
PAVEMENT FATIGUE CONCEPTS: A HISTORICAL REVIEW

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INTRODUCTION

One of the most critical aspects of a mechanistic-based pavement design procedure is the so-called *transfer function*, which converts a pavement system response (usually a stress or a strain value) to a number of repetitions of a particular load level, allowable before a selected failure state is reached. For both Portland cement concrete (PCC) and hot mix asphalt (HMA) pavements, current mechanistic-based approaches incorporate some version of Miner's linear cumulative fatigue hypothesis (1). A considerable number of fatigue *transfer functions* have been proposed over the years, but there are widespread discrepancies in their respective predictions (2). This reflects a lack of consensus among researchers regarding the factors controlling fatigue behavior of pavements, and their relative significance. In addition to its application in design against fatigue, Miner's rule is often used for other distresses, including pumping in PCC (3) and rutting in HMA pavements (4).

The crucial role played by fatigue concepts in pavement design has prompted the U.S. Army Corps of Engineers (USACE) to initiate a study for an objective assessment of their validity and applicability. This Paper presents the highlights from the first stage of that USACE study, in which the historical background and evolution of modern-day fatigue concepts are traced and evaluated. A number of studies are reviewed: data presented show that the linear cumulative hypothesis could have been as easily rejected in pavement design as accepted. Impetus for the adoption of Miner's hypothesis in both PCC and HMA pavement design was provided in the aftermath of the AASHO Road Test (1958-1960), which also produced the Equivalent Single Axle Load (ESAL) concept.

Because of the large scatter exhibited by fatigue data, it is recommended that alternatives be sought to enhance current fatigue concepts, e.g., through the implementation of sophisticated fracture mechanics concepts, recently promulgated in the United States, Europe and Russia. The aforementioned USACE study is expected to continue for at least three more years and to produce an improved computerized methodology for accounting for pavement fatigue.

FATIGUE TESTING FOR PCC PAVEMENTS

Intense interest in fatigue behavior of pavements and in fatigue-related distresses in such systems can be traced to the earliest days of scientific interest in the subject of fatigue in general, i.e., to the end of the 19th century, at least as far as concrete pavements are concerned.

A 1960 bibliography by the American Concrete Institute (5) documents fatigue studies of concrete between 1898 and 1958, and confirms that a number of the earliest studies were at least partly motivated by an interest in the fatigue behavior of concrete pavements. Additional historical information used in the preparation of this section has been extracted from a 1965 report to the Illinois Division of Highways by Murdock (6).

Fatigue testing of concrete specimens can be subdivided into three distinct classes, according to the mode of load application:

- (a) Axial tensile tests;
- (b) Axial compressive tests; and
- (c) Flexural tests.

The first of these classes is the least comprehensive, presumably because this type of loading is not a common occurrence in concrete structures. In fact, the late 19th century tests conducted in France by De Joly (7) are exceptional, in the sense that they remain the only ones related to the behavior of concrete under direct axial tensile loads (8). Murdock (6) suggests that "the difficulties inherent in devising a suitable tension specimen and subjecting it to repeated axial tensile loads are more probable reasons for the fact that no further work has been done in this area." Interest in this type of testing may be renewed as application of fracture mechanics concepts to concrete progresses.

The early 20th century fatigue tests by van Ornum (9) at Washington University, St Louis, MO, are among the first examples of studies involving axial compressive loads. They indicated a fatigue strength of approximately 55% of the static ultimate strength at 7000 cycles of load, but failed to indicate the existence of a fatigue limit. *Fatigue strength* refers to the maximum repeated stress ratio sustainable over a selected number of repetitions, while *fatigue* (or *endurance*) *limit* denotes the corresponding ratio below which an indefinite number of repetitions may be applied. Murdock (6) credits van Ornum's tests with establishing "the existence of the fatigue phenomenon for concrete" and for recording "the observation of progressive failure." Subsequently, van Ornum (10) showed that a reduction of the modulus of elasticity occurred progressively during repetitive loading, in one case resulting in a modulus of about 70% of its initial value. A series of tests conducted over the following thirty years at the Technische Hochschule of Karlsruhe by Probst and his co-workers, e.g., (11), substantiated van Ornum's results and provided a firm basis for research into the mechanisms of fatigue failure.

