GAP-GRADED ASPHALT MIXTURE BEHAVIOR IN REPEATED FLEXURE *

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1. INTRODUCTION

Although it is a well known fact that the behavior of asphalt concrete is greatly affected by aggregate grading, there are still many problems that require further investigation. For example, there is the question of what is the most suitable grading to use for a specific pavement application. In the United States and Japan, continuous aggregate grading is popular in asphalt mixtures. Recently, the use of gap-graded asphalt mixtures for heavy traffic road construction and snow fall area was tentatively approved for inclusion in the Japan Asphalt Pavement Code. In part based on the fact that it has been successfully used in hot-rolled asphalt is the United Kingdom (BS 594 type mixes) (1) and South Africa (2), (3), (4). At this time it is not clear which of the gradings is better, gap or continuous, or if they each have specific application depending on the pavement section and the environment.

Yoshimoto (5) has stated, based on Marshall test results, "If the ratio of fine and coarse aggregate content is suitably selected by the fine aggregate grading content, the fine aggregate grading itself has little effect on the stability of asphalt mix."

However, there are limits to what can be defined by means of the Marshall testing method. This is for the following reason: Although the practicality of this testing method is established, and this method is widely used throughout the world in determining the asphalt content, it cannot be said that it is always sufficient for defining the basic properties of materials. Hence, the author has conducted a series of experiments to define mixture response in flexure fatigue.

This report summarizes the results of these tests.

2. TEST SPECIMENS

2. 1. Materials

Asphalt cement The asphalt cement was a 40-60 penetration grade with a specific gravity of 1.01 and was supplied by Chevron Asphalt Company.

Aggregate Aggregate used for this investigation was crushed granite from Watsonville, California, with an apparent specific gravity of 2.92.

To insure uniformity in the test specimen, the aggregate was oven dried, separated into individual size fractions, that is 1/2″×3/8″, 3/8″×♯4, ♯4×♯8, ♯8×♯16, ♯16×♯30, ♯30×♯50, ♯50×♯100, and ♯100 below, and then recombined to obtain four gradings shown in Fig. 1. Filler was not used.

2. 2. Aggregate Gradation

Four different aggregate gradings were used for this investigation as shown in Fig. 1. The aggregate grading curve designated S represents a continuous grading which appro-

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ximates the median of the 1975 California Standard Specifications for 1/2 inch maximum size, medium grading (6). The curves designated A, B, and C are gap-gradings which are devoid of ♯4～♯8, ♯8 ～♯16 and ♯4～♯30 aggregate materials respectively. They have been developed, based on the BS594 grading. A BS594 specification grading for hot-rolled asphalt and Japan Asphalt Pavement Code (⑤ and ⑧ dense and gap-graded asphalt concrete) is shown on Fig. 1 for comparison.

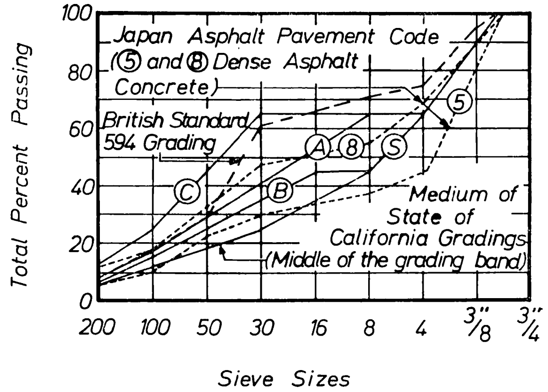


Fig. 1 Aggregate grading curves.

2. 3. Asphalt Content

Only one asphalt content, 6.7 percent (by weight of aggregate) was used in the test specimens.

It should be noted that both the stability and fatigue characteristics of asphalt mixtures vary with asphalt content and that there is an optimum asphalt content for each characteristic. The asphalt content chosen for this investigation does not necessarily correspond to the optimum value for either of these new characteristics.

Monismith (7) investigated the effect of asphalt content on fatigue behavior by using a basalt aggregate grade according to the California 1/2 inch maximum medium specification and mixed with a 60-70 penetration asphalt cement. Asphalt contents varied from 5.3 to 8.7 percent by dry weight of aggregate. Results of his tests suggested that a maximum fatigue life at a stress level of 150 psi occurred at an asphalt content of 6.7 percent. In addition, the optimum asphalt content based on fatigue behavior was about 0.8 percent greater than the asphalt content which could be selected for the stability requirement.

Pell (8) and Jimenez (9) have also studied the effect of asphalt content on fatigue life. Pell's tests were conducted on a British base coarse mix containing a 40-50 penetration and with asphalt contents ranging from 4.1 to 12.5 percent. Specimens were tested at 10°C (50° F) at a stress level of 165 psi. A maximum fatigue life was obatined at approximately 7.5 percent asphalt by weight of total mix (8.1% by weight of aggregate).

