Pavement Response and Load Restrictions on Spring Thaw-Weakened Flexible Pavements

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Agencies faced with maintenance of secondary roads in frost areas often choose to restrict vehicle or axle loads during spring thawing to minimize the detrimental effects of heavy loads on severely weakened pavements. Thirty-two summer pavement structures were defined to represent "typical" restricted pavements. Layered elastic analyses were performed for these pavements for different levels of reduction in resilient moduli at three different times during spring thawing, including (a) base thawing, (b) 4 in. of subgrade thawing, and (c) total thawing. Allowable loads for deflection, fatigue, and subgrade vertical strain were identified by comparing the spring thaw response to the summer response. It was found that many thin pavements [2 in. asphalt concrete (AC)] reached critical conditions by the time of base thaw, and asphalt tensile strain was the critical response parameter for the majority of these pavements in spring. Four-inch AC pavements did not experience strains or deflections in excess of those in summer until some subgrade thawing occurred; subgrade vertical strain was the critical parameter for these pavements. It was also found that deflections are not a reliable indicator of when critical conditions are realized in a thaw weakened pavement. Finally, a method of evaluating the relative benefits of applying various levels of spring load restrictions is presented.

During spring thawing the strength of the ground may be measurably weakened compared with its summer/fall state as a result of moisture migration into the soil during the preceding freezing period and, possibly, the development of excess hydrostatic pressure in base and subgrade materials as moisture is liberated during thawing.

Recognition of seasonal variation in material properties is necessary for realistic estimates of pavement performance. For primary road facilities it is necessary to minimize the detrimental effects of substantial thaw weakening because it is anticipated that these roads will perform at a high level of serviceability throughout the year under high traffic volumes. For many secondary roads with lower traffic volumes, however, it is not economically feasible to provide adequate frost protection throughout for spring thawing. Agencies faced with secondary road maintenance in frost areas often choose to restrict vehicle and/or axle loads during the critical period in the spring to reduce damage at this time.

Although the use of load restrictions is the only feasible pavement maintenance strategy for many secondary roads, restricting roadways is never a popular practice. As it is desirable to minimize load restrictions during periods of severe weakness, it is of some use to identify pavement response during the thawing period. The location of segments of roads to be restricted is generally selected on the basis of experience. Pavement sections where excessive rutting, fatigue failures, or extensive potholing have occurred in the past during spring thawing are likely to be candidates for restrictions.

Individuals who are responsible for restricting pavements during spring thawing have had very little information or guidelines available for selecting (a) the time to place spring load restrictions or (b) what magnitude of load restrictions would be beneficial without unduly restricting pavements (*1*). The purpose of this work was to identify guidelines in these two specific areas. Often pavements are not restricted until some visible fatigue cracking or potholing has occurred. This practice does not result in optimal use of load restrictions because some permanent damage has already resulted.

One of the first decisions made to perform the study was to select some criteria for evaluating allowable spring load levels. Some pavement design methods use deflection as a criterion for evaluating performance. Results from previous work on pavement response during spring thawing (*2–4*) suggested that tensile strain at the bottom of the asphalt concrete (AC) layer and/or maximum vertical strain at the top of the base or subgrade material reached high levels before the development of large deflections. This occurs when one or more weak layers are present between stiffer materials, which is the case when only a small amount of thawing has taken place. From these observations it was concluded that several pavement response parameters (deflection, δ; asphalt tensile strain, ε_t; and subgrade vertical strain, ε_{vs}) would be evaluated. Further, it was decided that comparisons would be made of these response parameters between a reference time in the summer and several times during spring thawing rather than use some absolute value of strain or deflection levels as criteria for the need for load restrictions. The summer reference time selected was when the asphalt concrete temperature was at 77°F and the unbound materials were performing optimally, with moderate moisture contents and saturation levels. This time was compared with three times during spring thawing when the greatest changes in resilient stiffness were occurring because of the movement of the thawing plane. Using this approach, the results obtained indicated the relative performance of the pavement sections analyzed at selected times during spring thawing and summer.

