low PR will give a high COR; high PR will give a lower COR.

Data for calculating CORs were submitted by six state highway agencies from around the country. Their PR estimates ranged from 5 to 25 percent. CORs for average thin and thick pavements were calculated for each agency. The results are shown in Table 1. Overall, the CORs ranged from 0.59 to 0.95. Although the COR range is smaller within an agency, it still appears large enough to necessitate separate COR calculations for specific pavements.

Many highway agencies use one COR value, in the range of 0.60 to 0.75, depending on the type of laboratory moisture-damage test used and on experience. Some agencies do use different COR values that take into account the regional factor.

The calculation procedure appears to be an aid to current experience. No new research is required, but new analytical techniques may be necessary. For instance, a better match-up is needed between a set PR value and the calculated COR. When the calculated COR is higher than expected, there may be several reasons: (a) the PR value is too high; (b) the agency needs to design its mixes to perform at a higher COR; (c) the pavement thickness design method for changes of cohesion-adhesion in the asphalt concrete coefficients is not accurate enough; (d) a better method for estimating the moisture damage stages in the field is needed; or (e) a combination of these factors. Nevertheless, the CORs calculated using these steps usually result in acceptable values. This is encouraging.

PART B: LIFE BENEFIT-INITIAL COST RATIO

Calculation of Benefit-Cost Ratio

If an untreated asphalt concrete mix has a retained strength ratio less than the calculated COR, antistripping additives will usually be used and evaluated in the mix. Effective additives and dosages will increase the retained strength ratio of the untreated mix up to or above the COR, which should increase the pavement life. The following procedure for calculating the benefit-cost ratio (B/C) predicts the dry-wet pavement life for the untreated and the treated mix. The ratio of these lives, which is greater than 1.0, is compared with the cost ratio of the treated mix versus the untreated mix, which is also greater than 1.0. The life and cost ratios are divided to obtain the B/C ratio. The B/C ratio is usually greater than 1.0, although it may be compared with a larger ratio, such as the maximum allowable dry/dry-wet ratio, to determine if changing to the particular additive-dosage combination would be worthwhile.

The procedure is divided into steps with related explanations, and the AASHTO thickness design terminology is used.

Step 1. The pavement design information is obtained for the particular pavement to be constructed (see Step 1 of the retained strength cut-off procedure).

Step 2. The cost ratios for liquid and for mineral additives are calculated. The ratio is equal to all the associated costs for the additive at the asphalt plant added to the cost per ton for untreated hot mix divided by cost per ton of the untreated hot mix.

Step 3. Two retained strength ratios are determined in the laboratory: the untreated mix ratio (R_U) and the treated mix ratio (R_T) for a specific additive type and dosage.

Step 4. The unweighted structural number of the pavement is calculated by using the regional factor and the in-place future pavement thicknesses along with the pavement thickness design procedure, the normally used layer coefficients, and the specific pavement parameters. The corresponding basic 18-kip axle load equivalents per year are found for the 20-yr design period.

Step 5. The dry-wet life of the untreated asphalt concrete is calculated as follows:

a. The reduced asphalt concrete layer coefficient (A_{1RU}) is calculated for the wet condition using

$$A_{1RU} = R_U\ (A_1 \text{ normal} - 100 \text{ percent stripped } A_1) + 100 \text{ percent stripped } A_1.$$

b. Using the in-place pavement thickness and A_{1RU} for the asphalt concrete, the weighted wet condition structural number is calculated. Using the regional factor, the unweighted wet condition structural number is found.

c. Using the unweighted wet condition structural number, the wet condition reduced traffic rate, (Equivs/yr) wet-u, is found from the unweighted structural number, soil support, and traffic rate design relationship for the desired terminal serviceability.

