3. F.E. Crory. Settlement Associated with the Thawing of Permafrost. Proc., 2nd International Conference on Permafrost, Yakutsk, USSR, July 1973.
4. N.R. Morganstern and J.F. Nixon. One Dimensional Consolidation of Thawing Soils. Canadian Geotechnical Journal, Vol. 8, No. 4, 1971, pp. 558-565.
5. J.L. Wood. Influence of Repetitious Freeze-Thaw on Structure and Shear Strength of Leda (Messena) Clay. Clarkson College of Technology, Ph.D dissertation, May 1976, 152 pp.
6. S. Thompson and E.F. Lobacz. Shear Strength at a Thaw Interface. Proc., 2nd International Conference on Permafrost, Yakutsk, USSR, July 1972, pp. 419-426.
7. J.M. Morrison. Response of Soil to Undrained Freeze-Thaw and Repeating Loading. Michigan Technological University, Thesis, Houghton, MI, 1982.
8. M. Oda. The Mechanism of Fabric Changes During Compressional Deformation of Sand. Soils and Foundations, Japanese Society of Soil Mechanics and Foundation Engineering, Vol. 12, No. 2, June 1972, pp. 1-18.
9. B.D. Alkire and J.M. Morrison. Comparative Response of Soils to Freeze-Thaw and Repeated Loading. Proc., 3rd International Symposium on Ground Freezing, Hanover, NH, 1982, pp. 85-95.
10. W. Czeratzki and H. Frese. Importance of Water in Formation of Soil Structure. In Water and Its Conduction in Soils, HRB Special Rept. 40, 1958, pp. 200-211.
11. E.J. Chamberlain. A Model for Predicting the Influence of Closed System Freeze-Thaw on the Strength of Thawed Clays. Proc., Frost Action on Roads, Oslo, Norway, 1973, pp. 94-97.
12. H.B. Seed. Evaluation of Soil Liquifaction Effects on Level Ground During Earthquakes. Liquifaction Problems in Geotechnical Engineering, ASCE, New York, Preprint 2752, Sept. 1976, pp. 1-104.
13. D.A. Sangrey, G. Castro, S.J. Poulos, and J.W. France. Cyclic Loading of Sands, Silts, and Clays. Earthquake Engineering and Soil Dynamics, ASCE, New York, Vol. 2, 1978, pp. 836-850.
14. J.A. Egan and D.A. Sangrey. Critical State Model for Cyclic Load Pore Pressure. Earthquake Engineering and Soil Dynamics, Vol. 1, ASCE, 1978, pp. 410-425.
15. W.D.L. Finn, K.W. Lee, and G.R. Martin. An Effective Stress Model for Liquifaction. Liquifaction Problems, ASCE, Preprint 2752, 1976, pp. 169-189.

Fatigue-Based Criteria for Seasonal Load Limit Selection

JAMES H. HARDCASTLE, ROBERT P. LOTTMAN, AND TRI BUU

During spring thaw, restrictions on allowable axle weights (load limits) are often applied to flexible pavement sections in seasonal frost areas to prevent premature failure of thaw-weakened pavements. Currently, load limits are selected on the basis of experience. An approach to load limits that is based on controlling seasonal rates of fatigue consumption is described. Fatigue consumption can be determined from fatigue curves that relate critical tensile strains in the pavement section to the number of load repetitions causing fatigue failure. By using a layered-elastic computer program, strain is determined for the traffic loads applied to the pavement while it is in various seasonal states. Seasonal values for elastic-response parameters (resilient modulus and Poisson's ratio) are determined in laboratory tests on appropriately conditioned specimens. By relating the fatigue damage produced to the number and magnitude of loads applied during each of the seasonal pavement conditions, the effects of alternative load limit policies on remaining pavement life can be compared. In an application of the method to an existing pavement it was decided that the maximum axle load permitted during the spring-thaw period should be one that produced the same rate of fatigue consumption as the normal summer-fall legal maximum of 18.9 kips. Using this criterion, the maximum spring-thaw load for the pavement would be 11.5 kips. Comparisons indicated that the remaining service life under the posted 14-kip load limit would be 80 percent of the life remaining if the 11.5-kip load limit were imposed. If no special spring-thaw period load limit is imposed, the remaining service life of the pavement will be reduced to 40 percent of the life remaining under the 11.5-kip limitation.

Highway managers recognize that the load-carrying capability and the rate of decrease of useful service life of flexible pavements vary during the year. Under uniform traffic, these variations reflect seasonal changes in the physical state (e.g., temperature and water content) of the materials within the pavement structure. In areas of seasonal frost, the critical period in the annual cycle of temperature and moisture changes occurs during the spring-thaw (spring breakup) period. The increased water content that results from melting of accumulated ice in the subgrade soil and in the unbound granular layers within the pavement section can cause reductions in both the strength and stiffness of the materials (1). The application of normally acceptable, heavy axle loads while the pavement materials are in the moisture-weakened condition leads to an accelerated deterioration rate and premature permanent failures.

Two general approaches are currently available to the pavement manager to account for seasonal variations in pavement performance. For a new pavement, anticipated variations in pavement condition may be accounted for by using design parameters based on measurements of materials conditioned to reflect an average or a worst in-service condition instead of the immediate post-construction condition. Examples of this approach are the 4-day soaking period to which California bearing ratio (CBR) test specimens are subjected before testing and the compression of compacted stabilometer (R-value) test specimens at higher than immediate post-construction degrees of saturation. In addition to special conditioning of materials, regional factors also may be used to account for adverse climatic and environmental conditions (1).

In recognition of the markedly increased vulnerability of flexible pavements to unusual damage during the spring-thaw period, highway managers in many northern states impose special temporary restrictions on vehicle speeds and maximum axle weights (load limits) for selected highway sections. Seasonal load restrictions are usually limited to older routes designed for relatively low traffic

Figure 1. Seasonal surface Dynaflect deflection and Dynaflect SCI of a Minnesota pavement (2).