The analysis was performed by developing hypothetical pavement sections that represented typical pavements currently receiving load restrictions during spring thawing (*1*). Several different load configurations and load levels were

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applied to these pavements, and the pavement response was obtained from layered linear elastic analyses. The results obtained from the elastic analyses demonstrated how the hypothetical pavement cross sections responded with respect to deflection, asphalt tensile strain, and subgrade vertical strain. The pavement sections developed for the study were analyzed at three different times during thawing to evaluate (a) when pavement performance relative to summer was compromised and (b) how long the pavement was in a weakened condition.

The following questions are proposed to identify some of the issues to be addressed from the results of the analysis regarding the use of load restrictions and pavement response during spring thawing:

1. After thawing began, when were the pavement cross sections analyzed in a weakened condition relative to the summer reference condition?
2. To what extent was the load-carrying capacity of the weakened pavement compromised relative to summer?
3. How did pavement response change during the thawing period for the hypothetical pavements analyzed?
4. What response parameters resulted in the greatest reductions in allowable loads for the pavement cross sections analyzed?
5. How were deflections correlated with pavement weakening?
6. How did pavement response vary for different wheel and axle configurations during spring thawing?
7. Can we quantify the benefits of applying load restrictions on the pavements analyzed?
8. What can be concluded about "real" pavements from these results?

A description of the pavement cross sections and materials selected for the study, the analysis methods, and the results are presented next to provide some insights into these issues.

DESCRIPTION OF ANALYSIS

Hypothetical pavement cross sections were developed to represent, to the best extent possible, the types of road construction and subgrade materials existing in currently restricted pavements. Data obtained from a survey of pavement structures currently receiving spring load restrictions (*1*) were weighed heavily in the development of these sections. The data suggested that pavement cross sections on which load restrictions are currently being applied range as follows:

	Range	*Normal*
Asphalt surface, in.	1½–6	2–4
Aggregate base, in.	4–18	6–12

On the basis of this information 2- and 4-in. asphalt surface courses and 6 and 12 in. unbound aggregate base courses were selected for the cross sections for the analysis.

The predominant subgrade material present where load restrictions have reportedly been applied was clay. Silts, gravels, granular materials, and tills were also mentioned as subgrade types requiring restrictions in the survey of current practice (*1*). Because of this information, both fine and coarse subgrade materials were modeled in the analysis. The material properties required for the elastic analyses are the resilient modulus and Poisson's ratio. The resilient moduli selected to model fine subgrade materials for the summer reference condition were 8 and 12 ksi. The resilient moduli selected for coarse subgrade materials during summer were 15 and 25 ksi. These values were selected to represent low- to medium-range resilient stiffness properties of unbound fine and coarse materials. It was anticipated that unbound coarse and fine materials with low to average resilient stiffness properties would be the most likely candidates for significant reductions in resilient stiffness during spring thawing. Resilient modulus values for pavement subgrade materials compiled by Rada et al. (*5*) suggest that these values are reasonable. The values of Poisson's ratio assumed for the analysis were 0.45 and 0.40 for fine and coarse subgrades, respectively.

The hypothetical pavement sections were analyzed using ELSYM5, a layered elastic pavement analysis program developed at the University of California at Berkeley (*6*). The variation in pavement response during the spring thaw period was evaluated relative to the summer pavement response, as described earlier. Material properties for the layers in each pavement structure were selected to represent the behavior at three distinct times during the spring thaw period when the most significant changes in material properties were expected to occur. The times selected were the following: (a) when thawing reached the bottom of the base material, (b) when the thawing plane was 4 in. into the subgrade material, and (c) when thawing was complete. The total thickness of the frozen material was assumed to be 4 ft before the start of thawing.

The material properties for each pavement layer for the summer reference condition are given in Table 1. The resilient modulus (M_r) assumed for the asphalt concrete was 300 ksi. Two unbound base materials were included with assumed M_r values of 25 and 50 ksi. Four subgrade materials were assumed for the analyses with resilient moduli of 8, 12, 15, and 25 ksi in summer to represent a range of resilient response.

Tables 2 through 4 give the material properties for the three analysis times during spring thawing. The asphalt concrete resilient stiffness in spring was assumed to be 1,200 ksi. The change in resilient stiffness from summer to spring was based on a change in average temperature of the asphalt layer from 77°F in the summer to 40°F in spring (*7*). Base M_r values were reduced by 25 and 50 percent during early thawing and by 15 and 40 percent at total thaw (see Tables 2 to 4). The reduction in base course resilient stiffness from summer to spring assumed for the analysis was based on M_r values from nondestructive field evaluation of base course resilient stiffness (*5*) and laboratory results of the change in resilient behavior (S_r) for granular materials in dry ($S_r \leq 60$ percent) and wet ($S_r \geq 85$ percent) conditions (*8*).

