FIELD AGING EFFECTS ON THE FATIGUE OF ASPHALT CONCRETE AND ASPHALT-RUBBER CONCRETE

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ABSTRACT

This paper describes a study to investigate the influence of field aging on the fatigue performance of asphalt concrete and asphalt-rubber concrete. Two California mixes were investigated: 1) Conventional asphalt concrete dense-graded mix (CAC-DG) and 2) Asphalt-rubber hot mix gap-graded (ARHM-GG). Laboratory fatigue tests were conducted on beam specimens obtained from a 10-year old pavement section in southern California. Both stiffness and fatigue were determined using controlled-strain fatigue beam tests performed at 22°C and –2°C. Results were compared with previously published data for the original (unaged) materials. Stiffness and fatigue data were also used in pavement analysis in order to assess the influence of aging on predicted fatigue performance. Results indicate that field aging reduced the beam fatigue resistance of CAC-DG and to a lesser extent, ARHM-GG. Aging effects on beam fatigue life were more severe at –2°C than at 22°C. The influence of aging on predicted pavement fatigue life depends not only on the stiffness of the mix and its fatigue properties but also on the stiffness or layer moduli of the pavement components. For new pavement construction and overlaid pavement sections, longer fatigue life predictions were obtained for ARHM-GG than CAC-DG, for both aged and unaged conditions. Aging of the CAC-DG could be detrimental to pavement fatigue. In comparison, aging of ARHM-GG showed increased fatigue life performance.

Key Words: asphalt, asphalt rubber, fatigue, aging, pavements, performance, prediction

INTRODUCTION

Fatigue is considered to be one of the more significant distress modes in pavements associated with repeated traffic loads. The use of crumb rubber modifiers (CRM) with the asphalt binder, as part of the wet-process application in paving materials seems to enhance the fatigue resistance as illustrated in a number of studies (*1*, *2*, *3*, *4, 5*). The improved performance of asphalt-rubber pavements compared with conventional asphalt concrete pavements has been attributed to improved rheological properties of the asphalt-rubber binder (*6*), and improved resistance to aging (*7*). The influence of aging on the fatigue behavior of asphalt rubber mixes is critical to the development of more realistic mechanistic design procedures.

Increase in the viscosity of asphalt rubber as a result of laboratory oven aging has been reported by Liang and Lee (*8*) and by McGennis (*9*). Bahia and Davies (*6*) studied the effect of aging on asphalt binders before and after treatment with different types of crumb rubber modifiers. The binder specimens were aged using thin film oven (TFO) and pressure aging vessel (PAV). The resistance of the binder to fatigue was determined from the dissipated energy per load cycle (G”) as obtained from the dynamic shear rheometer test. Results show that all asphalt rubbers at all test temperatures exhibited less G” upon aging in TFO and PAV than the original binder, thereby indicating increased resistance to fatigue. Improvement in fatigue resistance of the asphalt rubbers compared to the original binders is more prominent at higher temperature.

Vallerga et al. (*10*) evaluated the effects of laboratory aging on the stiffness and fatigue of asphalt concrete. An increase in beam fatigue resistance under controlled-stress loading has been observed. When applied to the analysis of thick pavement sections, aging of the asphalt concrete resulted in increased pavement fatigue life. Harvey and Tsai (*11*) conducted a laboratory study to investigate the influence of long-term oven aging on the fatigue of asphalt concrete beam specimens using controlled-strain loading. They used two sources of asphalt AR-4000 and one type of aggregate. Their results show that aging is sensitive to the type of asphalt used and that stiffness increase associated with aging does not necessarily reduce the beam fatigue life. The application of the beam fatigue and stiffness results in the analysis of thin and thick pavement sections indicated that aging prolonged the fatigue life of the pavement structure.

In this paper, the effects of long-term field aging on the fatigue behavior were investigated for two California mixes: 1) Conventional asphalt concrete dense-graded mix (CAC-DG), and 2) Asphalt-rubber hot mix gap-graded (ARHM-GG). These materials were obtained from a test section that was constructed 10 years ago in southern California. After construction, field specimens were tested to determine the fatigue characteristics of CAC-DG and ARHM-GG. Results of these tests were published elsewhere (*4, 12*). In this study, laboratory fatigue tests were conducted on beam specimens obtained from the 10-year field section. Both stiffness and fatigue were determined using controlled-strain fatigue beam tests performed at 22°C and –2°C. The fatigue behavior of CAC-DG and ARHM-GG for both new and aged materials was compared. Stiffness and fatigue data were also used in pavement analysis in order to assess the influence of aging on predicted fatigue field performance.

LABORATORY STUDY

Materials

The field test section under consideration was part of a parking lot and was not subjected to any substantial traffic. Field slabs 300 mm wide, 500 mm long and 100 mm deep were cut from the pavement section. These slabs were then cut in the laboratory into beam specimens that were 50 mm by 50 mm by 410 mm. Properties for CAC-DG and ARHM-GG are summarized in Tables 1 and 2.

Fatigue Testing

Controlled-strain flexure beam testing was used in the fatigue study. All tests were conducted using MTS closed loop hydraulic testing equipment and a haversine displacement pulse having a width of 0.10 sec and a frequency equal to 60 cpm. Fatigue tests were performed at 22°C and –2°C in an environmental chamber where the temperature of the specimens was maintained within ±1°C of the set temperature. The variation of applied load, and tensile and compressive strains across the center of the beam specimen was monitored with number of load applications. Fatigue failure was assumed to occur when the flexure stiffness determined from central beam deflections reduced by 50 percent.