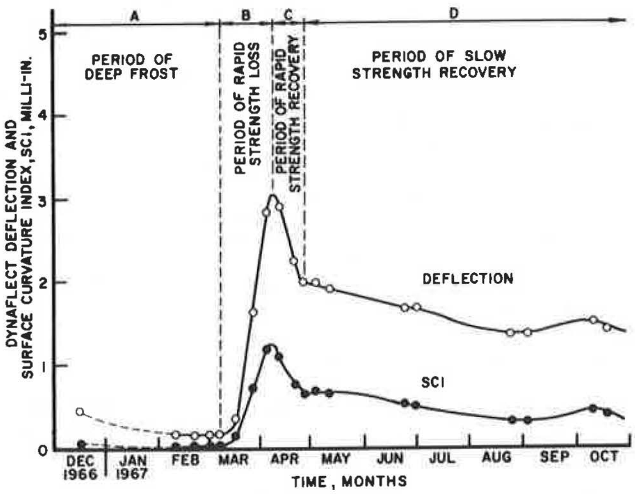
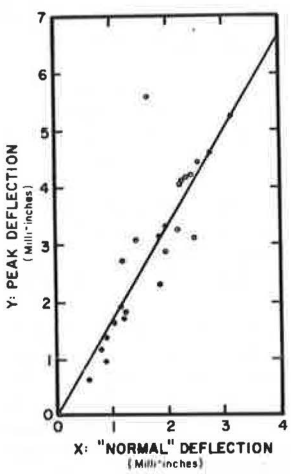


Figure 2. Relation of peak to normal Dynaflect deflections for 24 Minnesota and Illinois pavements (2).



volumes. In current practice, decisions concerning the magnitude of seasonal load limits, the dates of their imposition, and the duration of the restricted period are usually made on the basis of local experience. In Idaho, for example, load limits are selected by the district highway engineers.

Empirical methods of quantifying local experience based on observations of seasonal pavement surface deflections have also been used to select load limits. The surface deflection method described in National Cooperative Highway Research Program (NCHRP) Report 76 (2) is typical of these approaches.

The enforcement of load limits established on the basis of sound engineering judgment and experience has unquestionably prolonged the life of many pavements. Recently developed methods of pavement-response analysis and materials testing suggest that a new approach could be applied to the problem. This paper describes an application of the mechanistic models of pavement behavior and fatigue theory to the problem of selecting spring-thaw period load limits. The NCHRP surface deflection method is also briefly reviewed. Comparisons of the load limits computed for an in-service Idaho pavement are made and an evaluation of the effects of alternative load limits on pavement life is presented.

1969 NCHRP DEFLECTION METHOD

The purpose of the 1969 NCHRP study was to find a simple, nondestructive means of measuring seasonal variations in flexible pavement performance and to develop criteria for imposing load limits to protect pavements from being overloaded during critical periods. Measurements of seasonal changes in surface deflection were made on 24 in-service pavements located in Illinois and Minnesota. Devices used were the Benkelman beam, Dynaflect, and static plates. Deflected pavement surface curvature was also measured with the Dynaflect and the McCullough curvature meter. Strong linear correlations were observed between Dynaflect surface curvature index (SCI), Dynaflect deflection, and Benkelman beam deflection. Because bending stresses and strains in the asphalt-bound layers of a pavement are more closely related to the radius of curvature of the deflected pavement than to deflection itself, SCI was chosen for the load-limit criterion.

A typical relationship between time and both Dynaflect SCI and maximum surface Dynaflect deflection obtained in the NCHRP study is shown in Figure 1. From such plots normal and peak values of SCI and deflection could be identified at each location for which observations were made. Normal SCI for a pavement section was defined as the average value of the SCI observed during August, September, and October. Peak SCI (or deflection) was defined as the largest value observed during that year.

Load Limit Criteria

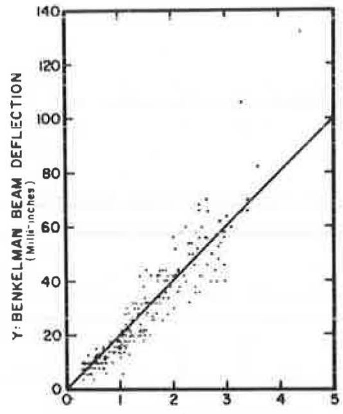
In the 1969 NCHRP study, measurements were made only on pavements for which local policy permitted (but did not require) the imposition of seasonal load limits. It was found that, of the roads with normal-period SCI values greater than 0.35 milli-in., an average of only one road in three was actually restricted on the basis of local experience, whereas 11 out of 12 roads with normal-period SCI greater than 0.38 milli-in. were restricted. Based on these observations the criterion in NCHRP Report 76 for determining whether critical-period load limits are needed was stated as follows (2):

> In areas with a mean freezing index exceeding about 200 (degree-days), a road should be restricted to light axle loads during the critical season if the average normal SCI measured during the previous fall exceeded 0.35 (milli-in.). Pavements having SCIs less than that value need not be restricted provided, of course, they are constructed of frost-resistant materials.

The normal-period SCI (or deflection) instead of the critical-period (peak) value was selected as a criterion for load limit because it was desirable to establish the need for axle load limits in advance of the critical period itself. Moreover, a strong correlation existed between peak and normal SCI or deflection values. Figure 2 shows the observed relationship between peak and normal values of Dynaflect deflections.

Given the strong correlation between Dynaflect deflections and Benkelman beam deflections shown in Figure 3, it is also possible to state the 1969 NCHRP criterion as follows: In areas with a mean freezing index exceeding about 200 degree-days, a road should be restricted to light axle loads during the critical season if the average Benkelman beam

Figure 3. Relation of Benkelman beam deflections to Dynaflect deflections for 24 Minnesota and Illinois pavements (2).



deflection measured during the previous fall exceeded 22.9 milli-in. (0.0229 in.).