It would appear that the earliest flexural fatigue tests were also conducted in late 19th century France by Considere (12), who used an apparatus similar to that used later in the Purdue tests of the 1920s, and by Feret (13), who tested 50x50 mm beams on a 500-mm span and 100x360 mm beams on a 3.25 m span. A long series of fatigue tests at the University of Illinois was also initiated at about the same time (14); these tests can be considered as precursors to subsequent concrete fatigue investigations at Illinois whose influence on pavement design concepts has been profound, as discussed in later sections.

Interest in concrete pavement behavior led to a series of flexural fatigue tests conducted by the Illinois Division of Highways in the early 1920s. Their primary objective was to examine corner breaks under repeated loads, as observed at what became known as the Bates Road Test, completed in 1923 (15; 16). In conformity to the prevailing understanding of concrete pavement slab corner behavior (17), about one hundred cantilever beams 150x150x915 mm (6x6x36 in.) in size were tested. The applied loading was intended to simulate actual pavement loads. These tests confirmed that fatigue failure did occur under repeated flexural loads, and suggested a fatigue limit of approximately 53% of the static ultimate strength. Results therefrom were cited in 1938 by Bradbury (18) and again in 1959 by Yoder (19), and have provided the basis for design procedures ever since, retrospective assessments of their limitations notwithstanding (6). Additional tests, subjecting beam specimens to the now conventional third-point loading, were also conducted in Illinois, e.g., (20).

The Purdue tests already mentioned were also conducted in the early 1920s, and were similarly motivated to a great extent by interest in concrete pavement behavior, e.g., (21). Unlike those at Illinois, the ingenious Purdue setup subjected the upright cantilevered specimens to a pair of eccentric loads, producing what was essentially pure bending with complete stress reversals. Results suggested a fatigue limit of approximately 55% of the static ultimate strength, and hinted that concrete fatigue performance may be influenced by loading sequence (i.e., by stress history),

by loading frequency and by rest periods between successive load applications. Interestingly, these same issues continued to attract the interest of investigators in the following decades.

Ending a 15-year long hiatus in American concrete fatigue studies, the 1943 paper by Williams (22) refuted the existence of a true fatigue limit, yet reported an approximate fatigue strength of 40 to 50% at one million repetitions. Williams also speculated that fatigue failure may be "associated with aggregate imperfections and that crack propagation is assisted, if not caused, by the 'stress raisers' at the [tip] of the crack" (6). Following another dormant period, a new series of concrete fatigue tests was initiated in the 1950s at the University of Illinois by Kesler (23) and co-workers. These tests confirmed the absence of a fatigue limit through ten million load cycles. With regard to the mechanism of fatigue failure Murdock and Kesler (24) postulated that the aggregate-paste bond might be critical.

A major concept introduced in the mid-1950s pertained to the realization of a need for statistical interpretation of concrete fatigue tests. McCall (25) is credited with adding this "most important 'third dimension' to the fatigue studies" (6), the other two being the applied stress level and the number of cycles to failure. While affirming the emerging consensus concerning the absence of a fatigue limit, McCall reported a fatigue strength of about 50% through 20 million load repetitions, with failure probability slightly below 0.5. This probability increased to 0.8 for an applied stress ratio of 58%, and decreased to 0.1 for a stress ratio of 35%.