Test Results and Limiting Criteria

Results of fatigue testing were presented to illustrate the influence of aging on the initial flexural stiffness and beam fatigue life for CAC-DG and ARHM-GG. The initial stiffness corresponds to the beam stiffness at the 50^{th} load repetition. The effect of aging on the average initial stiffness value for the tested beam specimens is shown in Figure 1. As expected, ARHM-GG exhibits lower stiffness at $22^{o}C$ and $-2^{o}C$, than CAC-DG, for both aged and original (unaged) conditions. The increase in stiffness of ARHM-GG as a result of aging is minimal (less than 6 percent) at both test temperatures. On the other hand, the stiffness of CAC-DG increases by about 30 percent for testing at $22^{o}C$. The average stiffness of CAC-DG for tests conducted at $-2^{o}C$ is about 12 percent smaller for aged specimens than for original specimens. A possible explanation could be that the influence of decreasing temperature on the increase in stiffness is less significant for aged than for unaged CAC-DG specimens.

The fatigue behavior of both CAC-DG and ARHM-GG is illustrated in Figures 2-5. Both, tensile strain and distortion energy are used as limiting criteria. Although tensile strain on the underside of the pavement surface layer is considered in general as the critical response parameter for fatigue behavior, the use of distortion energy seems to be more appropriate for conditions of small tensile strain values or when the strain is compressive (*4, 12*). Compressive strains could occur on the underside of overlay layers depending on the relative stiffness of the pavement components.

According to Timoshenko and Goodier (*13*), the strain energy per unit volume for a linear elastic isotropic material is sometimes used as a limiting criterion to determine the stress state at failure. However, since in many isotropic materials, volumetric component of this energy does not contribute to failure, only the distortion energy component is considered. For a given state of normal stress (σ_x, σ_y, σ_z) and shear stress (τ_{xy}, τ_{yz}, τ_{zx}) at a given point relative to a Cartesian system of co-ordinates x-y-z in a linear elastic isotropic material, the distortion energy per unit volume, DE, is given by,

$$DE = [(1 + \upsilon)/6E][(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2] + (1/2G)(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2) \quad (1)$$

where

E, G, and υ are the modulus of elasticity, the shear modulus, and Poisson's ratio, respectively.

In a beam fatigue test, the critical tensile stress, σ, alone is different than zero (i.e. uniaxial stress condition), and Equation 1 can be written as,

$$DE = (1+\upsilon)\sigma^2/3E \quad (2)$$

In this case, the initial DE is determined from initial bending stress σ and initial flexural stiffness, E. A Poisson's ratio of 0.35 was used for all beams tested in this study.

Test results for CAC-DG (Figures 2 and 4) clearly illustrate that aging reduces the beam fatigue life for the testing conditions used in this study. The reduction is essentially more significant for tests run at –2°C than at 22°C. It is interesting to note that although the average stiffness for aged CAC-DG at –2°C is slightly smaller than the unaged specimens, the reduction in fatigue life is quite significant. Observations by other researchers (*11*) indicate that increased stiffness associated with laboratory aging does not necessarily reduce beam fatigue life under controlled-strain loading. In case of ARHM-GG (Figures 3 and 5), aging has negligible effect on fatigue life for testing at 22°C. At –2°C, the reduction in fatigue life for ARHM-GG becomes more evident, but remains less significant than CAC-DG.

The fatigue test data were regressed to establish limiting criteria between load repetitions to failure, N_f, and the critical response parameters, in this case, tensile strain ε and initial distortion energy DE.

The following relationships were determined for both CAC-DG and ARHM-GG:

$$N_f = a\,(1/\varepsilon)^{b} \quad (3)$$

$$N_f = a\,(1/DE)^b \qquad (4)$$

$$N_f = a\,(1/\varepsilon)^b(1/E)^c \qquad (5)$$

$$N_f = a\,(1/DE)^b(1/E)^c \qquad (6)$$

Regression coefficients a, b, and c were independently determined for each relationship and are summarized in Tables 3-6.

APPLICATIONS

In order to assess the influence of field aging on the fatigue performance of pavements, multilayer elastic analysis using ELSYM5 software was performed on typical pavement sections that included both new pavement construction, and overlay construction. The response of the pavement was determined for an applied 40 kN wheel load with tire pressure equal to 690 kPa. A summary of layer properties is presented in Table 7.

It should be noted that increased stiffness associated with aging would result in increased beam fatigue under controlled-stress loading but would on the other hand cause a decrease in beam fatigue under controlled-strain loading. The fatigue mode of the pavement structure is therefore crucial to assessing the influence of aging on the asphalt concrete surface. Monismith and Deacon (14) concluded that for three layer pavements (i.e. asphalt concrete surface, base, and subgrade) the controlled-strain fatigue mode is more applicable to thin pavement surfaces (i.e. less than 50 mm) whereas the controlled-stress fatigue mode is applicable to thicker pavement surfaces (i.e. greater than 150 mm). Between these two thicknesses some intermediate mode of loading prevails. In order to determine the mode of fatigue loading applicable to overlays, analyses were conducted as part of this study for a number of cases summarized in Table 7. Results presented in Figure 6 indicate that controlled-strain fatigue mode is more applicable than the controlled-stress mode for overlays with thickness ranging between 40 mm and 120 mm.

In this study, a controlled-strain fatigue mode was assumed in the analyses. Critical values for tensile strain and distortion energy were calculated in the surface layer. Fatigue criteria represented by Equations 3 and 4 for 22^{o}C were used to predict pavement fatigue life. Fatigue life was plotted as a function of pavement or overlay thickness. Results are illustrated in Figures 7 to 10.