In addition to the criterion for determining the need for load limits, the 1969 NCHRP Report provides an equation for selecting the magnitude of the allowable spring-thaw period load limit. The equation is based on the hypothesis that the maximum safe axle load, L_s, that can be applied to a given highway during the critical period is inversely proportional to the peak SCI measured during that period, i.e.,

$$L_s = k/\text{maximum SCI} \quad (1)$$

The constant of proportionality, k, can be evaluated by noting that if the maximum SCI is less than 0.70 milli-in. (maximum SCI equals 2.0 times the normal SCI), no restriction is necessary during the critical period. The safe axle load that can be applied with no restriction is equal to the legal, maximum axle load of 9 tons (18 kips). The constant of proportionality is thus 6.3. By again making use of the strong correlations between SCI, Dynaflect deflection, and Benkelman beam deflection, the equation for the maximum allowable axle load, in tons, during the critical period can also be expressed as follows:

$$L_s = 346/\text{maximum } \delta_{B18} \quad (2)$$

where δ_{B18} is the peak period Benkelman beam deflection, in milli-in., measured with an 18-kip axle load.

Evaluation

The 1969 NCHRP approach is essentially a method for quantifying local experience gained from in-service pavements in Minnesota and Illinois that had previously demonstrated poor spring-thaw period performance. The method uses rapid nondestructive field tests and provides a specific criterion for determining where load limits are needed as well as the magnitude of the allowable load limit during the spring-thaw period. The method directly accounts for seasonal changes in pavement performance.

For the pavements studied, critical-period peak SCIs and deflections were linearly related to normal-period values. As a result of differences in the response of materials to freezing and moisture changes, it is likely that there are pavements in other regions of the country for which critical-period peak SCIs and deflections are excessive even though the normal-period SCI values are less than 0.35 milli-in. Before the NCHRP approach can be applied to pavements constructed on soil types other than those of the original study, appropriate correlations between normal- and peak-period deflection parameters need to be established. A limitation of the NCHRP surface deflection approach is that it does not directly relate the criteria for establishing load limits to pavement damage. Hence, the method does not provide a means for evaluating the effects of alternative load-limit decisions on pavement life expectancy. Such knowledge is essential if the economic ramifications of highway load-limit policies are to be considered.

PROCEDURE FOR SELECTING RATIONAL LOAD LIMIT

The essential premises of the procedure for selecting the rational load limit suggested here are the following:

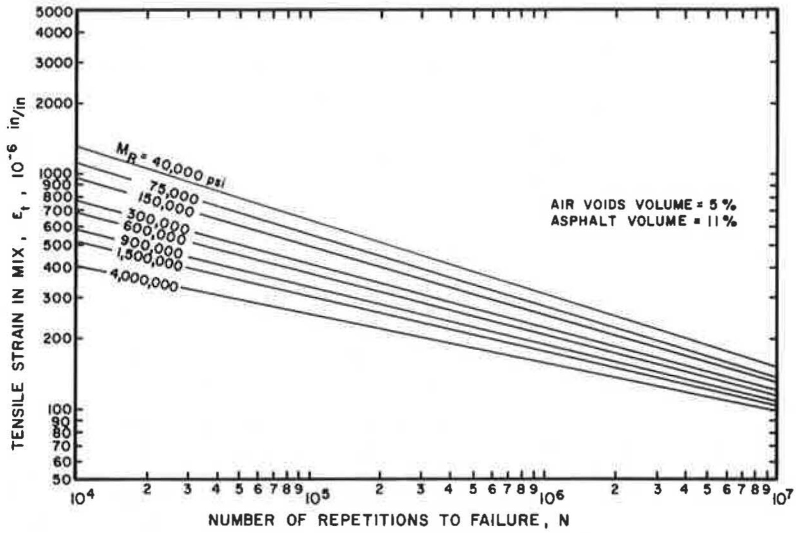
1. Flexible pavement damage is due to fatigue cracking of the asphalt-bound layers. Fatigue cracking occurs as a result of repeated bending of the layers under traffic. The service life of the pavement depends on its fatigue life, where fatigue life is the cumulative number of repetitions of various loads that cause the pavement surface to crack (3,4).
2. The parameter for critical pavement response that determines the number of repeated loads required to cause fatigue failure is the horizontal tensile strain, ϵ, developed at the bottom of the asphalt-bound layer (4,5).
3. Fatigue curves relating the magnitude of the critical tensile strain, ϵ, to the number of repetitions of this strain to cause failure, N_f, can be developed. Examples of fatigue curves are shown in Figure 4.
4. The magnitude of the critical tensile strain, ϵ_{ij}, produced by various axle loads (designated by subscript i) while the pavement is in its various seasonal conditions (designated by subscript j) can be computed using layered-elastic theory and seasonal values of the pavement's elastic-response parameters. The necessary response parameters are the resilient modulus, M_R, and Poisson's ratio, ν. Seasonal values of these parameters can be determined using well-established laboratory procedures and appropriately conditioned test specimens (1,6,7).
5. The cumulative damage, D, produced by a variety of axle loads, i, applied to the pavement while it is in its various seasonal physical conditions, j, is stated by Miner's hypothesis of the linear summation of cycle ratios (4,8).

$$D = \sum_{j}\sum_{i} (n_{ij}/N_{ij}) \quad (3)$$

where n_{ij} is the number of applications of the ith load while the pavement is in the jth condition, and N_{ij} is the number of applications of the ith load that would produce fatigue failure of the pavement while it is in the jth condition. N_{ij} is a function of the critical tensile strain, ϵ_{ij}, and is obtained from fatigue curves such as those shown in Figure 4. A pavement is considered to have failed in fatigue when the cumulative damage under repetitive loading reaches 100 percent of its original fatigue life.

6. Pavement damage produced by alternative load-limit policies, A and B, can be evaluated by comparing the fatigue life remaining or the cumulative

Figure 4. Fatigue curves for asphalt mixes (10).



damage produced by each alternative. Such comparisons could take the following form

$$D_A/D_B = \left[\sum_j \sum_i (n_{ij}/N_{ij})\right]_A \Big/ \left[\sum_j \sum_i (n_{ij}/N_{ij})\right]_B \quad (4)$$

Critical tensile strain, ϵ_{ij}, can be computed for a large number of traffic loads, i, applied to the pavement in its various seasonal states, j. In practice, pavement loads can be grouped into a few load ranges or equivalent axle loads. Seasonal variations in pavement response can also be grouped under two or three physical states such as the spring breakup condition, the normal summer-fall condition, and the winter-frozen condition.

