TRANSPORT and ROAD
RESEARCH LABORATORY

Department of the Environment

TRRL REPORT LR 496

SOME EFFECTS OF LOADING HISTORY ON THE FATIGUE PERFORMANCE OF ROLLED ASPHALT

by

K.D. Raithby

and

A.B. Sterling
(formerly of the Refined Bitumen Association)

Structural Properties Division
Structures Department
Transport and Road Research Laboratory
Crowthorne, Berkshire
1972

CONTENTS

SOME EFFECTS OF LOADING HISTORY ON THE FATIGUE PERFORMANCE OF ROLLED ASPHALT

ABSTRACT

Results are given of fatigue tests under direct stress axial loading conditions on a typical rolled asphalt base-course material, to investigate the significance of varying the load-time history.

Rest periods between successive loading cycles had a beneficial effect on fatigue performance, both by increasing the resistance to cracking and by reducing the rate of loss of dynamic stiffness due to repeated loading. Rest periods of the order of 1s increased the number of cycles to failure by a factor of up to 25, when compared with the life under continuous sinusoidal cyclic loading. The improvement in life was less at high temperatures; it also appeared to be affected somewhat by the magnitude of the applied cyclic stress, although this effect was not clearly established.

A comparison of fatigue performance under square, sinusoidal and triangular waveforms indicates some significant differences but these are small compared with the effects of rest periods.

1. INTRODUCTION

Laboratory fatigue tests are being used increasingly to provide data from which the structural performance of different bituminous mixes may be compared and to establish strength and stiffness values for use in the structural design of flexible pavements[1,2,3]. In such tests the loading conditions must necessarily be very much simplified compared with conditions in the road and it is therefore essential to establish the degree to which fatigue performance in laboratory tests is affected by the type of loading.

This Report considers how the performance of a particular rolled asphalt material is affected by varying the loading history in a simple uniaxial fatigue test. The investigation covered the effects of rest periods and the shape of the waveform of the applied loading. This work forms part of a co-operative research programme between the Transport and Road Research Laboratory and the Refined Bitumen Association to investigate the behaviour of bituminous materials under repeated loading. Much of the experimental work and some of the analysis of the results was performed by staff of the Refined Bitumen Association working in the joint research team at TRRL.

The effects on fatigue performance of additional compaction under traffic may also be considered to come under the general heading of effects of loading history. A recent experimental study[4] which is complementary to the tests reported herein has shown that changes in fatigue performance can be related directly to changes in dynamic stiffness resulting from increased densification under traffic.

2. SIGNIFICANCE OF LOADING HISTORY ON FATIGUE PERFORMANCE

With the availability of more refined methods of stress analysis for multi-layer road pavements and a better knowledge of the mechanical properties of the constituent materials it is becoming possible to relate structural design more closely to the loading conditions likely to be encountered in service. An essential part of this process is to develop laboratory fatigue tests to determine the ability of typical road materials to withstand the cumulative effects of traffic loads, taking account of the fact that stresses and strains within the pavement arise from a wide variety of vehicles moving at different speeds on a composite slab structure which is subjected to variable temperature and sub-grade support conditions.

For simplified accelerated fatigue tests on road materials it is convenient to apply continuous sinusoidal loading to a test specimen under controlled conditions of temperature, rate of loading, and stress or strain amplitude and this type of test has been used by many research workers. Such tests, however, cannot be used directly to assess road performance without some knowledge of the errors involved in ignoring the effects of multi-directional stress interactions, rest periods and differences in the shape of the strain waveform which occur in practice.

If the results of uniaxial direct stress fatigue tests under continuous cycling are used to calculate the fatigue life of a typical flexible pavement under heavy traffic, such as the M1 motorway, the calculations indicate that fatigue failure of such a road might be expected in less than two years - obviously an unduly pessimistic prediction. One possible source of discrepancy is the difference between the stress (or strain) history experienced by an element of material in the road and that applied in a simple laboratory test.

Under traffic loading each point in the pavement structure will experience a succession of load pulses as traffic passes. The duration, spacing and waveform of the load pulses will depend on many factors, including vehicle speed, axle configuration and headway between vehicles. The resultant stress and strain pulses within the pavement structure will in turn be affected by the response to dynamic loading of the component layers.

For flexible road construction the resistance to fatigue loading of an element of material within the road structure is likely to depend largely on the magnitude and duration of the cyclic strains induced by the traffic loads[2,4]. These strains will depend on the dynamic response of the material to the imposed stresses and, for a viscoelastic material such as rolled asphalt, will be dependent, amongst other things, on the time history of these stresses. The extent to which delayed elastic recovery can take place between successive load pulses on the road may be expected to affect the resultant life of the road structure.

The fact that rest periods between load pulses may be important for visco-elastic materials has long been recognised and some research workers have used pulsed cyclic loading rather than continuous cycling, as being more representative of what happens in the road. For example, flexural fatigue tests have been made at the University of California[5] in which a square wave pulse loading, having a loading time of 0.1s, was followed by a rest of between 0.5 and 1.9s. Similar tests at the Chevron Research Company[6] used a loading time of 0.05s with a rest of 0.55s between each pulse. In neither case was the performance compared with that obtained from continuous cycling, however, nor was the significance of varying the duration of the rest period explored in any depth.

The tests described herein represent a more detailed investigation of the effect of rest periods than appears to have been undertaken hitherto, in that direct comparisons are made between the performance under continuous cycling and the performance obtained by introducing rests of up to 1s after each load cycle. As well as assessing the significance of rest periods it is also necessary to consider whether differences in the shape of the waveform are likely to affect the fatigue performance significantly. This aspect also has been considered and comparative results are given for the same stress amplitude applied with differing waveforms.

3. AXIAL LOAD FATIGUE TESTS

3.1 Method of test

Prismatic specimens, 75 mm square and 225 mm long, were subjected to direct cyclic tensile and compressive loading in a servo-controlled electro-hydraulic testing machine. The method of test is illustrated in Fig. 1 and Plate 1. A steel loading plate was bonded to each end of the specimen with an epoxy resin adhesive (Araldite) and the upper plate was attached rigidly to the reaction frame of the testing machine. The lower loading plate was connected directly to a strain-gauged load cell attached to the piston rod of the hydraulic actuator. Great care was taken to ensure accurate alignment of loading by using a steel jig for positioning the loading plates on the specimen and by adjusting the top attachment point to ensure that there was no bending on the specimen.

The loading was controlled by electrical command signals from a function generator which could produce sinusoidal, triangular or square waves over a range of frequencies. These could be applied either continuously or as a series of pulses with a rest period after each pulse. The load amplitude was kept constant throughout a particular test and was controlled by feedback from the load cell, using a specially developed Amplitude Control Unit to compensate for changes in specimen stiffness in the course of the test[7].

Linear variable displacement transformers (LVDT's) were used to measure the overall dynamic deflection between the end plates throughout each test, as shown in Plate 1. A digital transfer function analyser and data logger were used to measure and record rms values of load and displacement during continuous cycling, together with phase differences between them. For the rest period tests, load and deflection traces were displayed on a cathode ray oscilloscope and photographed throughout each test to study changes in load-deflection characteristics.

In order to maintain a constant temperature, the specimen and upper part of the reaction frame were enclosed in a temperature-controlled cabinet (not shown in Plate 1). The temperature cabinet controls the local air temperature within ± 0.5°C over a range from 0 to 40°C. A general view of the test set up is shown in Plate 2.

3.2 Preparation of test specimen

To provide a direct comparison with earlier tests performed by the University of Nottingham under a different type of loading[8], the tests reported here were carried out on an asphalt basecourse mix having the same mix proportions as Pell's reference mix ("Mix G") for which a good deal of fatigue test data already existed. This mix conforms with BS 594 for basecourse material although the stone content is somewhat lower than would normally be used in practice. The mix proportions are given in Table 1. The coarse aggregate used was a crushed porphyry from Bardon Hill, Leics and the fine aggregate was Hoveringham sand. The aggregate grading is shown in Fig. 2.

In order to ensure that the state of compaction and the orientation of the aggregate particles were reasonably representative of conditions in the road, the test specimens were prepared from material cut from a rolled asphalt carpet laid in one of the Laboratory's pilot scale buildings. This carpet measured approximately 26 m x 4 m x 130 mm thick and was laid in a single lift on a compacted sand base, using a Blaw-Knox PF 90 paver and a 6-ton steel road roller. Mixing was performed in the Laboratory's pilot scale batch mixing plant at a temperature of 160°C and rolling was carried out at 130°C. After being laid, the carpet was first sawn into 1 m square slabs, which were stored under cover on wooden pallets until required for the preparation of test specimens. Final cutting of the specimens was performed on a 610 mm diameter diamond-tipped circular saw, with the length of the specimen cut in the direction of rolling. A cutting jig was used to ensure dimensional accuracy, which was within 0.5 mm of the nominal dimensions.

Mix proportions were checked by sampling material at various times during the mixing process. Penetration and softening point of the binder at the time of mixing were also measured. Thereafter the density of each test specimen was determined by weighing in air and water before commencing the fatigue test. Samples of the mixed material were analysed to determine aggregate grading, binder content and the penetration and softening point of the bitumen. Typical results are given in Tables 1 and 2.

In the early part of the fatigue test programme specimens were cut from slabs selected randomly from the rolled carpet. However, after testing had proceeded for some time it became evident that the variability from slab to slab was greater than the variability within individual or adjacent slabs; for the later tests specimens were prepared from adjacent slabs when more than one slab was required, in order to reduce the overall variability.

3.3 Conditions of test

3.3.1 Variable rest periods

Endurance curves under continuous sinusoidal cyclic loading at 16.7 Hz with approximately zero mean load (conditions for Pell's Mix G[8]), were first derived for two different temperatures (10°C and 25°C). Further experiments were then made at 10°C, 25°C and 40°C to study the effect of allowing a rest period after each loading cycle. The duration of the rest period varied between 0 and 1s and was kept constant throughout each test. Most of these tests were performed with a loading cycle period of 40 ms (equivalent to 25 Hz for continuous cycling) but a limited number of tests were made at 400 ms (2.5 Hz). The stress levels for the rest period tests were chosen to give mean fatigue lives under continuous cycling within the range 5000 - 50,000 cycles; details are given in Table 3.

