Remaining Fatigue Life Analysis: Comparison Between Dense-Graded Conventional Asphalt Concrete and Gap-Graded Asphalt-Rubber Hot Mix

LUTFI RAAD, STEPHAN SABOUNDJIAN, AND JOHN CORCORAN

A procedure for estimating the remaining fatigue life of existing bituminous pavements has been developed. This procedure incorporates laboratory fatigue data for tensile strain or surface curvature in terms of repetitions to failure. It also utilizes laboratory data on reduction of flexural stiffness with load repetitions. The proposed method was applied to investigate the remaining fatigue life of a dense-graded conventional asphalt concrete mix (CAC-DG) and a gap-graded asphalt-rubber hot mix (ARHM-GG) using laboratory flexure fatigue data and multilayer elastic analysis of typical pavement sections. Results show that for a given initial state of fatigue damage, the remaining fatigue life of ARHM-GG could be significantly longer than that of CAC-DG. It is also illustrated that thinner sections of ARHM-GG, compared with CAC-DG, will exhibit the same remaining fatigue life. This reduction in thickness becomes more significant with increasing foundation support under the pavement surface layer.

The use of asphalt-rubber binder in pavements has progressed from its application in asphalt-rubber and aggregate membranes (ARAM), also referred to as stress-absorbing membranes (SAM), and ARAM interlayers, also referred to as stress-absorbing membrane interlayers (SAMI), which began in 1968, to the incorporation of asphalt-rubber hot mix (ARHM) in pavement overlays, which began in 1975 (*1–3*). In addition to overlays, asphalt-rubber mixtures have been used as a surface course in reconstructed pavement sections (*4*). Field performance data on ARHM pavements indicate significant improvement in resistance to fatigue, abrasion, and aging compared with conventional asphalt concrete mixtures (*5,6*). These field data support laboratory fatigue test results that illustrate improved fatigue and fracture properties of asphalt-rubber mixtures compared with conventional asphalt concrete (*7–9*). Results of a recent study by Raad et al. (*8*) show that overlay thickness determinations using laboratory fatigue data support recommendation guidelines proposed by the California Department of Transportation (Caltrans) on overlay thickness equivalencies between gap-graded ARHM (ARHM-GG) and dense-graded conventional asphalt concrete (CAC-DG). Although asphalt-rubber overlays seem to provide a cost-effective option for pavement rehabilitation (*2,7*), the determination of the remaining fatigue life of the existing pavement needs to be assessed for the purpose of improved overlay thickness selection. This assessment would be essential particularly in lieu of research presented by Seebaly et al. (*10*) indicating a lag between structural capacity reduction and surface cracking of field test sections. In this case, the back-calculated moduli of the asphalt layer were reduced by 50 percent before lineal cracking, or before AASHO Class 2 and 3 cracking was observed on the pavement surface. Structural damage in terms of reduction of the modulus of the bituminous surface therefore occurs before any visual fatigue cracking in the pavement. Such deterioration could be assessed through nondestructive testing using, for example, the falling weight deflectometer (FWD).

In this paper, a procedure for estimating the remaining fatigue life of existing bituminous pavements is summarized. The proposed method utilizes flexure fatigue data for ARHM-GG and CAC-DG. The remaining life is expressed in terms of the reduction of the modulus of the pavement surface and the applied wheel load and does not require knowledge of previous wheel load magnitudes and repetitions. In this respect, the proposed method provides a definite advantage over current procedures that use Miner's cumulative damage hypothesis (*11*) to estimate remaining life. Fatigue criteria are expressed in terms of (a) flexure tensile strains and (b) surface curvature. Results are used to compare the fatigue behavior of ARHM-GG and CAC-DG pavements. Specifically, the number of load repetitions required to induce a given degree of fatigue damage are compared. In addition, the remaining fatigue life of ARHM-GG and CAC-DG pavements is determined for similar sections with the same degree of fatigue damage (i.e., equal reduction in surface layer modulus). Thickness equivalencies between ARHM-GG and CAC-DG pavements associated with fatigue performance are also established using both strain and curvature criteria.

EXPERIMENTAL WORK

Materials

CAC-DG and ARHM-GG beam specimens were obtained from new pavement sections that were constructed in California for the purpose of comparing the field performance of CAC-DG and ARHM-GG materials. The crumb rubber ma-

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terial used is scrap tire, vulcanized, with a specific gravity of 1.15 to 1.20, containing a minimum of 25 percent natural rubber. All materials meet Caltrans specifications. A summary of specifications for aggregate gradations, asphalt-rubber binder properties, and CAC-DG and ARHM-GG properties is presented in Tables 1 and 2.

Fatigue Testing

The fatigue behavior of CAC-DG and ARHM-GG was investigated using controlled strain flexure beam testing. A detailed description of the testing procedure and equipment is presented elsewhere (*8*). The beam specimens were cut to about 2 in. by 2 in. by 15 in. and were loaded at 5-in. interval third points. The density of the CAC-DG specimens varied between 152 lb/ft^3 and 153 lb/ft^3, whereas the density of ARHM-GG specimens varied in the range of 146 lb/ft^3 and 148 lb/ft^3. All tests were conducted using MTS Systems Corporation closed-loop hydraulic testing equipment and a haversine displacement pulse with a width of 0.10 sec and a frequency of 60 cpm. Fatigue tests were performed in an environmental chamber, and the temperature of the specimens was maintained between 70°F and 73°F. For a given displacement pulse, the variation of applied load and tensile and compressive strains across the center of the beam specimen was monitored with a number of pulse applications. Fatigue failure was assumed to occur when the flexure stiffness (E) determined from the central beam deflections and the applied load using simple beam theory assumptions was reduced by 50 percent.

Results

Fatigue criteria were developed in terms (a) maximum tensile strain in the middle beam section and (b) central beam curvature, with number of load repetitions to failure. These criteria are shown in Figure 1. The strain criterion is expressed as follows. For CAC-DG

$$N_f = 1.471 \times 10^{-10} \left(\frac{1}{\varepsilon_t}\right)^{4.55} \qquad (r^2 = 0.93) \tag{1}$$

For ARHM-GG

$$N_f = 2.350 \times 10^{-12} \left(\frac{1}{\varepsilon_t}\right)^{5.41} \qquad (r^2 = 0.93) \tag{2}$$

TABLE 1 Mix Aggregate Gradation Specification Limits for CAC-DG and ARHM-GG

Sieve Size	Percent Passing			
	Per Specification		Actual Field Results	
	CAC Dense Graded	ARHM Gap Graded	CAC Dense Graded	ARHM Gap Graded
3/4 in.	100	100	100	100
1/2 in.	95-100	90-100	97	96
3/8 in.	80-95	78-92	91	78
No. 4	59-66	28-42	68	39
No. 8	43-49	15-25	53	28
No. 30	22-27	5-15	35	16
No. 200	0-11	2-7	13	4.7
Asphalt Binder %	5.2 - 6.5	7.5 - 8.7	6.2	7.9

Note:
Asphalt Cement (AR-4000) in CAC-DG

Components of Asphalt-Rubber Binder:
AR-4000 Asphalt Cement
2% - 6% Asphalt Modifier (by total weight of Asphalt -Rubber binder)
78% - 82% Asphalt Cement and Modifier
18% - 22% Rubber

CAC-DG Caltrans Standard Specifications, 1988 Edition, Section 39-2.02
ARHM-GG Proposed Standard Specifications for Public Works Construction, Section 203-11.3

TABLE 2 Properties of Asphalt-Rubber Binder

Property	Specification Limits	Actual Average Results of Binder Tested
Field Viscosity, Haake at 375 °F in Centipoise (ASTM D2669)	1350 - 3050	1775
Penetration, Cone at 77 °F in 1/10 mm (ASTM D217)	20 - 70	51
Resilience 77 °F in Percent Rebound (ASTM D3407)	15 Minimum	27
Field Softening Point in °F (ASTM D36)	125 - 165	142

where ε_t is the tensile strain and N_f is the number of repetitions to failure.