APPLICATION OF THE RATIONAL APPROACH

In order to evaluate the approach to establishing a rational load limit, a trial application was carried out on a section of an Idaho highway for which spring breakup load limits have been imposed. A section of State Highway 3, 4.5 miles north of Bovill, Idaho, was selected. The pavement is subjected to heavy logging and chip truck traffic throughout the year. At the location selected, the pavement is constructed on approximately 4 ft of decomposed granite fill material placed over flood plain deposits.

Criterion for Load Limit

In the trial application the authors decided to use the following criterion as the basis for selecting the spring-thaw period load limit.

The maximum axle load allowed during the spring-thaw period should be restricted to one which produces a horizontal (critical) tensile strain at the bottom of the asphalt-bound layer equal to the strain produced by the maximum legal axle load that is allowed during the normal summer-fall period (18.9 kips in Idaho). If the number of heavy axle loads does not vary seasonally, the selected criterion will result in a uniform rate of damage and fatigue-life consumption throughout the year. This criterion takes into account the existing condition of the pavement and does not impose unduly restrictive limits on pavements already nearing the end of their service lives.

Load Limit Procedure

The field work, materials testing, and analysis necessary to apply the criterion stated above can be divided into the following four phases:

1. Field sampling programs to define the structure of the pavement section as well as the condition of the materials during the normal summer-fall operating period and during the spring-thaw period.
2. Laboratory resilient-modulus testing program to determine parameters for the pavement and subgrade elastic response in both the normal-period and critical-period conditions.
3. Calculation of the pavement's response (stresses, strains, and deflections) for the maximum axle load while the pavement is in normal operating condition.
4. Determination (by back-calculation) of the maximum axle load that can be applied to the pavement during the critical period without exceeding the horizontal tensile strains induced by the normal axle load during the normal operating period.

The laboratory testing and computer analyses necessary to complete the procedures are all well established and are described elsewhere (4,5,7,10). In the interest of brevity, only the principal results for the trial application are included here. Complete details of the procedures used and the numerical results are contained in a report by Hardcastle and Lottman (11).

Results of the Field Sampling Programs

Field trips to the study pavement were made in October 1977 and March 1978. With the assistance of personnel and equipment from the Idaho Transportation Department, cores of the asphalt-bound layers were taken at six locations across the pavement. The pavement was also drilled with a hand auger at two locations to determine the thickness of the unbound layers and to obtain samples for determining classification and water content. Sufficient quantities of the granular subbase and subgrade soil were taken from the pavement shoulders for laboratory resilient modulus tests. During both field trips, pavement surface deflections were measured with the Benkelman beam by using the Idaho standard axle load for deflection of 15 kips on dual tires.

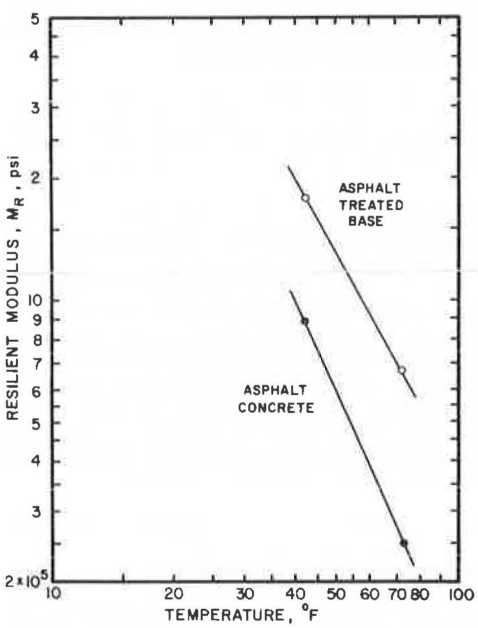
Measured deflections were used as a check against computed values as well as for data for the NCHRP load-limit method. Average values of the thickness, temperature, dry density, and water content of the pavement layers for the summer-fall condition and the spring-thaw condition are summarized in Table 1.

Laboratory Test Program

Laboratory repeated-load tests were conducted to define the resilient-modulus values required for the pavement-response analyses. Test specimens for asphalt stabilized layers and unstabilized layers were prepared and conditioned to be representative of the summer-fall and spring-thaw conditions.

1. Asphalt stabilized layers. The resilient moduli of the 1.6-in.-thick asphalt-concrete surface and the 1.9-in.-thick asphalt-treated base were determined by using the testing device for measuring diametral resilient modulus and the procedures described by Schmidt (10). Figure 5 shows the modulus-temperature relationships established from the tests.

Figure 5. Relation of resilient modulus of asphalt-stabilized layers to temperature.



2. Unstabilized (granular) layers. Resilient moduli of the 8-in.-thick silty sand (SW-SM, A-1) subbase and the sandy silt (ML, A-4) subgrade were determined in repeated load triaxial tests. Because it was not possible to recover undisturbed samples of the subbase and subgrade during the field sampling program, resilient modulus tests were conducted on specimens reconstituted from disturbed materials. Test specimens representing both the summer-fall and spring-thaw conditions were compacted to a dry density approximately equal to the dry density used in the Idaho R-value tests. These values were also within 1.5 pcf of the maximum AASHTO T-99 dry density. The decision to use the R-value density was based on the assumption that the materials originally had been placed at densities near the AASHTO T-99 maximum and, subsequently, have experienced little change in void ratio.

Test specimens of the fine-grained subgrade soil were compacted by using kneading compaction to ensure that the grain structure developed in the test specimens was the same as that developed in the field. The subbase sand was judged to be coarse enough to have a compacted structure independent of compaction method. As a matter of convenience, static compaction was used to prepare these specimens.