Jimenez has shown that the optimum asphalt content in fatigue is a function of the type of aggregate used.

Thus it appears desirable to perform fatigue tests which identify the peak asphalt content necessary for optimum fatigue response for each of the mixes tested herein. Unfortunately there was not enough time to define this parameter for each mix and only the asphalt content, 6.7 percent by weight of aggregate, was used. This asphalt content is considered close to the optimum value for the continuous grading S, at least, from earlier test results (7). On the other hand, asphalt contents for the gap-graded mixtures A, B and C should be higher than that of the continuous grading S, e.g.: Reference (10).

2. 4. Specimen Preparaton

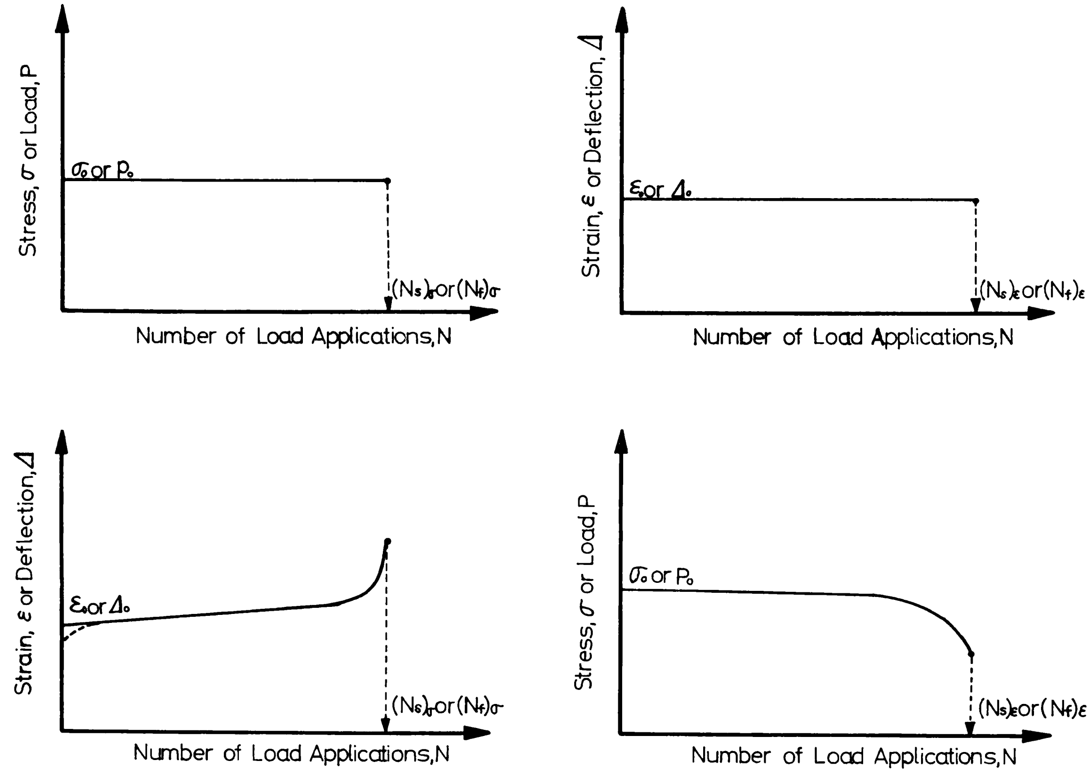
Aggregate and asphalt were heated to a temperature of 270°F and then combined. Mixing was accomplished by hand stirring, aided by a mechanical mixer for a period of three minutes. Mixes were then allowed to cure for 15-20 hours in a forced draft oven at 140°F. Prior to compaction, each mix was reheated for 2½ hours in a 230°F oven.

Flexural teste specimens Compacted block specimens were 3.5×4.5×15 in., and were prepared using a Triaxial Institute Kneading Compactor as follows: Each was compacted in three layers to obtain uniform density throughout its height. The lower layer was compacted with 20 tamps at 145 psi and 60 tamps at 375 psi; the intermediate layer was compacted with 20 tamps at 145 psi, 80 tamps at 375 psi; the surface layer was compacted with 20 tamps at 145 psi and 100 tamps at 375 psi. After compaction, a 1,670 psi leveling load was applied to the surface of the specimen, and maintained for one minute. The block was then sawed into four 1.5×1.5×15 in. specimens for repeated flexural tests with a diamond-tipped table saw.