The curvature criterion, on the other hand, can be written in terms of curvature (ρ) or the inverse of the radius of curvature ($1/R$) at the center of the beam as follows. For CAC-DG

$$N_f = 8.232 \times 10^{-12} \left(\frac{1}{\rho}\right)^{4.94} \quad (r^2 = 0.90) \tag{3}$$

For ARHM-GG

$$N_f = 4.205 \times 10^{-13} \left(\frac{1}{\rho}\right)^{5.68} \quad (r^2 = 0.92) \tag{4}$$

where ρ is $(\varepsilon_t + \varepsilon_c)/h$; h is beam thickness in inches; ε_t, ε_c are tensile and compressive strains at the top and bottom of the middle beam section, respectively.

It is interesting to note that the curvature criterion incorporates the thickness of the beam in the fatigue equation. This implicitly implies that, for a given strain condition, thicker beam sections will exhibit longer fatigue life. This finding is consistent with fatigue fracture propagation described by the Paris law and applied to asphalt concrete and asphalt-rubber hot mix (*7*).

Fatigue damage associated with a given number of load applications can be described as a loss in flexural stiffness. The reduction in flexural stiffness, tensile stiffness, and compressive stiffness for both CAC-DG and ARHM-GG as deduced from the fatigue tests is shown in Figure 2. Tensile and compressive stiffness in this case are determined from the applied load and the measured tensile and compressive strains at the top and bottom of the middle section of the beam specimen. As shown, the loss in stiffness seems to proceed at a much faster rate after 10^3 repetitions for CAC-DG compared with ARHM-GG, in which the decrease proceeds at a slower rate. Best-fit correlations of the stiffness reduction defined as the ratio of flexural stiffness E after N load applications to the initial flexural stiffness E_i are developed in terms of tensile strain ε_t and beam curvature ρ as follows. For CAC-DG

$$\left(\frac{E}{E_i}\right) \cdot (\varepsilon_t)^{1/4} = 0.19056 - 0.01964 \cdot \log N \quad (r^2 = 0.74) \tag{5}$$

$$\left(\frac{E}{E_i}\right) \cdot (\rho)^{1/4} = 0.18832 - 0.01919 \cdot \log N \quad (r^2 = 0.73) \tag{6}$$

For ARHM-GG

$$\left(\frac{E}{E_i}\right) \cdot (\varepsilon_t)^{1/4} = 0.17226 - 0.01509 \cdot \log N \quad (r^2 = 0.76) \tag{7}$$

$$\left(\frac{E}{E_i}\right) \cdot (\rho)^{1/4} = 0.17288 - 0.01501 \cdot \log N \quad (r^2 = 0.77) \tag{8}$$

The results of stiffness reduction E/E_i are shown in Figures 3 and 4. These results indicate that for a given repetition of ε_t or ρ, the reduction in E will be slightly higher for CAC-DG compared with ARHM-GG, thereby exhibiting more fatigue damage.

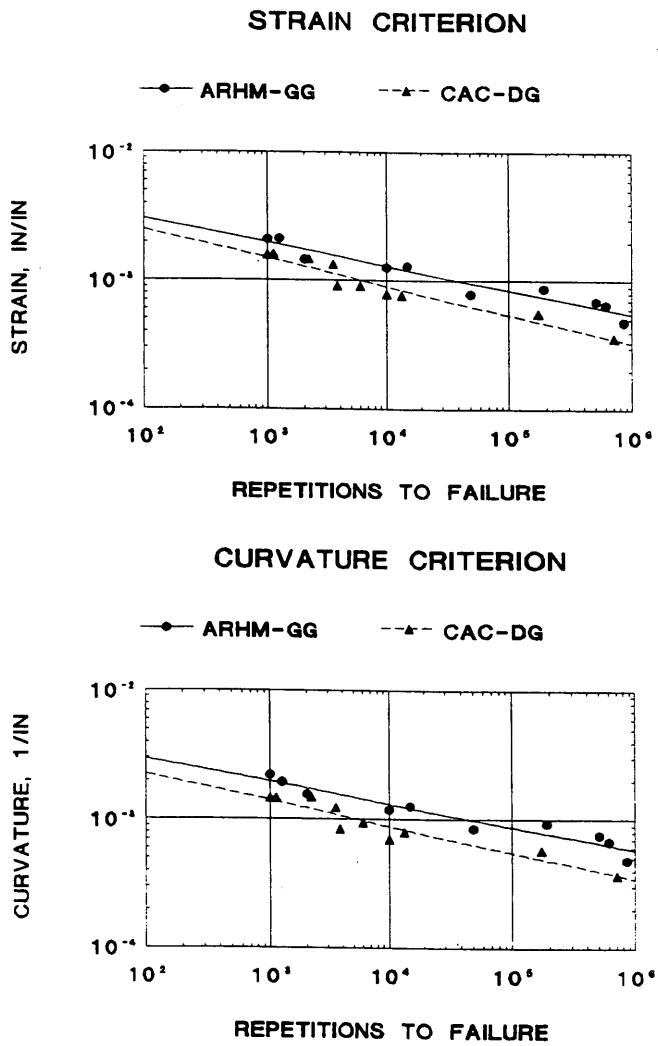

FIGURE 1 Fatigue failure criteria for CAC-DG and ARHM-GG.