For new pavement construction (Figures 7 and 8) and a given thickness of surface layer, the ARHM-GG resulted in longer fatigue life compared with CAC-DG, for both the aged and unaged conditions. Aging of the CAC-DG reduced the predicted fatigue life. In comparison, aging of ARHM-GG showed increased pavement fatigue life. Similar trends were obtained for both tensile strain (Figure 7) and distortion energy (Figure 8) criteria. The use of soft (75 MPa) versus stiff (150 MPa) subgrade in the analysis had negligible effect on the predicted fatigue life of the surface layer.

For overlay construction (Figures 9 and 10), the fatigue life of the existing pavement surface was assumed to be fully consumed and only the fatigue of the overlay layer was considered in analysis. The influence of aging on predicted overlay fatigue life exhibited a similar trend to that obtained for new pavement construction.

The use of the distortion energy fatigue criterion resulted in lower predictions of pavement fatigue life than the tensile strain criterion. For pavement surface thickness greater than 40 mm, the location of the most critical distortion energy coincided in general with the maximum tensile strain on the underside of the pavement. For thinner sections, maximum distortion energy occurred at the surface of the pavement under the center of the applied wheel load. More research is needed to verify the application of distortion energy as a limiting criterion in fatigue analysis of pavements.

SUMMARY AND CONCLUSIONS

In this paper, the effects of field aging on the fatigue behavior were investigated for two California mixes: 1) Conventional asphalt concrete dense-graded mix (CAC-DG), and 2) Asphalt-rubber hot mix gap-graded (ARHM-GG). Laboratory fatigue tests were conducted on beam specimens obtained from a 10-year old field section in southern California. Both stiffness and fatigue were determined using controlled-strain fatigue beam tests performed at 22^{o}C and –2^{o}C. Results were compared with previously published data for the original (unaged) materials. Stiffness and fatigue data were also used in pavement analysis in order to assess the influence of aging on predicted fatigue field performance. The following conclusions were made from the results of this study:

1. ARHM-GG exhibited lower stiffness at 22°C and –2°C, than CAC-DG, for both aged and original (unaged) conditions. The increase in stiffness of ARHM-GG as a result of aging is minimal (less than 6 percent) at both test temperatures.

2. Aging increased the stiffness of CAC-DG by about 30 percent for testing at 22°C. The average stiffness of CAC-DG for tests conducted at –2°C was 12 percent smaller for aged specimens than for original specimens. A possible explanation could be that the influence of decreasing temperature on the increase in stiffness is less significant for aged than for unaged CAC-DG specimens.

3. Aging reduced the beam fatigue life of CAC-DG for the testing conditions used in this study. The reduction was essentially more significant for tests run at –2°C than at 22°C. Although the average stiffness for aged CAC-DG at –2°C was slightly smaller than the unaged specimens, the reduction in fatigue life was quite significant.

4. In case of ARHM-GG aging had negligible effect on fatigue life for tests conducted at 22°C. At –2°C, the reduction in fatigue life for ARHM-GG became more evident, but remained less significant than CAC-DG.

5. For new pavement construction and overlaid pavement sections, longer fatigue life predictions were obtained for ARHM-GG than CAC-DG, for both aged and unaged conditions. Aging of the CAC-DG could be detrimental to pavement fatigue. In comparison, aging of ARHM-GG showed increased fatigue life performance. It should be emphasized in this case that fatigue life predictions depend on the stiffness and fatigue characteristics of the surface layer and also on the stiffness or layer moduli of the pavement components. Although aging could reduce beam fatigue life, pavement fatigue life could increase or decrease accordingly.

ACKNOWLEDGMENT

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(distortion energy criterion).

TABLE 1 CAC-DG Mix Properties *(4)*

Aggregate gradation

Sieve (mm)	% passing	Specf.
3/4" (19)	100	100
1/2" (12.7)	97	95-100
3/8" (9.5)	89	80-95
#4 (4.75)	65	59-66
#8 (2.4)	48	43-49
#30 (0.6)	29	22-27
#200 (0.075)	8	0-11

The CAC-DG mix, placed in 1990, is according to Caltrans Standard Specifications, 1998 Edition, Section 39-2.02

Binder : AR-4000
Binder content : 5.7 % by weight of total mix
Voids : 1.6 %
Density : 24.1 KN/m^3 (153 pcf)

TABLE 2 ARHM-GG Mix Properties *(4)*

Aggregate Gradation		
Sieve (mm)	% Passing	Specf.
3/4" (19)	100	100
1/2" (12.7)	95	90-100
3/8" (9.5)	81	78-92
#4 (4.75)	35	28-42
#8 (2.4)	24	15-25
#30 (0.6)	15	5-15
#200 (0.075)	5	2-7

Rubber Gradation	
Sieve (mm)	% Passing
#8 (2.4)	100
#10 (2)	95-100
#16 (1.2)	40-80
#30 (0.6)	5-30
#50 (0.3)	0-15
#200 (0.075)	0-3

The ARHM-GG mix, placed in 1990, is according to the Proposed Standard Specifications for Public Works Construction, Section 203-11.3

Binder : Asphalt-Rubber consisting of :
AR-4000 asphalt cement
4% asphalt modifier (by weight of asphalt-rubber)
80% asphalt-cement and modifier
20% rubber
Binder content : 7.3 % by weight of total mix
Voids : 1.6 %
Density : 23.4 KN/m^3 (148 pcf)

