This paper reviews the state of knowledge resulting from laboratory research into the phenomenological characterization of fatigue behavior. In particular, it considers the influence of various factors that affect the fatigue performance of asphalt mixes. The definition of laboratory service life and the values obtained depend on the method of testing; controlled stress loading appears to be applicable for materials used in thick asphalt construction, and controlled strain loading is more appropriate for thin layers. Fatigue performance can best be characterized by a strain ϵ and life N_s relation of the form $N_s = C(1/\epsilon)^m$. The factors C and m depend on the composition and properties of the mix and are also affected by the testing method. Under controlled stress conditions, mixes having maximum stiffness will give longer lives; and, therefore, the choice of mix composition should be such that under compaction maximum tensile stiffness associated with minimum voids is obtained. Under controlled strain condition, longer lives are likely to be obtained from more flexible, less stiff materials. Ideally, general strain-life relations can be established for various mixes by laboratory testing and used for design purposes. Alternatively, use may be made of empirical relations relating fatigue performance to mix properties.

Characterization of Fatigue Behavior

P. S. Pell
University of Nottingham, England

The term "fatigue" implies a mode of distress in an asphalt concrete pavement resulting from the repeated application of traffic-induced stresses. In particular, this symposium was concerned with fatigue fracture, and the purpose of this paper is to consider the influence of various factors that affect the fatigue performance of asphalt mixes. A considerable amount of laboratory research has been carried out and documented (1, 2, 3, 4, 5, 6) on the phenomenological characterization of fatigue and enables certain overall conclusions to be drawn. As well as providing useful information for optimum mix design against fatigue cracking and a means of comparing the performance of different mixes, the current state of the art can be used to predict that cracking will occur after the application of a particular traffic volume.

However, a considerable amount of crack propagation will have to occur over a wide area before any serious deterioration of the pavement structure results from the possible penetration of water or from increase in stresses in the underlying layers or from both. Pavement performance under traffic depends not solely on the characteristics of the materials in the individual layers but rather on the interaction of the various layers, and that aspect of the problem is discussed in other papers (30, 31).

Besides the phenomenological approach to the problem of fatigue of asphaltic concrete pavements with which this paper is concerned, a more recent development is the mechanistic approach based on fracture mechanics (7), and that is discussed in another paper (33). Although the primary object of this present paper is to emphasize the existing state of knowledge that can be applied, certain areas requiring further research in order to improve the accuracy of fatigue life predictions will be mentioned.

DEFINITIONS

Fatigue has been defined (2) as "the phenomenon of fracture under repeated or fluctuating stress having a maximum value generally less than the tensile strength of the material." However, in practice and in the laboratory, fatigue failure is often loosely considered to be the point at which the material or specimen is unable to continue to perform in a satisfactory manner. The failure or the end point of a fatigue test has been defined by investigators in many ways. It may be the point corresponding to complete fracture of the test specimen, the point at which a crack is first observed or detected, or the point at which the stiffness or some other property of the specimen has been reduced by a specific amount from its initial value. The choice is often arbitrary depending on the method of testing being used, and hence an intelligent interpretation of fatigue results requires that the point of failure be explicitly defined.

Service life N_s is the accumulated number of load applications necessary to cause failure in the test specimen. In general, the service life as defined here has often been called the fatigue life, but it is a function of the manner in which failure is defined. Fracture life N_f is the accumulated number of load applications necessary to completely fracture a specimen. When the failure point is complete fracture, then the service and fracture lives are identical.

The fatigue behavior of a specimen subjected to repeated loading depends primarily on the load, environmental, and specimen variables. Load condition refers to the particular set of values that the appropriate load and environmental variables assume for a particular load application. Simple loading occurs when the load condition remains unchanged throughout the fatigue test. Compound loading results from the repeated application of loads in which the load condition changes during the fatigue test. In practice, asphalt pavements are subjected to a form of compound loading with a succession of load pulses of varying sizes and durations and with varying time intervals between pulses depending on the details of the traffic. Changes, such as ambient temperature and moisture conditions, are also taking place in the environment. Few attempts have yet been made in the laboratory to study cumulative damage by compound loading, and most laboratory fatigue tests have been of the simple loading type with the load-time curve being sinusoidal, triangular, square, or some other regular wave form.

TYPE OF FATIGUE TEST

Generally, testing methods are either controlled stress mode when the loading is in the nature of an alternating stress of constant amplitude or controlled strain mode when the loading is in the form of an applied alternating strain or deflection of constant amplitude (Fig. 1). In controlled stress loading, if the stiffness of the specimen reduces during the test, then the strain will gradually increase; in controlled strain, the resulting stress on the specimen will fall with decreasing stiffness. In many cases, the service life of the specimens greatly depends on which of the 2 modes of testing is used.

Because the method of testing influences the results of fatigue tests, the question arises as to which method is preferable. Monismith and Deacon (2) have proposed a more quantitative basis for differentiation between the 2 modes of loading by introducing the mode factor, a parameter defined as

$$\text{Mode factor} = \frac{|A| - |B|}{|A| + |B|} \qquad (1)$$

where $|A|$ and $|B|$ are the percentage changes in stress and strain respectively for an arbitrary but fixed percentage reduction in stiffness. The mode factor has a value of -1 for controlled stress loading and +1 for controlled strain conditions. For intermediate modes, where both stress and strain are changing during the test, the mode factor lies between the limits of -1 and +1.

The applicability of types of fatigue tests to actual road conditions has been considered in various types of pavement construction analysis using layered elastic theory to investigate the effect of variations in asphalt stiffness on the stresses and strains occurring in the asphalt layer. Figure 2 (2) shows a typical example of a 3-layer structure where $E_2 = 20{,}000$ psi, $E_3 = 6{,}000$ psi, and $h_1 + h_2 = 26$ in. As the thickness and stiffness of the asphalt layer increase, the mode factor decreases and a controlled stress condition is approached. It is, therefore, suggested that controlled stress testing conditions are appropriate for thicker asphalt layers, say, 6 in. or more, and controlled strain tests are suitable for thin asphalt layers of 2 in. or less, for under those conditions the strain is little affected by the mixture stiffness.