In each case the cyclic load amplitude was maintained constant throughout the test and the direction of loading was such that the first half of the cycle subjected the test specimen to tensile stress. Slight zero errors in the loading system could lead to small errors in the mean load (nominally zero) in each loading cycle. Although deviation of the mean load from zero was less than 1 per cent of the dynamic load amplitude this was sufficient to produce considerable creep in long-term tests which, if unchecked, could lead to eventual failure. This was particularly true at high temperatures, where the test specimens were very susceptible to plastic flow. A control circuit was therefore developed which continuously applied a correction to the mean load so as to minimise creep.

3.3.2 Variable waveform

Two series of tests were run. In the first (Table 4) mean lives to failure under controlled load continuous cycling were compared for three widely different waveforms: triangular, sinusoidal and square. The object of these tests was to give some guidance as to the errors involved in ignoring differences in shape between the waveforms applied in simple uniaxial laboratory tests and those which occur in critical layers of the road pavement, for example, longitudinal strains in the base.

In the second series of tests the effects of changes in direction of straining were studied. Sinusoidal load pulses with rest periods were applied in several different ways to explore the relative significance of stress level and stress range and their effects on strain response and fatigue performance at 25°C. In some tests the loading pulse was a full sinusoidal cycle with zero mean stress, while in others the peak stress was kept the same but with a minimum stress in the cycle of zero. Four cases were investigated. These are illustrated in Table 5 and detailed below:-

1. Single sinusoidal pulses of duration 40 ms, with zero mean stress and 80 ms rests after each pulse. Direction of loading such that the applied stress was tensile during the first half cycle, compressive during the second half (i.e. $\pm \sigma_a$).

2. Similar to Case 1 but with the direction of loading compressive during the first half cycle, tensile during the second half (i.e. $\mp \sigma_a$).

3. Same peak stress as in Case 1 but with the loading applied in a wholly tensile direction, i.e. stress varied sinusoidally from zero to $+ \sigma_a$ and back to zero. To keep the average rate of loading comparable with Case 1 the pulse duration was reduced to 20 ms.

4. As in Case 3 but with stress wholly compressive, 0 to $-\sigma_a$ to 0.

4. RESULTS OF TESTS

4.1 Fatigue lives

4.1.1 Endurance curves – continuous cycling

Stress-endurance curves previously obtained[9] under continuous sinusoidal loading at 16.7 Hz are given in Fig. 3 for two temperatures, 10°C and 25°C, each curve having been drawn through the geometric mean value (not shown) of several tests. Using mean values of dynamic stiffness obtained from later tests (see Section 4.2) these curves have been converted to strain-endurance lines, shown in Fig. 4, where the ordinate is the 'initial' strain amplitude, i.e. the strain corresponding to conditions at the beginning of a fatigue test.

The results of the zero rest period tests (see Section 4.1.2) and the sinusoidal waveform shape tests of Section 4.1.3, together with a few other tests also made under continuous sinusoidal cycling at 25 Hz on nominally identical material, are plotted on Figs 3 and 4 for comparison with the curves shown. Many of the test points on Fig. 3 lie above the lines, as might be expected from the higher loading frequency, and there is considerable scatter in the individual lives, which could well be due to minor variations in the test material when sampled from different parts of the rolled asphalt carpet. When the results are expressed in terms of initial strain, however, they lie quite close to the predicted strain-endurance lines of Fig. 4. This tends to support the hypothesis[4] that changes in fatigue endurance due to minor changes in the material or in loading conditions can be accounted for in terms of the effects on dynamic stiffness and hence on resultant strain in the mix.

4.1.2 Pulsed loading with rest periods

The number of cycles to failure for each of the test conditions described in Section 3.3.1 is given in Table 3, expressed as the geometric mean life and standard deviation of log endurance for each group of tests. (All statistical calculations have been performed on the basis of logarithmic endurance, following Taylor's demonstration that the life distribution for Mix G was approximately log-normal[8]).

4.1.3 Effects of waveform shape

Table 4 gives the results of the first series of "waveform" tests carried out under controlled stress continuous cycling at one temperature and loading frequency and a single stress amplitude 0.33 MN/m^2.

The results of the second series are given in Table 5. In these tests sinusoidal load cycles with rest periods were applied in various ways to give the same peak tensile or compressive stresses with varying amounts of strain reversal.

4.2 Dynamic stiffness

The dynamic stiffness varied considerably throughout each test. After an initial rapid decrease in stiffness in the early stages of loading there was a period when there was an almost linear decrease with time, followed by a final stage in which the stiffness again decreased more rapidly. The latter stage was associated with the appearance and development of small surface cracks.

For the tests with rest periods, the rate of decrease of stiffness with number of load cycles applied was considerably less than for continuous cycling, consistent with the mean life to failure being extended. With 1s rests (illustrated in Fig. 5) the stiffness remained almost constant for a high proportion of the life at 10°C and 25°C; at 40°C the rate of reduction in stiffness was more marked, although still appreciably less than for continuous cycling.

In a series of subsidiary tests the effects of stress level and temperature on dynamic stiffness were determined under continuous sinusoidal loading. Some results are given in Fig. 6 and these were used to convert the stress-endurance curves of Fig. 3 to the strain-endurance lines of Fig. 4. Full details of the dynamic stiffness tests will be published when further studies of stress-strain relationships with and without rest periods have been completed.

4.3 Stress/strain characteristics

Although the applied loading in the tests with rest periods was approximately symmetrical about zero mean load, the resulting deflections were markedly asymmetrical, the deflection during the first half of the loading cycle being appreciably greater than during the second. The same effect was observed whether the initial direction of loading was tensile or compressive. Typical resultant strain histories for a single sinusoidal stress pulse of ± 0.15 MN/m^2, given in Fig. 7, show the time to recovery at various temperatures. In some of the fatigue tests reported here the rest period was long enough to allow complete recovery of delayed elastic strain, while in others only partial recovery took place. The significance of this is discussed in Section 5.1.

4.4 Mode of failure

In all cases the test was terminated by rupture of the test specimen. Depending on the test conditions three distinct modes of failure were observed.

The first sign of failure was usually the appearance of small cracks in the binder matrix between 80 and 90 per cent of the total life, followed by propagation of one or two major cracks until tensile failure of the specimen occurred. Such small cracks were always preceded by a reduction in dynamic stiffness and were usually observed when overall deflections started to increase rapidly. Cracks appeared to originate at the surface of the specimen and to propagate within the binder matrix close to individual particles of coarse aggregate.

In the tests at 40°C the failure point was less well defined, because excessive plastic flow occurred as soon as cracks began to form.

Under wholly compressive loading at 25°C (Case 4 of Table 5) final failure occurred by shearing at approximately 45°. There was no evidence of any vertical cracks due to tensile strains normal to the direction of loading.

5. DISCUSSION OF TEST RESULTS

5.1 Rest periods

5.1.1 Effect on fatigue life

For the majority of the tests reported here the duration of the loading pulse was 40 ms and the following discussion is based on the results of these tests.

The results of all the rest period tests are summarised in Table 3, in which the effect on fatigue performance is expressed in terms of a "Life Ratio", which is the ratio of mean life with rests to mean life without rests. In Fig. 8 the Life Ratio is plotted against rest duration for the various temperatures and stress levels. The curves suggest that with very short rests the life increases rapidly and then appears to reach a limiting value at about 400 ms, beyond which increasing the duration of the rest period has very little further effect. Detailed analysis of the results confirms that at any particular temperature and stress level the observed differences in mean lives with rests of up to 400 ms are statistically significant at the 5 per cent level. Any apparent differences beyond 400 ms are not significant, either at 10°C or at 40°C. (the few tests made with a loading pulse duration of 400 ms show a similar trend, i.e. a significant increase in mean life due to rest periods if the ratio of rest period to loading pulse duration is kept the same.)

Fig. 8 suggests that the limiting value of Life Ratio depends on temperature and perhaps on stress level. Assuming a log normal distribution of fatigue lives, the results have been assessed statistically to compare the values of Life Ratio for each temperature and stress level. The results of the analysis are given in Table 6 and are discussed in 5.1.2 and 5.1.3 below.

Where differences are significant they may be due to changes in the test parameters or they may be attributed to some combination of factors, including the variability of material from slab to slab. There are as yet insufficient data to make this distinction and further experiments are being made to this end.

5.1.2 Effect of stress amplitude on life ratio

Tests at 10°C and 25°C were each made at two stress levels and there was a tendency for Life Ratios at the higher stresses to be less than those at the lower stresses. For rests of 80 ms, the difference in Life Ratio is significant at the 5 per cent level at 10°C but not at 25°C (Table 6). For rests of 400 ms the differences are significant at the 10 per cent level at 10°C but with 1000 ms rests differences due to stress level are not significant at either temperature.

It is not clearly established, therefore, whether stress amplitude affects the limiting value of Life Ratio; real differences may have been masked by the relatively high scatter of results due to some of the specimens having been cut from different slabs.

5.1.3 Effect of temperature on life ratio

There was no clear correlation between Life Ratio and temperature with rests of 80 ms. At 400 ms the Life Ratio at 40°C is significantly lower than those observed at 10°C. No figures are available for 25°C under these conditions. For rests of 1000 ms the value of Life Ratio at 40°C is again significantly less than the values obtained at 10°C and 25°C but differences between 10°C and 25°C are generally not significant. As noted above the results may have been affected by the fact that some test specimens were cut from different slabs.