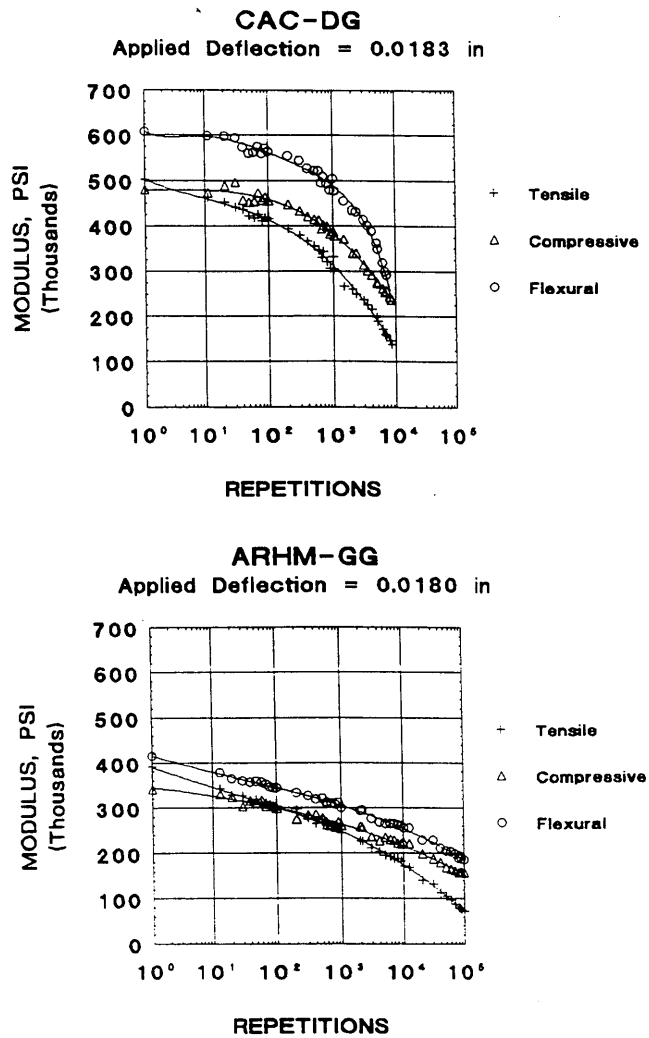

FIGURE 2 Variation of stiffness with load repetitions for CAC-DG and ARHM-GG.

REMAINING LIFE ANALYSIS

The remaining fatigue life for a pavement with a given E/E_i is defined as the number of repetitions of a given load (expressed in terms of tensile strain or surface curvature) required to induce ultimate fatigue damage by reducing E/E_i to 0.50. The remaining fatigue life can be estimated using the laboratory-determined relations for E/E_i in terms of load repetitions and applied tensile strain or surface curvature (Equations 5 through 8). For a given fatigue damage, expressed as E/E_i, these equations can be used to determine the equivalent number of repetitions (N_e) of a given load provided the corresponding load-induced strain or curvature is known. In this case, a remaining fatigue life factor (R_f) could be defined as

$$R_f = 1 - \frac{N_e}{N_f} \tag{9}$$

where N_e and N_f are both determined from Equations 5 through 8, depending on the mix type (CAC-DG or ARHM-GG) and strain or curvature criterion applied. N_f is the number of repetitions to failure for a new pavement estimated by substituting $E/E_i = 0.50$. For CAC-DG

$$R_f = 1 - 10^{-[(E/E_i - 0.50)/0.01964]\cdot\varepsilon_t^{1/4}} \tag{10}$$

$$R_f = 1 - 10^{-[(E/E_i - 0.50)/0.01919]\cdot\rho^{1/4}} \tag{11}$$

For ARHM-GG

$$R_f = 1 - 10^{-[(E/E_i - 0.50)/0.01509]\cdot\varepsilon_t^{1/4}} \tag{12}$$

$$R_f = 1 - 10^{-[(E/E_i - 0.50)/0.01501]\cdot\rho^{1/4}} \tag{13}$$

The corresponding remaining fatigue life N_{rf} can then be expressed as follows. For the strain criterion

$$N_{rf} = R_f \cdot (A1) \cdot \left(\frac{1}{\varepsilon}\right)^{A2} \tag{14}$$

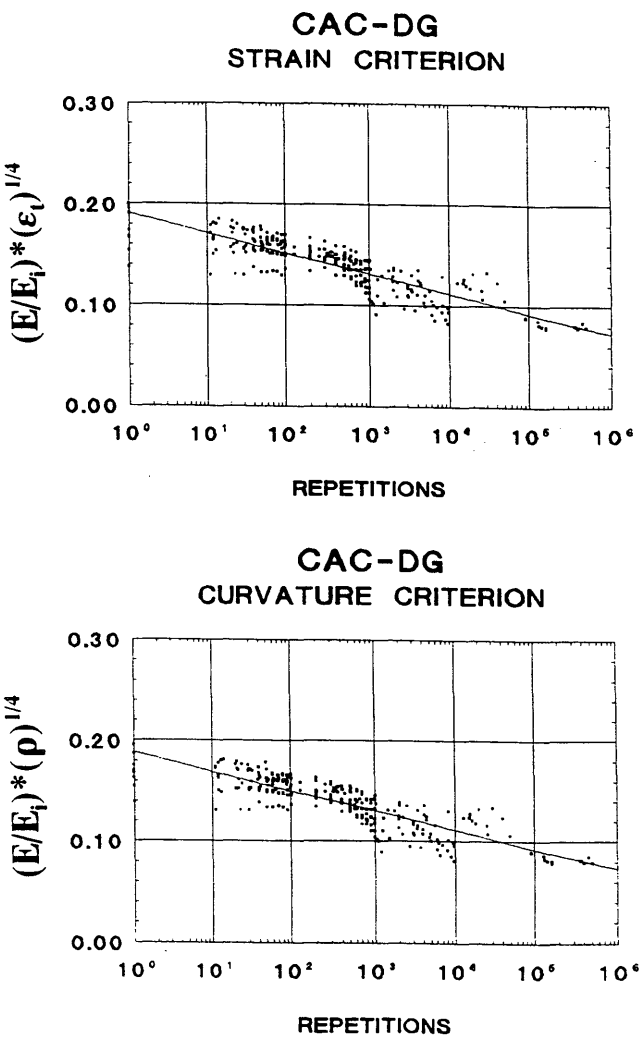

FIGURE 3 Stiffness reduction as a function of tensile strain and curvature for CAC-DG.

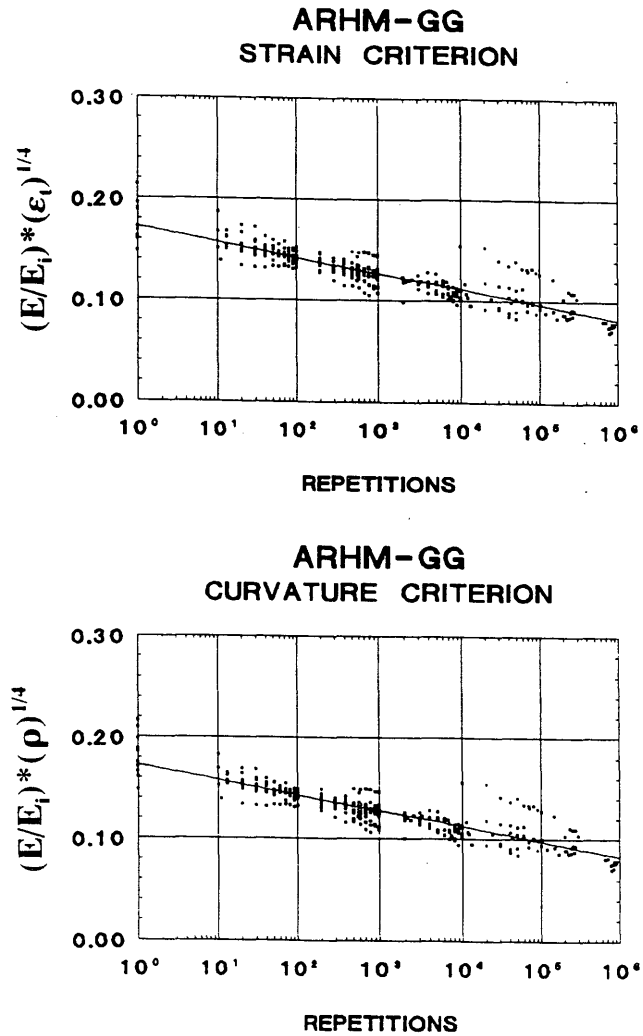

FIGURE 4 Stiffness reduction as a function of tensile strain and curvature for ARHM-GG.