APPLICATION OF MINER'S HYPOTHESIS IN PCC PAVEMENT DESIGN

It is apparent from the preceding review that concrete fatigue studies prior to 1960 focused on a number of aspects of interest to pavement engineers, notably: the existence -at least from a practical viewpoint- of an endurance limit; and the repercussions of the method of load application (i.e., axial-flexural, compression-tension, frequency, stress reversals, stress range, rest periods, etc.). Nonetheless, what is perhaps the most important aspect of conventional pavement fatigue considerations, namely the use of Miner's cumulative linear fatigue hypothesis in assessing the effects of mixed loading, is conspicuously absent from practically all studies between 1890 and 1960. The adoption and widespread acceptance of this hypothesis for pavement design is surprisingly a much more recent development. It may be argued that since the original publication of Miner's paper occurred during war-time (1945), its relatively belated adoption by pavement engineers is understandable. The argument, however, is untenable when one considers that earlier statements of the same linear cumulative fatigue hypothesis can be found in works by Palmgren in 1924 (26), Langer in 1937 (27), and even Bradbury in 1938 (18).

It is submitted that the impetus for the adoption of Miner's fatigue hypothesis for pavement design was provided by the introduction of the ESAL concept, in the years immediately following the AASHO Road Test. Extensive review of the pertinent literature and of the historical record reveals that use of the statistical/empirical ESAL concept necessitated the simultaneous acceptance of Miner's fatigue hypothesis, since the former concept "presupposes and is based on a concept of linear cumulative damage, a popular if arbitrary, extrapolation Miner's fatigue hypothesis" (28). It is hardly a historical coincidence that the roots of both of these widespread concepts can be traced to two short and relatively obscure 1940s articles by Grumm (29; 30). In those publications, however, what has now become the conventional method of accounting for pavement fatigue, had been presented merely as a qualitative speculation inspired by Bradbury's (18) own speculations, which incidentally had received little attention for more than fifteen years.

It will be shown below that following the AASHO Road Test, Miner's fatigue hypothesis was first adopted for HMA pavement design, as a result of research conducted at the University of California, Berkeley. Its acceptance for PCC pavement design was largely an afterthought, prompted by the increasing popularity of the AASHO statistical/empirical methodology. The much needed intellectual underpinnings for the broad professional consensus that developed in the ten years following the AASHO Road Test regarding pavement fatigue concepts were provided by concrete fatigue research conducted at the University of Illinois in the late 1950s and early 1960s under the general

direction of Prof. Clyde E. Kesler. Reviewing the original reports on these studies, however, shows that the Illinois investigators had significant reservations concerning several of what have since become conventional practices, and sometimes even summarily dismissed them, e.g., (24); (31). Nonetheless, the ease of application of Miner's hypothesis, its fortuitous fit into the general pavement design philosophy emerging following the AASHTO Road Test, and -admittedly- the lack of a better alternative, have all contributed to its gradual widespread acceptance far more than the studies that have been cited in justifying current practices.

Visiting the University of Illinois at that time was another respected investigator, Prof. Hubert K. Hilsdorf of the aforementioned Karlsruhe Technische Hochschule, one of the European centers for concrete fatigue studies. Hilsdorf and Kesler (31) undertook a joint investigation to examine the validity of Miner's hypothesis, particularly with regard to rest periods and load sequencing. A major contribution by Hilsdorf was his "ingenious and meticulous" experimental technique, a distinct improvement compared to earlier Illinois studies, which gave "substantial weight to his conclusions" (6). With regard to rest periods, the study found that they were generally beneficial when up to five minutes long, whereas no additional significant improvement in fatigue performance was observed with longer rest periods. This finding was qualitatively consistent with those from earlier investigations into relaxation or recovery effects. The part of the study to evaluate the applicability of Miner's hypothesis entailed three series ("programs") of tests: one in which a "block" of cycles of a lighter load were followed by applications of a heavier load; a second in which the sequence of load application was reversed; and a third in which the lighter load "block" was applied first but subsequently the two load levels were continuously alternated. Murdock (6) provides the following account of the results:

"For the simplest conditions of loading, as employed in the first and second test series, the Miner hypothesis was found to be in error. In the first instance the stress level required to produce failure was less than that predicted by the Miner theory. In the second case, the reverse was true and the Miner theory was found to be conservative... In the third series of tests ... the fatigue response was found to depend on parameters which reflected the difference in stress levels, and the number of cycles of load at each level which was applied in a given 'block'... This study is significant in that it refutes the applicability of the Miner hypothesis for even the simplest of loading patterns. It is too brief, however, to provide an adequate substitute for the theory. It points the way to additional studies, and one could scarcely ask for a firmer base from which to advance."