It is concluded that the results of these tests indicate that there is a limiting value of Life Ratio which, for loading pulses of 40 ms duration, is reached in less than 1s at temperatures within the range 10°C to 40°C (Fig. 8). The numerical value of the Life Ratio is lower at 40°C (mean value approximately 5) than at 25°C or 10°C (mean value 15 to 25). A limited theoretical evaluation of the behaviour of typical road structures at various temperatures, using stress and strain endurance curves derived from continuous sinusoidal loading, suggests that high temperature conditions are likely to be more damaging than low. This tendency would be accentuated if rest periods due to vehicle headway were less beneficial at the higher temperatures. Further work is required to study the relative importance of axle spacing and vehicle spacing at various temperatures.

5.1.4 Effect of temperature on fatigue damage and recovery

The mechanisms of fatigue damage and recovery in materials having bituminous binders have not yet been defined. However the results reported above in 5.1.3 suggest that behaviour relevant to fatigue recovery changes relatively little between 10°C and 25°C, but does alter markedly between 25°C and 40°C. Neither dynamic stiffness, nor stress or strain amplitude to cause failure in a given number of load cycles, respond to temperature in this way. However the rate of creep recovery of residual strain at the end of a single loading cycles does vary with temperature in a manner qualitatively similar to the limiting value of Life Ratio; Table 7 shows that recovery times at 10°C and 25°C were not distinguishable, but that at 40°C was greater by almost 50 per cent.

The above is insufficient evidence to support a conclusion linking the mechanism of fatigue damage and recovery with that of creep recovery. It does suggest, however, that it would be worthwhile attempting to correlate fatigue behaviour with the quasi-static response of the material. This work should be accompanied by a study of changes in the nature of the binder throughout the fatigue process, so that it may become possible to define desirable binder properties which will provide a good resistance to fatigue loading for mix design.

5.1.5 Dynamic stiffness

Examination of the changes in dynamic stiffness due to the effects of repeated loading (Fig. 5) shows an important difference in behaviour when rest periods are included. All the curves have the same basic form, i.e. a short initial period during which the stiffness falls rapidly, followed by a comparatively long period when the stiffness falls more gradually and finally a period when the stiffness again falls rapidly (this latter stage being associated with the onset of visible cracking). In the case of the tests which included rest periods the stiffness changed more gradually than with continuous cycling and in fact remained nearly constant for over half the life at the two lower temperatures (10°C and 25°C). By the time an increase in deflection of the order of 25 to 50 per cent was observed in the rest period tests an appreciable proportion of the fatigue life had elapsed. This may be an observation of some practical importance because it could give some guidance as to how a "service life" may be defined in relation to the prediction of road performance from laboratory tests, such that major failure may be anticipated and avoided.

It is interesting to compare these observations with the results of full-scale road experiments. Long-term deflection measurements taken over a number of years at Alconbury Hill[9] indicate that for a rolled asphalt base the road structure is likely to be reaching a critical state, requiring some remedial action, when surface deflections in the nearside wheel tracks have increased by between 20 and 40 per cent over the deflections measured during the first year or two of the life of the road. Comparing these figures with the stiffness curves of Fig. 5 it will be seen that, for temperatures of 10°C and 25°C, by the time that the stiffness had dropped by 25 per cent in the tests with 1s rest periods, the test specimens had already used up nearly 80 per cent of their fatigue life, an observation which appears consistent with the behaviour of full-scale roads. For the same loss of stiffness in the continuous cycling tests, however, the indications are that well over half the life still remained. This suggests that a "failure" criterion based on loss of stiffness in the continuous cycling type of test could be unduly pessimistic for the prediction of service life; for realistic changes in stiffness the continuous cycling test indicates an unnecessarily high margin of life remaining.

5.2 Shape of waveform

Ideally the loading applied in a laboratory fatigue test should reproduce the stress and strain histories occurring in the road but this is usually impracticable. The sensitivity of fatigue performance to differences in the shape of the applied waveform was investigated by running the tests described in Section 3.3.2. The results (Table 4) show that there were some differences in mean life between sinusoidal, triangular and square waves and that these could to some extent be related to both the magnitude and duration of the resultant strains during the loading cycle. However, the differences are sufficiently small to suggest that the assumption of a sinusoidally shaped load pulse to represent the shape of the stress pulse that occurs in the road is unlikely to lead to significant error.

At critical points in the road structure, where the horizontal tensile stresses and strains reach a maximum, such as at the lower surface of the road base, strain gauge records show that the longitudinal strains arising from a single wheel load have the form shown in Fig. 9. Portion BC of the longitudinal strain response bears a marked resemblance to the resultant strain in the single cycle rest period tests in which the stress waveform was sinusoidal (Fig. 7).

To assess the significance of the portion AB when combined with BC, the effect of the initial direction of straining was first investigated. It is clear from Table 5 that with single sinusoidal cycles followed by rest periods the initial direction of loading is important. The application of tensile, followed by compressive stress (Case 1) gave a mean life some 70 per cent greater than when compressive stress was followed by tensile (Case 2) even though the resultant peak tensile strain was considerably greater in Case 1. This can possibly be explained in terms of the effective range of tensile-going strain. In Case 1 forced tensile straining occurs by load applied during the period DE and this is followed by a period EF when the load is being reduced and reversed; further tensile-going strain is imposed by the loading FG, followed by a period of relaxation during the ensuing rest period. In Case 2, although the ranges of both stress and strain are about the same as in Case 1, the forced tensile-going strain resulting from E′ to F′ is approximately 1.5 times that from D to E in Case 1.

In the second group of tests (Cases 3 and 4), the effect of loading-direction was studied when the applied stress had the same peak value as in Cases 1 and 2 but was unidirectional, either wholly tensile or wholly compressive. For wholly tensile loading (Case 3) the mean life was apparently lower than in Case 1 but the difference is not statistically significant. The peak strains in Cases 1 and 3 were very similar and the similarity in lives lends support to the conclusion that it is the tensile-going strain excursion rather than the absolute strain level that is important. In Case 4 (wholly compressive stress) a very much longer, but still finite, life was achieved, although the mode of failure was different, being a shear failure on a plane at 45° to the axis of loading instead of cracking normal to the loading which occurred in Cases 1, 2 and 3.

Considering the complete strain cycle of Fig. 9 it is concluded from the above that a sinusoidal stress pulse having zero mean stress and with the initial direction of loading tensile, produces a strain waveform the shape of which is likely to give a reasonably good representation of fatigue damage in bituminous materials due to longitudinal strains in the road base imposed by traffic loading. The damage due to the initial (compressive) lobe is likely to be small compared with that from the main tensile and second compressive lobes, although it does have some effect on the range of tensile-going strain imposed on the material.

5.3 Additional compaction under traffic

In another part of the research programme the effect of additional compaction under traffic was explored by subjecting a slab of the same rolled asphalt basecourse material to a large number of rolling wheel loads at 25°C until maximum compaction had been achieved. Fatigue tests were then made under continuous cycling on specimens cut from the fully compacted slab[4]. The mean fatigue life under a cyclic stress of 575 kN/m^2 was nearly 3 times the life of untrafficked specimens. The increase in life could be accounted for largely by the increased dynamic stiffness resulting from densification under traffic. If significant densification occurs in critical layers of the road and the effects of such densification are combined with the effects of rest periods, then it is possible that the life predicted from fatigue tests on untrafficked material under continuous cycling could be underestimated by a factor of 50 or more.

6. CONCLUSIONS

1. Fatigue tests on a rolled asphalt basecourse material have shown the importance of the effects of short rest periods, such as occur in practice between successive axle loads on a flexible road. Both axle spacing and vehicle spacing are significant in this respect. Compared with continuous cyclic loading at 25 Hz, the life to failure with 1s rests was up to 25 times longer, the increase in life depending largely on the test temperature. There was also a marked reduction in the rate at which the dynamic stiffness was reduced by cyclic loading. The increased resistance to fatigue may be even greater in the road if significant densification takes place under traffic.

2. At temperatures above 25°C there appears to be a decrease in the benefit accruing from short rest periods, lending weight to the suggestion that fatigue damage in the road is likely to be more rapid under high temperature conditions.

3. The differences observed underline the dangers of using the results of simple laboratory fatigue tests under continuous cyclic loading to predict directly the behaviour of full-scale roads in service.

4. The effect of varying the waveform of the applied loading was not very great. For a practical laboratory test on bituminous materials, a pulsed sinusoidal load input gives a reasonable representation of the time history of horizontal tensile strains recorded in the road base.

7. PROPOSALS FOR FUTURE RESEARCH

1. Further work is needed to check the relative importance of axle spacing and vehicle spacing. Further tests are proposed on the same material in which trains of loading pulses are applied with the time interval between loading pulses varied to represent various axle configurations.

2. The possibility of correlating fatigue behaviour with the quasi-static response of the material should be investigated. This work should include a study of the role of the binder in resisting repeated loading as an aid to optimum mix design.

8. ACKNOWLEDGEMENTS

The work reported forms part of a broad research programme on the dynamic strength properties of road materials, being carried out in the Structural Properties Division (Head: Mr. D F Cornelius). The assistance of Mr. R T N Goddard and Mr M E Nunn, of the Refined Bitumen Association, in performing some of the test work and in presentation of the results is gratefully acknowledged.

9. REFERENCES

1. BURT, M E. Progress on Pavement Design. TRRL Report LR 508, 1972.

2. PELL, P S and S F BROWN. The Characteristics of Materials for the Design of Flexible Pavement Structures. 3rd Int. Conf. on the Structural Design of Asphalt Pavements. London 1972.

3. ASCE Committee on Structural Design of Roadways (W R Hudson, Chairman). Problems of Designing Roadway Structures, Transportation Engineering Journal of ASCE, Vol 95, No TE2 Proc. Paper 6542, May 1969.

4. RAITHBY, K D and J T RAMSHAW. Effects of Secondary Compaction on the Fatigue Performance of a Hot-Rolled Asphalt. TRRL Report LR 471. 1972.

5. MONISMITH, C L. Asphalt Mixture Behaviour in Repeated Flexure. Report No. TE-66-6. University of California, Berkeley, 1966.

6. SANTUCCI, L E and R J SCHMIDT. The Effect of Asphalt Properties on the Fatigue Resistance of Asphalt Paving Mixtures. Proc. Assoc. of Asphalt Paving Technologists. Vol. 38, 1969.