d. Using the simplified field moisture stage of 4 years dry followed by remaining years in the wet condition (simulated by the accelerated conditioning of the laboratory test specimens) and by using Miner's cumulative fatigue damage rule, wet life (Y_{WU}) of the untreated asphalt concrete is calculated from the following relationship

$$[4 \text{ yr dry} \times (\text{Equivs/yr})_b/20 \text{ yr} \times (\text{Equivs/yr})_b] + [Y_{WU} \times (\text{Equivs/yr})_b/20 \text{ yr} \times (\text{Equivs/yr}) \text{ wet-u}] = 1.$$

e. The untreated dry-wet life (Y_{DWU}) is, therefore,

$$Y_{DWU} = 4 \text{ yr dry} + Y_{WU}.$$

Step 6. The dry-wet life of the treated asphalt concrete is calculated by using procedures similar to Step 5 (untreated dry-wet life) as follows:

a. A_{1RT} is calculated using R_T. A_{1RT} will be greater than A_{1RU} since R_T is greater than R_U.

b. The unweighted wet condition structural number is calculated. It will be greater than the unweighted wet condition structural number for the untreated asphalt concrete.

c. Using the unweighted wet condition structural number, the wet condition reduced traffic rate for the treated asphalt concrete is obtained: (Equivs/yr) wet-t. (Equivs/yr) wet-t will be greater than (Equivs/yr) wet-u.

d. Using the same simplified method for the field moisture stages, wet life of the treated asphalt concrete (Y_{WT}) is calculated from the following relationship:

$$[4 \text{ yr dry} \times (\text{Equivs/yr})_b/20 \text{ yr} \times (\text{Equivs/yr})_b] + [Y_{WT} \times (\text{Equivs/yr})_b/20 \text{ yr} \times (\text{Equivs/yr}) \text{ wet-t}] = 1.$$

e. The treated dry-wet life (Y_{DWT}) is, therefore,

$$Y_{DWT} = 4 \text{ yr dry} + Y_{WT}.$$

Step 7. The life benefit ratio is calculated from the untreated and treated dry-wet lives calculated in Steps 5 and 6 using

$$\text{Life Benefit Ratio} = Y_{DWT}/Y_{DWU}.$$

This ratio will be greater than 1.0 if R_T is greater than R_U.

Step 8. The life benefit-to-initial cost ratio (B/C) is calculated for the additive treatment using

$$B/C = \text{Life Benefit Ratio/Cost Ratio}.$$

Results and Discussion of Benefit-Cost Ratios

The B/C calculated in Step 8 of the preceding section is compared with an acceptable B/C. Three levels of comparison are described below:

1. Comparison with B/C minimum = 1.0. If the calculated B/C is less than 1.0, the additive treatment should not be used. Even if there is a gain of life benefit, the associated treatment cost is too great. Other additive types and dosages should be evaluated or a change of mix design should be recommended. If the calculated B/C is equal to 1.0, the gain of life benefit equals the associated treatment cost. This is a break-even point and, in most instances, the treatment will not be used. Therefore, the calculated B/C should be greater than 1.0.

2. Comparison with a B/C minimum that is greater than 1.0 to make the cost of the additive worthwhile. This B/C minimum could be the maximum allowable dry/dry-wet ratio calculated from PR in the COR procedure. These dry/dry-wet changeover ratios are greater than 1.0 and can be as high as 1.333 if a PR of 25 percent is used. Sometimes the calculated B/C is not as large as the dry/dry-wet changeover ratio. If the changeover ratio is a firm number, either the untreated retained strength (R_U) is too high for the treated retained strength obtained (R_T) or the R_T is not high enough. However, most of the cases will show calculated B/C greater than the changeover ratio.

3. Comparison with B/C optimum. Different combinations of additive types and dosages are evaluated to maximize R_T. The combination that gives the maximum calculated B/C is used. If there are several combinations that provide approximately equal maximum calculated B/C, the combination is chosen that has the least cost for the performance expected as based on documented experience.

Table 2. Life benefit-initial cost data and ratios.

