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Fatigue Performance of a Bituminous Road Mix Under Realistic Test Conditions

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A study whose purpose was the verification of Miner's rule for estimating the cumulative damage resulting from the phenomenon of fatigue is reported. A repeated-bending apparatus driven by a minicomputer, which was devised to generate and control stress or strain waves of variable amplitudes, is described. The fatigue behavior of a bituminous mix subjected to nine different loading patterns (simple, random, and block) was determined. The influence of rest periods of different lengths was studied for these cases. It is concluded that (a) to the extent that the spectrum of load amplitudes is known, a prediction method derived from Miner's law is applicable with an acceptable accuracy for random sequences that include no rest periods and (b) rest periods markedly increased fatigue life for the three loading patterns considered. These initial conclusions were used to derive a generalized form of Miner's law for loading conditions in which both stress amplitudes and the duration of rest periods are variable. This generalized law was verified by simulating actual conditions of traffic loading in fatigue tests.

Intensive worldwide laboratory research on the mechanical properties of bituminous mixes has led to the establishment of methods of estimating fatigue performance (or number of loading cycles at failure). One of the major criticisms of these methods concerns the simplicity of applied loading. It is a fact that the continuous cycles of loading of constant stress or strain amplitude generally applied in laboratory tests are not realistic enough to simulate the compound-loading conditions to which a road material is subjected under actual traffic loads.

To take account of compound loading in structural design methods, Miner's law is used. Miner's law assumes a linear cumulative effect of damage irrespective of the true history of the applied loads. Several authors who have made experimental investigations to estimate the degree of accuracy of this law (1-6) have come to different conclusions depending on the type of loading history used.

In fact, the experimental approach to realistic conditions may be manifold: Even when it ignores variations in temperature, the realistic test history must include a succession of loading cycles followed by rest periods that are distributed randomly in both duration and size according to statistical distributions that reflect traffic characteristics. Fundamental understanding of such a process can only be attained through a stepwise progression in the degree of complexity of test conditions.

Enough is now known about the fatigue process under simple loading to allow a better understanding of more complicated loading patterns. For this reason, the Centre de Recherches Routières has undertaken an experimental research project to study realistic fatigue testing.

EXPERIMENTAL PROCEDURE

The mechanical part of the apparatus used in this research is identical to that used in earlier investigations (7): Trapezoidally shaped specimens 9×3 cm at the base, 35 cm in height, and 3 cm thick are fixed at their larger bases and submitted to a bending force that acts tangentially to their smaller bases by means of an electromagnetic exciter. Transducers fitted to the tops of the specimens and connected to the input of an analog-to-digital converter allow the continuous measurement of force and displacement.

A periodic command signal computed by a 16K data processor is fed to the power amplifier of the exciter by a digital-to-analog converter. This signal is servocontrolled and fitted to the preset reference level according to the mean measured amplitudes of either force or displacement (calculated over 16 consecutive cycles). The mode of loading of the test may thus be controlled stress or controlled strain. The control level depends on the values introduced by the user before the start of the test.

At each cycle, the computed control can be performed at a different level of stress or strain, proportionally, to a sequence of up to 8000 integer numbers between 0 and 15 (called here "level indices") introduced in memory registers by the user and continuously scanned by the computer program, one number being assigned to each cycle. By looping on this numerical sequence, the processor is able to generate any distribution of stress or strain amplitudes in any order of succession to be decided by the user.

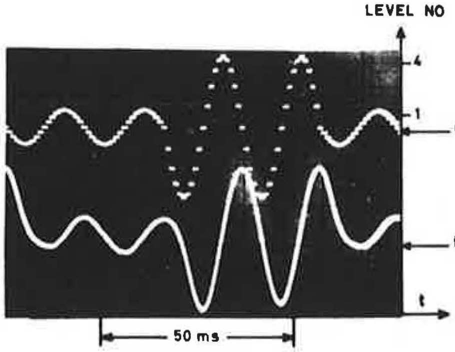
Typical test conditions, such as cycle blocks with different lengths, pseudorandom sequences, or stationary sine waves, can easily be generated and controlled merely by introducing the appropriate sequence of level indices in memory before the start of the test. Rest periods can be obtained by introducing zero values at the desired places in the sequence.

Figure 1 shows the sinusoidal signal generated at a frequency of 50 Hz by using a sequence of four numbers (1, 1, 4, 4) as well as the corresponding displacement signal. Other loading patterns are also visible in the photographs shown in Figure 2.