For the intermediate thicknesses, some form of testing between those 2 extreme modes would strictly be appropriate; but for an engineering design approach, controlled stress tests would seem sensible because they give a conservative estimate of fatigue life.

The method of performing simple loading fatigue tests is to test specimens in controlled stress loading at different stress levels (or in controlled strain loading at different strain levels) and to determine the corresponding service life. A variety of testing equipment has been used; each type of apparatus and its associated specimen size and shape has certain advantages and disadvantages. To date, most results have been obtained from bending or flexure tests on rectangular specimens tested as simply supported beams (1, 5, 8, 9, 10), trapezoidal-shaped specimens tested as cantilevers (11, 12), or specimens having a circular cross section with varying diameter tested as rotating cantilevers (4, 6, 13). Cylindrical and rectangular specimens are increasingly being used both under direct uniaxial (tension-compression) loading (13, 14) and under triaxial states of stress (15). Plate specimens (16) and torsional specimens (17) have been used to obtain biaxial stress conditions, and the indirect tensile test has also recently been adapted for repetitive loading (18).

Most laboratory fatigue tests have been carried out under uniaxial stress conditions either in flexure or in direct loading, but in the pavement the material is subjected to complex, 3-dimensional stressing (13). In the case of bituminous-bound materials, it is not expected that the effect of confining stress and shear reversal will be as significant as with unbound materials; but nevertheless fatigue tests under more realistic stress conditions need to be carried out to confirm that expectation (12).

PRESENTATION OF FATIGUE TEST RESULTS

There is always considerable scatter of results in any fatigue testing of nominally identical specimens, and that is particularly so in the case of asphaltic mixtures because of the inherent inhomogeneity of the material and the unavoidable variation in specimen preparation. That means that fatigue life must be considered in a statistical manner and strictly as only a distribution of individual values. It is usually assumed that there is a logarithmic normal distribution of fatigue lives at a particular loading condition, and a histogram (Fig. 3) constructed from the results of tests on 100 nominally identical specimens tested under the same loading conditions supports that assumption (4).

Because of the normal scatter, it is necessary to test several specimens at each stress or strain level, and the results are usually plotted on log-log scales as stress or strain versus cycles of load to failure. Figure 4 shows some typical results of controlled stress testing. Individual lives are plotted at +10 C, and it can be seen that a straight line passes through the mean of the logarithm of the lives at each stress level. That type of result has generally been found to be true, and an equation representing that relation can be written as

$$\log N_s = \log K - n \log \sigma \qquad (2)$$

where

N_s = mean service life obtained at particular loading conditions,
σ = amplitude of applied tensile stress, and
K and n = coefficients that can be determined by linear regression analysis techniques.

Figure 1. Types of fatigue tests.

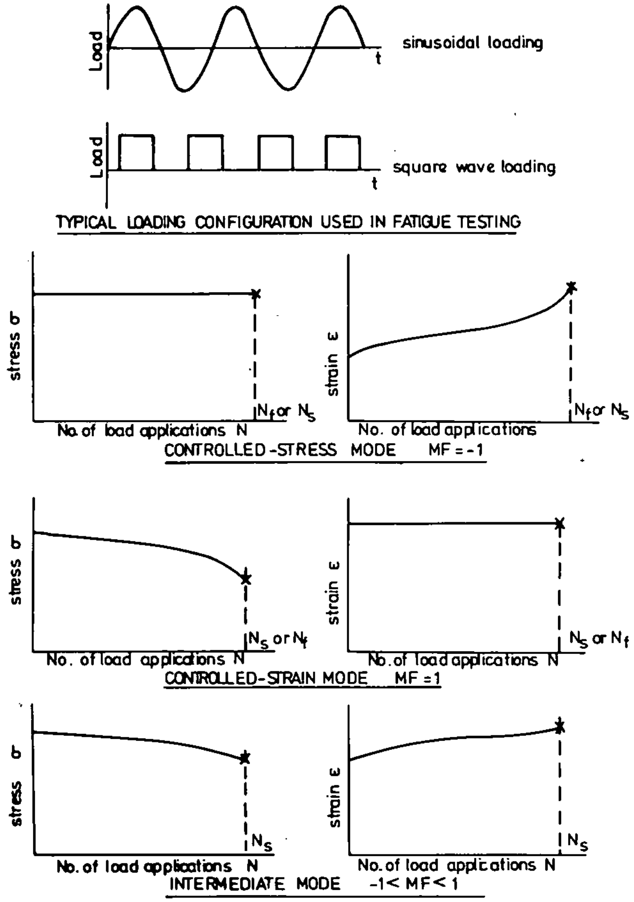
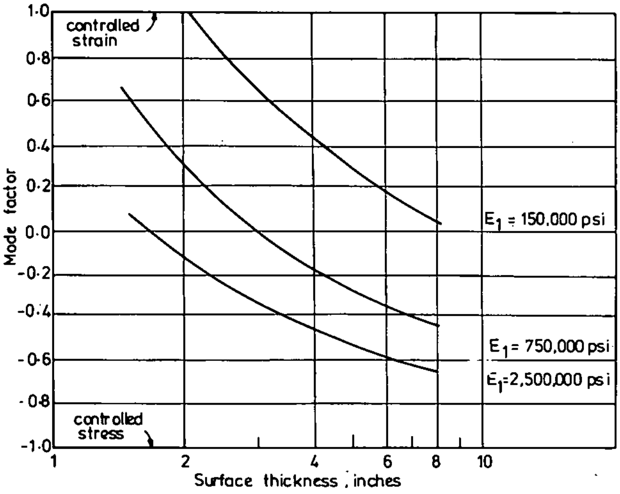


Figure 2. Variation of mode factor with surface thickness.