Agency	Max. Allow. Dry/Dry-Wet Ratio	Approximate Retained Strength Ratios: Untreated (R_U)	Approximate Retained Strength Ratios: Treated (R_T)	Pavement Life Benefit Ratio: Thin Pavement	Pavement Life Benefit Ratio: Thick Pavement	Additive Cost Ratio: Liquid Additives	Additive Cost Ratio: Mineral-Type Additives	Calculated Benefit-Cost Ratio (B/C): Thin Pavement	Calculated Benefit-Cost Ratio (B/C): Thick Pavement	Comparison: Calculated B/C Higher or Lower than Max. Allow. Dry/Dry-Wet Ratio: Thin Pavement	Comparison: Calculated B/C Higher or Lower than Max. Allow. Dry/Dry-Wet Ratio: Thick Pavement
A	1.053	0.50	0.70	1.31	1.14	1.040	1.050	1.26 liq. 1.25 min.	1.10 liq. 1.09 min.	Higher[a]	Marginally higher[b]
B	1.053	0.30	0.75	2.12	2.02	1.030	1.040	2.06 liq. 2.04 min.	1.96 liq. 1.94 min.	Higher[a]	Higher[a]
C	1.176	0.40	0.75	1.65	1.75	1.016, 0.5% 1.030, 1%	1.038	1.61 liq. 1.59 min.	1.71 liq. 1.69 min.	Higher[a]	Higher[a]
D	1.176	0.60	0.75	1.21	1.16	1.040	1.160	1.167 liq. 1.047 min.	1.118 liq. 1.003 min.	Slightly lower[c]	Slightly below[e]
E	1.333	0.45	0.70	1.31	1.64	1.030	1.034	1.27	1.59	Slightly lower[d]	Higher[a]
F	1.333	0.55	0.85	1.09	1.18	1.030	1.090	1.06 liq. 1.00 min.	1.14 liq. 1.08 min.	Moderately lower[e]	Moderately lower[e]

[a]Treatment favorable.
[b]Treatment minimally favorable.
[c]Try TSR for treated mix = 0.80 to 0.75.
[d]Try TSR for treated mix = 0.75.
[e]Lower TSR required for untreated mix.

The calculated B/Cs do not include future economic return. Methods for calculating the economic value of pavement life will, in effect, increase the B/C when the treated pavement life is several years greater than the untreated pavement life. But the B/C, as calculated here, would be helpful for decision making by evaluating the advantages of an additive in asphalt concrete mixes.

Calculated B/Cs are shown in Table 2 with the data submitted by the six state highway agencies. The B/C range from 1.0 to 2.06. The larger B/Cs appear to be associated with greater untreated to treated retained strength ratio ranges. On the average, the agencies agreed that the goal for treated ratios is about 0.75, although they would like higher ratios. The untreated ratios (~ 0.40) represent severely stripped mixes as based on laboratory moisture damage tests. Lower ratios were found, but the ratios listed are for average low values experienced by the agencies over the past years.

An evaluation for Agency F is of interest. Based on the pavement design procedure and the moisture damage stage simplification, the calculated B/Cs are slightly greater than 1.0 but are less than the changeover ratio of 1.33. Because the COR listed for F in Table 1 is between 0.69 and 0.74 for the two pavements evaluated, it appears reasonable to require a treated retained strength ratio greater than the R_T target of 0.85. Therefore, the untreated retained strength ratio of 0.55 is not low enough to achieve a favorable comparison between the calculated B/C and the changeover ratio. If the basis for the calculation procedure is reasonably accurate, the agency should either treat mixes when their untreated ratios are less than 0.55 or it should stipulate a lower changeover ratio (or lower PR). But this will not help matters much since the calculated B/C is so close to 1.0. It is possible that the reduction of asphalt concrete layer coefficient due to loss of cohesion-adhesion in Agency F's design method is not sensitive enough, or that this is the actual manner in which its pavements perform with additive treatment; i.e., treatment is not that effective in this retained strength ratio range even though the untreated retained strength ratio of 0.55 is less than the COR.

The calculated B/C and implications for Agency B are in contrast to Agency F's results. Agency B's B/C is 2.0, about twice as large as the B/C for Agency F. Even though B's treated retained strength ratio is 0.75 (less than its COR of about 0.94), it appears that Agency B's low untreated retained strength ratio of 0.30 combined with its cohesion-adhesion sensitivity in its pavement thickness procedure and parameters result in the prediction that their additive treatment is very effective.

The cost ratios using mineral-type additives such as hydrated lime and portland cement are higher than for liquid antistripping additive at approximately 1 percent weight dosage. The 1 percent mineral additive dosage is based on aggregate or total mix weight, whereas the 1 percent liquid additive dosage is based on asphalt weight. At these dosages, both types of additives should give retained strength ratios around 0.75; however, sometimes different dosages (and additive types) are required depending upon asphalt and aggregate characteristics. Combinations of liquid and mineral additives in an asphalt concrete mix have also been effective at somewhat smaller dosages than if the additives were used separately.