Regrettably, the anticipation for further studies in search of a Miner substitute was never fulfilled. In fact, the Hilsdorf and Kesler results were not published in a reasonably accessible forum until six years later (32). On the contrary, as time went on and as highway applications of Miner's hypothesis became more widespread, Kesler himself abandoned the early reservations he had expressed when co-authoring the paper with Hilsdorf, and lent his belated affirmation to the emerging pavement practices. Consider, for example, the difference in tone between the following two pertinent excerpts from publications by Kesler. The first comes from a 1968 report to the Illinois Division of Highways (33):

"[The results by Hilsdorf and Kesler (31;32)] indicated the complexity of fatigue behavior under even a semi-random variation in maximum stress levels and demonstrated conclusively that the assumption of linear accumulation of fatigue damage in concrete in fatigue is false. Hilsdorf and Kesler illustrated a method of adjusting their results which permitted the use of the Miner hypothesis. An S-N diagram based on a probability of failure concept was also constructed from the average results of Program 3 loading. This diagram was based on tests in which the lower load was 17 percent of the upper load. For this reason and because of the limited range of their study, Hilsdorf and Kesler were careful to point out that their results were not suggested as being directly applicable to design."

The second excerpt is much less cautious and comes from the 1970 Stanton Walker Lecture presented at the University of Maryland by Kesler (34):

"Because the Miner hypothesis is easy to apply it is frequently used, although it does not give accurate predictions of failure of concrete. Consequently, design curves, incorporating the probability of failure, have been developed so that when the Miner hypothesis is applied to them reasonable results are obtained. [This figure] is based on tests limited in scope."

This justification of Miner's hypothesis on the basis of probability and ease of application is in unison with similar sentiments expressed by leading pavement professionals at that time. Following an extensive laboratory study conducted by the Federal Highway Administration, Ballinger (35) asserted that "the Miner hypothesis represents the cumulative damage characteristics of plain concrete in a reasonable manner." Nonetheless, the raw test results obtained during that study show that the value of Miner's number, R (i.e., the value of Miner's sum at failure, which should equal unity if Miner's hypothesis were valid) ranged from 0.15 to 1785, with a mean of 146 and a coefficient of variation of 275%. Ballinger (35) provided no justification for his assertion in support of Miner's hypothesis, except perhaps the fact that even static and constant amplitude cyclic tests also exhibit considerable scatter. Similarly, Siemes (36) concluded that "Miner's rule describes the average cumulative damage due to variable-amplitude loadings remarkably well!" His own data, however, indicate that the median value of R ranged between 0.39 and 13.87. Siemes based his conclusion on the argument that adjusting the applied stress by about 4% would restore the value of R to 1, as required by Miner. This, however, is also a cause for concern regarding the undue sensitivity of the hypothesis to small errors in stress calculation, and provides little reassurance of its validity. The following 1976 remarks by Witczak (37) are more typical of the attitudes of pavement engineers toward Miner's hypothesis (note their exclusive dependence on Kesler's Stanton Walker Lecture):

"Laboratory studies [(34)] have shown that the load history (sequence of load applications) directly affects the fatigue strength... This observation is in direct contrast to the validity for using Miner's linear damage law for cumulative fatigue effects. Studies have indicated that application of this rule is unsafe for high loads but too conservative for low loads (34). However, recognizing these factors and the relative ease to problem solutions using Miner's hypothesis, fatigue curves have been developed [(34)] using a probabilistic concept to compensate for these effects... From this discussion it should be apparent that one should not expect a precise solution from the direct application of laboratory fatigue results with a linear cumulative damage model approach for design. Fortunately, if unconservative factors affecting fatigue behavior are recognized and accounted for (e.g. application of high stress ratios), use of constant amplitude fatigue testing with continuously applied loadings will generally result in a safe fatigue life estimation of the structure."