For the curvature criterion

$$N_{rf} = R_f \cdot (B1) \cdot \left(\frac{1}{\rho}\right)^{B2} \tag{15}$$

where $A1$, $A2$, $B1$, and $B2$ are material constants defined in Equations 1 through 4.

The variation of the remaining life factor R_f with E/E_i, ε_t, and ρ is shown in Figures 5 and 6. Results indicate that R_f increases with an increase in E/E_i, ε_t, and ρ and attains slightly larger values for ARHM-GG compared with CAC-DG. The limits of variation are between 0 and 1 by definition.

Remaining fatigue life prediction requires the assessment of E/E_i at any given period during the service life of the pavement. E/E_i could be determined through backcalculation procedures using nondestructive pavement deflection equipment such as the FWD. Response parameters in terms of strains or surface curvature associated with a given wheel load are then used, together with E/E_i, to determine the remaining fatigue life as described in Equations 10 through 15. Surface curvature can be easily estimated from surface deflection data. This calculation could provide a direct estimation of pavement remaining life following FWD measurement of a simulated wheel load. The estimation of load repetitions required to induce a given fatigue damage in CAC-DG or ARHM-GG in terms of stiffness reduction E/E_i could also be obtained by substituting $(1 - R_f)$ for R_f in Equations 14 and 15.

Remaining fatigue life analysis has been investigated using multilayer elastic theory and the proposed material models. Typical three-layer pavements with CAC-DG and ARHM-GG surfaces were analyzed using the ELSYM5 (*12*) computer program. A summary of the cases considered is presented in Table 3. A standard 9,000-lb wheel load with tire pressure equal to 100 psi was used. The analysis aimed at comparing the fatigue performance of CAC-DG and ARHM-GG pavements. Specifically, the number of load repetitions required to induce a given reduction in surface layer modulus, the number of load repetitions associated with remaining fatigue life for a given state of fatigue damage E/E_i, and the equivalent thickness correlation between CAC-DG and ARHM-GG were investigated.

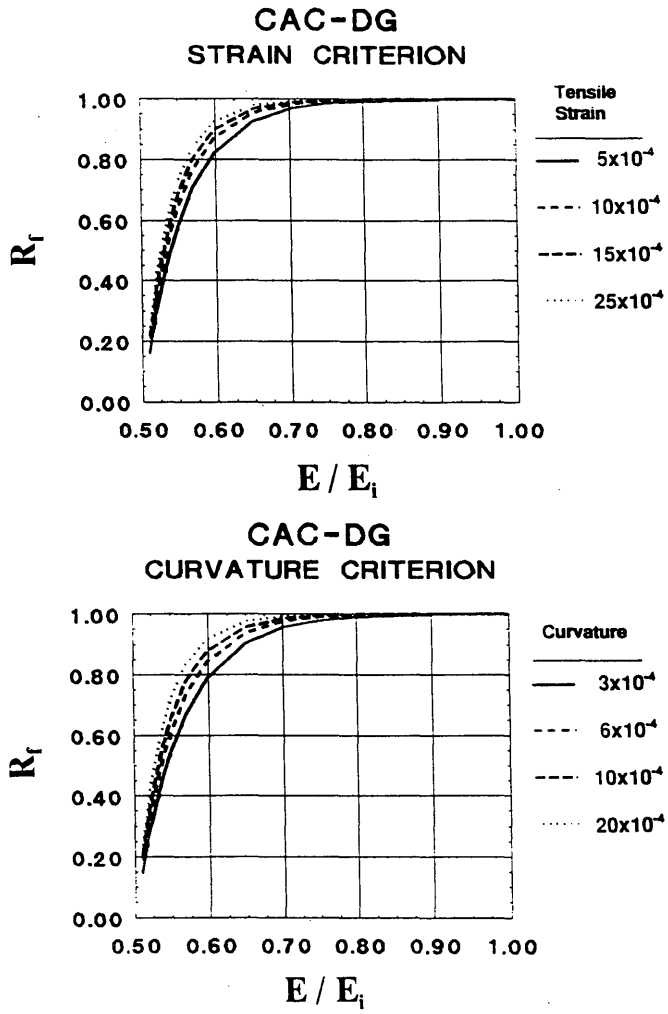

FIGURE 5 Variation of remaining fatigue life factor with stiffness reduction for CAC-DG.

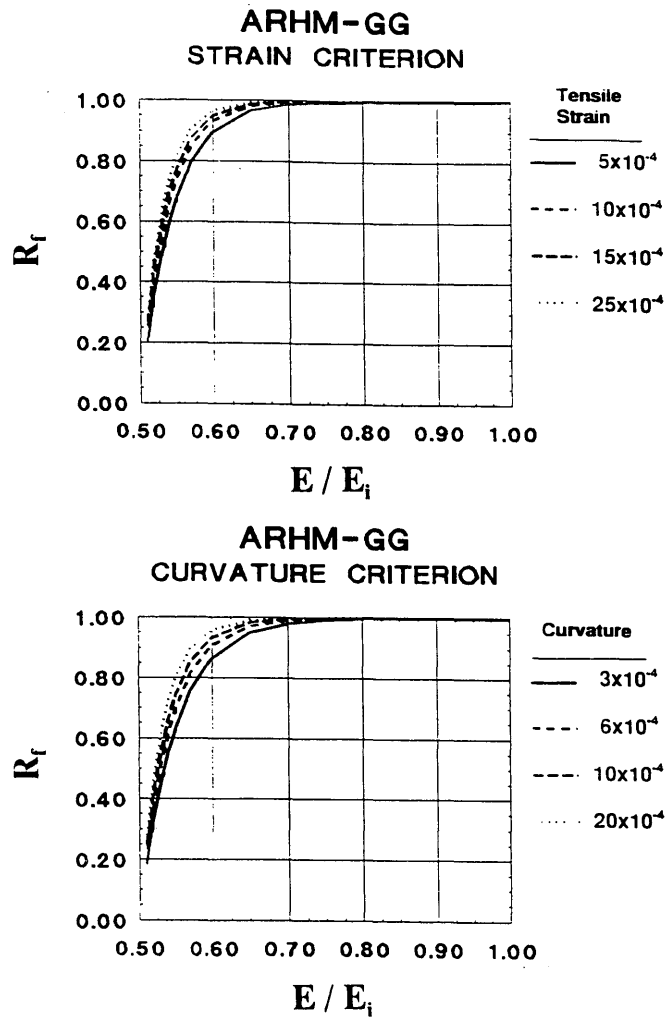

FIGURE 6 Variation of remaining fatigue life factor with stiffness reduction for ARHM-GG.