TABLE 3 Fatigue Regression Coefficients for All Mixes at 22°C

		a	b	R^2
$N_f = a\,(1/\varepsilon)^b$	Original CAC-DG	2.252E-09	4.147	0.893
	Original ARHM-GG	3.085E-11	5.022	0.941
	Aged CAC-DG	7.931E-10	4.022	0.683
	Aged ARHM-GG	2.342E-16	6.842	0.979
$N_f = a\,(1/DE)^b$	Original CAC-DG	9757	2.574	0.948
	Original ARHM-GG	24762	2.891	0.946
	Aged CAC-DG	1216	3.647	0.852
	Aged ARHM-GG	31446	2.351	0.912

Note : *N_f = Repetitions to 50% Initial Stiffness (Fatigue Life)*
ε = Initial tensile Strain, m/m
DE = Initial Distortion Energy, KPa

TABLE 4 Fatigue Regression Coefficients for All Mixes at -2°C

		a	b	R^2
$N_f = a\,(1/\varepsilon)^b$	Original CAC-DG	3.158E-20	6.993	0.838
	Original ARHM-GG	4.320E-20	7.342	0.828
	Aged CAC-DG	8.517E-45	13.464	0.904
	Aged ARHM-GG	1.797E-10	4.152	0.607
$N_f = a\,(1/DE)^b$	Original CAC-DG	6313	5.170	0.848
	Original ARHM-GG	37739	3.603	0.888
	Aged CAC-DG	574	6.008	0.493
	Aged ARHM-GG	18005	1.993	0.692

Note : *N_f = Repetitions to 50% Initial Stiffness (Fatigue Life)*
ε = Initial tensile Strain, m/m
DE = Initial Distortion Energy, KPa

TABLE 5 Coefficients for Fatigue Life-Strain-Stiffness Regressions

	$N_f = a\,(1/\varepsilon)^b(1/E)^c$			
Mix	a	b	c	R^2
Original CAC-DG	1.096E-03	4.964	2.296	0.802
Original ARHM-GG	1.154E-05	5.846	2.387	0.844
Aged CAC-DG	6.775E-09	7.416	3.328	0.755
Aged ARHM-GG	2.200E+01	3.287	1.997	0.818

Note : N_f = Repetitions to 50% Initial Stiffness (Fatigue Life)
ε = Initial tensile Strain, m/m
E = Initial Flexural Stiffness, MPa

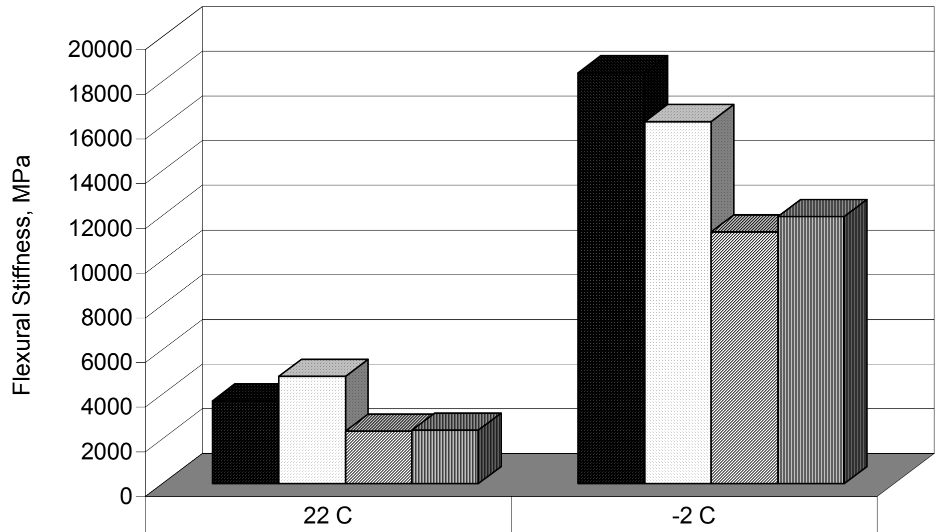
TABLE 6 Coefficients for Fatigue Life-Initial Distortion Energy-Stiffness Regressions

	$N_f = a\,(1/DE)^b(1/E)^c$			
Mix	a	b	c	R^2
Original CAC-DG	1.344E+05	3.001	0.318	0.821
Original ARHM-GG	5.758E+03	3.102	-0.181	0.923
Aged CAC-DG	2.820	4.005	-0.687	0.732
Aged ARHM-GG	191755	2.138	0.246	0.857

Note : N_f = Repetitions to 50% Initial Stiffness (Fatigue Life)
DE = Initial Distortion Energy, KPa
E = Initial Flexural Stiffness, MPa

TABLE 7 Summary of Pavement Layer Properties

		New Pavement Construction		
		Thickness (cm)	E (MPa)	Poisson's Ratio
CAC-DG (22^{o}C)	original	4, 6, 8, 10, 12	3700	0.35
	aged	4, 6, 8, 10, 12	4800	0.35
ARHM-GG (22^{o}C)	original	4, 6, 8, 10, 12	2350	0.35
	aged	4, 6, 8, 10, 12	2386	0.35
Base		25	300	0.40
Subgrade		Infinite	75	0.45
		Overlay Construction		
CAC-DG (22^{o}C)	original	4, 6, 8, 10, 12	3700	0.35
	aged	4, 6, 8, 10, 12	4800	0.35
ARHM-GG (22^{o}C)	original	4, 6, 8, 10, 12	2350	0.35
	aged	4, 6, 8, 10, 12	2386	0.35
Existing AC		4	1000	0.35
Base		25	300	0.40
Subgrade		Infinite	75	0.45



	22 C	-2 C
Original CAC-DG	3700	18379
Aged CAC-DG	4800	16211
Original ARHM-GG	2350	11266
Aged ARHM-GG	2386	11960

FIGURE 1 Stiffness variation for original and aged mixes.