FATIGUE CONCEPTS AND MINER'S HYPOTHESIS IN HMA PAVEMENT DESIGN

Despite the caveats against the adoption of Miner's fatigue hypothesis for the design of PCC pavements, its applicability to the design of HMA pavements became increasingly widespread following the AASHTO Road Test. A catalyst in this direction was the doctoral study by Deacon (38), who received his D.Eng. degree under Prof. Carl L. Monismith at the University of California, Berkeley in 1965. Deacon's contribution to the acceptance of the ESAL concept has been documented elsewhere (28): it is neither surprising nor coincidental that his work was instrumental in the adoption of Miner's fatigue hypothesis, as well. Excellent reviews of the history, research and development of conventional fatigue concepts used in bituminous pavement design and evaluation can be found in two reports, one by Deacon and Monismith (39) and another by Witczak (37). These publications have been used extensively in the compilation of the historical information contained in this section.

Interest in the fatigue behavior of bituminous materials and of HMA pavements appears to have been spurred on the one hand by the aforementioned studies on Portland cement concrete specimens,

particularly those of the early 1960s, and on the other by the geotechnical engineering work into repeated loading of soils by Prof. Harry Bolton Seed and co-workers at the University of California, Berkeley (40). To be sure, earlier investigations, including (41)-(44), among others, had recognized the fatigue phenomenon as operative in observed distresses of so-called "flexible" pavements. Yet, prior to the AASHO Road Test it was generally agreed that "while the effects of load repetition may lead to 'distress' in both cases, the mechanism of 'failure' in plastic material [such as HMA] is not necessarily identical with fatigue failures in a relatively rigid body [such as a PCC slab]" (42). Interestingly, of the publications cited by Deacon and Monismith (39), the oldest is the aforementioned 1942 paper by Grumm (30). Although this brief article already postulated the existence of a linear cumulative rule even before Miner's paper had been published, it was not until twenty years later that Monismith, et al. (45) invoked "Miner's Law", suggesting that "a similar line of reasoning could possibly be applied to asphalt concrete pavements [but] instead of the use of stress, strain would appear to be the appropriate criterion."

Intense experimental studies into the fatigue behavior of asphalt concrete specimens were initiated in the late 1950s and continued for at least fifteen to twenty years, if not more. Prominent among these are those by Monismith and co-workers at the University of California, Berkeley, and by Professors Peter S. Pell and Steven F. Brown at the University of Nottingham in England. From the beginning, the coincidence in philosophical direction between these two groups of investigators and the similarity of their findings would allow one to treat both as belonging to a single school of thought. Additional studies were conducted at the Brussels Centre de Recherches Routieres by J. Verstraeten; by J.M. Kirk at the Danish Road Research Laboratory; by L.W. Nijboer, W. Huekelom and A.J.G. Klomp at the Koninklijke Shell Laboratorium in Amsterdam; by R.I. Kingham, B.F. Kallas and V.P. Puzinauskas at the Asphalt Institute (United States); as well as by many others. As a result, the pertinent literature is voluminous --see, for example, (37)-- and a number of important conclusions concerning fatigue of bituminous materials in general have been established. Surprisingly, however, the number of investigations into the applicability of Miner's fatigue hypothesis itself --an area in which one might expect a concentration of research, given its cardinal importance in pavement design-- is rather limited. In fact, this literature review has revealed only three investigations specifically designed to evaluate the validity of Miner's hypothesis for bituminous mixes. The first is described in the aforementioned report by Deacon and Monismith (39), and bears a number of interesting parallels to the corresponding Hilsdorf and Kesler (31) investigation of PCC. Like the latter, the study by Deacon and Monismith (39) is often cited as justifying the widespread use of Miner's hypothesis in HMA pavement design, despite its authors' original reservations and caveats. The second investigation of the validity of Miner's hypothesis for HMA pavement design identified in this literature review effort was conducted by McElvaney and Pell (46), while the third was the work of Ruth and Davis (47).