The water content used for test specimens representing summer-fall conditions were equal to the AASHTO T-99 optimums. Although the in situ water content of the subbase sand (as shown in Table 1) was slightly lower than the optimum, it was necessary to use the higher value to obtain a coherent test specimen. The results of the resilient-modulus tests for specimens of subbase sand and subgrade soil representing the summer-fall pavement condition are shown in the upper parts of Figures 6 and 7, respectively.

A great deal of direct, as well as indirect, evidence indicates that the water content (and degree of saturation) of well-graded granular materials beneath pavements in seasonal frost areas can increase sharply immediately following the thaw period (1,2). Although the in situ water content of the subbase and subgrade during the spring-thaw period was not known at the time the resilient modulus tests were conducted, it was believed that the degree of saturation would be very close to 100 percent. In order to achieve a degree of saturation as close to 100 percent as practical, test specimens representing the spring-thaw condition were prepared by combining the dry material necessary to produce the desired dry density with an amount of water sufficient to completely fill the voids of the com-

Table 1. Pavement section and materials properties used in pavement response analysis.

		Summer-Fall Condition						Spring-Thaw Condition					
				Water Content (%)						Water Content (%)			
Pavement Layer	Thickness (in.)	Temp. (°F)	Dry Density (pcf)	Field	Lab.	Resilient Modulus (psi)	Poisson's Ratio	Temp. (°F)	Dry Density (pcf)	Field	Lab.	Resilient Modulus (psi)	Poisson's Ratio
Asphalt-concrete surface	1.60	78	146.0	-	-	210,000	0.40	55	146.0	-	-	480,000	0.40
Asphalt-treated base	1.90	76	146.0	-	-	600,000	0.40	52	146.0	-	-	1,200,000	0.40
Silty-sand subbase	8.00		118.3	9.0	11.3	5,500	0.35		118.0	16.1	16.0	3,000	0.35
Sandy-silt subgrade	-		112.0	16.5	15.3	4,600	0.40		112.0	19.0	18.6	2,500	0.40

Figure 6. Resilient modulus of silty-sand subbase soil.

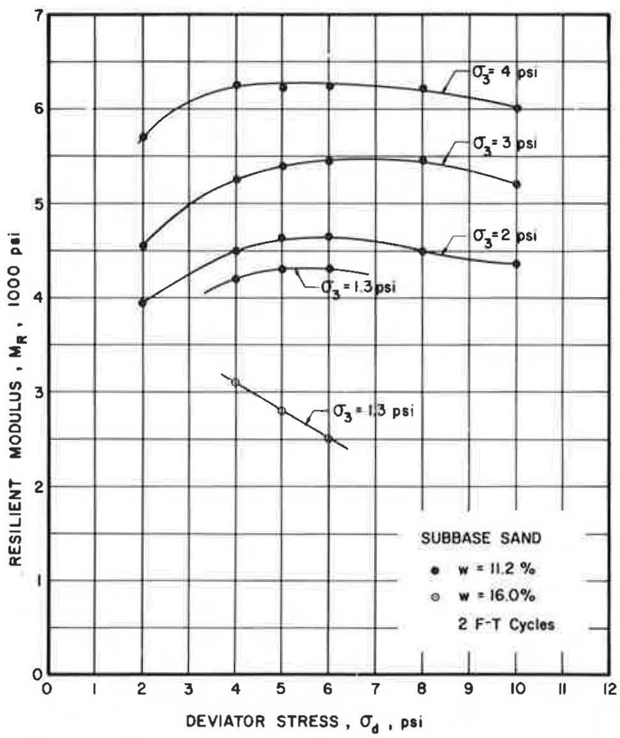
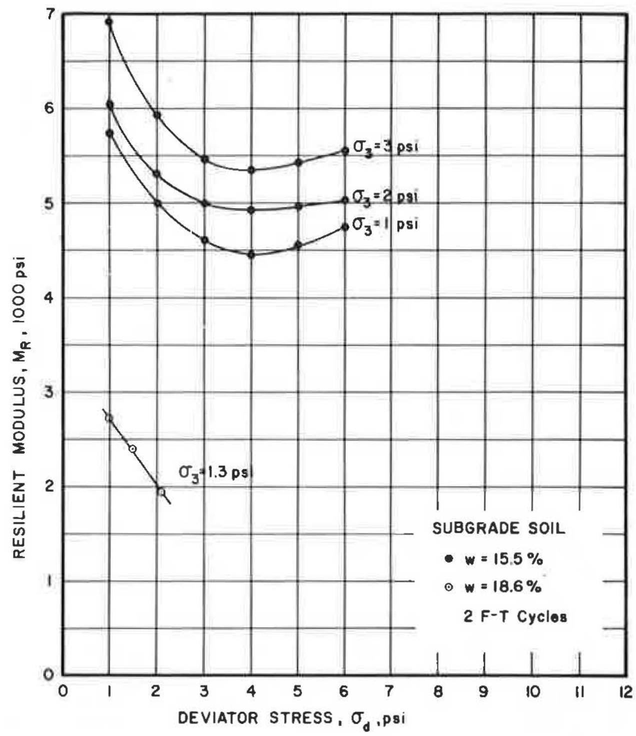


Figure 7. Resilient modulus of sandy-silt subgrade soil.



pacted material. Although a small amount of water was necessarily expelled along with air during compaction, the resulting degrees of saturation of the test specimens were close to 100 percent. As can be seen from the data in Table 1, the water contents which resulted from this procedure are similar to those measured in the field during the spring.

Evidence also indicates that freezing of soils at constant water content can contribute directly to decreases in strength and stiffness (1,6). In an attempt to account for the effects of freezing, test specimens representing the spring-thaw condition were subjected to two cycles of freezing and thawing prior to testing. Each freeze-thaw cycle consisted of placing the compacted, membrane-enclosed specimen in a freezer at 4°F for 12 hr followed by 12 hr at room temperature (68°F). The results of the resilient modulus tests on these specimens is shown in the lower parts of Figures 6 and 7.