A fatigue test can be run on one sample once the initial strain or stress at level index 1 has been assigned by the user during the starting procedure. The fatigue curve of the mix is obtained from several fatigue tests run at different initial stress or strain values at level index 1. Histograms of the level indices as well as of the amplitudes of force and displacement are continuously implemented while the test is in progress. Values of the resilient modulus and relevant numbers of cycles are recorded every time the uncontrolled signal (displacement or force) has varied by a fixed fraction of its initial value.

Seven control tests are executed at each loading cycle to detect the rupture of the specimen or any failure of the system. Histograms and recorded values that describe the mechanical evolution of the sample are listed at the end of the test, just before the cutdown of the power supply of the whole system.

Figure 1. Variable-amplitude command signal and corresponding displacement of viscoelastic specimen.



The equipment works fully automatically and complies with German specification DIN 51228.

MIX COMPOSITION

One of the major problems in the fatigue testing of composite materials is the broad scatter of observed lifetimes. Because of this, in any investigation of the influence of factors that affect fatigue behavior, many experiments must be performed to get a statistically significant result.

The mix used in this investigation was selected for its low variability in test results (low standard deviation about mean life). It contains 35 percent stones, 52.8 percent sand (particles <2 mm), and 12.2 percent 0.075-mm limestone filler bound with 8 percent bitumen of 40-50 penetration grade. This type of mix, similar to British hot-rolled asphalt, is used in Belgian road construction as a wearing course to be covered with precoated chippings.

EFFECT OF LOADING HISTORY AND REST PERIODS

The tests conducted on the selected mix in the first part of the experimental program consisted of the nine loading patterns shown in Figure 2. These experiments were carried out under controlled stress and at constant temperature (15°C) and frequency (55.6 Hz, period = 18 ms).

The results of the normal fatigue test C_0 were used as reference for the other conditions; the mean cumulative fatigue life obtained under these conditions was close to one.

The statistical distribution of amplitude levels (number of cycles per level) shown in Figure 3 was used in all the tests carried out at eight levels. This nearly Gaussian distribution centered on the fourth level (mean = 4 and standard deviation σ = 1.12) has a shape that is similar to the spectrum of contact pressures induced by commercial vehicles on Belgian roads (8).

Rest periods were introduced after each loading cycle on tests C_1, C_2, B_1, B_2, R_1, and R_2. In the B block tests, the number of cycles repeated in each block was fitted to obtain the loading spectrum in Figure 3. The different blocks were arranged in increasing or decreasing order to avoid abrupt level changes. Rest periods in tests B_1 and B_2 were gathered in one block and placed between the blocks of level 1 beginning or ending the pattern of repeated loading. The fatigue life of the mix was determined for each type of test on at least eight specimens tested at different stresses.

The set of test conditions considered here allows the investigation of the influence of (a) the arrangement of the different amplitudes of stresses, (b) the effect of rest periods and their length on fatigue life, and (c) the combination of these two factors.

Fatigue Life Under Simple Loading

First, fatigue tests were carried out on the mix in accordance with the usual procedure, i.e., constant amplitude of stress without rest periods. The fatigue law can be expressed as

$$\epsilon_i = K N_i^{-a} = \epsilon_{N=10^6} (N_i/10^6)^{-a} \qquad (1)$$

where

ϵ_i = initial strain,
K = factor dependent on mix properties,
N = cycles to failure, and
-a = an empirical factor.