3. TEST METHODS

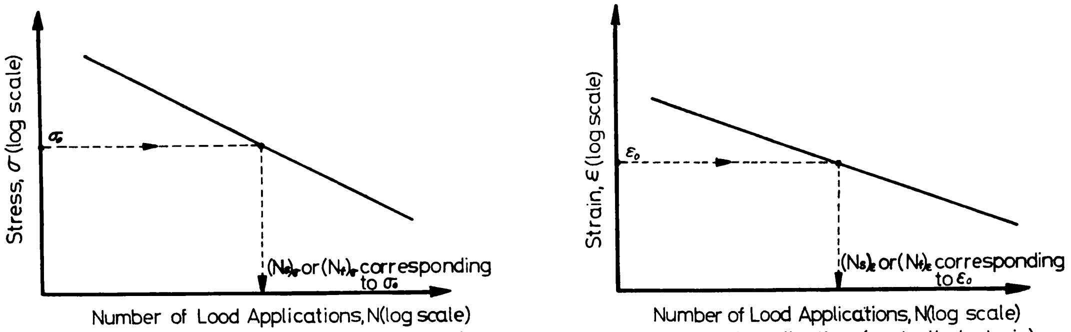
3. 1. Selection of Test Method

To study the influence of aggregate grading on the fatigue behavior of asphalt mixes requires a consideration of the method to be used for determining fatigue response. In addition, because certain conflicting conclusions might be drawn with respect to desirable mix characteristics, the method for determining fatigue response in the laboratory should be similar to the way in which the actual pavement structure undergoes fatigue. Therefore, the mode of loading that is used should descride how stress and strain levels are



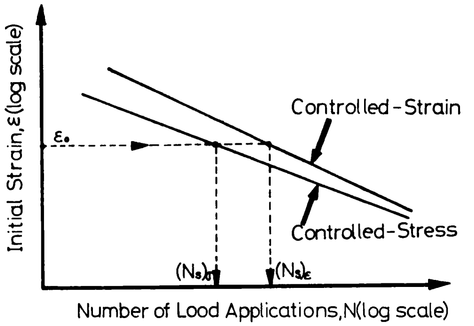
a. Controlled-Stress b. Controlled-Strain

Fig. 2 Schematic representation of behavior of materials in controlled-stress and controlled-strain fatigue test.



a. Stress vs. load applications(controlled-strain).

b. Strain vs. load applications(controlled-strain).



c. Initial Strain vs. load applications, comparison for controlled-stress and controlled-strain tests.

Fig. 3 Fatigue diagrams.

permitted to vary during fatigue loading. If the nominal stress or load is maintained at a constant level throughout the life of the specimen, testng is of the controlled-stress or controlled-load mode. If the nominal strain or deflection is maintained at a constant level, testing is of the controlled-strain or controlled-deflection mode. Both modes of loading are shown schematically in Fig. 2. By performing tests in either mode of loading at different stress or strain levels, one may obtain fatigue diagrams such as shown in Fig. 3.

Using a computer to analyze various types of three-layer system constructions, Monismith (11, 12) suggested that for pavements with an asphalt layer less than about 2″ thick controlled-strain tests would be suitable, since under these conditions the tensile strain at the underside of the asphalt layer is little affected by mix stiffness. For thicker asphalt layers, 4″ and over, the stifness of the mix was found to have a comparativly large influence on the strain value, and a comparatively small influence on stress, hence, under these conditions controlled-stress tests were recommended. Furthermore, information(13) suggested controlled-stress tests will provide a conservative estimate of fatigue response for any mixture regardless of the thickness of the asphaltic concrete. For these reasons controlled-stress tests were used in this study.

3. 2. Controlled-Stress Fatigue Test Procedures

Controlled-stress tests in this study have been performed with the repeated flexural apparatus developed dy Deacon (14).

A four-point loading system applied a uniaxial bending stress to the simply supported specimen and thus created a region of constant bending moment throughout the central 4 inches of the specimen. The time of loading employed in these tests was approximately 0.1 sec; 100 repetitions per minute were also utilized. The specimen was returned to its original unflexed position after each load application. In the controlled-stress tests loading is continued until the beam completely fractures, at which time a limit switch stops the machine; the number of repetitions of load to failure is recorded on a counter. The controlled-stress tests were done at three stress levels (250, 200, and 150 psi). The test temperature was set at 68°F for all tests performed in this study. Dynamic-deflection measurements were obtained during loading through the use of a linear variable differential transformer (LVDT) and recorded on a Sanborn strip chart recorder.