7. STILL, P B. Amplitude Control and Detection in an Electrohydraulic Dynamic Loading System. RRL Report LR 415. 1971.

8. PELL, P S and I F TAYLOR. Asphaltic Road Materials in Fatigue, Proc. Assoc. of Asphalt Paving Technologists, Vol. 38, 1969.

9. LISTER, N W. Deflection criteria for flexible pavements and the design of overlays. 3rd Int. Conf. on the Structural Design of Asphalt Pavements, London, 1972.

TABLE 1

Mix proportions

	Nominal	Mean of 10 samples at mixing plant'	Range of composition from analysis of test specimens	
Stone Content (above No. 7 sieve) % by weight	60.0	61.4	61.9	59.4
Soluble bitumen content % by weight	6.0	6.4	5.9	6.6
Sand content (pass No. 7 sieve) % by weight	34.0	32.2	32.2	34.0
Bitumen content adjusted to 60% stone		6.5	6.2	6.5
Void content – % by volume	3 to 6	3	0.5 to	5
Coarse Aggregate Grading				
% by weight passing 1" B.S. sieve	100.0	100.0	100.0	100.0
3/4"	97.5	99.5	100.0	97.1
1/2"	55.5	56.1	58.2	60.1
3/8"	44.5	44.0	45.0	47.1
1/4"	38.2	37.3	37.3	39.7
Fine Aggregate Grading				
% by weight passing No. 7 B.S. sieve	35.6	34.4	33.4	35.7
No. 25	30.0	31.3	29.0	31.2
No. 72	4.3	5.3	3.3	4.6
No. 200	0.7	0.8	0.7	1.0

TABLE 2

Properties of binder

	Nominal	At mixing plant* before mixing	Typical values recovered from test specimens
Penetration at 25°C	45	38	25
Ring and Ball temp† (°C)	-	57.3	67.5
Penetration Index	-	- 0.2	+0.7

* After one week's storage in heated circulating tanks

† Tested to I.P. Standard 58/65.

TABLE 3

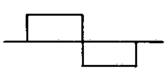
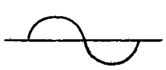
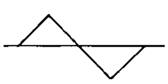
Results of rest period tests

Loading period ms	Temperature °C	Alternating stress MN/m^2	Rest period ms	Number of tests	Geometric mean life cycles	Std. devn. of Log. life	Life* ratio
40	10	1.5	0	5	6,625	0.192	1.0
			80	6	16,110	0.262	2.4
			400	4	80,870	0.317	12.2
			1000	4	100,500	0.346	15.1
40		1.0	0	7	34,680	0.551	1.0
			80	6	215,400	0.618	6.2
			400	4	896,800	1.015	25.8
			1000	5	843,100	0.637	24.3
40	25	0.76	0	2	4,690	0	1.0
			80	3	11,190	0.287	2.4
			1000	3	111,400	0.396	23.6
40		0.43	0	6	40,440	0.124	1.0
			40	2	89,130	0.115	2.2
			80	3	158,700	0.042	3.9
			1000	1	1,088,510	-	26.9
40	40	0.20	0	4	10,360	0.282	1.0
			80	3	34,000	0.052	3.3
			400	4	68,960	0.257	6.7
			1000	4	42,330	0.156	4.1
400	25	0.27	0	3	18,600	0.268	1.0
			800	2	91,580	0.301	4.9

* Geometric mean life with rests/geometric mean life under continuous cycling.

TABLE 4

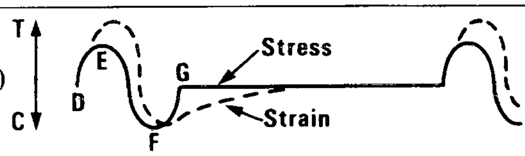
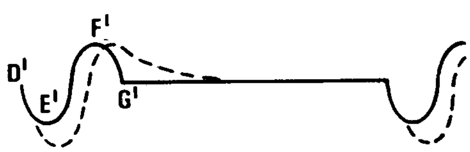
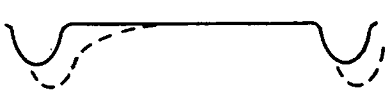
Effect of shape of waveform on fatigue life

Waveform	Temp °C	Stress amp. MN/m^2	Initial strain amp.	Geometric mean fatigue life cycles	Relative lives
	25		1.7×10^{-4}*	24,690	0.42
	25	± 0.33	1.2×10^{-4}*	58,950	1.0
	25		0.67×10^{-4}*	85,570	1.45

* These represent values after approximately 200 cycles

TABLE 5

Effect of strain reversal on fatigue life

	Waveform	Geometric mean fatigue life cycles
(1)		11,190
(2)		6,649
(3)		8,748
(4)		196,200

Peak stress 0.76 MN/m^2 in each case. Temperature 25°C.

TABLE 6

Significance levels of differences between life ratios
(t test, single tailed)

Test conditions	25°C 0.76 MN/m^2	25°C 0.43 MN/m^2	10°C 1.5 MN/m^2	10°C 1.0 MN/m^2
40°C 0.2 MN/m^2	NS	NS	NS	5%
25°C 0.76 MN/m^2		NS	NS	5%
25°C 0.43 MN/m^2			NS	2.5%
10°C 1.5 MN/m^2				5%

80 ms rests

Test conditions	10°C 1.5 MN/m^2	10°C 1.0 MN/m^2
40°C 0.2 MN/m^2	5%	2.5%
10°C 1.5 MN/m^2		10%

400 ms rests

Test conditions	25°C 0.76 MN/m^2	25°C 0.43 MN/m^2	10°C 1.5 MN/m^2	10°C 1.0 MN/m^2
40°C 0.2 MN/m^2	0.5%	0.05%	0.05%	0.1%
25°C 0.76 MN/m^2		NS	NS	NS
25°C 0.43 MN/m^2			5%	NS
10°C 1.5 MN/m^2				NS

1,000 ms rests

NS means not significant at 10 per cent level.

TABLE 7

Strain recovery during rest period

Test Temperature °C	Time (ms) for residual strain to reduce by		Limiting life ratio
	50%	75%	
40	12.5	29	5
25	9.0	19	15/25
10	8.7	20	25