TABLE 3 Summary of Material Properties and Pavement Cases Studied

PROPERTY	MATERIAL		
	CAC-DG	ARHM-GG	BASE/SUBGRADE
Modulus, ksi	E_i = 550 E/E_i = 1, .85, .75, .65, .55	E_i = 350 E/E_i = 1, .85, .75, .65, .55	E_b/E_s = 80/20, 60/20, 40/20, 20/10
Poisson's Ratio	0.40	0.40	0.30/0.45
Thickness, in.	2, 3, 4, 6, 8, 10	2, 3, 4, 6, 8, 10	8 in. Base over Infinite Subgrade

Note : E_i = Initial Modulus of Surface Layer
E = Modulus of Surface Layer after N Repetitions
E_b = Modulus of Base Layer
E_s = Modulus of Subgrade

Results of the analysis are presented in Figures 7 through 15. The number of wheel load repetitions (N_d) required to cause a given fatigue damage represented by stiffness reduction E/E_i is generally larger for ARHM-GG than for CAC-DG. This difference increases with an increase in surface layer thickness, underlying base and subgrade support and degree of fatigue damage (i.e., decreasing E/E_i) (Figures 7 through 10). A similar trend is observed for the variation of remaining fatigue life for a pavement with a given E/E_i. In this case, the difference in remaining fatigue life between CAC-DG and ARHM-GG pavements increases with increasing thickness and underlying pavement support but decreases with the increase in initial degree of fatigue damage (Figures 11 through 14). Results of the analysis were also used to establish thickness equivalencies between CAC-DG and ARHM-GG layers. In this case, the two materials are assumed to have initially the same fatigue damage state (*i.e.*, E/E_i). Layer thicknesses for both CAC-DG and ARHM-GG are then selected to provide equal remaining fatigue life. As illustrated in Figure 15, thinner sections of ARHM-GG will exhibit the same remaining fatigue life compared with CAC-DG pavements. The reduction in thickness is more significant for pavements with higher base and subgrade moduli. For example, assuming the base and subgrade moduli equal to 80 and 20 ksi, respectively, and a CAC-DG surface layer with a thickness in the range of 6 and 10 in., then the corresponding equivalent ARHM-GG thickness will be between 2 and 5 in., respectively. In case of overlay applications, more support will be provided by the underlying pavement compared with that provided by the base and subgrade in a typical new pavement structure. It is therefore expected that the equivalent ARHM-GG overlay thickness could be significantly smaller, as demonstrated by Raad et al. (*8*).

SUMMARY AND CONCLUSIONS

In this paper a method is proposed for predicting the remaining fatigue life of existing bituminous pavements. This method incorporates laboratory fatigue data for tensile strain

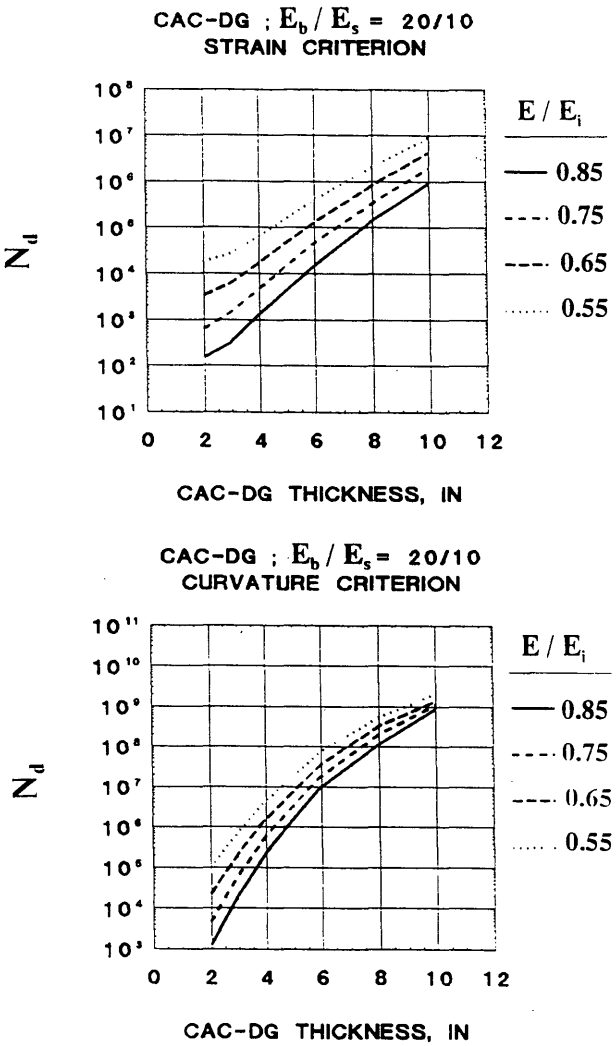

FIGURE 7 Variation of N_d with CAC-DG surface layer thickness for E_b/E_s = 20/10.

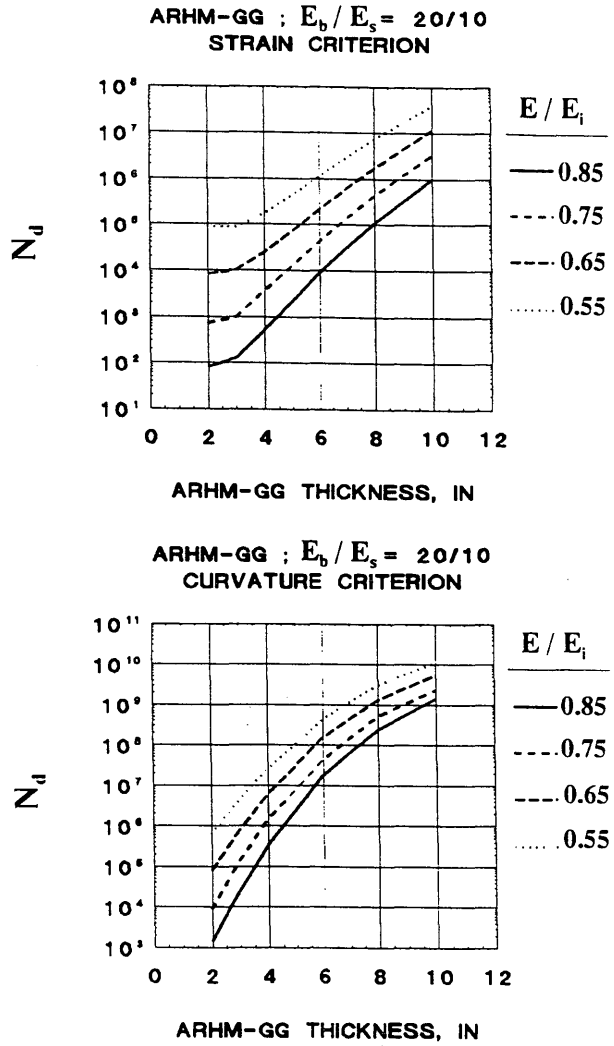

FIGURE 8 Variation of N_d with ARHM-GG surface layer thickness for E_b/E_s = 20/10.