3. 3. Calculated stiffness and strain

Measured load and deflections at 200 stress applications were used to compute the stiffness and strain by means of the following relationships:

$$S=\frac{Pa\,(3\ell^2-4^2)}{48I\Delta} \tag{1}$$

$$\varepsilon=\frac{12t\Delta}{3\ell^2-4a^2} \tag{2}$$

where S = the flexural stiffnss
ε = the flexural strain
P = dynamic load applied to deflect the beam
l = reaction span length
a = distance reaction through point to load point
t = specimen depth
I = specimen moment of inertia
Δ = dynamic beam deflection at center point

TABLE 1 - MEAN, STANDARD DEVIATION AND COEFFICIENT OF VARIATION OF STIFFNESS, STRAIN, AIR VOIDS AND FATIGUE LIFE AND MEAN OF DENSITY

Mix Grading	Stress Level psi	No. of Bars	Mean of Density g/cm^3	Percent Air			Stiffness			Strain			Fatigue Life		
				Mean	Std. Dev.	C_v	Mean psi × 10^3	Std. Dev. psi × 10^3	C_v	Mean in. per in. × 10^{-6}	Std. Dev. in. per in. × 10^{-6}	C_v	Mean	Std. Dev.	C_v
S Continuous Grading	150	6	2.55	2.5	0.51	20.3	510	50	9.8	297	29	10.1	304776	117295	38.5
	200	6	2.54	2.7	0.50	19.9	509	82	16.0	402	64	15.9	95489	22128	23.2
	250	6	2.54	2.5	0.44	17.6	446	39	8.7	565	50	8.9	33871	20689	61.1
A Gap-graded (#4 × 8)	150	6	2.49	4.6	0.89	19.3	498	83	16.6	308	49	15.9	203577	66920	32.9
	200	6	2.48	4.9	0.41	8.4	591	12	21.1	332	47	14.2	71465	37614	52.6
	250	6	2.48	4.9	0.77	15.8	428	9	2.2	585	13	2.2	25170	11118	44.2
B Gap-graded (#8 × 16)	150	5	2.53	3.1	0.47	15.2	540	74	13.7	282	39	13.7	608184	325480	53.5
	200	5	2.52	3.3	0.56	17.0	502	73	14.5	405	64	15.7	100175	34205	34.1
	250	5	2.51	3.8	1.15	30.3	477	26	5.5	526	29	5.5	36138	21426	59.3
C Gap-graded (#4 × 30)	150	5	2.36	9.6	1.03	10.7	392	21	5.3	383	20	5.1	32132	12583	39.2
	200	5	2.34	10.3	0.25	2.4	385	102	26.4	563	132	23.5	9105	2760	30.3
	250	6	2.35	9.8	0.44	4.5	324	9	2.9	772	22	2.9	4391	1242	28.3

4. TEST RESULTS

4. 1. Regression Lines on Fatigue Life

Test results are summarized in Table 1 and include means, standard deviations, and coefficients of variations at the three stress levels for stiffness, strain, percent air voids, density, and fatigue life for four mixtures. Individual test results, linear regression line (calculated least square method) for initial bending strain vs. number of repetitions to failure (N_f) and stress vs. number of repetitions of failure (N_f) relationships for the continuously graded mix S, are shown on Fig. 4. Similarly Fig. 5, 6 and 7 show the data for the gap-graded mixtures, A,B and C respectively. Fig. 4,5,6 and 7 suport the view that a linear relationship can be approximated for the log strain vs. log N_f and the log stress vs. N_f plots.

As shown in Figures. 4, 5, 6 and 7 differences in fatigue life exist on both the strain vs. N_f and the stress vs. N_f plots for the mixes considered. Comparing the results shown in Fig. 4 and Fig. 6, it can be seen that the gap-graded mix B exhibits a longer fatigue life on both the strain vs. N_f and the stress vs. N_f plots than the continuously grade mix S. On the other hand, the gap-graded mix A exhibits somewhat shorter fatigue lives than the continuously graded mixes. while the gap-graded mix C exhibits shorter lives than all the other mixes.

In general, it is said the greater the stiffness, the flatter the slope of the regression line and the longer the life. With this in mind, the slope of the regression lines of strain-N_f and stress -N_f for the gap-graded mix B are flatter than for the same curves for the continously graded mix S. Those for the gap-graded mixes A and C are steeper than for the continuosly graded mix S. Accordingly, it seems that the order for long fatigue life can be arranged as follows, the gap-graded mix B. The continously graded mix S, the gap-graded mix A and the gap-graded mix C.

Fig. 8 shows comparisons of the fatigue relationships of Monismith (7), Pell (8), and the

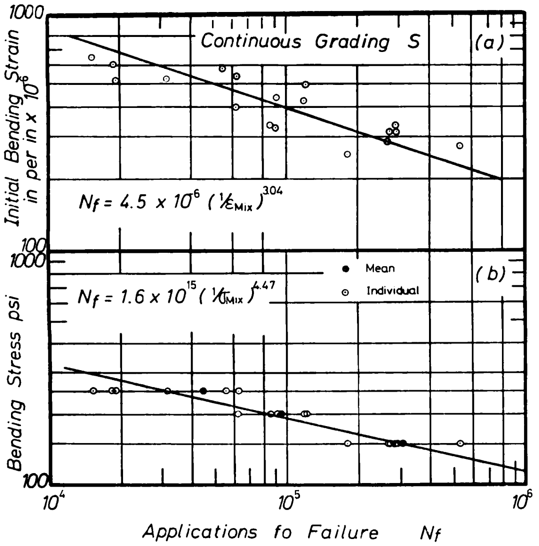


Fig. 4 Initial mixture bending strain (a) and mixture bending stress (b) vs. fatigue life, Continuous grading S.