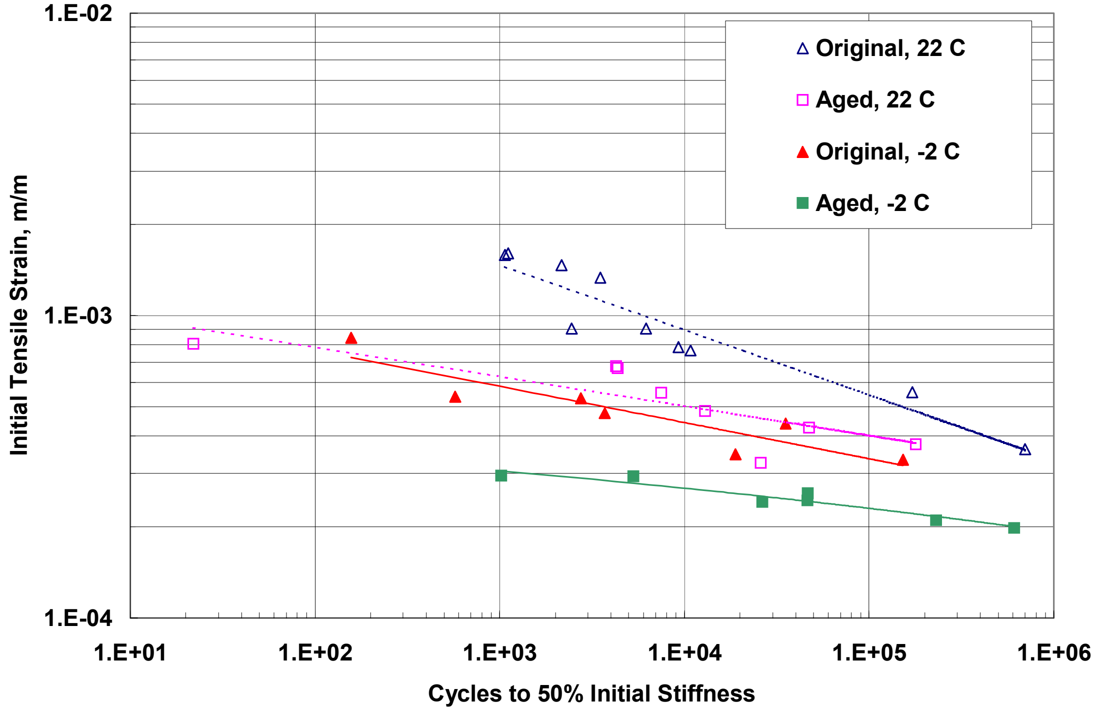


FIGURE 2 Fatigue relationships for CAC-DG using tensile strain criterion.

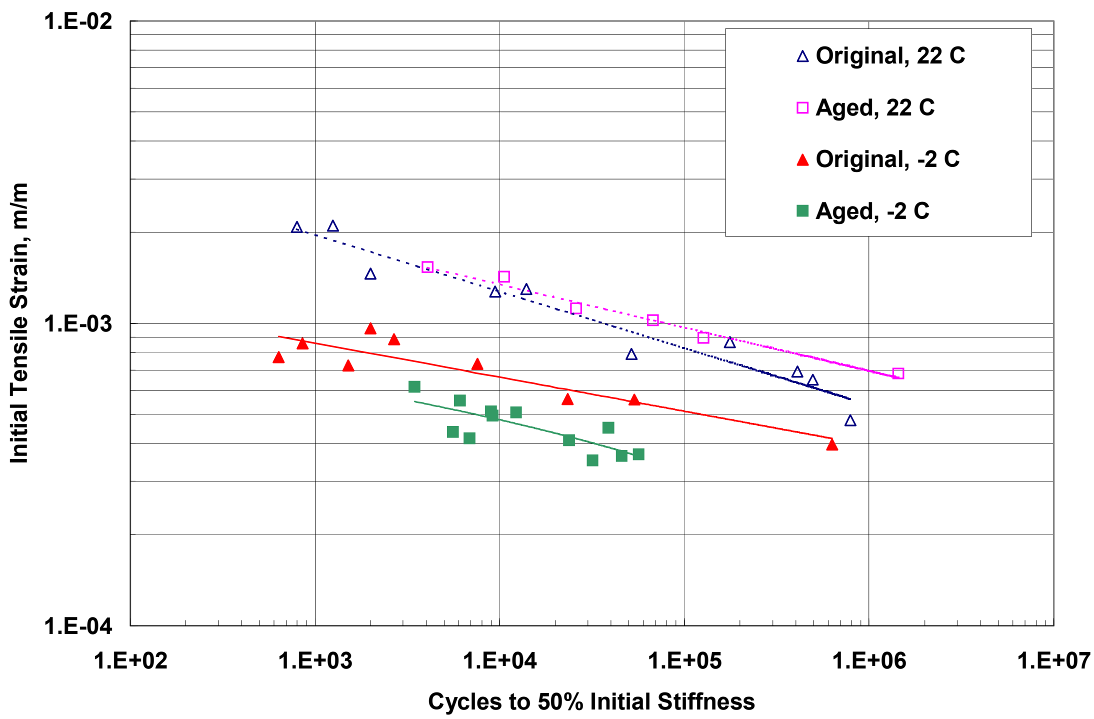


FIGURE 3 Fatigue relationships for ARHM-GG using tensile strain criterion.