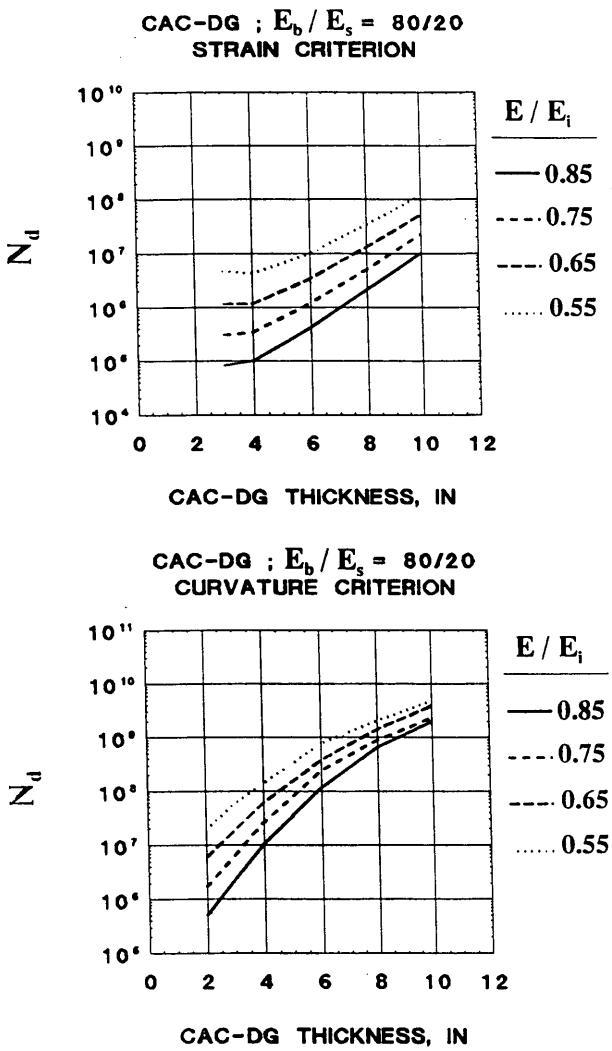

FIGURE 9 Variation of N_d with CAC-DG surface layer thickness for E_b/E_s = 80/20.

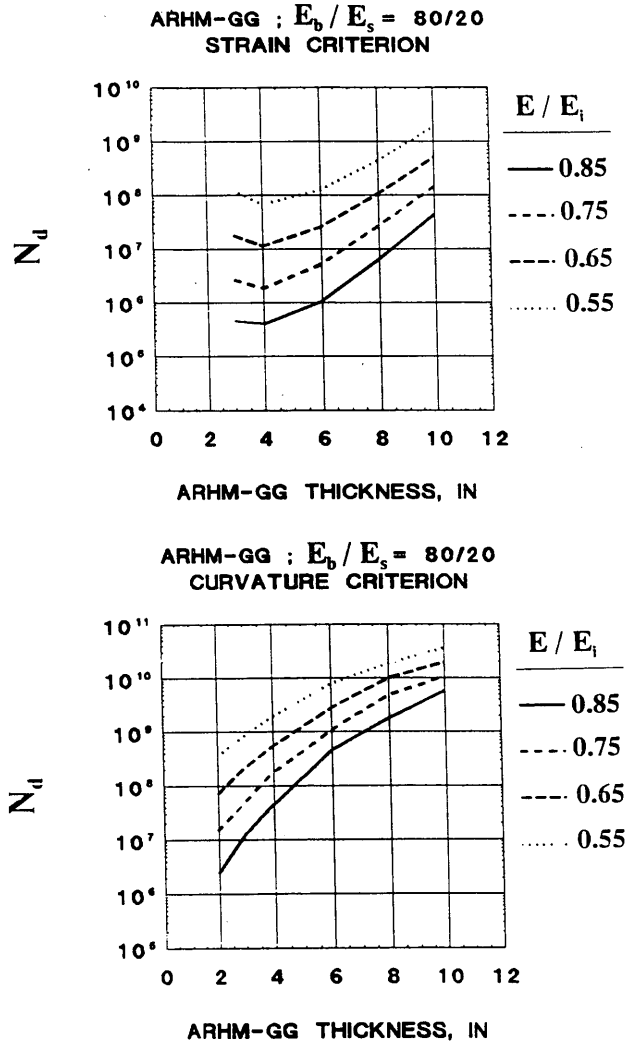

FIGURE 10 Variation of N_d with ARHM-GG surface layer thickness for E_b/E_s = 80/20.

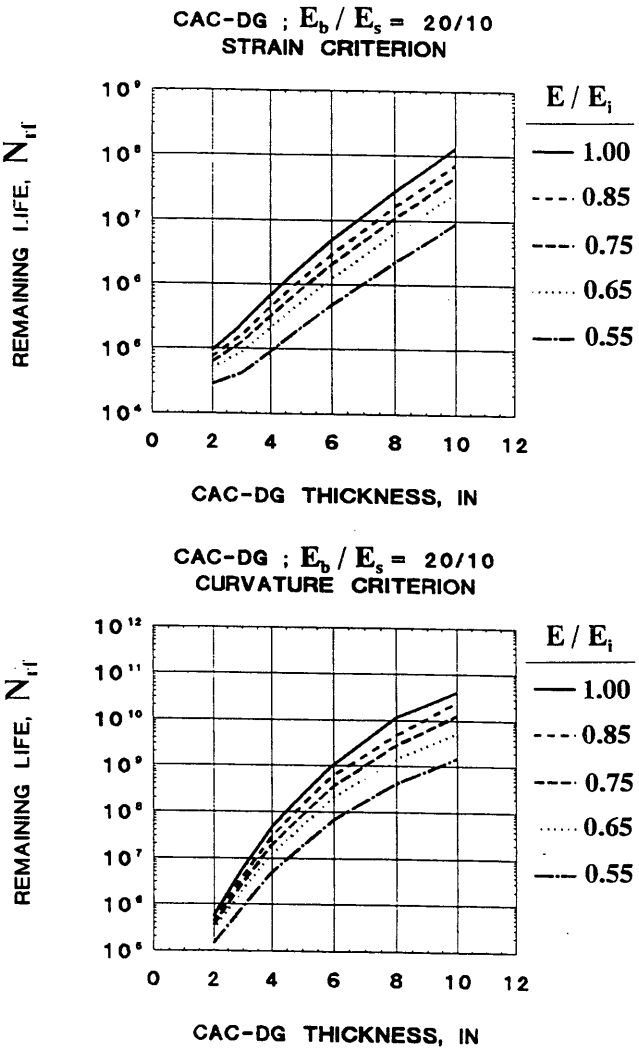

FIGURE 11 Variation of N_{rf} with CAC-DG surface layer thickness for E_b/E_s = 20/10.