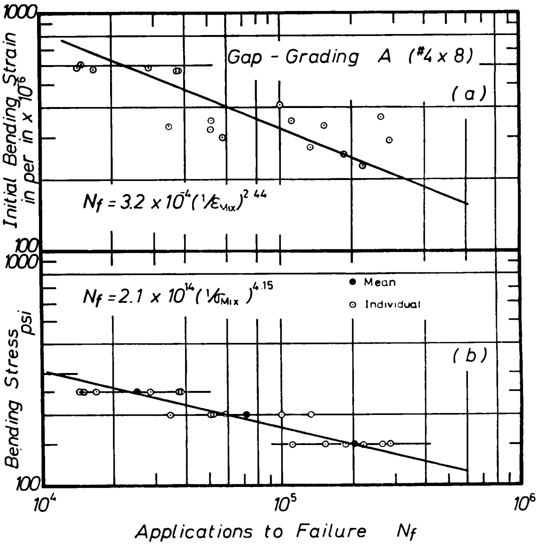


Fig. 5 Initial mixture bending strain (a) anb mixture bending stress (b) vs. fatigue life, Gap-grading A.

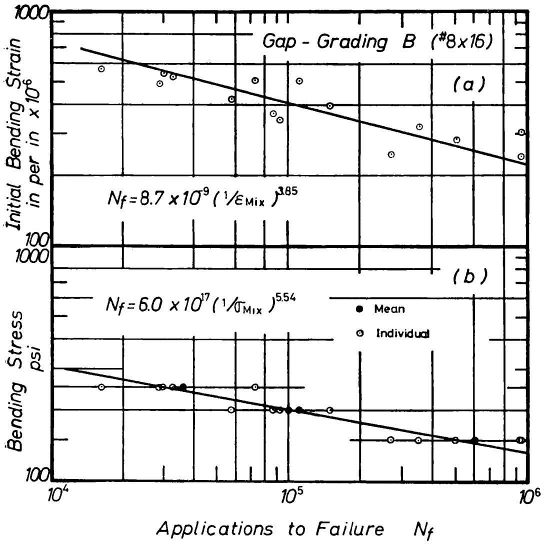


Fig. 6 Initial mixture benbing strain (a) and mixture bending stress (b) vs. fatigue life, Gap-grading B.

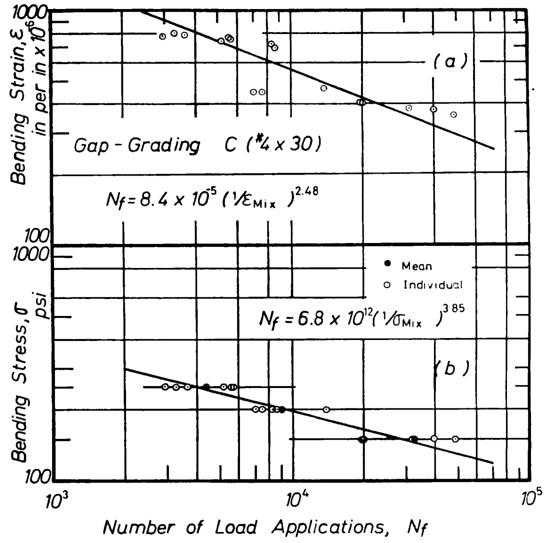


Fig. 7 Initial mixture bending strain (a) and mixture bending stress (b) vs. fatigue life, Gap-grading C.

results of this study. Monismith suggested that that the British mix (D-line) has a mean stiffness of 570,000 psi and an average air void content of 5.4 percent while the California mix (E-line) has a stiffness of 656,000 psi and an air void contens of 4.7 percent. However, the British mix, even with its lower stiffness and higher air void content, provides a longer fatigue life at strain levels expected in pavements.

4. 2. Statistical Analysis

The purpose of this section is to present a statistical comparison of the various mixes tested in this investigation.

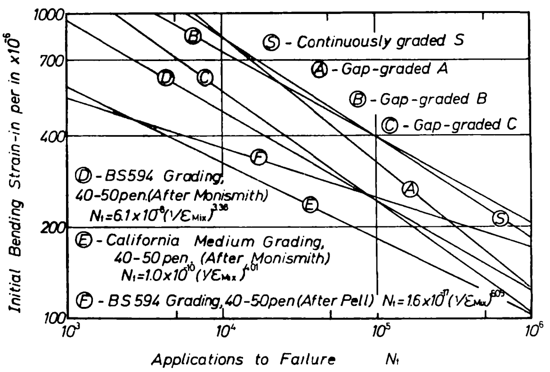


Fig. 8 Comparison of fatigue results from Monismith, Pell and this time - initial mixture bending strain vs. fatigue life.