In Figure 8, resilient modulus of the subgrade soil is plotted against the number of load repetitions to illustrate the significant recovery of modulus that resulted from the application of load. A similar response was exhibited by the silty sand subbase soil. Specimens of both these materials tested while in the summer-fall condition exhibited only slight changes in modulus with repetition of load. Comparisons of the modulus values shown in Figures 7 and 8 show that the first few hundred post-thaw load applications can eliminate the freezing-caused modulus reductions but not the moisture-caused modulus reductions.

Pavement Response Analysis

To complete the trial application of the suggested approach, the pavement's response to the maximum legal axle load applied in the summer-fall condition was determined using a layered-elastic computer program. An axle load producing the same horizontal tensile strain at the bottom of the asphalt-treated base during the spring-thaw period was then selected for the spring breakup limit.

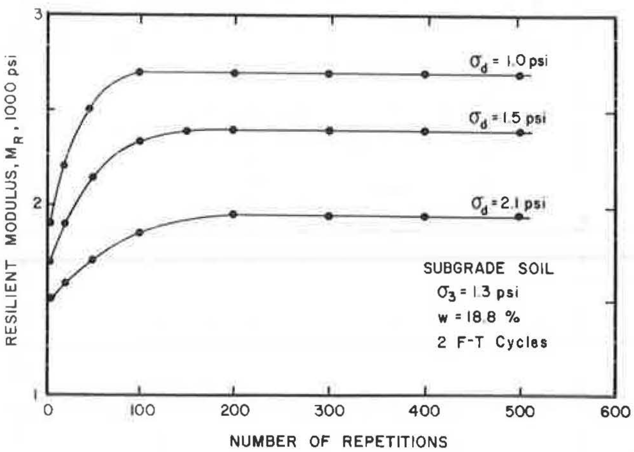
The layered-elastic-theory computer program used was the CHEV5L, which was developed by the Chevron Research Corporation (12). The program calculates stresses, strains, and deflections at specific points in the pavement structure and subgrade caused by a single distributed load. Because truck axle loads are applied with dual tires spaced at approximately 13.5 in. between centers, pavement responses were calculated along a vertical line 6.5 in. from a single applied tire load. Computed stresses, strains, and deflections were then doubled (superimposed) to account for the two adjacent tires. Data required for the CHEV5L program are as follows:

1. Tire load and pressure applied to the pavement surface,
2. Thicknesses of the component layers (up to 5), and
3. Resilient modulus and Poisson's ratio of each layer.

Summer-Fall (Normal) Period Pavement Response

The tire load applied to the pavement by the Idaho maximum axle load of 18.9 kips on dual tires is 4,725 lb; tire pressure is 80 psi. Four layers were used with thicknesses as shown in Table 1. Resilient moduli of the asphalt-bound layers were taken from Figure 5 corresponding to temperatures of 78° and 76°F for the surface and base courses, respectively. As can be seen in Figures 6 and 7, the resilient moduli of the unbound subbase and subgrade depend on both the deviator stress, σ_d, and the confining pressure, σ_3. The iterative procedure described by Lottman (9) were therefore used to obtain modulus values for the subbase and subgrade that were compatible with the stress levels existing in the pavement. Table 1 summarizes the materials parameters used for the summer-fall operating condi-

Figure 8. Influence of load repetitions on resilient modulus of frozen and thawed sandy-silt subgrade soil.



tion response calculations. The computed horizontal tensile strain at the bottom of the asphalt-treated base was 7.77 x 10^{-5}in./in.

Spring-Thaw (Critical Period) Pavement Response

The maximum axle load for the spring-thaw period was determined by completing the steps of the iterative procedure for successively smaller tire loads until a pavement response was obtained in which the computed horizontal tensile strains at the bottom of the asphalt-treated base were the same as the value previously calculated for the summer-fall condition. Temperatures, moduli of the asphalt stabilized layers, and the stress-compatible moduli of the subbase and subgrade for the final iteration are shown in Table 1. The maximum allowable spring-thaw period tire load (producing a strain of 7.98 x 10^{-5}in./in.) was 2,875 lb. The maximum allowable axle load for this condition under the equal tensile strain criterion is therefore 11.5 kips.

Comparisons of Measured and Computed Deflections

If it is assumed that the layered-elastic computer program accurately calculates the pavement response, an indication of the validity of the laboratory-measured resilient modulus values can be obtained by comparing the computed and measured pavement surface deflections. In comparisons for both summer-fall and spring-thaw period deflections, pavement responses were computed for a tire load of 3,750 lb corresponding to the dual-tire 15-kip axle load used for the Benkelman beam deflections. Using stress-compatible modulus values obtained in the iterative procedure and superposition to account for the fact that Benkelman beam deflections are measured midway between the dual tires, computed surface deflections for the summer-fall and spring-thaw period conditions were 48.4 milli-in. and 67.0 milli-in., respectively. Average measured deflections were 44.5 milli-in. and 60.5 milli-in. for the same conditions. These results suggest that the resilient moduli and other data used in the various computer analyses of the study were reasonably accurate.

COMPARISONS OF ALTERNATIVE LOAD LIMIT POLICIES

The maximum allowable axle load limit posted for the study pavement during the 1978 spring breakup period was 14.0 kips. In the following paragraphs the spring-thaw load limits computed by the two methods described in the paper are compared to the posted limit. The implications of the alternative load limits are analyzed in terms of their effects on the remaining fatigue life of the study pavement.

1969 NCHRP Criterion

According to the 1969 NCHRP criterion, pavements exhibiting normal period 18-kip axle load Benkelman beam deflections greater than 0.0229 in. should be restricted during the critical spring-thaw period. The deflection measured for the study pavement in October 1977 using a 15-kip axle load was 0.0445 in. and the spring-thaw period deflection was 0.0605 in. Using Equation 5 as modified to account for the 15-kip axle load used in the study, the 1969 NCHRP load limit is

$$L_s = 346/60.5\ (18/15) = 4.8 \text{ tons} \qquad (5)$$

In units of kips, the maximum allowable axle load is 9.6.