Equation 2 may be expressed as

$$N_s = K\left(\frac{1}{\sigma}\right)^n \qquad (3)$$

The exponent n defines the slope of the fatigue line; lower values of n denote a steeper line.

A similar type of relation but one in terms of applied tensile strain ϵ is obtained from controlled strain tests.

There is no evidence of an endurance limit up to lives of 10^7 applications of load, but the slope of the fatigue line is such that a small change in stress level can result in a considerable change in life.

EFFECT OF STIFFNESS AND CRITERION OF FAILURE

Possibly the greatest difficulty in interpreting fatigue test results arises from the fact that they are influenced by the method of testing. That is well illustrated by the effect of stiffness on the service life of identical specimens tested in both controlled stress and controlled strain.

If specimens are tested in controlled stress, such as in a rotating bending type of machine producing a sinusoidally varying bending stress of constant amplitude, then 4 different stiffness results, such as those shown in Figure 5a, are obtained. At a particular stiffness S, the mean fatigue lives can be represented by a straight line on a log-log plot of stress σ against number of cycles of load N_s to cause failure. Different stiffnesses are represented by parallel lines showing that, with this type of testing, the fatigue life is highly dependent on stiffness; the stiffer the mix is, the longer the life is.

The stiffness, defined as the ratio of stress amplitude to strain amplitude, is dependent on the temperature and speed of loading. If the results of the fatigue tests under controlled stress are replotted in terms of strain ϵ, as shown in Figure 5b, it has been found that for a wide temperature range all the results from different stiffnesses coincide, indicating that strain is a major criterion of failure and that the effects of temperature and speed of loading can be accounted for by their effect on stiffness. There is some evidence that at higher temperatures, above about 25 C, longer lives are obtained that cannot be explained in this manner.

If identical specimens are tested in a controlled strain machine, which applies an alternating strain of constant amplitude, results such as those shown in Figure 5c are obtained. Although the lines at high stiffnesses, S_1 and S_2, say, coincide, those at lower stiffnesses show an effect of stiffness that is the reverse of that found from controlled stress tests.

The reason is that the mode of failure is different in the 2 types of test. In the controlled stress test, the formation of a crack results in an increase in actual stress at the tip of the crack due to the stress concentration effect, and that leads to rapid propagation and complete fracture of the specimen and termination of the test. In the constant strain test, on the other hand, cracking results in a decrease in stress and hence a slow rate of propagation. At low stiffnesses and, hence, low stresses, the measured fatigue life includes a considerable length of time necessary to propagate a crack or cracks sufficiently to reach an arbitrary state when the specimen is considered to have failed (service life).

If measurements of stiffness are taken during a controlled strain test, the stiffness reduces with increasing number of load applications at low stiffnesses, i.e., high temperatures; and that, no doubt, is partially due to formation of small cracks. At high stiffnesses, coincident with lines for S_1 and S_2 (Fig. 5c), there is negligible fall in stiffness during a fatigue test.

In some types of controlled stress tests, there is little increase in deflection and hence strain during the test even at low stiffnesses, but other types of controlled stress tests show a decrease in stiffness. Therefore, when the results are plotted in terms of strain, it is usual to take the value of stiffness of the specimen at the start of the test and quote the initial strain.

Figure 3. Results of 100 fatigue tests under 1 loading condition.

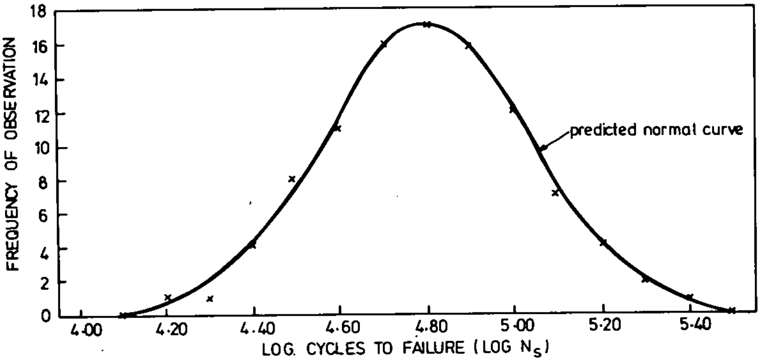


Figure 4. Results of fatigue tests under controlled stress at various temperatures.

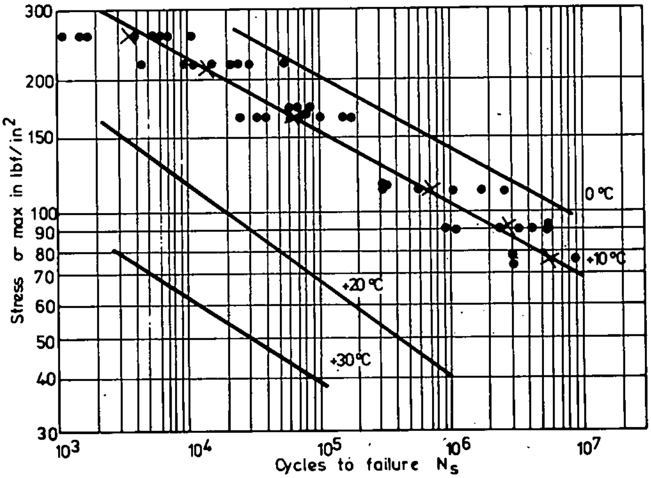
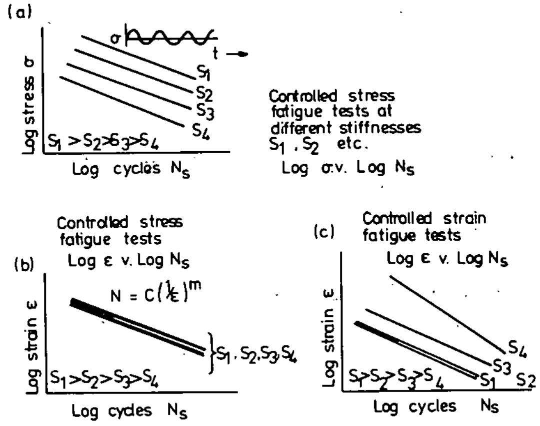


Figure 5. Effect of stiffness on fatigue life under different modes of loading.