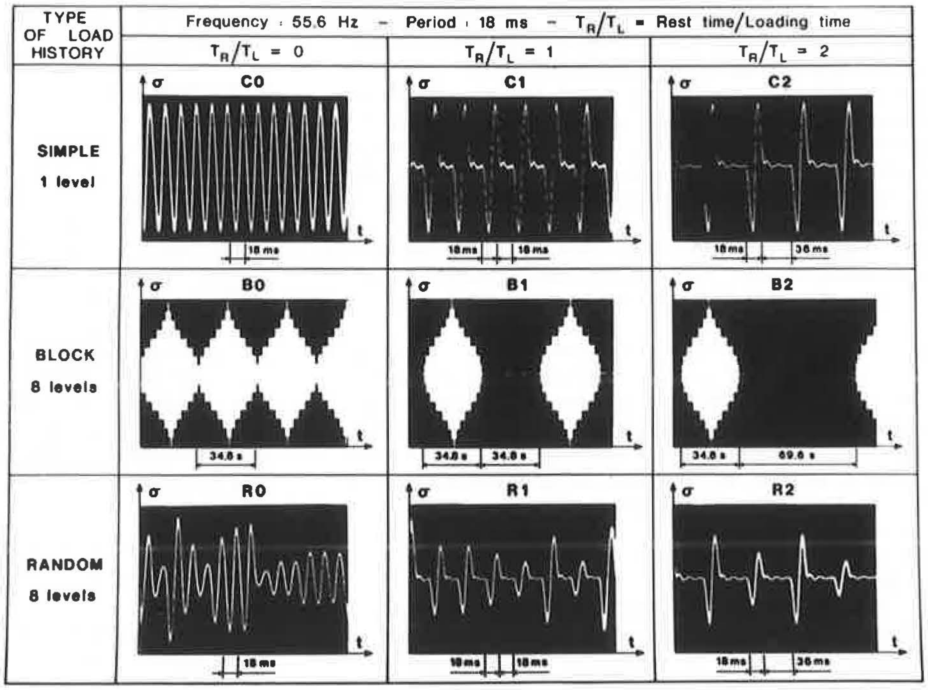


Figure 2. Compound test conditions.

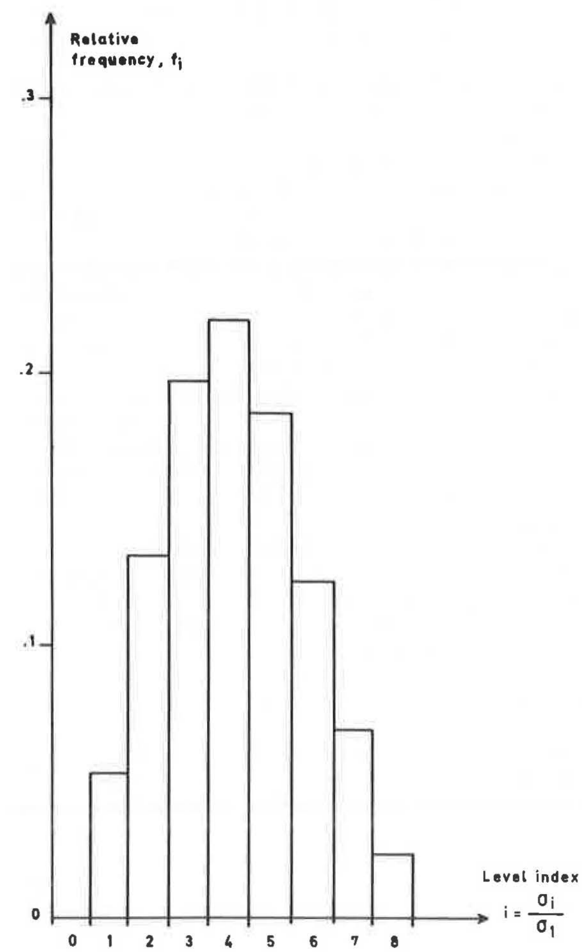


Figure 3. Spectrum of load amplitude for compound tests.

The parameters of the fatigue law were obtained by least-squares adjustment through the experimental points shown on the double log scale in Figure 4. Notice that these points are located along a curve that is not exactly straight. The fracture lives corresponding to the lowest and highest levels of applied stress are systematically higher than those than can be predicted by Equation 1.

This particular shape, which is visible thanks to the low scatter in the experimental results, reveals that the general form of the fatigue law (Equation 1), although close to the observed points, may lead to underestimated values of fatigue life, especially in the case of very small stresses where the slope of the fatigue curve is lower.

A relation of the following type gives a better fit of the experimental results and can be used to calculate interpolated fatigue lives:

$$\log \epsilon = C(\log N)^{-D} \qquad (2)$$

Results and Interpretation of Compound Tests

The usual way of interpreting results of compound fatigue tests is to calculate for each specimen the cumulative cycle ratio M:

$$M = \sum_{i=1}^{q} (n_i/N_i) \qquad (3)$$

where

q = total number of applied loading levels,
n_i = number of applied loading cycles at level i, and
N_i = fatigue (or service) life of the mix under simple fatigue test at level i.

The deviation from unity of the mean M-value obtained from different fatigue tests for a given loading pattern indicates the degree of discrepancy from Miner's hypothesis.

It is possible to establish a generalization of the fatigue law for the case of tests carried out at q stress

Figure 4. Fatigue diagram for simple mode of loading (C_0 = controlled stress at constant amplitude).