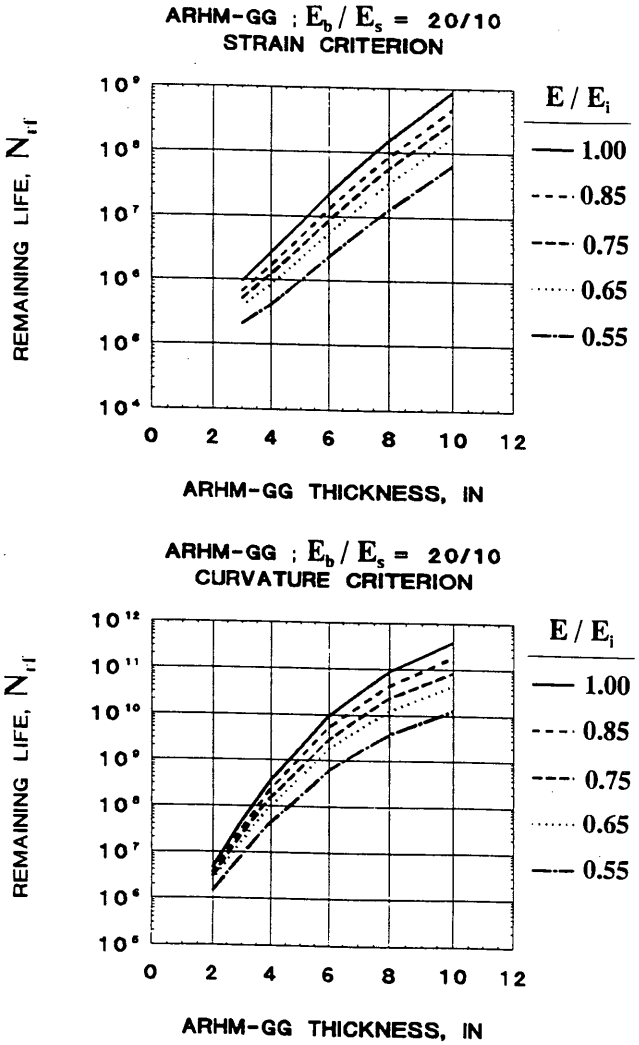

FIGURE 12 Variation of N_{rf} with ARHM-GG surface layer thickness for E_b/E_s = 20/10.

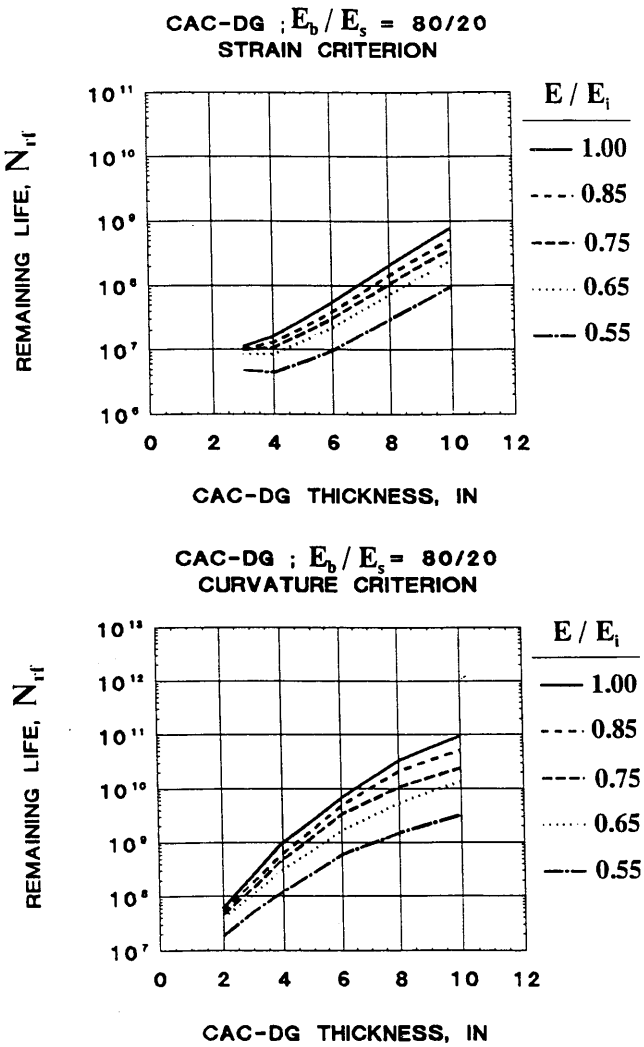

FIGURE 13 Variation of N_{rf} with CAC-DG surface layer thickness for E_b/E_s = 80/20.

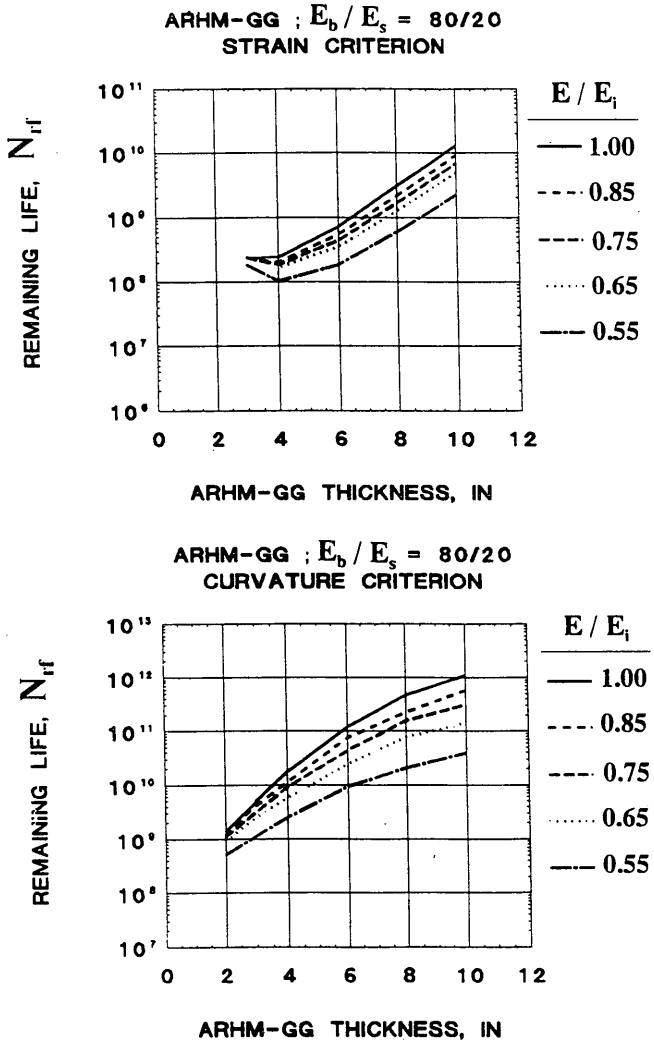

FIGURE 14 Variation of N_{rf} with ARHM-GG surface layer thickness for E_b/E_s = 80/20.