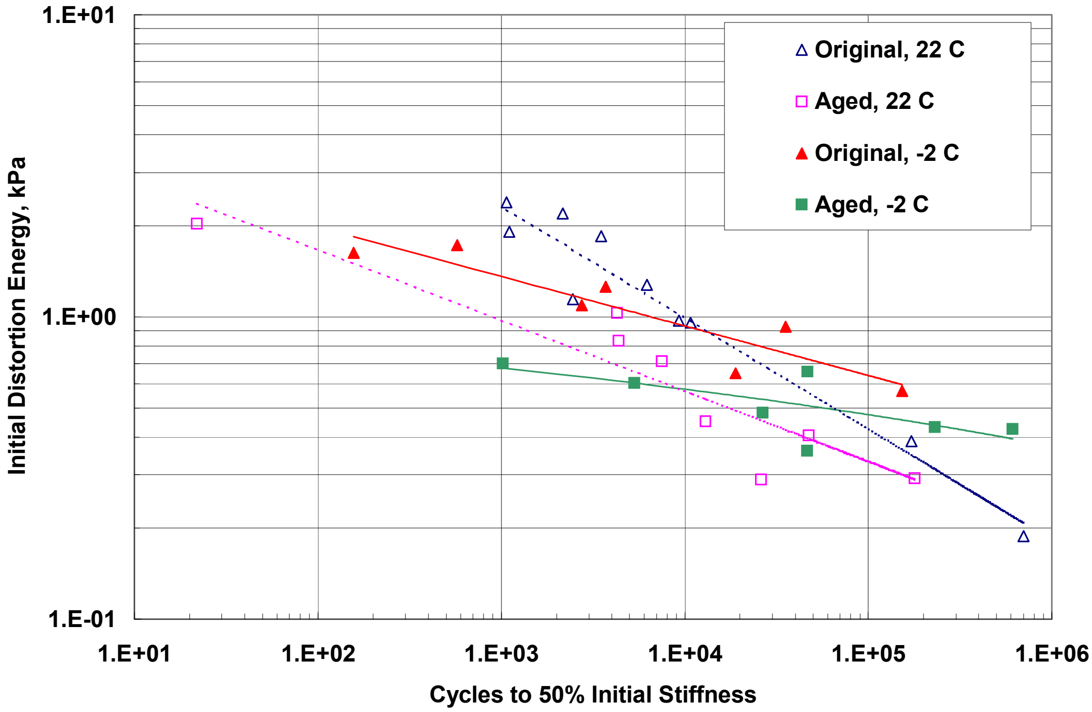


FIGURE 4 Fatigue relationships for CAC-DG using distortion energy criterion.

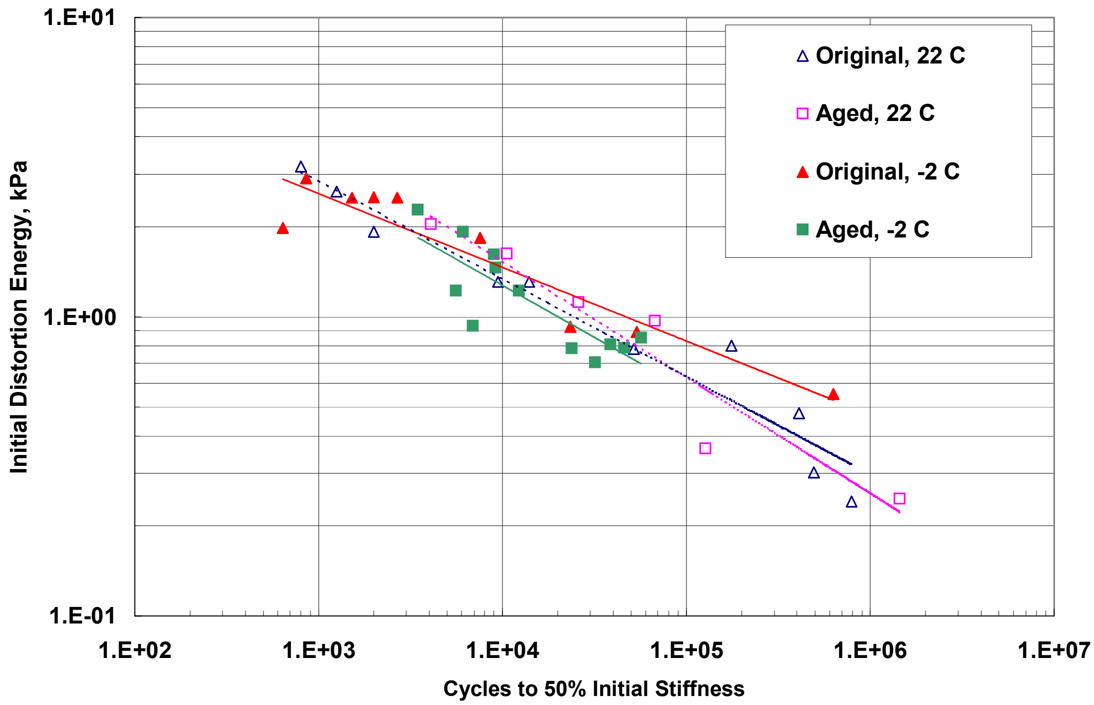


FIGURE 5 Fatigue relationships for ARHM-GG using distortion energy criterion.