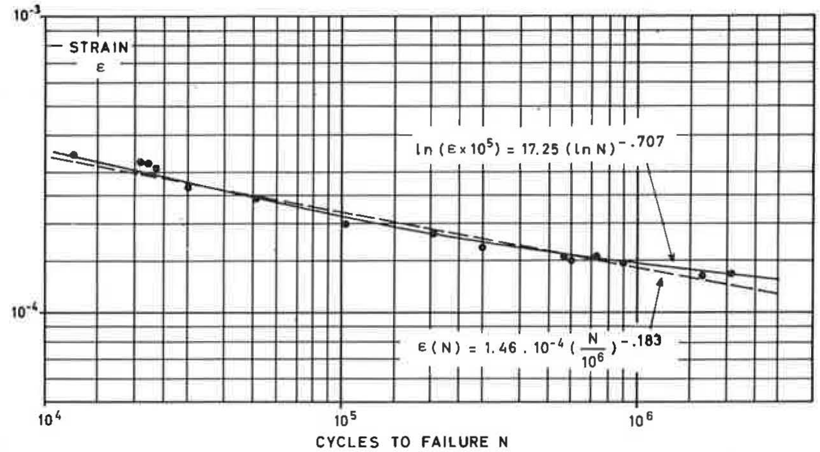


Table 1. Results of compound tests.

Type of Test	Number of Tests	Based on Fatigue Law $\epsilon = K(FN)^{-a}$: $\epsilon_{N=10^6}$ (0.10^4)	a	Correlation Coefficient	Standard Deviation of Log Life	$M = \sum_{i=1}^{q} n/N$	Standard Deviation on M	Based on Equation 2: M	Standard Deviation on M	$\Sigma n_i/N_T$ at $N = 10^6$
C_0	14	1.46	0.183	-0.99	0.041	1.07	0.414	1.04	0.313	1.03
C_1	8	1.79	0.192	-0.99	0.058	3.39	1.262	3.04	1.333	3.73
C_2	12	1.96	0.167	-0.98	0.068	4.83	1.884	4.78	2.849	5.58
C_6	15	2.17	0.177	-0.94	0.098	9.27	4.376	6.104	4.132	7.65
C_{10}	8	2.42	0.208	-0.99	0.061	19.62	7.467	7.91	6.48	9.72
C_{20}	8	2.76	0.150	-0.91	0.122	32.84	20.53	11.78	17.66	11.11
B_0	15	1.64	0.166	-0.99	0.041	1.676	0.447	1.686	0.588	2.15
B_1	7	1.70	0.191	-0.99	0.028	2.47	0.628	2.174	0.606	2.71
B_2	8	1.93	0.173	-0.997	0.033	4.260	0.732	3.288	1.734	4.24
R_0	14	1.60	0.152	-0.99	0.043	1.337	0.501	1.414	0.568	1.79
R_1	16	1.89	0.199	-0.97	0.072	4.881	1.820	3.336	1.766	4.34
R_2	14	2.06	0.182	-0.98	0.054	6.672	1.671	4.478	2.198	5.82

levels by using the following assumptions:

1. The fatigue law at constant level is given by Equation 1 with the same exponent a for all levels.
2. The spectrum of the q stresses σ_i is known, which means that frequencies $f_i = n_i/N_T$, where N_T is the total number of loading cycles applied up to failure, are known for the q-level indices $i = \sigma_i/\sigma_1$.

If these assumptions are verified, M can be expressed as a function of the parameters of the fatigue law, the strain ϵ_1 at level 1, and the stress spectrum, as follows:

$$M = N_T(\epsilon_1/K)^{1/a} \sum_{i=1}^{q} (f_i i^{1/a}) \quad (4)$$

In the case in which Miner's law is valid (M = 1), the following relation arises between N_T and ϵ_1:

$$(\epsilon_i/i)\left(\sum_{i=1}^{q} f_i i^{1/a}\right)^a = K N_T^{-a} \quad (5)$$

This expression is identical to the prediction technique proposed by Deacon and Monismith (6) for both random and repeated block loading.

Equation 4 shows that the relation between initial strain at level 1 ($\epsilon_1 = \epsilon_i/i$) and total service life N_T is identical to the simple fatigue law given in Equation 1 if the initial strain at the lowest level is multiplied by a correcting factor

$$F = \left(\sum_{i=1}^{q} f_i i^{1/a}\right)^a \quad (6)$$

that depends only on the loading spectrum and on the exponent a of the fatigue law. The value of this factor for the loading spectrum in Figure 3 is 5.26.

Equation 5 allows the graphical interpretation of the results of tests (carried out at different levels and obeying the same distribution function) on the same basis as the simple fatigue test by plotting the corrected strains $\epsilon_1 F$ versus N_T. Hence, Miner's law can be verified by determining the parameters K (or $\epsilon_{N=10^6}$) and a of this modified fatigue diagram and by comparing the resulting values with the relevant values at the simple fatigue test C_0. The numerical results obtained in this way for the nine loading patterns considered are given in Table 1. Strain corresponding to a life of 10^6 cycles was calculated by use of Equation 5 for each case.