Criterion for Equal Surface Deflection

For purposes of comparison and because many highway engineers have experience with surface deflections, load limits were calculated based on a criterion of maintaining equal pavement surface deflections in the spring-thaw and summer-fall conditions. Calculations of the spring-thaw period axle load that produces the same surface deflection as the 18.9-kip legal load allowed during the summer-fall involves essentially the same steps as described previously for the equal strain criterion. According to this criterion, the maximum spring-thaw period axle load should be restricted to 13.8 kips.

Cumulative Damage and Fatigue Life Comparisons

An essential step in making economic comparisons of alternative load limit policies is the determination of the cumulative damage to the pavement or its remaining fatigue life under each of the alternatives. As a final part of the trial application of the proposed method, the relative amount of remaining fatigue life of the study pavement was determined for the 11.5-kip load limit, the 14-kip load limit, and for the alternative of no special restrictions on spring-thaw period axle weights.

Spring-Thaw Period Axle Weights Restricted to 11.5 Kips

The fatigue life remaining for the study pavement for each of the alternatives was evaluated using Miner's Law (Equation 3), computed tensile strains at the bottom of the asphalt-treated base, and the fatigue curves shown in Figure 4. In Equation 3, N_{ij} is defined as the number of repetitions of an axle load that cause failure while the pavement is in a particular state. To obtain N_{ij} from Figure 4, use the horizontal tensile strain, ε_{ij}, computed for the pavement in the appropriate physical state under the axle load. The limiting number of repetitions corresponding to the asphalt concrete stiffness in condition j is then read out of the graph. For a spring-thaw load limit based on the equal tensile strain criterion, the computed ε_{ij} for both the 18.9- and 11.5-kip axle loads is 77.7 x 10^6. Using a weighted stiffness modulus of 420,000 psi for the 1.6-in.-thick asphalt-concrete surface course and the 1.9-in.-thick asphalt-treated base course, N_{11} for the 18.9-kip normal-period axle load is 45 x 10^6 repetitions. During the critical

Table 2. Load limit and fatigue life comparisons.

Origin of Method	Spring-Thaw Load Limit Criterion	Maximum Spring-Thaw Axle Load, L_s, (kips)	Critical Tensile Strain, ϵ_t	Remaining Fatigue Life[a] Repetitions	Relative Remaining Fatigue Life (%)
This study	Equal tensile strains in asphalt-treated base	11.5	80×10^{-6}	44×10^6	100
Idaho Transportation Dept.	Experience and judgment	14.0	106×10^{-6}	35.3×10^6	80
This study	Equal surface deflection	13.8	104×10^{-6}	36×10^6	80
-	No restriction	18.9	157×10^{-6}	17.1×10^6	39
NCHRP Rpt. 76 (Ref 9)	Surface deflection correlated with experience and policy	9.6	Not computed	Not computed	>100

[a]For comparisons only.

spring-thaw period, the weighted asphalt mix modulus is 871,000 psi, and N_{22} is 35×10^6 repetitions.

With the assumption that the critical spring-thaw period lasts one month, n_{11} represents the number of 18.9-kip axle loads applied for 11 months of the year, and n_{22} represents the number of 11.5-kip axle loads applied during the critical period. If the monthly number of axle loads remains constant during the year, n_{22} equals 1/11 n_{11}; and the total number of axle loads that can be applied during the remainder of the pavement's life is the sum of n_{11} and n_{22}. Substitution into Equation 3 yields the result that n_{11} is 40.3×10^6 repetitions, and n_{22} is 3.7×10^6 repetitions. The total number of load repetitions, including both 18.9- and 11.5-kip axle loads, is 44×10^6. It should be noted again that the true number of repetitions (fatigue life) remaining for the study pavement is undoubtedly much less than 44×10^6. The computed value was determined from the fatigue curves of Figure 4, which are representative of new, initially uncracked pavements, whereas the study pavement has been in service for several years. However, the computed fatigue life remaining can serve as a basis for the following approximate comparisons provided the same fatigue curves are used for all the alternatives.

Spring-Thaw Period Axle Weights Restricted to 14 Kips

The computed horizontal tensile strains, ϵ_{22}, for the 14-kip axle loads applied during the critical period was 106×10^{-6}, and N_{22} was 10.5×10^6 repetitions (weighted asphalt mix modulus of 871,000 psi). With N_{11} still equal to 45×10^6, Equation 3 yields values of n_{11} and n_{22} of 32.4×0^6 and 3.0×10^6, respectively. The computed total relative remaining fatigue for the 14-kip axle load limit is 35.4×10^6 repetitions or 80 percent of the repetitions that remain if spring axle weights are restricted to 11.5 kips for one month each spring.

No Special Restriction on Spring-Thaw Period Axle Loads

For this alternative, n_{12} represents the number of 18.9-kip axle loads applied during the assumed 1-month long spring-thaw period and n_{12} equals 1/11 of n_{11}. The horizontal tensile strains, ϵ_{11}, and N_{11} for the 18.9-kip axle loads applied during the normal operating condition are the same as for the two previous alternatives.

For the 18.9-kip axle load during the spring-thaw period, computed horizontal tensile strain, ϵ_{12}, is 157×10^{-6}. With the weighted spring-thaw asphalt mix modulus of 871,000 psi, N_{12} is 2.2×10^6 repetitions. Substitution of these values into Equation 3 yields 15.7×10^6 for n_{11} and 1.4×10^6 for n_{12} or a total remaining fatigue life of 17.1×10^6 repetitions. This result indicates that if no special load restrictions are applied (or enforced) during the spring-thaw period, the remaining pavement surface life is reduced to 40 percent of the life remaining with a critical-period axle load limit of 11.5 kips.

Summary of the Fatigue Life Comparisons

The numbers used and the results of the comparisons of fatigue life for the three alternatives are summarized in Table 2.