Deacon and Monismith (39) tested 133 beam specimens in flexural compound loading, i.e., under "repeated application of loads in which the load condition changes during the service life of any particular specimen in some prescribed manner." In view of the wide variety of loading conditions that could conceivably be examined, the investigators stated that their statistical "sample sizes were limited." Nonetheless, the study by Deacon and Monismith (39) provided the following answers to three important questions:

(a) "Is the fatigue behavior affected by the order or sequence of load application?"

"These data indicate that the load sequence does affect the observed fatigue behavior at least for small applied percentages of the larger stress level... Any compound-loading hypothesis applicable to sequence load histories must, therefore, be able to account for the order of application of the various load conditions."

(b) "Does the fatigue behavior observed under a random load history differ significantly from that observed under a repeated-block load history?"

"While differences in the mean lives are readily apparent, they are inconsistent and may be explained in terms of specimen variability and the influence of the initial stiffness modulus..."

The experimentally observed mean life for test C [which according to Miner's hypothesis should have been more destructive] was larger than that for test B, a fact that can be explained only on the basis of the small [statistical] sample size and the large variability inherent in the fatigue data."

- (c) "Which of nine techniques [examined (including Miner's hypothesis)] is most appropriate for predicting a mean compound-loading fracture life?"

"None of the nine compound-loading techniques [examined] can be used to predict a mean fracture life for sequence tests for all possible applied percentages, because none is capable of treating the sequence of loading."

The preceding excerpts from the report by Deacon and Monismith (39) suggest that rather than validating Miner's hypothesis their results could have provided adequate justification for abandoning it, primarily on account of its failure to accommodate load sequence effects. For their part, however, Deacon and Monismith (39) dismiss such an interpretation of their results, however, stating:

"This failure of all of the compound-loading hypotheses to apply to sequence loading of the type employed in this study [i.e., one that subjects the specimen first to a fixed number of applications of a given load condition followed by a fixed number of applications of a second, different load condition and so forth until failure occurs] is not of much practical concern, because this form of loading is not normally considered to be encountered in service."

This argument may be a rather weak afterthought, when one considers that almost half the specimens tested by Deacon and Monismith (39) were subjected to sequence loading, presumably because such loading had been considered important while the testing program was being compiled. Typical loads applied daily on both HMA and PCC pavements resemble in many ways those applied during sequence loading tests, and a number of other investigators have used such loadings in their own fatigue studies, e.g., Ballinger for PCC (35).

A small statistical sample size and large variability certainly influence the outcome of fatigue tests. Nonetheless, addressing these issues will not necessarily result in better predictions unless the hypothesis tested is a correct one. To validate Miner's hypothesis, therefore, it is not enough to make postulates as to the sources of the large observed discrepancies between prediction and observation. Rather, studies are required to establish whether upon addressing the perceived shortcomings better agreement between reality and expectations is attained.

On the other hand, if it is not practically feasible to address such shortcomings, e.g., because the statistical sample size needs to be prohibitively large, this in itself should be cause for seeking an alternative hypothesis. Similarly, the explanation that specimen life is dependent on the initial stiffness modulus does not support but rather undermines the hypothesis tested. If the hypothesis were correct, any such effects would have been accounted for by concomitant changes in the stress or strain used in the application of the hypothesis. To require a different form of the hypothesis for each level of initial stiffness modulus is to affirm that the hypothesis has no general applicability.