Thus, it can be seen that the measurement of fatigue life is complicated by changes in stiffness that take place during a test and that are due to either the particular strain pattern or the propagation of small cracks or both. If the service life contains a lot of crack propagation time, then the simple criterion shown in Figure 5b, which applies essentially to crack initiation, no longer holds.

That criterion of fatigue crack initiation is one of applied tensile strain, and a general relation defining the fatigue life is as follows:

$$N_s = C\left(\frac{1}{\epsilon}\right)^m \tag{4}$$

where

N_s = number of applications of load to initiate a fatigue crack,
ϵ = amplitude of applied tensile strain, and
C and m = factors depending on the composition and properties of the mix.

For many dense mixes, the slope factor m has a value of approximately 5 or 6; but certain mixes, particularly those containing softer grades of bitumen, give steeper lines even under controlled stress testing that includes very little crack propagation time. Some typical results for different mixes are shown in Figure 6; the details of the composition of the mixes are given in Table 1.

The slope of the fatigue line appears to depend on the stiffness characteristics of the mix and the nature of the binder; mixes having high stiffnesses and linear behavior give a flatter line. That type of behavior is characteristic of dense surface-course mixes having a relatively high binder content of a harder bitumen. The leaner base-course mixes made with softer grades of binder show considerable nonlinearity, particularly at higher stress levels, and those mixes have a steeper fatigue line.

Although the logarithmic strain-life relation is usually shown as a straight line, it is probably curvilinear, particularly at high strains where nonlinearity is apparent.

If the method or conditions of testing are such that considerable crack propagation takes place during the test, then the line representing the service lives of specimens will be steeper as shown in Figure 7 because the rate of crack propagation depends on the stress level. That is likely to occur at higher temperatures (lower stiffnesses), particularly under controlled strain testing. However, a relation similar to Eq. 4 will still define the fatigue characteristics of the mix, but the values of factors C and m will be different.

EFFECT OF MIX VARIABLES

From the foregoing it will be realized that stiffness plays a predominant role in determining the fatigue behavior of bituminous mixes. It appears that maximum principal strain is a good criterion of crack initiation; and, therefore, in controlled stress tests, the stiffness will determine the strain level and hence the fatigue life. In controlled strain tests, which include crack propagation time in the measured life, stiffness again is important for it controls the stress level that determines the rate of crack propagation.

In general, increased stiffness results in longer lives at a given stress level in controlled stress testing and shorter lives in controlled strain testing at a given strain level.

It, therefore, follows that any mix variables that affect the stiffness are also going to affect the fatigue life of asphalt mixes. Those variables are aggregate type and grading, including filler, binder type, hardness (viscosity) and content, degree of mix compaction, and resulting air void content. The 2 factors that appear to be of primary importance are binder content and voids content.

Increasing voids reduces the fatigue life markedly (Fig. 8). The effect of increasing voids is twofold: reduced stiffness and increased stress concentrations due to the presence of voids in the material. Therefore, the detrimental effect of voids is likely to be more apparent in controlled stress testing or controlled strain testing at low temperatures. If increasing the bitumen content reduces the voids, then the fatigue life will be

Figure 6. Strain-life fatigue results for various mixes from controlled stress testing.

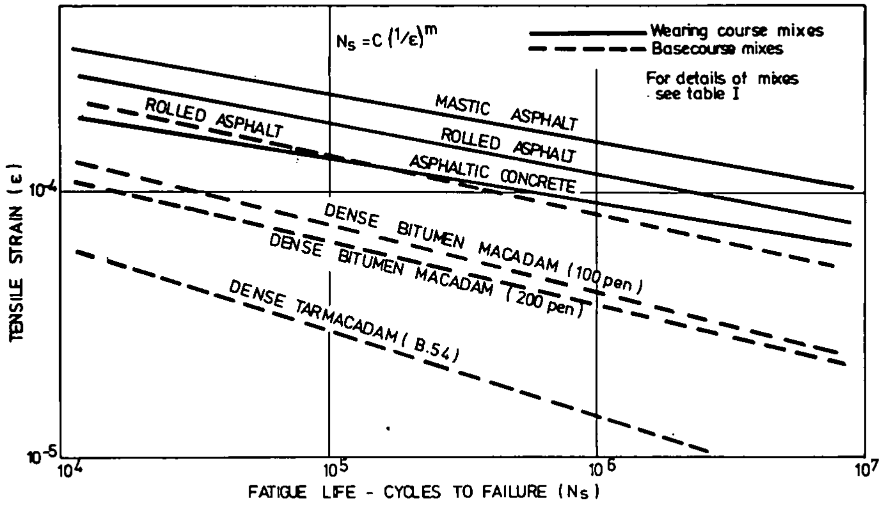


Table 1. Typical mixes tested in controlled stress.