OVERLAYS

The previous ratios are associated with the structural (thickness) portion of the pavement. The calculation methods, therefore, are also applicable to structural overlays. The calculations of cut-off ratio and benefit-cost ratio are applied to the overlay thickness rather than to the existing asphalt concrete. First, layer coefficients (A_{IRU}) of the older asphalt concrete are calculated by using the tensile strength ratio from cores (saturated strength/dry strength) and by applying the equation from Step 5 of Part B. (If cores are not available, an estimate is made of the layer coefficients, A_{IRU}, by visual stripping and other experience.) Then the planned overlay thickness is used in the agency's thickness-life method, and all the older pavement layers beneath and their reduced layer coefficients are included. The ratios for the overlay are calculated using the method in the same way as shown in Parts A and B. Depending on overlay mix permeability and climate, the years of dry pavement stage are determined, followed by remaining years of accelerated conditioned stage. The agency's prescribed design period is also used according to the pavement-life method. Some agencies may have, or will develop, shorter design life periods for overlays with corresponding thickness-traffic life design methods. If this is the case, then this design period and method should be used for overlays.

If the overlay is not considered to be structural but rather a pavement surfacing to improve smoothness, cover cracks, or provide better friction, the methods shown are not applicable for the calculation of ratios. In these instances it is important to sustain the minimal intrinsic properties of the asphalt concrete to withstand raveling, delamination, and crack propagation from moisture damage. Until quantitative methods become available for relating nonstructural overlay life to traffic volume, cut-off ratios and benefit-cost ratios are best determined by experience.

It appears that the required cut-off ratio for thin overlays, especially nonstructural overlays, would be higher than the cut-off ratio for structural asphalt concrete in the lower layers because of additional performance requirements. The overlay must also possess smoothness and minimal cracking; therefore, the cut-off ratio (and benefit-cost ratio) for thin overlays obtained by a calculation method similar to that shown previously for lower structural layers should be increased in most instances. It seems reasonable to require a minimum high cut-off ratio for the thin (nonstructural) overlay that is independent of the pavement structural variables.

RECOMMENDATIONS

Methods for calculating performance ratios can be an aid to laboratory personnel who are evaluating asphalt concrete mixes for field moisture damage sensitivity. The results of these calculations may prove to be helpful for decision makers: Will an additive be required? If an additive is required, will the associated pavement life increase be cost effective and worth the cost of the additive? When specific documented experience is available, it should be used along with the calculation procedure to assist the decision maker.

Highway agencies may desire to make the calculation procedure more accurate and comprehensive for their needs. The procedures can be programmed for small desk-type calculator-computers. This will require using an equation for structural number, traffic volume, soil support, and regional factor rather than the nomographs now customarily used.

If fatigue-mechanistic theory becomes routine for flexible pavement design and evaluation, the calculation procedures for performance ratios can be easily changed to accommodate the mechanistic procedure. The significant element affected would be the reduced traffic volume in the wet condition. Bending strains (or stresses) in wet and dry field conditions are used to obtain the wet/dry fatigue life ratios using laboratory-determined strain fatigue curves for dry and wet simulated-conditioned test specimens. The 20-yr basic fatigue life traffic is then reduced for the wet condition by multiplication with the strain fatigue life ratio.

ACKNOWLEDGMENT

At the conclusion of the NCHRP Project 4-8(3)/1, a number of state highway agency personnel expressed a need for a quantitative tie-in between laboratory test results (ratios) and predicted field performance. Their sustained interest for a practical method was helpful in developing the calculation methods shown in this paper. The calculation method and resulting evaluation, however, are based on the author's judgment and do not necessarily reflect the specific practice or operations of any highway agency.

The information was used to develop calculation procedures for moisture stage field lives. Reduction of asphalt concrete layer coefficients was obtained from the type of data associated with NCHRP Project 4-8(3)/1. Specific data used for calculations were supplied by the state highway agencies of Arizona, Colorado, Georgia, Idaho, Montana, and Virginia. (The agency codes used in the figures, tables, and text do not correspond to their alphabetical order.) The cooperation and interest of the agencies are appreciated.

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