In their aforementioned report, Deacon and Monismith (39) did not themselves select Miner's hypothesis as their preferred compound-loading technique. Yet, shortly thereafter, Monismith and Kasianchuk (48) stated that "while it has been demonstrated that [Miner's] cumulative damage hypothesis does not precisely predict the response of asphalt concrete in compound loading from the results of simple loading tests [(38)], it would appear, in the light of other assumptions which must be made, to be a reasonable engineering consideration to use at this time (1968)." In fact, in his doctoral thesis, Kasianchuk (49) adopted Miner's hypothesis with no additional justification. Regrettably, the hypothesis continues to dominate pavement design practices almost thirty years later, while the number of studies seeking an alternative is still extremely small.

As already indicated, the Nottingham group shares the view of the Berkeley investigators that "the results of simple tests may be used to predict performance under complex and varying loading by the use of a cumulative linear damage hypothesis, such as Miner's rule" (50). The main study cited by Pell (50) in support of this assertion is the doctoral study by McElvaney (51), who examined the validity of Miner's hypothesis when applied to laboratory flexural specimens, with particular emphasis on the influence of load sequence, temperature and rest periods. The most salient results of that study have been reported by McElvaney and Pell (52; 46).

Concerned about the significant scatter exhibited by fatigue tests, both of the constant and of the variable amplitude types, McElvaney and Pell took a number of steps intended to reduce the effect of such scatter. These included the following:

- (a) They postulated that under identically replicated conditions the observed number of repetitions to failure, N_i , at each stress level i obeys a log-normal distribution. In determining the value of R , therefore, the logarithmic rather than the arithmetic mean of N_i was used. This was determined from constant amplitude tests, typically with seven (7) or more replicates at each stress level. Note that for a typical case of twelve (12) replicate specimens considered, the average number of repetitions to failure was approximately 60,000 with a coefficient of variation (COV) of 24%, compared to a COV of only 2% when the respective logarithms are considered.
- (b) Sequence tests involving only two stress levels were performed. In these, the stresses applied during each of the two stages, σ_A and σ_B , as well as their relative frequencies, N_A and N_B were varied. The range of the ratio (σ_A/σ_B) was rather limited, spanning only from 0.4 to 2.5.
- (c) Comparisons were made using the mean values from several replicates (typically 7) rather than the individual test results themselves.

According to McElvaney and Pell (46), their results "suggested that a linear damage rule will yield a sufficiently accurate prediction of fatigue life under compound-loading and that the values of cumulative cycle ratio $[R]$ at failure ... do not deviate significantly from the value of unity proposed by Miner." This should not be interpreted, however, as a confirmation of Miner's hypothesis, since their data merely offer a justification thereof, at best. These authors concede that "the value of R is variable" yet they assert that "there is a reasonable probability that [it] will be equal to or greater than unity by an acceptable amount." Their reported values of R are indeed considerably closer to the value of 1 predicted by Miner than similar values reported by other investigators, primarily because of the three steps noted above.

McElvaney and Pell (46) also noted several aspects of behavior which are inconsistent with Miner's hypothesis. For example, their sequence tests showed that both the absolute and relative values of σ_A and σ_B , as well as their relative frequencies in the sequence may influence the calculated values of R . The latter ranged from 0.55 to 2, with a mean of 1.20 and a COV of 30%. Nonetheless, the fact that "no consistent trend is apparent from the observed variability" was interpreted as a justification for retaining Miner's hypothesis. In addition, an "apparent strengthening effect" was noted when a number of cycles at initial stress level σ_A led to a longer than expected fatigue life under subsequent higher stress level σ_B . Interestingly, this phenomenon sometimes occurred even when σ_A was greater than σ_B . In several instances, the relative counts of cycles at the two stress levels, N_A and N_B , appeared to have a stronger influence on R than the values of σ_A and σ_B , themselves. Such departures from the assumptions of Miner's hypothesis were attributed, however, to material variability and to the statistical nature of the fatigue process, or simply to factors for which "no satisfactory explanation can be offered."