Description of Mix	Coarse Aggregate[a] (percent by wt)	Fine Aggregate (percent by wt)	Filler (percent by wt)	Binder: Percent by Wt	Binder: Penetration	Mean Voids (percent)	C	Slope Factor
Mastic asphalt wearing course	42	23[b]	20[b]	15	70/30 TLA/20	0	1.13×10^{-15}	5.5
Rolled asphalt wearing course, BS 594, gap graded	30	52.2[c]	8.9[b]	7.9	45	2.9	8.8×10^{-15}	5.1
Asphaltic concrete wearing course, continuously graded	42	46.8[a]	4.7[a]	6.5	70	3.6	2.2×10^{-19}	6.1
Rolled asphalt base course BS 594, gap graded	65	29.3[c]	—	5.7	45	4.0	6.7×10^{-12}	4.2
Dense bitumen macadam base course, MOT spec., continuously graded	62	28.6[a]	4.7[a]	4.7	100	6.8	1.9×10^{-11}	3.8
Dense bitumen macadam base course, MOT spec., continuously graded	62.3	28.7	4.7[a]	4.3	200	6.9	1.8×10^{-12}	4.0
Dense tar macadam base course, MOT spec., continuously graded	61.7	28.4	4.7[a]	5.2	B 54	7.5	2.7×10^{-9}	3.0

[a] Crushed rock. [b] Limestone. [c] Sand.

Figure 7. Effect of crack propagation on the slope of the strain-life fatigue relation.

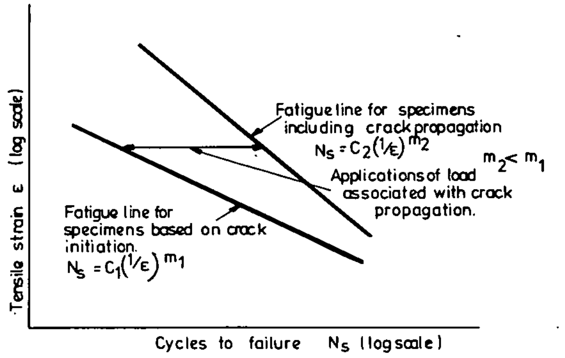
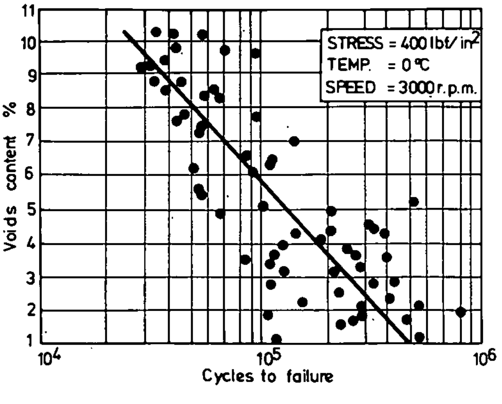


Figure 8. Effect of void content on fatigue life in controlled stress testing.



increased; but if the mix already has negligible voids, then further binder will reduce the stiffness and result in increased strain and hence reduced lives under controlled stress testing (Fig. 9).

The general effect on the strain-life relation of altering the binder and filler content of a particular mix is shown schematically in Figure 10. For a lean mix, increasing the binder and filler will result in a stiffer material and hence smaller strains and longer life. However, if too much binder is added, the stiffness is reduced and hence an optimum fatigue life exists.

Although other mix variables such as aggregate type and grading do affect the fatigue performance of asphaltic mixes, they can be largely accounted for by their effect on the 3 main factors: stiffness, binder content, and voids content. Figure 11 shows the results of 13 similar gap-graded, rolled-asphalt, base-course mixes made with different aggregates and binders as given in Table 2. The plotted points give the mean lives obtained at different stress levels and represent more than 400 individual fatigue tests. The general conclusion is that for mixes with similar binder contents aggregate type has little effect on the strain-life relation.

Figure 12 shows the strain-life lines for some continuously graded asphaltic concrete mixes made with different aggregates and binders. The important effect of binder content and void content is evident. Similar overall conclusions on the effect of mix factors on fatigue life have been presented by Epps and Monismith (5). There is some evidence that asphalt type does affect the strain-life relation; harder grades give slightly improved performance under controlled stress conditions. The importance of asphalt viscosity on controlled strain fatigue results has been shown by Santucci and Schmidt (19).

In conclusion, it may be stated that for good fatigue performance for thick asphalt construction a mix of maximum stiffness should be the objective and the quantities of filler and binder should be such that a condition of maximum tensile stiffness associated with minimum voids is produced.

EFFECT OF REST PERIODS

The fatigue characteristics discussed above have been obtained from tests carried out under simple loading conditions that mainly apply continuous cycles of loading of particular magnitudes. In practice, the material is subjected to a succession of load pulses of varying sizes and at varying time intervals between pulses depending on the details of the traffic. The question, therefore, arises as to the possible beneficial effect of periods of rest during a fatigue test.

Some workers (4, 17) have reported crack-initiation life did not increase in asphaltic mixes as a result of periods of rest that were at different temperatures and injected after varying portions of the expected life but did significantly increase in specimens made from bitumen alone under similar testing conditions. Bazin and Saunier (11), on the other hand, report that asphaltic concrete made with a very soft binder (200-penetration bitumen) had increased lives because of healing following rest periods under compressive stress.

More recent work reported by Raithby and Sterling (14, 20) and by Van Dijk et al. (12) show considerable beneficial effects of strain recovery if periods of rest are injected between each load pulse. Those findings mean that laboratory tests using continuous cycling load pulses may well underestimate the fatigue life to cause initiation of cracks in practice.

CUMULATIVE DAMAGE

In practice, asphalt pavements are subjected to a form of compound loading, and changes take place in the loading conditions during the life. In a recent review of some general cumulative damage theories, O'Neill (21) concludes that none of the hypotheses considered shows a clear general superiority to the rule of linear summation of cycle ratios. When satisfactory, constant-amplitude, simple load test data can be provided, the application of the linear rule, generally referred to as Miner's rule, is extremely simple.

Figure 9. Effect of binder content on fatigue life in controlled stress testing of continuously graded asphaltic mix using 200-penetration binder.