Notice that, although the slope a of the fatigue law varies between 0.15 and 0.20 from one test series to another, this variation is not systematically related to the type of test. On the other hand, important variations in the strain $\epsilon_{N=10^6}$ in connection with the loading history are to be seen:

1. When the loading pattern contains no rest periods, the variation is only 12 percent.
2. When rest periods are present, the variation may increase by more than 30 percent.

The same trend is observable when one considers the cumulative cycle ratios:

1. Without rest periods, longer service lives are obtained for compound-loading patterns, and the random case appears to be intermediate between the simple fatigue test and the block test. Because of the low value of the power factor a of the fatigue law, the 25 percent

increase in service life observed for the random case may be considered relatively unimportant.

2. When rest periods are incorporated in the tests, the increase in service life becomes more important and Miner's law completely fails even for the simple case C2, where the service life is practically multiplied by a factor of 5. This lengthening of life is of the same order of magnitude if rest periods are combined with the random type of loading.

Another important feature of these test results is the fact that, irrespective of loading history, the M obtained are always increasing with N_T. This means that the lengthening of the fatigue life is greater for the lower initial strains. This effect, which was observed in each of the six compound test series that included rest periods, may be attributed to the fact that (a) more experimental points were located in the almost horizontal part of the fatigue curve and (b) the presence of very low stresses might play a role similar to that played by rest periods. Because of that effect and in order to base our judgment on comparable test conditions, a value of M corresponding to a total fatigue life of 10^6 cycles was calculated by interpolation (see the final column in Table 1).

Up to rest periods of 2, the average M and $M(10^6)$ are very close. The difference becomes more important when longer rest periods are inserted between the loading cycles. To investigate this factor, test series C, at constant amplitude, was run with rest periods up to 20 (tests C6, C10, and C20). In the last case, a difference of a factor of 3 could be observed between $\overline{M}$ and $M(10^6)$.

The evolution of $M(10^6)$ as a function of the length of rest periods is shown in Figure 5. An empirical relation of the following form can be used to describe the lengthening effect caused by rest periods:

$$M(T_R/T_L) = 1 + 2.8(T_R/T_L)^{0.44} \quad (7)$$

It should be noted that this relation is only valid for the mix used in this investigation.

GENERALIZED FORM OF MINER'S LAW

The main conclusions of this experimental program are that

1. Miner's law can be considered a good approximation of the total lifetime of a mix when no rest periods are inserted between the loading cycles.
2. When rest periods are present, the life of the mix is extended by a factor M depending on the length of the rest periods.

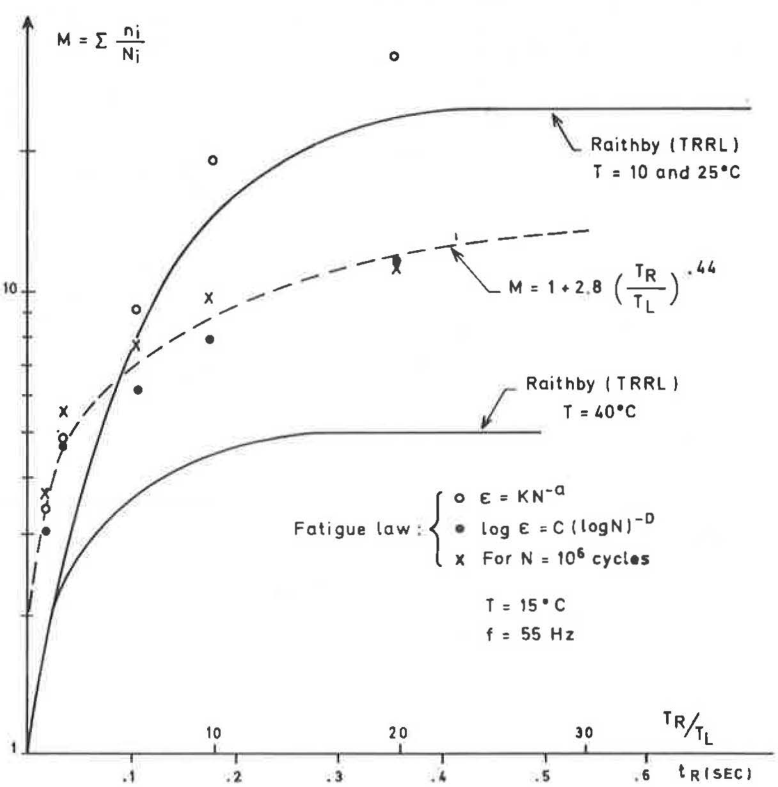
It is possible, on these bases, to establish a generalized form of Miner's law for the case in which the frequency is constant and both the applied stress amplitudes and the lengths of the consecutive rest periods vary randomly during a fatigue test.