Also contradictory to Miner's hypothesis are observations by McElvaney and Pell (52) concerning the effect of rest periods on fatigue life. Thus, they affirmed a trend "quite definitely towards longer fatigue lives" on account of rest periods, and concluded that "the extent to which a rest period of particular duration can influence fatigue life is related to the damage accumulated [under the loads applied] between rest periods." Similarly, Raithby and Sterling (53) noted that "with very short rests the life increases rapidly and then appears to reach a limiting [rest duration]

value of about 400 ms," and that the increase in fatigue life "depends on temperature and perhaps on stress level." The mean increase in fatigue life reported ranged from 5 to 25 times, more benefit being derived from rest periods at lower temperatures (e.g., 10°C cf. 40°C) and at lower stresses (e.g., 1.0 MN/m² cf. 1.5 MN/m²). Francken (54) concluded that "when rest periods are incorporated in the tests ... Miner's law completely fails even for [a] simple case, where the service life is practically multiplied by a factor of 5."

Particularly noteworthy is a less comprehensive study for the Florida Department of Transportation conducted at the University of Florida under the supervision of Prof. Byron E. Ruth. This investigation also examined the applicability of Miner's hypothesis and reached a diametrically opposite conclusion than that of the Berkeley and Nottingham studies. Five specimens were subjected to "indirect tensile fatigue tests with different conditioning processes," and the following conclusions were reached (47):

"It is obvious that no cumulative effect was observed, although some variations are due to difference in compacted density of test specimens... Conventional fatigue concepts and Miner's hypothesis for cumulative damage are not applicable to dynamic testing of asphalt paving mixtures in the laboratory. Test results indicate that a substantial number of fatigue cycles can be applied without damage to the material when strain recovery is accomplished by increasing temperature or allowing adequate rest time."

The Florida group continues to be at the forefront of efforts seeking viable alternatives to Miner's fatigue hypothesis, both for flexible and rigid pavements, e.g., (55); (56).

CONCLUSIONS

A detailed review of the literature pertaining to fatigue concepts and practices used in conventional pavement design for both Portland cement and bituminous concrete pavement systems has been conducted. A primary aim has been to trace the historical development of these concepts and practices, examining in particular the evidence in support of their validity. This review has confirmed that fatigue considerations in pavement design date from the beginning of this century, and have been investigated first for PCC pavements (since about 1905) and subsequently for HMA pavements (since about 1955).

There appears to be little doubt that both PCC and HMA specimens fail in fatigue when subjected to either constant or variable amplitude repeated loads. Test results exhibit considerable scatter, lending credence to the suggestion that fatigue is a stochastic phenomenon. Furthermore, the majority of investigators employ Miner's fatigue hypothesis, although most acknowledge that this is a matter of expediency rather than acceptance of its validity.

The number of studies identified that sought to establish the validity of Miner's hypothesis is extremely small (three for PCC and three for HMA). All provide adequate information that could have justified the abandonment of Miner's hypothesis. The historical record shows, however, that investigators have been generally reluctant to reject Miner and to seek an alternative approach. Rather, the passage of time has witnessed a relaxation of the caveats and concerns voiced in the early 1960s regarding the use of Miner's hypothesis. The influence of the philosophy emerging after the AASHTO Road Test has been a catalyst in this direction, particularly the adoption of the ESAL concept for accommodating mixed traffic effects.

Data reported in the literature suggest that predictions of life-cycle serviceability using Miner's hypothesis (whether in terms of time or number of repetitions) can only be expected to approximate reality at best within an order of magnitude, and more commonly within two or even three orders of magnitude. Such predictive ability is considered entirely unsatisfactory, and -inertia aside- this should encourage studies for a Miner replacement. It is recommended that alternatives be sought through the implementation of sophisticated fracture mechanics concepts, recently promulgated in the United States, Europe and Russia. A review of fracture mechanics applications to

pavement engineering may be found in a companion paper presented at the January 1997 Meeting of the Transportation Research Board (57).

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