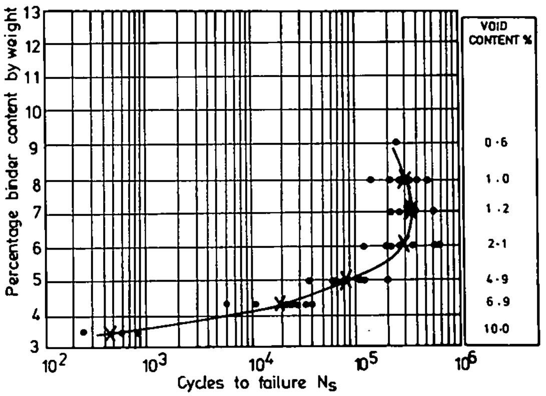


Figure 10. Effect of increasing binder and filler contents on fatigue life (strain criteria).

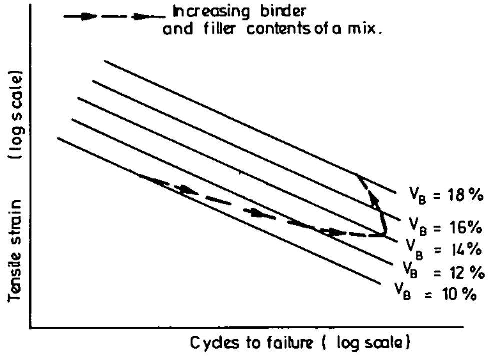


Figure 11. Effect of mix variables on fatigue performance of rolled asphalt.

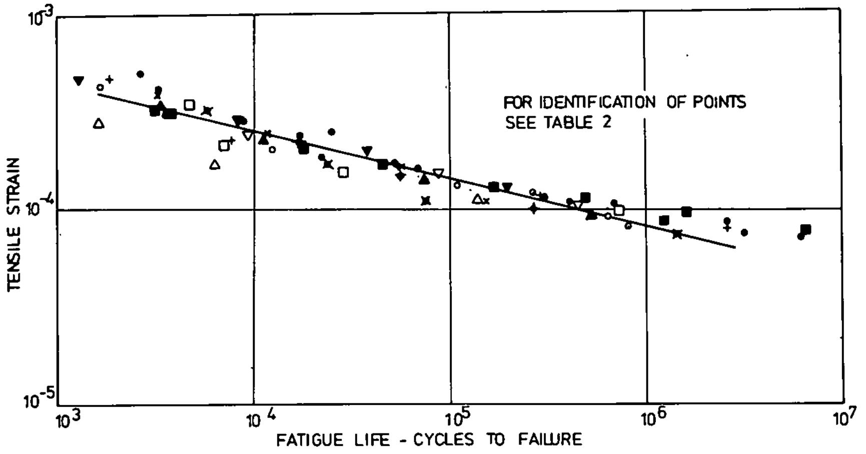


Table 2. Rolled asphalt base-course mixes.

Coarse Aggregate		Fine Aggregate		Filler (percent by wt)	Binder		Mean Voids (percent)	Symbol on Figure 11
Type	Percent by Wt	Type	Percent by Wt		Percent by Wt	Penetration		
Crushed rock	60	Sand	34	0	6	45	5.0	●
Crushed rock	60	Crushed rock	34	0	6	45	5.6	○
Crushed rock	60	Sand	34	0	6	35	4.2	✖
Crushed rock	65	Sand	29.3	0	5.7	45	4.0	✦
Crushed rock	60	Sand	34	0	6	100	4.8	⊙
Quartz gravel	60	Sand	34	0	6	45	5.3	■
Quartz gravel	60	Crushed rock	34	0	6	45	6.0	□
Quartz gravel	65	Sand	27.4	-*	5.6	45	3.5	+
Flint gravel	60	Sand	34	0	6	45	4.8	▲
Flint gravel	60	Crushed rock	34	0	6	45	6.9	△
Slag	60	Sand	33.7	0	6.3	45	5.0	▼
Slag	60	Crushed rock	33.7	0	6.3	45	5.6	▽
Slag	55	Sand	38.2	0	6.8	45	5.4	x

*2 percent cement.

Miner's rule for evaluating cumulative damage states that the condition at failure is given by

$$\sum_{i=1}^{r} \frac{n_i}{N_i} = 1 \tag{5}$$

where

n_i = number of cycles of stress σ_i applied to the test specimen, and
N_i = number of cycles to failure at constant stress amplitude σ_i from simple loading.

If N_c is the predicted fatigue life under variable amplitude conditions and $f_1, f_2, \ldots f_r$ are the relative proportions at each of the stress levels for which the fatigue lives are $N_1, N_2, \ldots N_r$ respectively, then by Miner's rule,

$$N_c = \frac{1}{\frac{f_1}{N_1} + \frac{f_2}{N_2} \cdots \frac{f_r}{N_r}} = \frac{1}{\sum_{i=1}^{r} \frac{f_i}{N_i}} \tag{6}$$

The application of this rule to the fatigue life of asphaltic mixes under compound loading conditions was considered by Monismith et al. (22), who suggested strain rather than stress to be the appropriate criterion. Although widely used in such design methods as employ load equivalency concepts, no experimantal justification of its use was available until 1965 when Deacon (23) published the results of an investigation into the behavior of asphaltic concrete under compound loading conditions. He concluded that the linear summation of cycle ratios governs the fatigue behavior of bituminous mixtures that are subjected to multiple strains of variable magnitude. That conclusion is supported by the results of a recent experimental investigation at Nottingham University (24). Variations in the level of strain during the course of a test were achieved either by changing the temperature of the specimen or altering the stress level.

In the application of Miner's rule, no allowance is made for intervals of "no-load" or rest periods. It may be assumed that the effect of such intervals will be beneficial or at worst of no consequence. If the effect is beneficial, then the rule, as it stands, is conservative for design purposes.