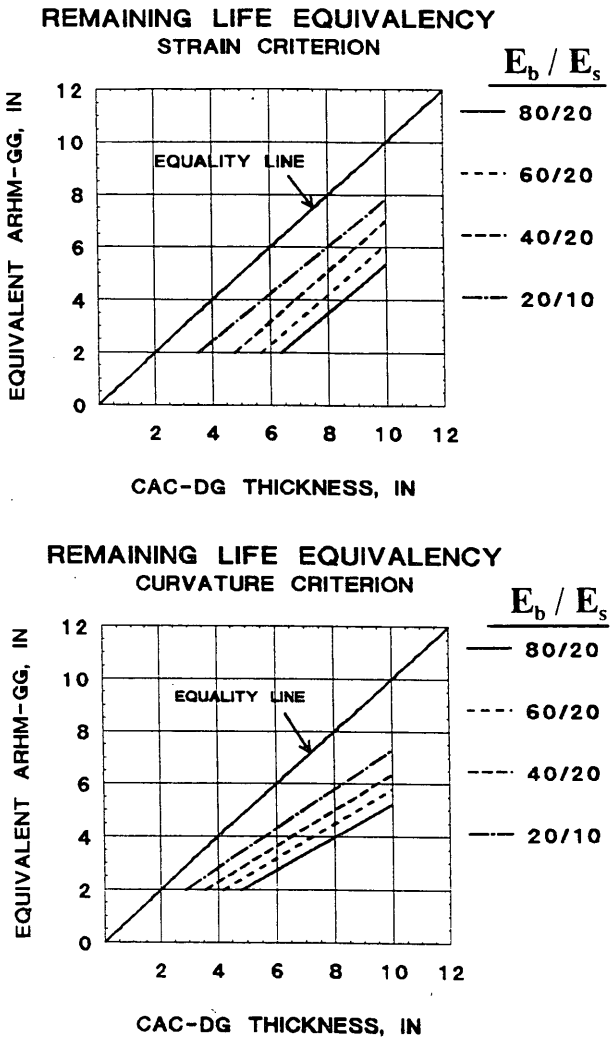

FIGURE 15 Thickness equivalencies for CAC-DG and ARHM-GG associated with a given remaining fatigue life.

or radius of curvature in terms of repetitions to failure. It also uses laboratory data on reduction of flexural stiffness with load repetitions. The proposed method is applied in the analysis of dense-graded conventional asphalt concrete (CAC-DG) and gap-graded asphalt-rubber hot mix (ARHM-GG) pavements. Controlled-strain fatigue test data for CAC-DG and ARHM-GG were incorporated in the analysis. Results indicate that the number of load repetitions required to induce a given fatigue damage, expressed in terms of the ratio of layer modulus after a given period of service to its initial modulus before the incurrence of any fatigue damage, could be significantly larger for ARHM-GG than for CAC-DG. Similar observations are made for the remaining fatigue life of CAC-DG and ARHM-GG, assuming a given initial state of fatigue damage. Thickness equivalencies are developed between CAC-DG and ARHM-GG on the basis of equal remaining fatigue life of pavement sections with similar initial fatigue damage. It is illustrated that thinner sections of ARHM-GG will be required for a given remaining fatigue life compared with CAC-DG pavements. This reduction in thickness becomes more significant with increasing foundation support under the pavement surface layer, which warrants consideration of using ARHM-GG in pavements and particularly in overlays.

The results presented in this paper are based on laboratory tests and simple multilayer elastic analysis covering limited loading and temperature conditions. Field research is needed to calibrate the proposed models and to verify the conclusions and trends obtained.

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REFERENCES

1. J. O. Kano and E. Charania. The Phoenix Experience Using Asphalt-Rubber. *Proc., National Seminar on Asphalt Rubber*, Kansas City, Mo., Asphalt Rubber Producers Group, Oct. 1989, pp. 366–393.
2. J. L. Van Kirk. Caltrans Experience with Asphalt-Rubber Concrete–An Overview and Future Direction. *Proc., National Seminar on Asphalt Rubber*, Kansas City, Mo., Asphalt Rubber Producers Group, Oct. 1989, pp. 418–431.
3. L. Schofield. The History, Development and Performance of Asphalt Rubber at ADOT. *Proc., National Seminar on Asphalt Rubber*, Kansas City, Mo., Asphalt Rubber Producers Group, Oct. 1989, pp. 328–365.
4. C. M. Turgeon. The Use of Asphalt-Rubber Products in Minnesota. *Proc., National Seminar on Asphalt Rubber*, Kansas City, Mo., Asphalt Rubber Producers Group, Oct. 1989, pp. 311–327.
5. A. Sainton. Advantages of Asphalt Rubber Binder for Porous Concrete. In *Transportation Research Record 1265*, TRB, National Research Council, Washington, D.C., 1990, pp. 69–81.
6. R. N. Doty. Flexible Pavement Rehabilitation Using Asphalt-Rubber Combinations. In *Transportation Research Record 1196*, TRB, National Research Council, Washington, D.C., 1988, pp. 212–223.
7. D. L. Hoyt and R. L. Lytton. Laboratory Behavior, Performance Prediction and Cost-Effectiveness of Asphalt-Rubber Concrete in Airport Pavements. *Proc., National Seminar on Asphalt Rubber*, Kansas City, Mo., Asphalt Rubber Producers Group, Oct. 1989, pp. 191–250.
8. L. Raad, S. Saboundjian, and R. Briggs. *Fatigue Behavior of Asphalt Rubber Hot Mix and Conventional Asphalt Concrete: A Comparative Study.* Final Report. Manhole Adjusting, Inc.; Transportation Research Center, Institute of Northern Engineering, University of Alaska, Fairbanks, Sept. 1992.
9. H. Al-Abdul-Wahab and G. Al Amri. Laboratory Evaluation of Reclaimed Rubber Asphaltic Concrete Mixes. *Journal of Materials in Civil Engineering*, Vol. 3, No. 3, Aug. 1991, pp. 189–203.
10. P. Seebaly, N. Tabatabaee, R. Bonaquist, and D. Anderson. Evaluating Structural Damage of Flexible Pavements Using Cracking and Falling Weight Deflectometer Data. In *Transportation Research Record 1227*, TRB, National Research Council, Washington, D.C., 1989, pp. 44–52.
11. M. A. Miner. Cumulative Damage in Fatigue. *ASME Transactions, Journal of Applied Mechanics*, Vol. 12, 1945, pp. A159–A164.
12. *ELSYM5. A Computer Program for the Analysis of Elastic Layered Systems with Normal Loads.* Coded by G. Ahlborn, ITTE, University of California, Berkeley, 1972.

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