To derive an expression equivalent to Miner's law, first we consider a loading cycle as consisting of two parts: a sinusoidal stress cycle of amplitude σ_i applied during time T_L followed by a rest period of duration T_R. The different stress levels σ_i are distributed in I discrete classes, and the rest periods T_R are distributed in J classes so that $\sigma_i = i\sigma_1$ (with i = 1, 2, . . . , I) and $T_R = jT_L$ (with j = 1, 2, . . . , J). Each loading cycle is thus defined by two indices (i, j) statistically distributed according to a two-dimensional distribution function f(i, j).

If N_T is the total life at a given initial strain ϵ_1, the fractional life of any type of loading cycle is $n_{ij}/N_{ij} = f(i, j)\, N_T/N_i\, M(j)$. The summation over indices i, j provides a new expression for the cumulative cycle ratio M′:

$$M' = N_T \sum_{i=1}^{I} \sum_{j=1}^{J} f(i, j)/N_i M(j) \quad (8)$$

Figure 5. Effect of rest periods on fatigue life.



By applying Miner's hypothesis ($M' = 1$) and replacing N_i deduced from Equation 1 in this formula, the relation between initial strain ϵ_1 at level 1 and the total life N_T becomes

$$(\epsilon_i/i)\left\{\sum_{i=1}^{I}\sum_{j=1}^{J}[f(i,j)i^{1/a}/M(j)]\right\}^{a} = KN_T^{-a} \qquad (9)$$

which again is similar to the normal fatigue law (Equation 1) provided ϵ_1 is multiplied by a correction factor that depends on a, the distribution function f(i, j), and M(j).

EXPERIMENTAL VERIFICATION BY TRAFFIC SIMULATION

Procedure

Experimental verification of the generalized Miner's law was performed on the tested mix so that Equations 1 and 7 can be used to calculate N_i and M(j). As a further step toward an actual field situation, the distribution functions f(i, j) and the configuration of the rest periods were adjusted so that they reflected as closely as possible the loading conditions induced by commercial traffic observed on major roads in Belgium (8). Thus, the simulation performed in the test program described here deals with heavy, strongly canalized traffic.

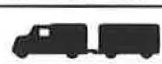
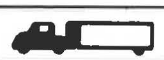
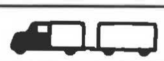
The statistical study of this traffic has shown that 95 percent of the commercial vehicles belong to the five types of vehicles shown in Figure 6. Approximately a third of these vehicles were unloaded; in this study, therefore, a total of 10 categories of vehicles (5 loaded and 5 unloaded) were taken into consideration. Characteristics of these vehicles are also shown in Figure 6.

For the experimental simulation, each vehicle is represented by two, three, or four axles. Each axle is represented by a sinusoidal pulse of amplitude $\sigma_i = i\sigma_1$ ($1 \le i \le 7$) followed by a rest period $T_R = jT_L$ ($7 \le j \le 30$) to simulate the time gap between successive axles or between a rear axle and the next vehicle (j = 30). This limitation at 30 of the time between successive vehicles was imposed to maintain a reasonable duration for the tests. As shown in Figure 5 and demonstrated by Raithby and Sterling (2, 3), there is a limiting value of M above j = 20; thus, the limitation at 30 should not seriously affect the realism of the test results.

The magnitude of the pulses (indices i) attributed to the different axles was chosen in order to approach as closely as possible a normal distribution P(i) (mean $\bar{i}$ = 4.5 and standard deviation σ = 1.39) similar to that of the contact pressures observed on the road. The resulting two-dimensional distribution f(i, j) and the corresponding one-dimensional distribution $f(i) = \sum_{j=1}^{J} f(i,j)$ [adjusted to P(i)] are given below:

i	j	f(i, j) (%)	f(i) (%)	P(i) (%)
1	17	1.1	1.1	1.22
2	17	1.9	5.8	5.72
	21	0.4		
	23	0.8		
	25	2.7		
3	22	8.9	17.8	16.0
	30	8.9		
4	7	2.3	27.3	26.8
	20	0.8		
	21	0.8		
	22	17.7		
	29	1.1		
	30	4.6		
5	17	6.1	26	26.8
	29	2.2		
	30	17.7		
6	7	3.9	15.6	16
	29	5.6		
	30	6.1		
7	7	0.8	6.7	5.72
	20	1.7		
	23	1.7		
	30	2.5		

Figure 6. Characteristics of simulated traffic.