Fig. 8 Comparison of fatigue results from Monismith, Pell and this time-initiai mixture bending stra invs. fatigue lite.

The results of the regression analysis of this study can be represented by the following equation for mix strain vs. number of load application N_f.

$$N_f = K_1 (1/\varepsilon_{mix})^{n_1} \tag{3}$$

where

N_f = cycles to failure

K_1 = constant depending on mix

ε_{mix} = initial extreme fiber mix flexural strain

n_1 = slope of line

and

$$N_f = K_2 (1/\sigma_{mix})^{n_2} \tag{4}$$

K_2 = constant depending on mix

TABLE 2 - LEAST SQUARES REGRESSION EQUATION AND STATISTICAL QUANTITIES

Mix Designation	No. of Bars	$N_f = K_1(1/\varepsilon_{mix})^{n_1}$		Correlation Coefficient	Standard Error of Estimate
		K_1	n_1		
S Continuous Grading	18	4.49×10^{-6}	3.039	0.852	0.250
A Gap-graded	18	3.18×10^{-4}	2.439	0.796	0.317
B Gap-graded	15	8.67×10^{-9}	3.852	0.868	0.221
C Gap-graded	16	8.38×10^{-5}	2.480	0.898	0.223

Mix Designation	No. of Bars	$N_f = K_2(1/\sigma_{mix})^{n_2}$		Correlation Coefficient	Standard Error of Estimate
		K_2	n_2		
S Continuous Grading	18	1.64×10^{15}	4.472	0.921	0.137
A Gap-graded	18	2.08×10^{14}	4.145	0.906	0.149
B Gap-graded	15	5.98×10^{17}	5.544	0.933	0.120
C Gap-graded	16	6.80×10^{12}	3.846	0.939	0.118

TABLE 3 - F-TEST - TEST OF THE EQUALITY OF THE POPULATIONS STANDARD ERROR OF ESTIMATE

Comparison of	With	Regression Equation	S_1^2	S_2^2	F	F^{α}	Reject	Accept or Reserve Judg.
Mix Designation	Mix Designation							
S Continuous Grading	A Gap-graded	$\sigma - N_f$ $\varepsilon - N_f$	.0187 .0627	.0221 .1005	1.18 1.60	2.67 2.67		x x
S Continuous Grading	B Gap-graded	$\sigma - N_f$ $\varepsilon - N_f$	.0187 .0627	.0144 .0491	1.30 1.28	2.90 2.90		x x
S Continuous Grading	C Gap-graded	$\sigma - N_f$ $\varepsilon - N_f$	.0187 .0627	.0139 .0499	1.35 1.26	2.72 2.72		x x
A Gap-graded	B Gap-graded	$\sigma - N_f$ $\varepsilon - N_f$	.0221 .1005	.0144 .0491	1.53 2.05	2.81 2.81		x x
A Gap-graded	C Gap-graded	$\sigma - N_f$ $\varepsilon - N_f$	.0221 .1005	.0139 .0499	1.59 2.01	2.80 2.80		x x
B Gap-graded	C Gap-graded	$\sigma - N_f$ $\varepsilon - N_f$	.0144 .0491	.0139 .0499	1.04 1.02	2.90 2.95		x x

$\alpha = 0.05$, $F\alpha/2(n_1 - 1 , n_2 - 1)$

σ_{mix} = maximum fiber flexural stress

n_2 = slope of line

for the mix stress - number of load application N_f.

The coefficient of correlation and the standard error of estimate have also been calculated for the regression lines. The coefficient of correlation and the standard error estimate can be represented by the following equation, respectively,

$$r = \frac{\Sigma(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\Sigma(x_i - \bar{x})^2} \cdot \sqrt{\Sigma(y_i - \bar{y})^2}} \qquad (5)$$

$$S = \sqrt{\frac{(1 - r^2)\Sigma(y_i - \bar{y})^2}{n - 2}} \qquad (6)$$

TABLE 4 - t-TEST - SIGNIFICANCE OF THE DIFFERENCE BETWEEN THE REGRESSION COEFFICIENTS b_1 and b_2 OF TWO SEPARATE EQUATIONS