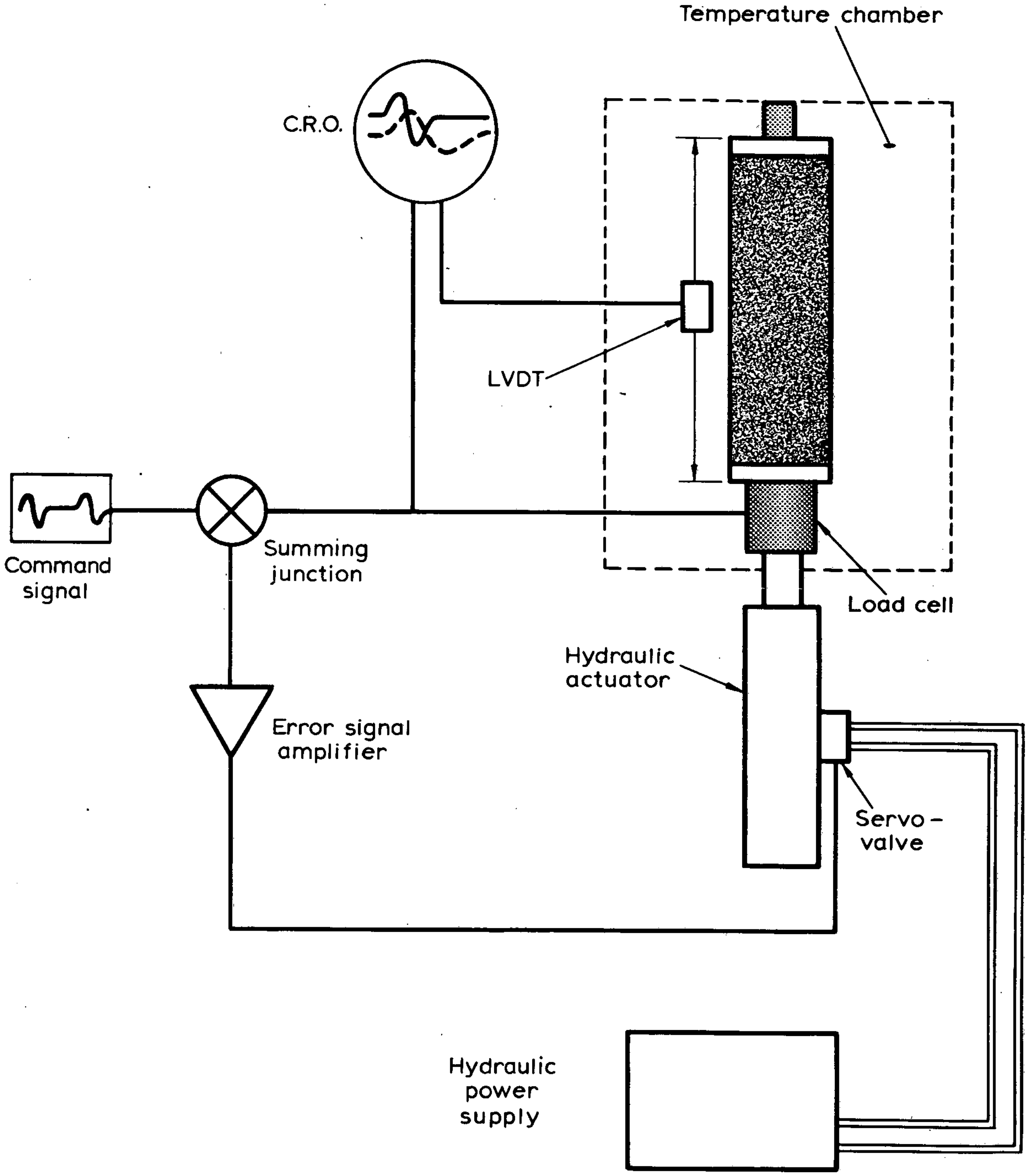


Fig. 1. SCHEMATIC REPRESENTATION OF METHOD OF TEST

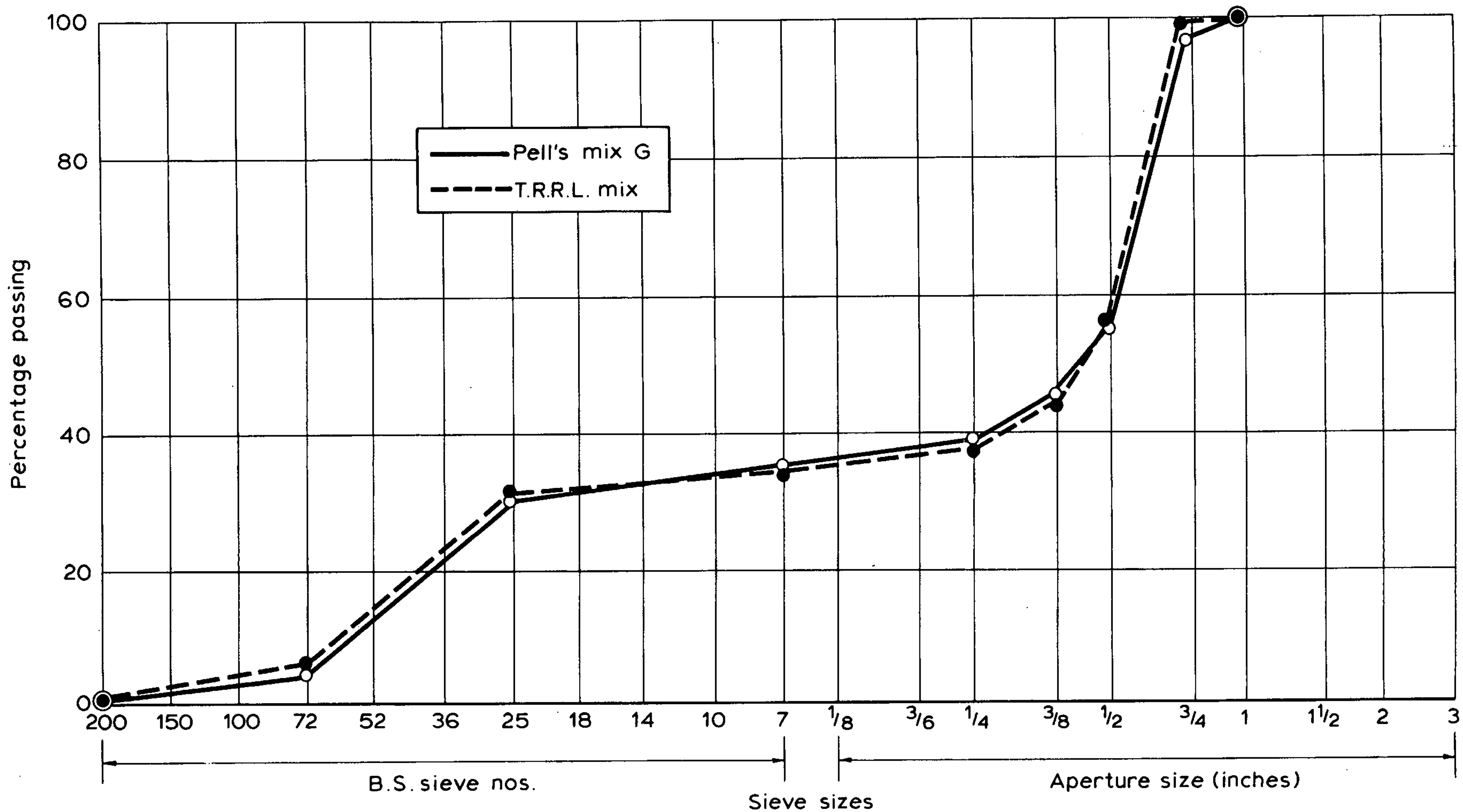


Fig. 2. AGGREGATE GRADING CURVE

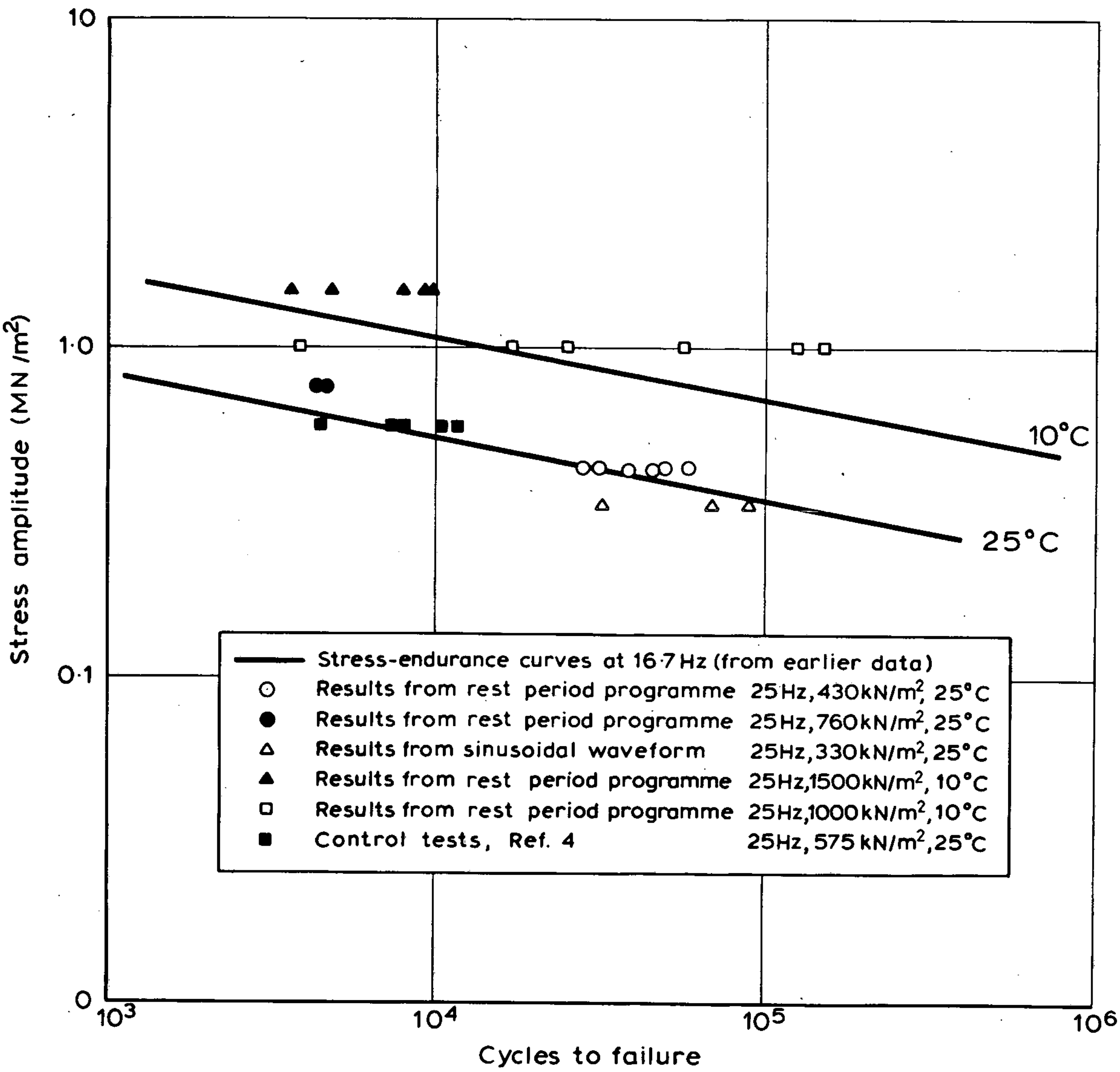


Fig. 3. STRESS-ENDURANCE CURVES, CONTINUOUS SINUSOIDAL LOADING AT 16·7 Hz (REPLOTTED FROM REF. 9)