PREDICTION OF FATIGUE CHARACTERISTICS

To establish the fatigue characteristics of a particular asphaltic mix necessitates long and somewhat involved testing techniques using specially designed and expensive equipment. It would clearly be extremely useful if fatigue performance could be related to a test using more standard equipment, and the approach of Epps and Monismith (25) to try and correlate fatigue with a simple, tensile test seems valuable.

To date, there is little convincing evidence that a simple nonrepetitive, loading test will be able to predict fatigue performance over the wide range of conditions and materials necessary, particularly in view of the difficulty of defining service life. However, a simple test may possibly be used to investigate stiffness characteristics for a number of mix variables, and further research in this direction is warranted.

As more and more fatigue tests are carried out by various research workers in different parts of the world, the fund of results that may be used for design purposes grows. But unfortunately, different test methods and criteria of failure make it extremely difficult to correlate that fund of information in a quantitative manner.

The most promising approach at present appears to be for each agency to produce general laboratory relations for the more common mixes that are used in its location and correlate those with pavement performance in its environment. For example, Epps and Monismith (5) have suggested that the fatigue characteristics C and m in the basic strain-life relation shown in Eq. 4 should be 6.28×10^{-7} and 3.01 respectively for dense-graded aggregate mixes in California. These values give the expression

$$N_f = 6.28 \times 10^{-7}\left(\frac{1}{\epsilon}\right)^{3.01} \qquad (7)$$

Similarly, values of the characteristics C amd m obtained by Pell and Brown (13) and given in Table 1 are appropriate for some British mixes tested under particular conditions.

A recent development by several research workers is the production of empirical relations between mix-design variables and fatigue properties of asphalt mixes. That involves the identification of the most important parameters and establishing the influence of these on the fatigue relationship.

Kirk (26) states that the primary parameter is the stiffness of the binder and that the fatigue life under controlled stress flexure at a particular stiffness depends on the strain per binder volume. A factor is then applied that indicates improved performance with maximum size of aggregate, and another correction factor is applied that reflects the effect of binder and voids content.

Verstraeten (27) has produced a general expression based on controlled stress bending tests on 34 different mixes:

$$\epsilon(N) = \Phi \times C \times \frac{V_B}{V_B + V_V} \times N^{-0.22} \qquad (8)$$

where

$\epsilon(N)$ = initial strain to produce failure after N cycles;
Φ = coefficient depending on the asphaltene content in the bitumen;
C = coefficient that correlated with $V_A/(V_B + V_V)$;
V_A = volume of aggregate, percent;
V_B = volume of bitumen, percent; and
V_V = volume of voids, percent.

Equation 8 implies that the characteristic m, which defines the slope of the strain-life line, has a constant value of 4.5 for all mixes. Verstraeten applied his expression to selected results obtained by Pell and Taylor (4) for 22 further mixes and shows good agreement in all but a few cases.

It is doubtful whether in general a relation developed from the data of one researcher can be accurately applied to that of another. This is mainly because of the differences in apparatus and testing techniques, but an important fact that emerges from all fatigue investigations is that basically the general qualitative conclusions are similar.

The fatigue performance of a mix is generally expressed by the strain-life relation, and many workers have shown that over the practical range of fatigue life and tensile strain that relation is linear when plotted on a log-log basis and can be expressed as

$$\log N = \log C - m \log \epsilon \qquad (9)$$

Therefore, factors m and C characterize the fatigue performance of a particular mix. At Nottingham University, when 1 particular type of controlled stress testing was used, values of m and C were obtained for a wide variety of mixes having a comparatively large range of fatigue performances. It was found that there is a linear relation between m and log C (Fig. 13), which may be expressed in the form

$$m = A \log C + B \qquad (10)$$

That general relation only becomes apparent when mixes having a wide range of fatigue performances are considered and is probably not revealed by small changes in mix variables on a particular type of mix because of the normal scatter. Values of m and C obtained by other investigators show similar trends.

The relation between m and C indicates that the log strain-log life lines tend to radiate from a common intersection point, and, if either factor can be related to mix properties, then a simple method of fatigue performance prediction would result.

Multiple regression analyses on the mix variables involved showed that the most significant factors were binder viscosity, binder content, and void content. However, because the basic strain-life relations obtained from the controlled stress tests were found to be independent of temperature, an equiviscous measure, such as Ring and Ball temperature, was chosen to characterize the binder viscosity. Dobson (28) states that the temperature dependence of the viscoelastic properties of a bitumen may be described by one parameter, which Brodnyan (29) suggests is similar to the softening point.

Binder content and void content are, of course, closely related, and aggregate grading and state of compaction affect that relationship, so binder content by volume V_B and void content V_v were combined in a single factor $V_B/(V_B + V_v)$, i.e., ratio of binder volume to voids in the dry compacted aggregate.

Service life at a strain of 10^{-4} was used as a measure of fatigue performance, i.e., $N_s(\epsilon = 10^{-4})$, in a simple regression analysis that was performed on the results of 54 mixes and that gave the following relation:

$$\log N(\epsilon = 10^{-4}) = -16.34 + 6.03 \log\left(\frac{V_B \times 100}{V_B + V_v}\right) + 5.99 \log(T_{R\&B}) \qquad (11)$$

the multiple correlation coefficient was 0.953, and the standard error of the estimate was 0.274. Values of measured fatigue life plotted against predicted values using Eq. 11 are shown in Figure 14. The service life at a strain of 10^{-4} was chosen for that analysis because in view of the inevitable scatter the results were considered more accurate at that strain level. However, either of the fatigue characteristic factors m or C could be related directly to the mix properties parameter by a similar approach, and further work is proceeding along those lines at the present time. In that case, the mix properties parameter consists of easily obtainable factors, namely, percentage volumes of binder and voids in the mix and the Ring and Ball temperature of the binder.