Comparison of	With	Regression Equation	b_1	b_2	n_1	n_2	t	t^{α}	Reject	Accept or Reserve Judg.
Mix Designation	Mix Designation									
S Continuous Grading	A Gap-graded	$\sigma - N_f$	4.472	4.145	18	18	0.71	2.04		x
		$\varepsilon - N_f$	3.039	2.439	18	18	0.93	2.04		x
S Continuous Grading	B Gap-graded	$\sigma - N_f$	4.472	5.544	18	15	2.28	2.05	x	
		$\varepsilon - N_f$	3.039	3.852	18	15	1.35	2.05		x
S Continuous Grading	C Gap-graded	$\sigma - N_f$	4.472	3.846	18	16	1.36	2.04		x
		$\varepsilon - N_f$	3.039	2.480	18	16	0.94	2.04		x
A Gap-graded	B gap-graded	$\sigma - N_f$	4.145	5.544	18	15	2.92	2.05	x	
		$\varepsilon - N_f$	2.439	3.852	18	15	2.13	2.05	x	
A Gap-graded	C Gap-graded	$\sigma - N_f$	4.145	3.846	18	16	0.64	2.04		x
		$\varepsilon - N_f$	2.439	2.480	18	16	0.06	2.04		x
B Gap-graded	C Gap-graded	$\sigma - N_f$	5.544	3.846	15	16	3.59	2.05	x	
		$\varepsilon - N_f$	3.852	2.480	15	16	2.29	2.05	x	

$t_{\alpha/2}(n_1 + n_2 - 4)$ $\alpha = 0.05$ 95% confidence

where:

r = the coefficient of correlation
S = the standard errror of estimate
x_i, y_i = actual values of two variables x, y ($i = 1, 2, \cdots\cdots, n$)
$\bar{x}$, $\bar{y}$ = $1/n\Sigma x_i$, $1/n\Sigma y_i$
n = number of items

Since the regressions are performed on the logarithms of the mix stress, stress and N_f, the distribution of fatigue life around the regression line is a normal log distribution and thus the reported value of the standard error of estimate is the log of the value.

Table 2 presents the regression lines, the correlation coefficient, and the standard error of estimate for the strain-fatigue life and the stress-fatigue life relationships.

To compare the slopes of the regression lines on the strain vs. N_f and stress vs. N_f plots, the F test was first used to test the null hypothesis that the standard errors of estimate for the two relations are equal. Table 3 contains tabulated values upon which the decision to reject or accept the apropriate hypothesis was made. The null hypothesis could not be rejected for an equal-tail test at a level of significance equal to 95 percent and thus we can assume that the standard errors of the estimate for the four possible comparisons are equal.

Since the standard errors of the estimate can be shown to be equal, it is now possible to use the t test. This test was used to test the null hypothesis that the difference between the slope of the lines equals zero. Table 4 presents the results of the t test. This hypothesis could not be accepted for a two-tail test at a level of significance equal to 95 percent.

Accordingly, from the statistical analysis presented above, it seems possible that grading may have an effect on the results of fatigue tests when represented on the stress-fatigue life and the strain-fatigue life plot.

van Dijk (15) has also recently presented data illustrating the effect of aggrregate gradation on fatigue life of asphalt mixes by applying the energy concept to date obtained in controlled-strain tests. The information suggested that since for several mix types the fatigue tests results were rather close together, the permissible strain fatigue curves have been grouped together in a few representative curves. However, the asphalt concrete of the state of California and the Rolled Asphalt Base Course mix from his results were shown to exhibit different responses.

Monismith (7) reported previously that aggregate grading for mixes with three different aggregte gradings (the extreme fine, the middle, and the extreme coarse portions of the grading band in State of California 1/2 in. maximum size aggregate gradings), does not significantly influence the results of fatigue tests when the tests are represented on a plot of mix strain vs. fatigue life. It should be pointed out that the judgment is based on a mix with three different aggregate gradings, identical asphalt contents and containing air voids that varied over a narrow range. However, the information also pointed out that the effect of aggregate grading might somewhat influence the results of fatigue tests when the test data are presented on a plot of mix stress vs. fatigue life.

4. 3. Asphalt Content in Mix

It should be recognized that asphalt content should be considered in the comparison of aggregate gradings. The asphalt content used in this study was 6.7 percent by dry weight of aggregate for all mixes.

As mentioned earlier, an asphalt content of 6.7 percent is approximately close to the optimum asphalt content for the continuously graded mix S. For the gap-graded mixes A, B and C more than 6.7 percent asphalt content would be required. If more asphalt content than 6.7 percent were added for the gap-graded mix B, the difference between the gap-graded mix B and the continuous grading mix S could have been more pronounced on the fatigue curve. Further more, if the gap-graded mix A had been tested at its optimum asphalt content, comparsion with the continuous grading mix S may have shown only slight differences in the the fatigue life.