STATE	Vehicle type	Relative frequency (%)	Code N°	Number of axles	Level index i of axle number				Rest period j of axle number			
					1	2	3	4	1	2	3	4
LOADED		45.03	1	2	4	5	-	-	22	30	-	-
		2.10	2	3	4	7	7	-	21	7	30	-
		5.59	3	3	5	5	6	-	17	29	30	-
		9.86	4	4	5	6	6	6	17	25	7	30
		4.23	5	4	6	7	7	7	25	23	20	30
UNLOADED		22.40	11	2	3	3	-	-	22	30	-	-
		1.01	12	3	2	4	4	-	21	7	30	-
		2.76	13	3	1	4	4	-	17	29	30	-
		4.89	14	4	2	2	4	4	17	25	7	30
		2.11	15	4	2	2	4	4	25	23	20	30

Each type of loading sequence that defines a particular vehicle type was put in the computer memory. During the tests, the generation of the loading sequence simulating the passage of an individual vehicle was initiated by the computer each time the code number of that vehicle was met in a pseudorandom sequence of 8000 integer numbers distributed according to relative vehicle frequencies (Figure 6). Figure 7 shows an oscillogram for the passage of three vehicles during such a simulated-traffic fatigue test.

The number n_{ij} of loading cycles that belongs to each vehicle type is continually counted while a fatigue test is in progress so that the individual distribution function f(i, j) is accurately known for each fatigue test. It should be noted that the distributions obtained in practice were always identical to the input distribution function as given in the table above.

Results

Fatigue tests were carried out on 16 specimens subjected to different values of initial strain at level 1 ($0.5 \times 10^{-4} < \epsilon_1 < 0.9 \times 10^{-4}$). This variation of initial strain amounts to observing the strain waves generated by actual traffic at different depths of the road pavement. The conditions applied as well as the results obtained in each case are given in Table 2.

Figure 7. Traffic simulation obtained by combining variable-amplitude sine waves and rest periods of different lengths.

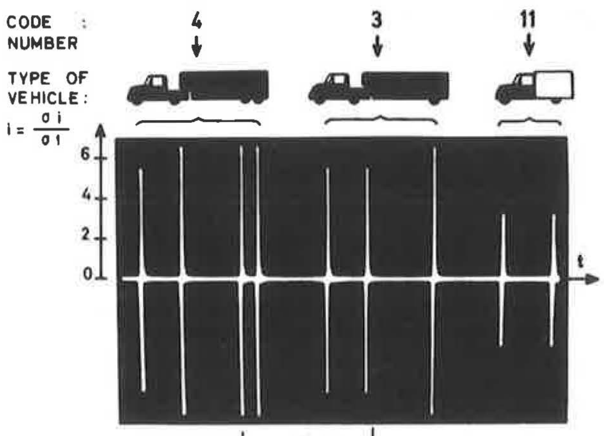


Table 2. Results of fatigue tests for simulated traffic.

Initial Strain $\epsilon_1 \times 10^4$	Number of Cycles N_T	Number of Vehicles	Cumulative Cycle Ratio at Failure: From Equation 1, M	From Equation 1, M′	From Equation 2, M	From Equation 2, M′
0.57	182 077	68 342	7.94	0.922	6.42	0.72
0.57	370 649	140 562	16.29	1.90	13.17	1.47
0.61	257 089	96 902	17.06	1.98	12.2	1.36
0.62	188 756	70 937	13.36	1.51	9.26	1.02
0.66	109 168	40 887	10.21	1.18	6.52	0.72
0.67	110 152	41 069	11.48	1.09	7.09	0.69
0.69	117 135	43 920	14.39	1.68	8.42	0.93
0.70	52 427	19 576	6.92	0.81	3.95	0.44
0.76	46 678	17 587	9.69	1.13	4.69	0.52
0.78	37 013	13 738	9.01	1.05	4.06	0.45
0.81	23 705	8 701	6.68	0.78	2.82	0.31
0.82	30 300	11 158	9.29	1.09	3.81	0.42
0.83	21 150	7 682	6.92	0.81	2.75	0.30
0.87	17 411	6 287	6.93	0.81	2.52	0.28
0.89	16 082	5 833	7.48	0.88	2.55	0.28
Mean			10.24	1.18	6.01	0.66
Standard deviation			3.51	0.40	3.46	0.38

The M cumulative fatigue lives deduced from the usual procedure (Equation 4) can be compared with that obtained from the generalized law (Equation 8) in which the fatigue lives N_i and the function M(j) are respectively given by Equations 1 and 7. The improvement of the prediction technique is clearly visible in the individual values as well as in the mean values. A fatigue curve that obeys Equation 9 can be drawn by plotting $\epsilon_1 = \epsilon_i/i$ versus N_T in a log-log scale.