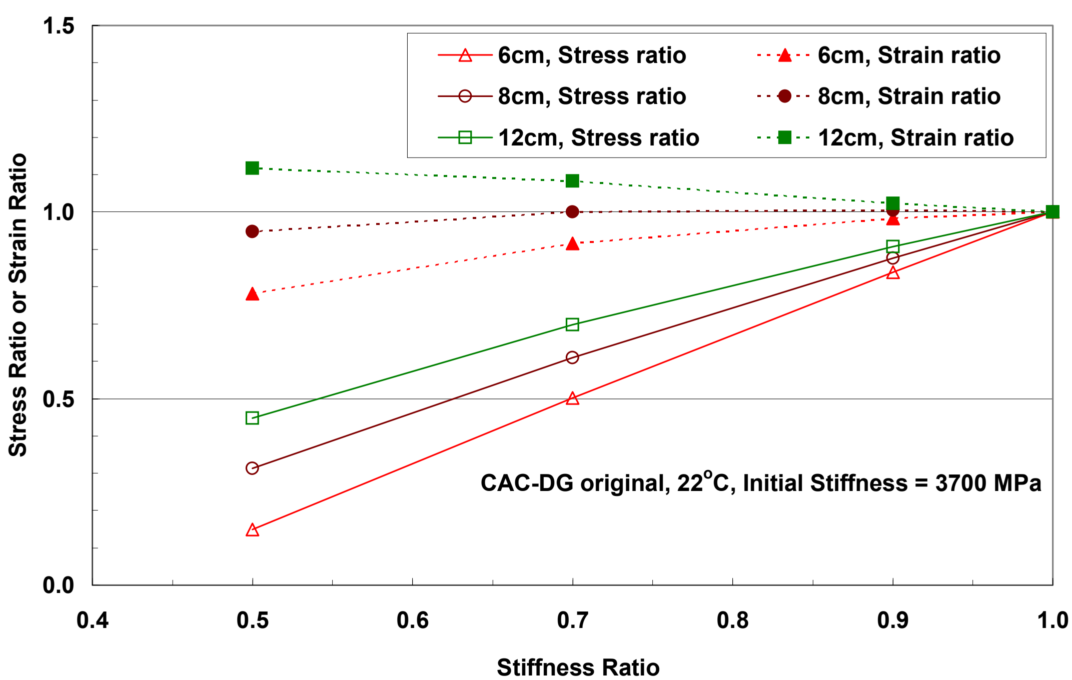


FIGURE 6 Stress or strain ratio variation with stiffness ratio for different overlay thicknesses.

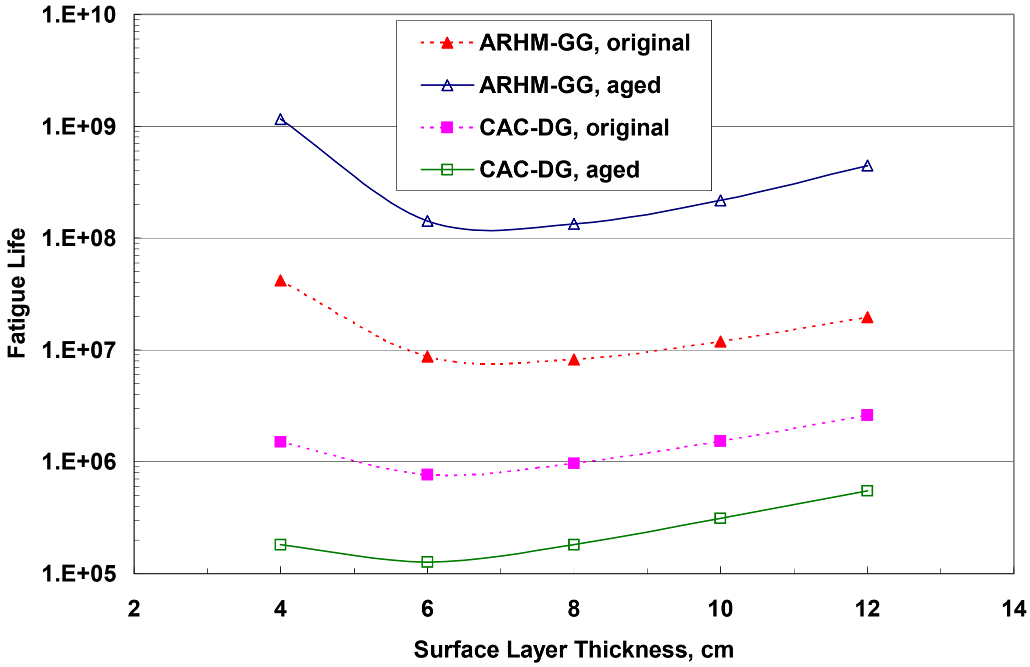


FIGURE 7 Fatigue life variation for new pavement construction (tensile strain criterion).