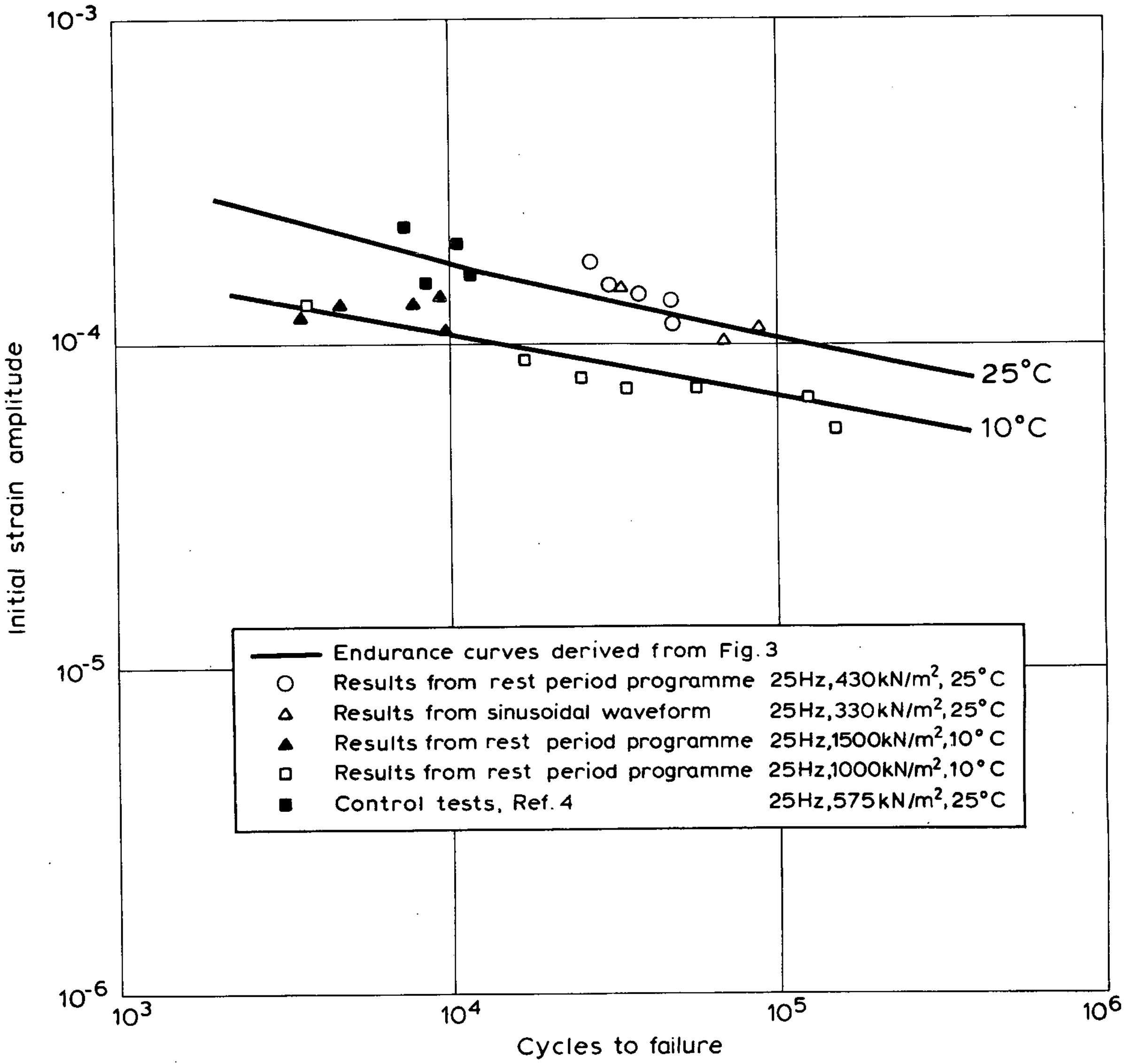


Fig. 4. STRAIN-ENDURANCE CURVES DERIVED FROM Fig. 3

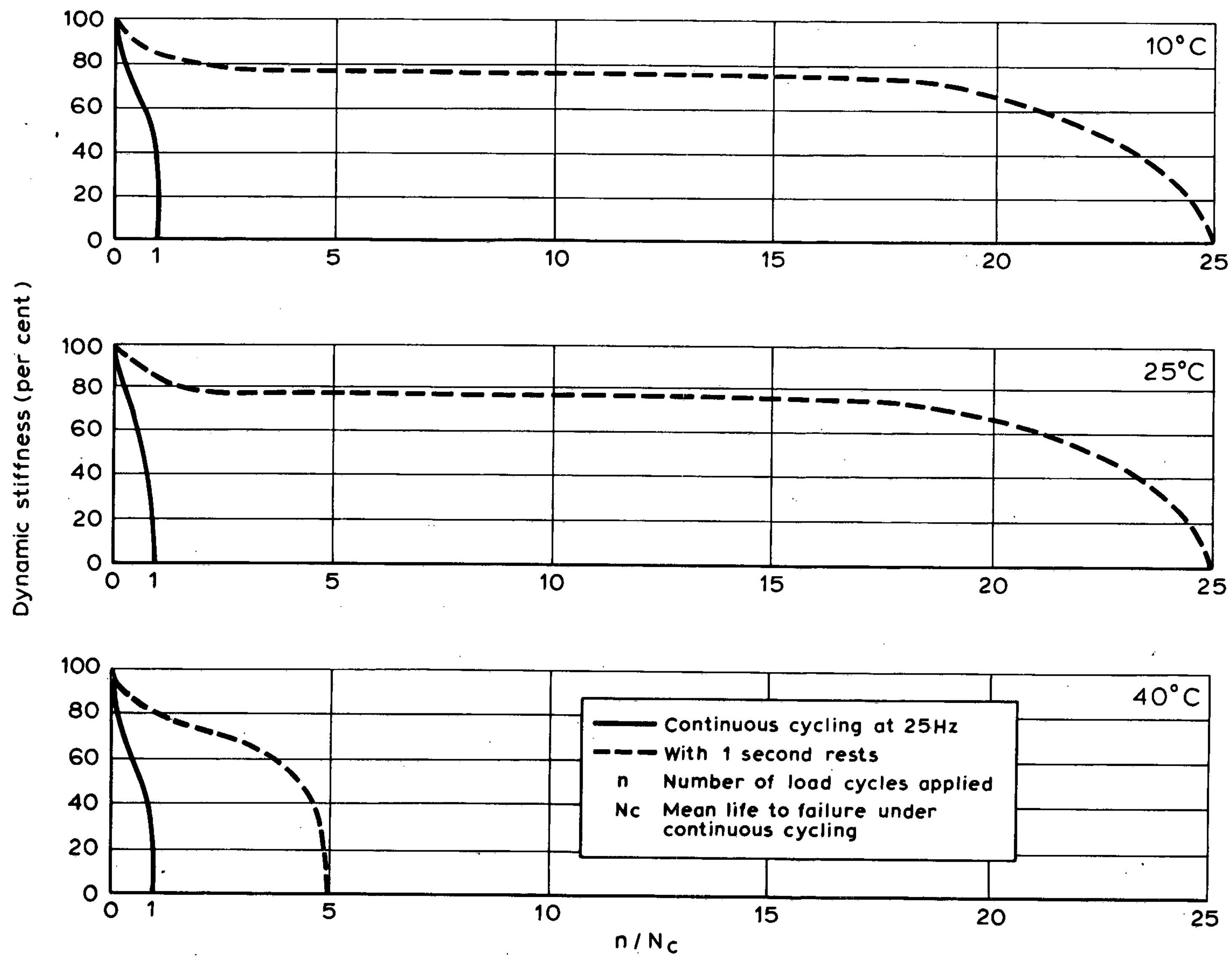


Fig. 5. TYPICAL VARIATION OF DYNAMIC STIFFNESS WITH LOADING CYCLES

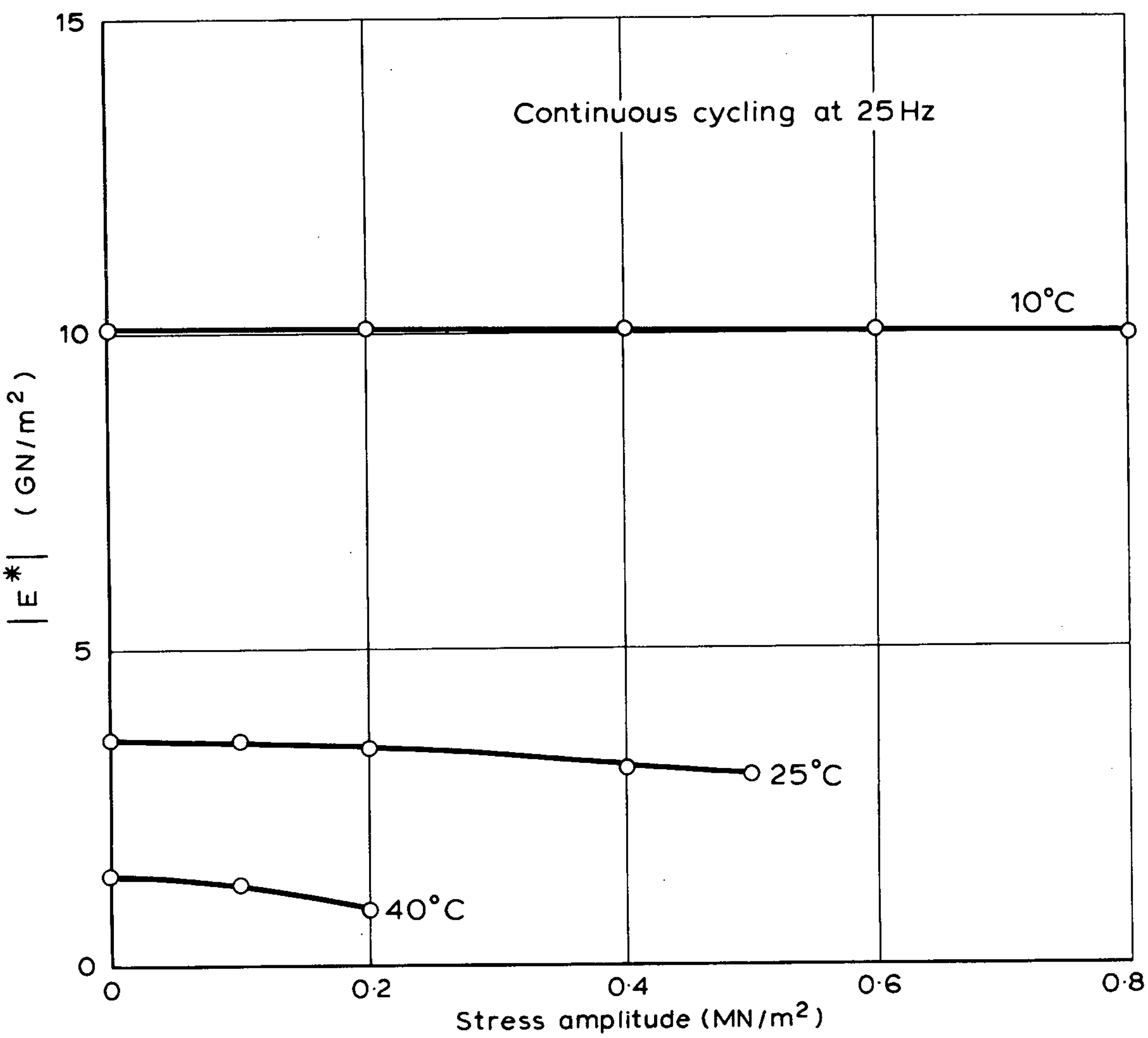


Fig. 6. VARIATION OF DYNAMIC STIFFNESS WITH STRESS AMPLITUDE AT VARIOUS TEMPERATURES

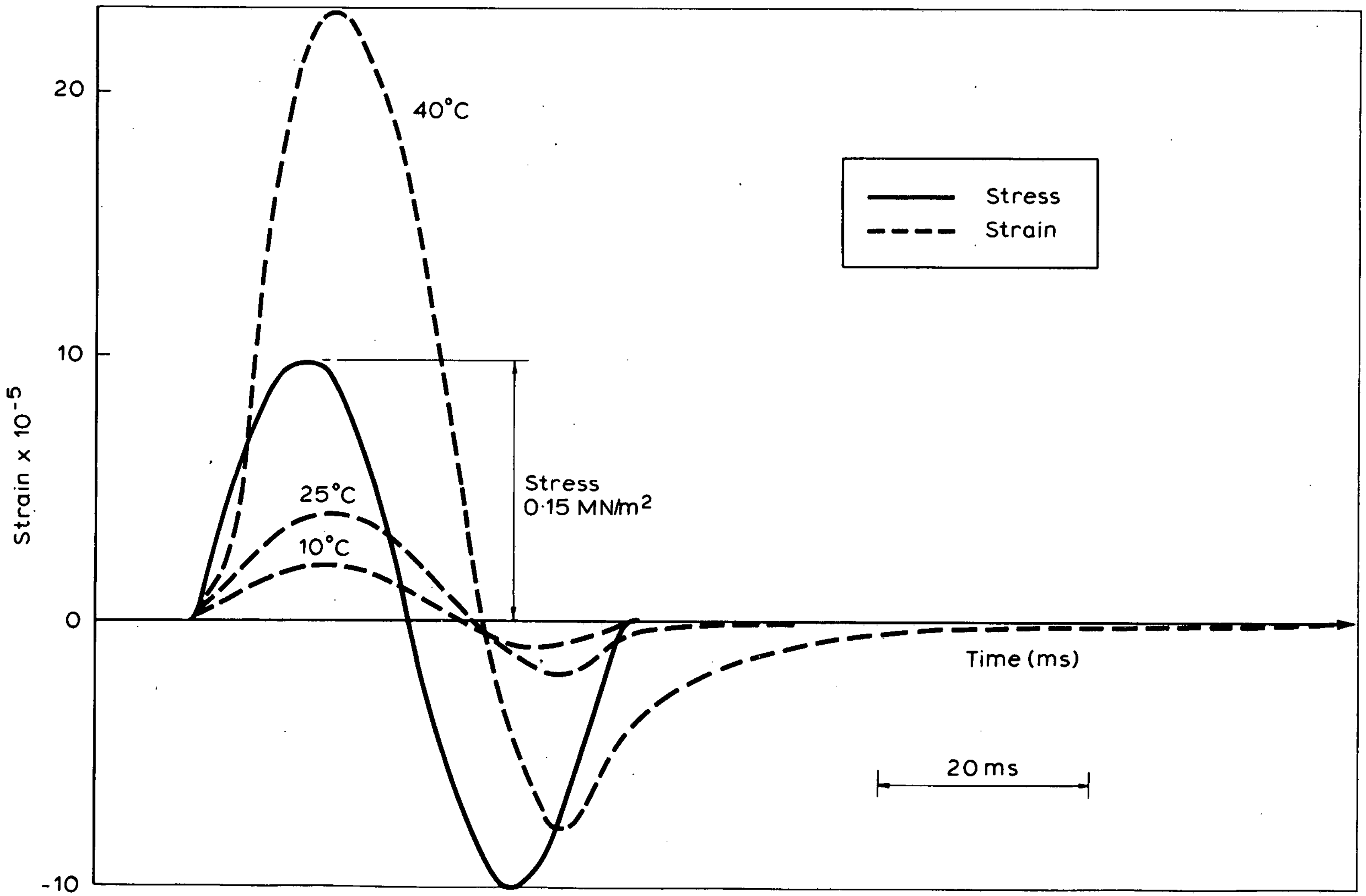


Fig. 7. STRESS AND STRAIN PROFILES, SINGLE SINUSOIDAL LOADING PULSE

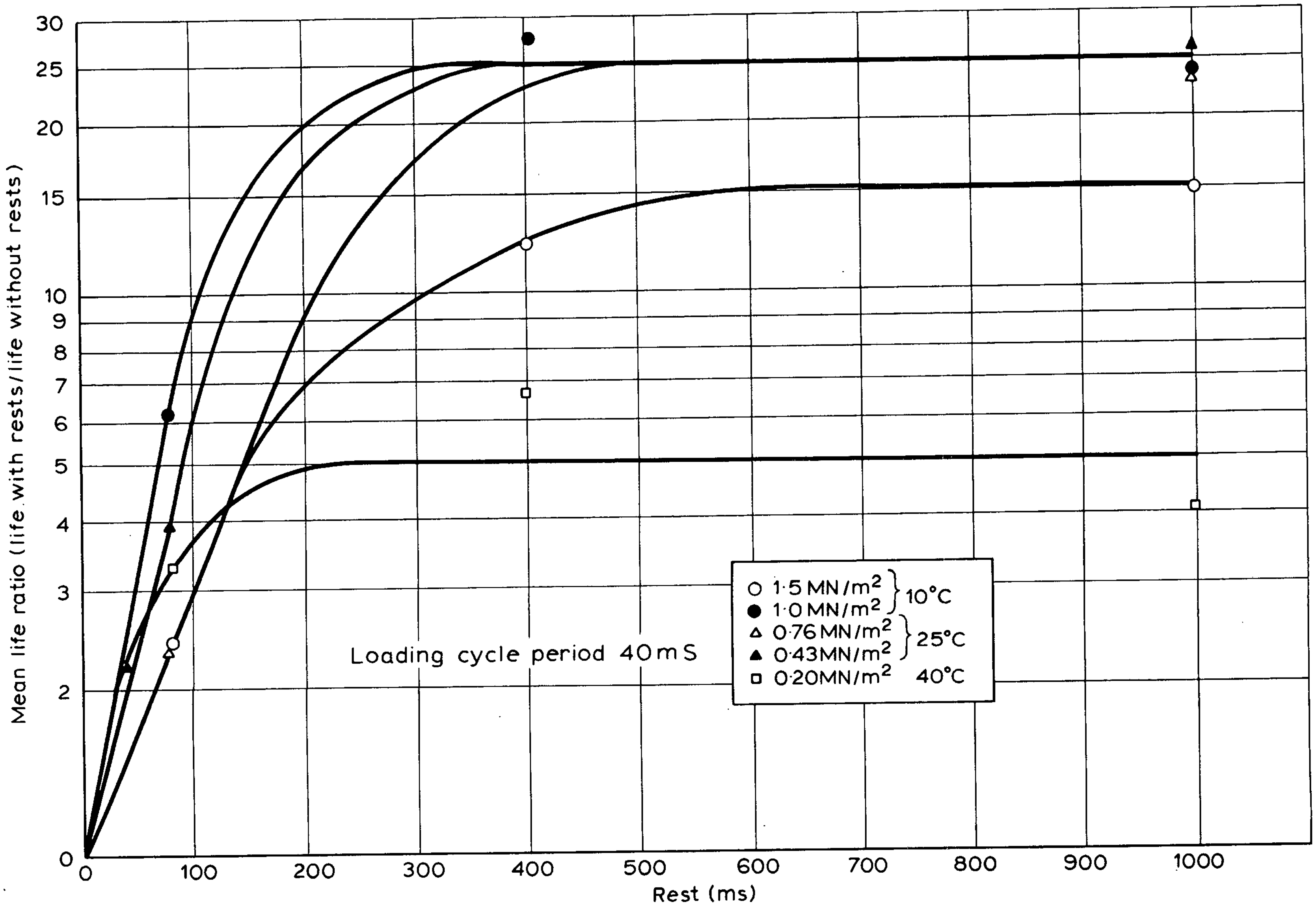


Fig. 8. LIFE RATIO v REST DURATION

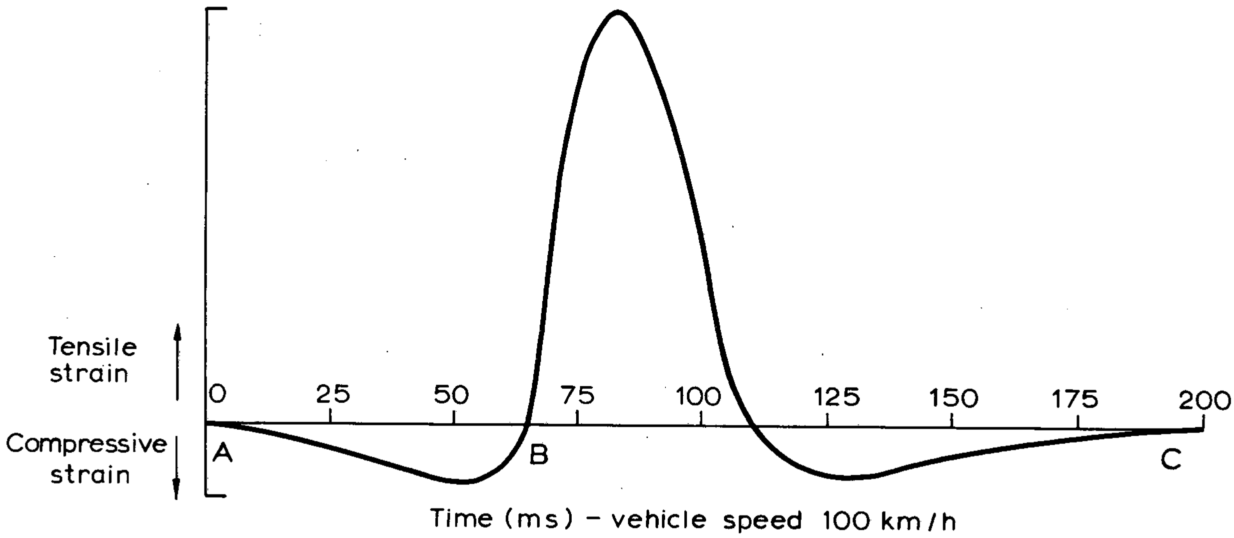


Fig.9. TYPICAL LONGITUDINAL STRAIN PROFILE RECORDED IN A ROLLED ASPHALT ROAD BASE UNDER A WHEEL

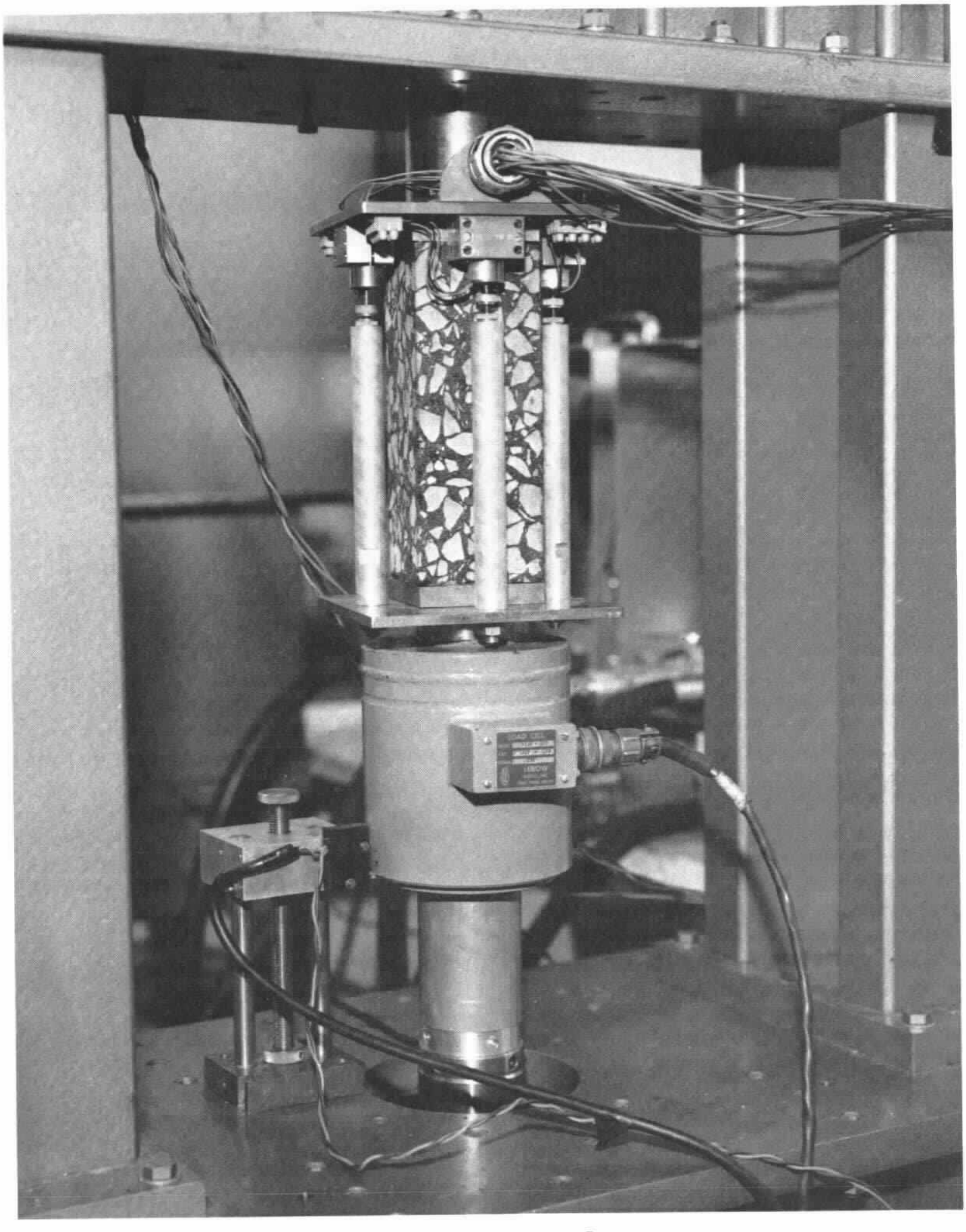


Plate 1. Fatigue Test in Progress

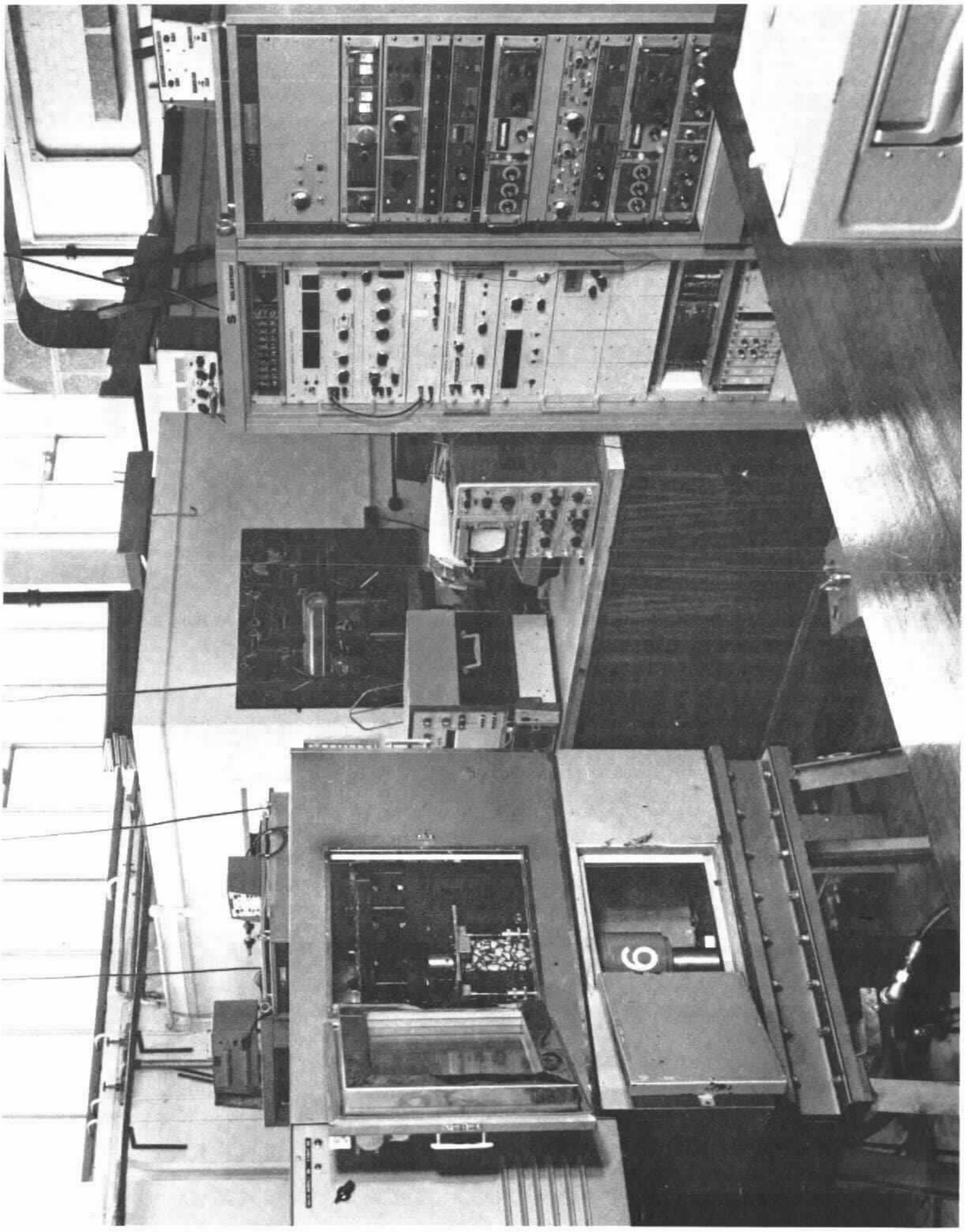


Plate 2. General View of Test Equipment

(1132) Dd.891796 4M 8/72 HP Ltd., So'ton G.1915
PRINTED IN ENGLAND

ABSTRACT

Some effects of loading history on the fatigue performance of rolled asphalt: K D RAITHBY and A B STERLING (formerly of the Refined Bitumen Association): Department of the Environment, TRRL Report LR 496: Crowthorne, 1972 (Transport and Road Research Laboratory). Results are given of fatigue tests under direct stress axial loading conditions on a typical rolled asphalt base-course material, to investigate the significance of varying the load-time history.

Rest periods between successive loading cycles had a beneficial effect on fatigue performance, both by increasing the resistance to cracking and by reducing the rate of loss of dynamic stiffness due to repeated loading. Rest periods of the order of 1 s increased the number of cycles to failure by a factor of up to 25, when compared with the life under continuous sinusoidal cyclic loading. The improvement in life was less at high temperatures; it also appeared to be affected somewhat by the magnitude of the applied cyclic stress, although this effect was not clearly established.

A comparison of fatigue performance under square, sinusoidal and triangular waveforms indicates some significant differences but these are small compared with the effects of rest periods.

ABSTRACT

Some effects of loading history on the fatigue performance of rolled asphalt: K D RAITHBY and A B STERLING (formerly of the Refined Bitumen Association): Department of the Environment, TRRL Report LR 496: Crowthorne, 1972 (Transport and Road Research Laboratory). Results are given of fatigue tests under direct stress axial loading conditions on a typical rolled asphalt base-course material, to investigate the significance of varying the load-time history.

Rest periods between successive loading cycles had a beneficial effect on fatigue performance, both by increasing the resistance to cracking and by reducing the rate of loss of dynamic stiffness due to repeated loading. Rest periods of the order of 1 s increased the number of cycles to failure by a factor of up to 25, when compared with the life under continuous sinusoidal cyclic loading. The improvement in life was less at high temperatures; it also appeared to be affected somewhat by the magnitude of the applied cyclic stress, although this effect was not clearly established.

A comparison of fatigue performance under square, sinusoidal and triangular waveforms indicates some significant differences but these are small compared with the effects of rest periods.