CONCLUSIONS

1. The results obtained in this research clearly show that it is possible to predict the fatigue life of a bituminous mix submitted to a stress history in which both the stress amplitude and the length of the consecutive rest periods vary randomly.
2. Use of this prediction method necessitates precise knowledge of (a) the fatigue law under continuous sinusoidal cycling, (b) the distribution function of applied amplitudes and rest periods, and (c) an empirical function that relates the cumulative cycle ratio M to the length of the rest periods.
3. There is experimental evidence that this method can be applied to actual traffic conditions.
4. The experimental procedure described in this paper allows the simulation of a broad variety of loading patterns and an unlimited choice of statistical distributions of loads and rest periods. It can thus be easily applied in many cases where heavier and less flexible machines are used.
5. Future research in this field should be concentrated on factors that were not considered in this study, such as mix composition and temperature variations.
6. Further research is also needed on the influence of this modified cumulative law on structural pavement design methods directed toward the limitation of fatigue failure.

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Effect of Laboratory Curing and Compaction Methods on the Stress-Strain Behavior of Open-Graded Emulsion Mixes

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Research into the curing of open-graded asphalt emulsion mixtures is described. Relations that characterize the development of the resilient modulus at different curing temperatures are developed, and comparisons are made between air curing and vacuum curing. The Marshall hammer and the vibratory air hammer are compared to determine the effects of compaction methods on resilient modulus. The results of testing at various levels of density are also reported. It was found that open-graded emulsion mixes develop final values of resilient modulus that vary with curing temperature and tend to be higher for increased curing temperatures. Vacuum curing was found to produce the highest values of resilient modulus. A comparison of methods of compaction showed that samples compacted by the vibratory hammer develop lower modulus values than samples compacted by the Marshall hammer. A comparison of test results obtained at different levels of density indicated that as density increased there was a substantial increase in modulus.

Open-graded emulsion mixes are mixtures of open-graded aggregates and emulsified asphalt, usually CMS-2. An open-graded mixture is characterized by high void contents of about 20-30 percent and less than 10 percent of the material passing the 2-mm (no. 10) screen (1). Common U.S. Forest Service specifications for aggregate gradations are given below (1 mm = 0.039 in):

Sieve Size (mm)	Percentage Passing
25	100
12.5	45-70
9.5	
4.75	0-20
2	0-6
0.075	0-2

The success of early projects led to increased use of open-graded emulsion mixes; it became evident, however, that the performance of these mixes varied. Simple modifications of methods of thickness design for hot mix were not always successful. Early failures of some projects have recently resulted in a reduction in the use of open-graded emulsion mixes by one of its largest users, Region 6 of the U.S. Forest Service (2). Although the causes of these failures have usually not been precisely determined, the emulsion mix has often been blamed whether it contributed or not. The common solution to failure is to increase the pavement thickness by adding an overlay and thus burying the problems.

As a result of this varied performance of open-graded-mix pavements, Region 6 of the U.S. Forest Service contracted with Oregon State University to develop a procedure for designing pavements with these materials. The overall objective of the project is to develop a procedure for determining layer coefficients for use in the Region 6 version of the AASHTO design guides (3). Specifically, the program includes development of

1. Test equipment and procedures to characterize stress-strain behavior of open-graded emulsion mixes,
2. A procedure for assigning layer coefficients for open-graded emulsion mixes by using the test data generated together with layered theory, and
3. A plan for extensive verification in the field of the proposed procedure to establish layer coefficients.

This paper describes work done to determine the effects of curing and compaction methods on the stress-strain behavior of open-graded emulsion mixes as a part of the first of these objectives. For hot-mix asphalt concrete, factors that are known to have a considerable effect on pavement performance include quality and gradation of aggregate, grade of asphalt, quality control of construction, and amount of traffic. These factors also affect the performance of open-graded emulsion mixes. Curing conditions also appear to have an important effect on the behavior of emulsion mixes (4).

This study examines chiefly the effects of time and temperature on curing. The effects of methods of com-