4. 4. Air void in mix

It is a well known fact that air voids play an important part in the behavior of asphalt concrete. The influence of air void content on fatigue life response has been reported by Monismith (11) and Vallerga (16). The results of these investigations indicated that mixes containing high air void contents exhibit comparatively short fatigue lives. In addition, Monismith(11) suggested that a smaller change in void content is required to change the fatigue life by a specific amount for the California graded mixes (4 to 6 percent increase in air voids to reduce the fatigue live by one order of magnitude than is required for the British standard mix (10 percent increase to reduce fatigue life by one order of magnitude). Furthermore, the information suggested that the structure of the voids (i.e., size, shape, degree of interconnection) as well as their absolute volume is of importance. Mean air void contents obtained by the same compaction conditions for the four different aggregate mixes in this study are 2.6, 4.8, 3.4 and 9.9 percent for the continuous grading S, gap-graded uses A, B and C respectively, Table1.

Air void content of the gap-graded mix B is higher than that of the continous grading S. Nevertheless, the stiffness and the fatigue life of the gap-graded mix B are larger and longer than that of the continuous grading mix S. The difference in air voids between the gap-graded mix A and the continuous grading mix S is 2.2 percent. However, the difference in stiffness and the fatigue life seem to be negligible. The gap-graded mix C, however, has a very high air void content compared to other mixes. Hence, the stiffness and the fatigue life of the gap-graded mix C are inferior.

With this in mind the difference in the stiffness and the fatigue life between continous grading and gap-graded mixtures may thus in part be due to the size and shape of the void in the two types of mixes since visual examination indicated that gap-graded mix contained smaller size voids than the continuous graded mix.

5. CONCLUSIONS

The influence of aggregate grading on the fatigue response may be summarized as follows:

1) Gap-graded mix B seems to be a little better than the continuous grading S in fatigue response.
2) Gap-graded mixes A and C seem to be somewhat inferior in comparison with the continuous graded mix S in fatigue response.
3) If aggregate grading could be compared at the optimum asphalt content in each of the mixes, gep-graded mixes would have compared favorably with continuous grading mixes.
4) Aggregate grading seems to have an effect on the slope and intercept of both the strain -N_f and stress- N_f regression lines.

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REFERENCES

1. Specification for Rolled Asphalt (Hot process), BS 594, 1961.
2. Marais, C. P., National Institute for Road Reserch, RR 172, "Gap-Graded Asphalt Surfacings- the South African Scene." Proceedings, Second Conference on Asphalt Pavements for Southern Africa, 1974.
3. Acott, S. M., The Development and Mix-Design of Gap-Graded Asphalt, National Institute for Road Research, South Africa, RB 1975.
4. Duthie, J. L., "Some Thoughts on the Design on the Design of Gap-Graded Mixes,"

Municipal Engineer, May/June, 1975.

5. Yoshimoto, A. and S. Ogino, "Influence of Grading of Fine Aggregate on Marshall Stability of Asphaltic Concrete, "Proceedings of the Japan Society of Civil Engineering, No. 166, June 1969.
6. State of California, Department of Public Works, Division of Highways, Standard Specifications, January, 1975.
7. Monismith, C. L., Epps, J. A., and Kasianchuk, D. A., Asphalt Mixture Behavior in Repeated Flexure, the Materials and Research Department, Division of Highways, State of California, University of California, Berkeley, Report No. TE 70-5, December 1970.
8. Pell, P. S., "Fatigue of Asphalt Pavement Mixes," Proceedings, Second International Conference on the Structural Design of Asphalt Pavements, University of Michigan, 1967.
9. Jimeneze, R. A., and B. M. Gallaway, "Behavior of Asphaltic Concrete Diaphragms to Repetitive Loading, "Proceedings, International Conference on the Structural Design of Asphalt Pavements, University of Michigan, 1963.
10. Pell, P. S., anp G. Boyd, "Fatigue of Asphalt Road Mixtures, "Civil Engineering and Public Works Review, April, 1966.
11. Monismith, C. L., Asphalt Mixture Behavior in Repeated Flexure, Report No. TE 66-6, University of California, Berkeley, December, 1966.
12. Monismith, C. L., Influence of the Shape, Size, and Surface Texture on the Stiffness and Fatigue Response of Asphalt Mixtures, Highway Research Board, Special Report 109, 1970.
13. Monismith, C. L., Kasianchuk, D. A., and Epps, J. A. Asphalt Mixture Behavior in Repeated Flexue; a Study of an In-Service Pavement Near Morro Bay, California. University of California, Berkeley. Report TE 67-4, December 1967.
14. Deacon, J. A., Fatigue of Asphalt Concrete. Graduate Beport, the Institute of Transportation and Traffic Engineering, University of California, Berkeley, 1965.
15. Dijk, W., and W. Visser, The Energy Approach to Fatigue for Pavement Design, The Annual Meeting of the Associaton of Asphalt Paving Technologists, Texas, February 1977.
16. Vallerga, B. A., F. N. Finn, and R. G. Hicks, "Effect of Asphalt Aging on the Fatigue Properties of Asphalt Concrete, "Proceedings, Second International Conference on the Structural Design of Asphhalt Pavements, University of Michigan, 1967.