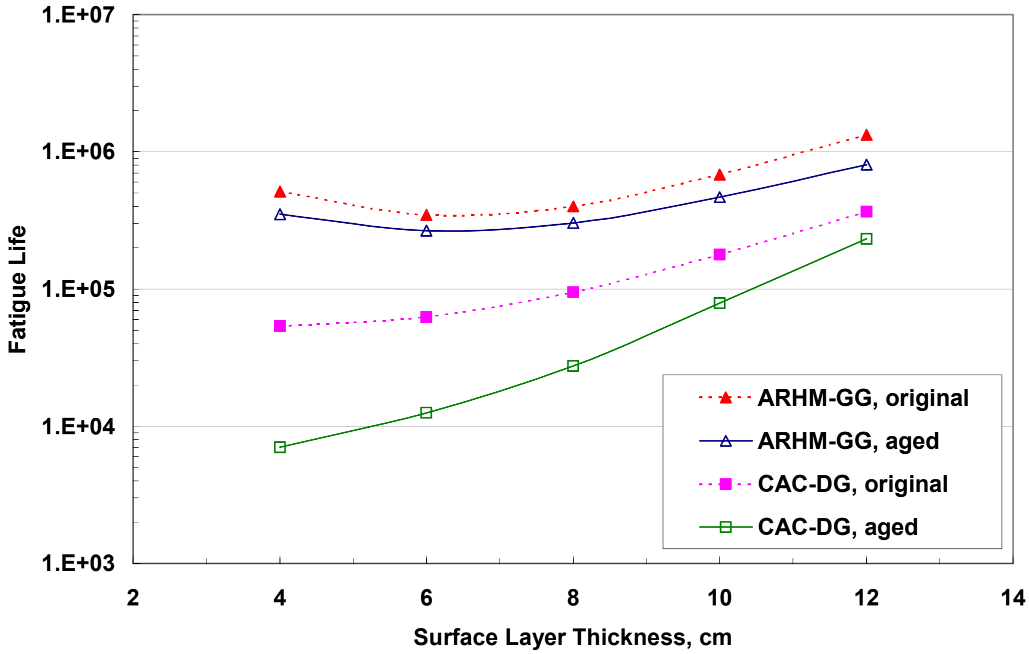


FIGURE 8 Fatigue life variation for new pavement construction (distortion energy criterion).

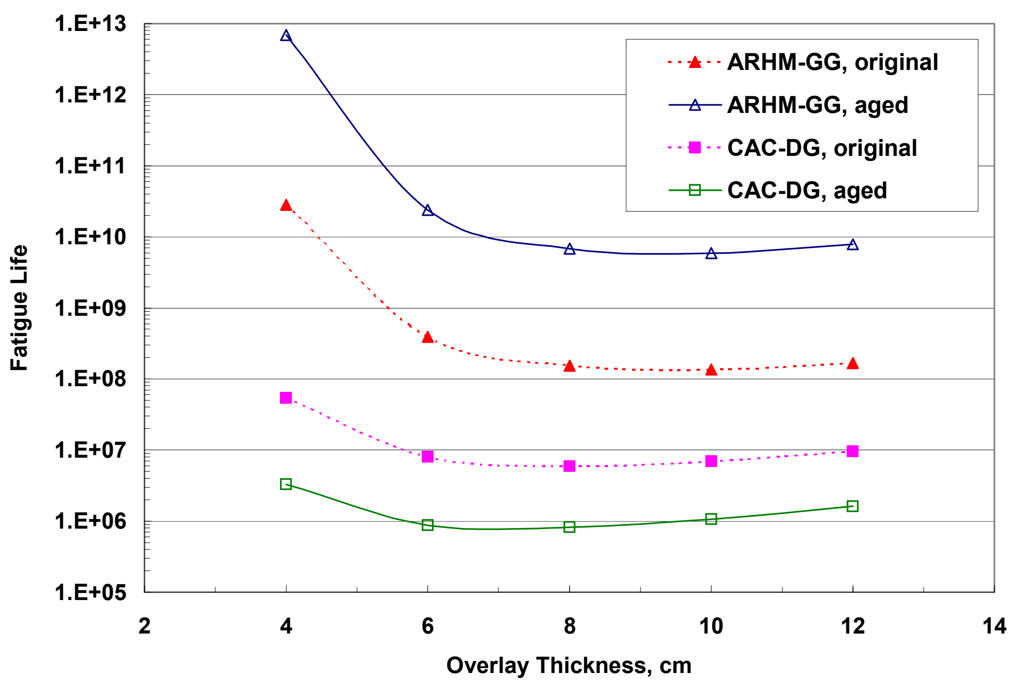


FIGURE 9 Fatigue life variation for overlay construction (tensile strain criterion).

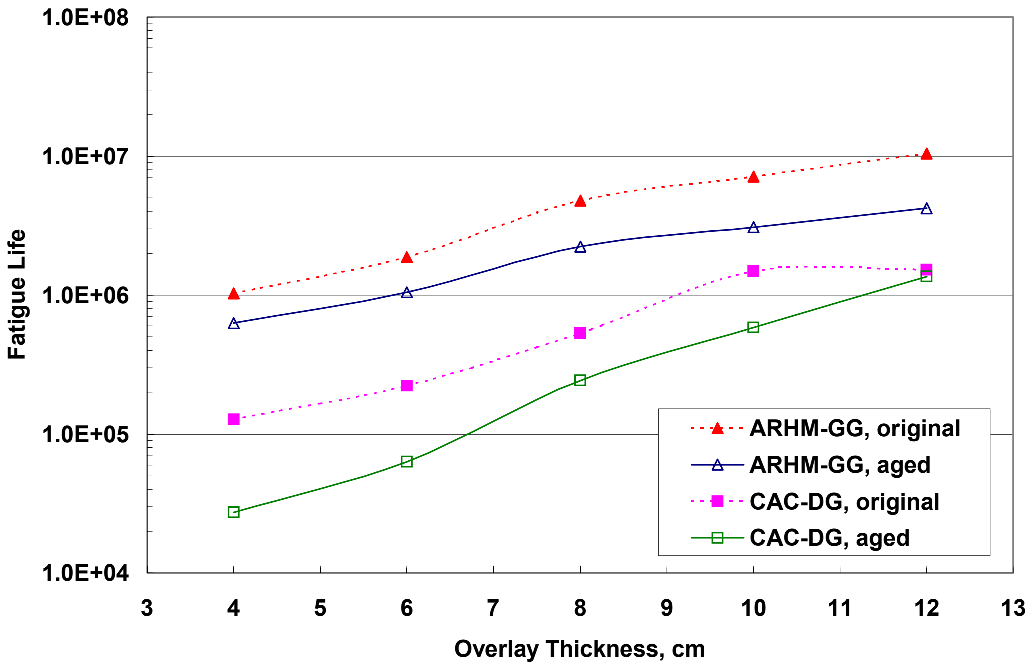


FIGURE 10 Fatigue life variation for overlay construction (distortion energy criterion).