SUMMARY AND CONCLUSIONS

1. The definition of laboratory fatigue service life depends on the method of testing; therefore, it is not possible to produce unique relations characterizing fatigue performance.
2. Service life of specimens greatly depends on the mode of testing. Controlled stress loading appears to be applicable for materials used in thick asphalt construction, i.e., 6 in. or more, but controlled strain loading is more appropriate for thin asphalt layers, i.e., approximately 2 in. or less. Results from controlled stress mode of loading will generally give shorter lives and, hence, are conservative.
3. Whichever method of testing is used, the fatigue performance can best be characterized by a strain-life relation of the form

$$N_s = C\left(\frac{1}{\epsilon}\right)^m$$

where N_s is the number of applications of tensile strain ϵ to cause failure with the particular method of testing used. Factors C and m depend on the composition and properties of the mix and will also be affected by the testing method.

4. Mixes having maximum stiffness characteristics will give longer lives under controlled stress conditions. Therefore, for thick asphalt construction the choice of mix composition, namely, aggregate type and grading, filler content, and binder type and content, should be such that under compaction a mix of maximum tensile stiffness associated with minimum voids is obtained.
5. For thin asphalt construction maximum lives are likely to be obtained from more flexible, less stiff materials. Thus, mixes having high binder contents of softer bitumens should be used.

Figure 12. Fatigue lines for continuously graded dense asphalt mixes.

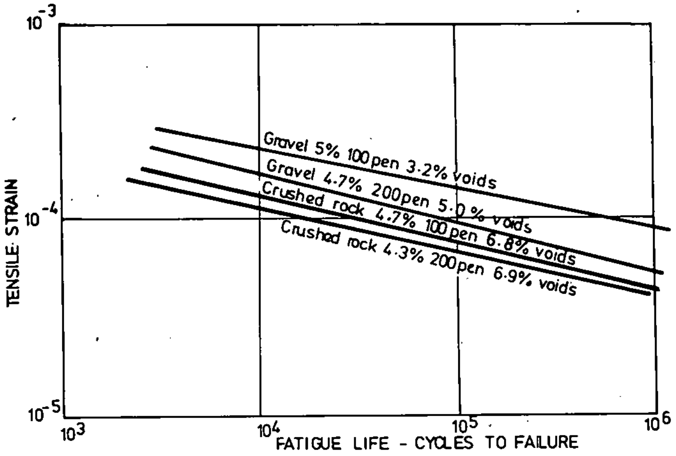


Figure 13. Relation between mix characteristic factors C and m.

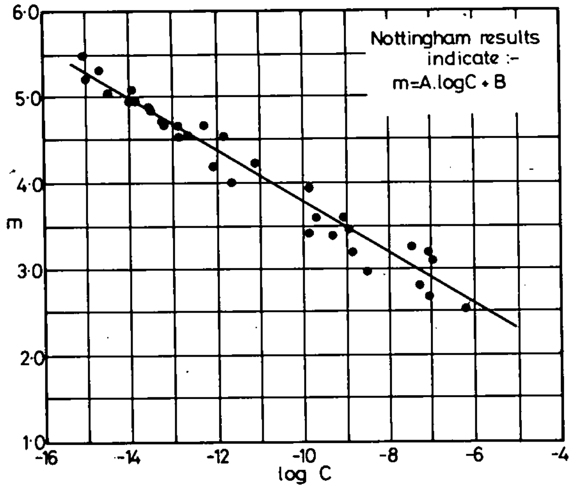
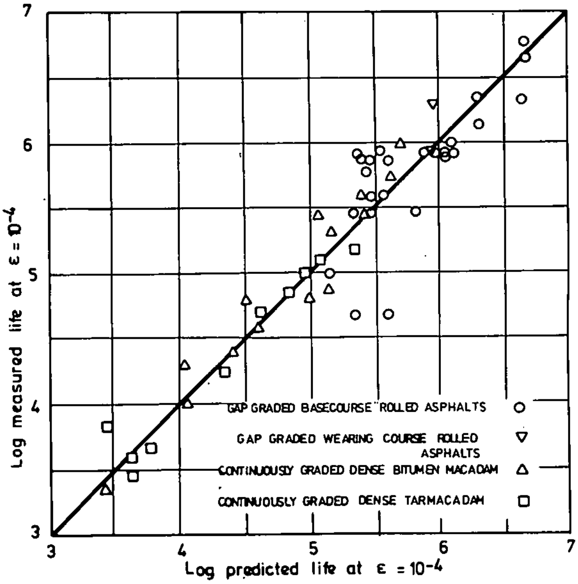


Figure 14. Measured versus predicted fatigue life.



6. A simple standard test probably using a single application of tensile load could usefully be developed to investigate, in a particular situation, the available mix compositions to give optimum stiffness characteristics.

7. General relations that have the form shown above in paragraph 3 and different values of mix characteristics C and m should be established by various agencies using their particular method of testing. Those relations can then be correlated with performance under the appropriate conditions of environment and traffic for design purposes.

8. The results of simple loading fatigue tests may be used for design in compound loading conditions by the use of Miner's rule, namely,

$$\sum_{i=1}^{r} \frac{n_i}{N_i} = 1$$

where

n_i = number of cycles of strain ϵ_i applied, and
N_i = number of cycles to produce failure under constant strain amplitude ϵ_i from simple loading tests.

The application of that rule is likely to yield conservative results for it neglects the beneficial effects of rest periods.

9. If it is not possible to characterize the material by fatigue testing, then use may be made of empirical relations relating the fatigue performance to mix properties. Various workers have produced relations that emphasize different mix parameters depending on the range of materials used to provide the data.

10. Because of the statistical nature of all fatigue results, it is important to realize that large numbers of specimens have to be tested before accurate relations can be established whether directly of the form shown above in paragraph 3 or indirectly based on previous results.

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