CONCLUSION

The purpose of imposing special temporary restrictions on maximum axle weights allowed on a pavement during the critical spring-thaw period is to prevent accelerated deterioration or premature failure of the pavement while it is in a thaw-weakened condition. The objective of the study described in this paper was to develop a rational procedure which would include consideration of the effects of load limit policies on fatigue life as well as the effects of seasonal changes in the pavement's response to load. The approach selected was based on the mechanistic methods for determining pavement response to load and fatigue theory. In mechanistic pavement analysis, stresses, strains, and deflections can be calculated for any desired physical condition of the pavement provided appropriate pavement response parameters are used. Fatigue theory and fatigue curves developed for the asphalt-bound layers make it possible to quantify the effects of variations in axle weights and pavement physical conditions in terms of the cumulative damage or life expectancy of the pavement for selected load limit alternatives.

The materials testing and analytical procedures necessary to apply the mechanistic approach are somewhat more sophisticated and expensive than those used in other empirical pavement design or load limits approaches. The rational approach requires that resilient moduli of pavement materials be determined both for the normal summer-fall condition and for the critical spring-thaw period condition. Digital computers must be used to calculate the pavement response. In view of the exponentially rising costs of pavement rehabilitation and construction, the additional effort is believed to be justified. Only with the approach described is the pavement manager able to evaluate quantitatively the effects of load limit decisions and to defend highway policies.

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REFERENCES

1. Roadway Design in Seasonal Frost Areas. NCHRP Synthesis of Highway Practice 26, 1974, 104 pp.
2. F.H. Scrivner, R. Peohl, W.M. Moore, and M.B. Phillips. Detecting Seasonal Changes in Load-Carrying Capabilities of Flexible Pavements. NCHRP Report 76, 1969, 37 pp.
3. Structural Design of Asphalt Concrete Pavement Systems. HRB, Special Rept 126, 1971, 207 pp.
4. Structural Design of Asphalt Concrete Pavements to Prevent Fatigue Cracking. HRB, Special Rept 140, 1973, 201 pp.
5. C.L. Monismith, J.A. Epps, D.A. Kaisianchuk, and D.B. McLean. Asphalt Mixture Behavior in Repeated Flexure. Institute of Transportation and Traffic Engineering, University of California, Berkeley, Report TE-70-5, 1971.
6. A.T. Bergen and C.L. Monismith. Characteristics of Subgrade Soils in Cold Regions for Pavement Design Purposes. HRB, Highway Research Record 431, 1973, pp. 25-37.
7. Test Procedures for Characterizing Dynamic Stress-Strain Properties of Pavement Materials. TRB, Special Rept 162, 1975, 38 pp.
8. M.A. Miner. Cumulative Damage in Fatigue. Journal of Applied Mechanics, Vol. 12, No. 3, 1945, pp. 159-164.
9. R.P. Lottman. Practical Laboratory Measurement and Application of Stiffness or Resilient Properties of Soils and Granular Base Materials for Idaho Flexible Pavement Design Procedures. Department of Civil Engineering, University of Idaho, Moscow, Final Rept, 1976, 102 pp.
10. R.J. Schmidt. A Practical Method for Measuring the Resilient Modulus of Asphalt Treated Mixes. HRB, Highway Research Record 404, 1972, pp. 22-31.
11. J.H. Hardcastle and R.P. Lottman. A Rational Method for Establishing Spring-Thaw Load Limits on Idaho Highways. Idaho Short Term Applied Research Program, University of Idaho, Moscow, Final Rept, 1978, 90 pp.
12. J. Michelow, H. Warren, and W.L. Dieckmann. Numerical Computation of Stresses and Strains in a Multiple-Layered Asphalt Pavement System. California Research Corp, Richmond, CA, 1963.

Prediction of Roadway Strength From Soil Properties

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An intensive performance study of 120 Alaskan asphalt-paved roadway sections was completed in 1980. Roadway-bearing strengths were measured weekly on each section during the period of thaw weakening by means of a Benkelman beam-type test procedure. Soil properties and layer thicknesses were evaluated by use of test pit sampling. This study, which included sections from the different climatic regions of Alaska, has indicated certain soil particle sizes to be the most critical factor in crack-free performance and resistance to spring thaw weakening. The data acquired in the performance study have provided a basis for the development of a new method of pavement design. This method predicts the maximum seasonal or design deflection level from the percentages of particles smaller than 0.075 mm (No. 200 sieve) in the different granular soil layers beneath the asphalt pavement. Required pavement thicknesses for the predicted traffic and design deflection levels are then determined by a previously developed overlay design procedure. This method is demonstrated to be more reliable than previous designs based on the frost susceptibility classification of the pavement layers.

In a field performance study of 120 existing Alaskan flexible highway pavement sections completed in 1980, more than 200 variables were analyzed to determine their effects on pavement performance (1). Each pavement was rated in terms of alligator fatigue cracking, wheelpath rut depth, thermal cracking, ride quality, and maximum springtime Benkelman beam deflection level. Construction materials were sampled from test pits at two locations within each highway section. Soils were sampled to a depth of 4.5 ft. Laboratory testing included soil gradations, percent fracture, and in situ moisture content. Laboratory frost-heave rate and Hveem R-value tests were also performed for many of the sections. Additional variables that described the environment in terms of climate, pavement age, and accumulated traffic loadings were introduced into the data base.

The factors found to relate most strongly to the springtime load-bearing capacity and to the amount of fatigue (or alligator) cracking were the percentages of particle sizes smaller than 0.075 mm in the base and subbase layers (2). These layers extend from a depth of 0 to 2 ft beneath the pavement (see Figure 1). Particles passing a No. 200 mesh sieve, i.e., particles smaller than 0.075 mm, and fractions smaller than 0.02 mm are generally used as indicators of frost susceptibility. Other ways of expressing these particle sizes in this paper are P_{200} sieve or fines, <0.075 mm, and <0.02 mm.

It was also found that peak spring Benkelman rebound deflection levels has a strong positive correlation with the observed severity of alligator cracking (Figure 2). Relationships between alligator cracking and pavement age indicate that this type of cracking propagates rapidly once it exceeds 5 percent of the combined wheelpath length of the test section. From these conclusions it was apparent that if an equation could be developed for maximum seasonal deflection levels based on soil and climatic factors, pavement cracking and fatigue life could be predicted.