Subgrade M_r values for fine-grained materials (8 and 12 ksi) were reduced by 75 and 90 percent relative to summer levels at early subgrade thawing and by 65 and 75 percent at total thaw. Coarse subgrade materials (15 ksi and 25 ksi) were reduced by 50 and 75 percent at early thaw and by 40 and 65 percent at total thaw. Many studies both in the laboratory and the field have been performed on the resilient response of frozen and thawed materials (*7*). The results have indicated that resilient stiffness may be reduced up to 99 percent depending on the material type, moisture content, saturation level, and other factors. The reductions in resilient stiffness

TABLE 1 PAVEMENT STRUCTURE MATERIAL PROPERTIES, SUMMER CASE

Layer	Material	Thickness (in)	Resilient Modulus (psi)
Surface	BST or ACP	2	300,000
	ACP	4	300,000
Base	Unbound	6	25,000; 50,000
	Unbound	12	25,000; 50,000
Subgrade	Fine-grained	<40	8,000; 12,000
	Coarse-grained	<40	15,000; 25,000
Bottom	Rigid	Infinite	100,000

TABLE 2 PAVEMENT STRUCTURE MATERIAL PROPERTIES, BASE THAW

Layer	Material	Thickness (in)	Resilient Modulus (psi)
Surface	BST or ACP	2	1,200,000
	ACP	4	1,200,000
Base	Unbound	6	50%, 75% summer
	Unbound	12	50%, 75% summer
Subgrade	Fine-grained	<40	50,000
	Coarse-grained	<40	50,000
Bottom	Rigid	Infinite	100,000

TABLE 3 PAVEMENT STRUCTURE MATERIAL PROPERTIES, 4 IN. SUBGRADE THAW

Layer	Material	Thickness (in)	Resilient Modulus (psi)
Surface	BST or ACP	2	1,200,000
	ACP	4	1,200,000
Base	Unbound	6	50%, 75% summer
	Unbound	12	50%, 75% summer
Subgrade	Fine-grained	4	10%, 25% summer
	Coarse-grained	4	25%, 50% summer
Subgrade	Frozen	<36	50,000
Bottom	Rigid	Infinite	100,000

TABLE 4 PAVEMENT STRUCTURE MATERIAL PROPERTIES, TOTAL THAW

Layer	Material	Thickness (in)	Resilient Modulus (psi)
Surface	BST or ACP	2	1,200,000
	ACP	4	1,200,000
Base	Unbound	6	60%, 85% summer
	Unbound	12	60%, 85% summer
Subgrade	Fine-grained	<40	25%, 35% summer
	Coarse-grained	<40	35%, 60% summer
Bottom	Rigid	Infinite	100,000

assumed for the study were selected to represent a range of resilient behavior for coarse and fine material types.

When an elastic analysis is performed on a pavement system with a stiff base course over a weak subgrade, tensile stresses may be obtained within the unbound base material. Such results are considered to be unrealistic in view of the lack of ability of unbound materials to sustain tensile stresses. Therefore, a limit on the ratio of base M_r to subgrade M_r of 4 was imposed, based on the work of Klomp and Dorman (*9*), to avoid developing unrealistic stress distributions in these materials.

The ELSYM5 program used for the analyses incorporates linear elastic material behavior. It has been demonstrated that resilient behavior of the layers within pavement systems is typically not linear. Stress-dependent resilient properties have been used to model response more accurately. Because hypothetical pavements were developed for this analysis, it was felt that it would be sufficient to identify resilient moduli and relative values of these moduli at the different analysis times in spring and summer. Adding more complexity to the analysis by introducing nonlinear behavior would not necessarily have resulted in improved results, given the nature of this analysis.

Three primary response variables used to evaluate flexible pavement performance are deflection, δ, maximum asphalt tensile strain, ε_t, and maximum subgrade vertical strain, ε_{vs}. These parameters were selected to observe the response through the spring thaw period. In addition, estimates of remaining life for fatigue using the equation developed by Finn et al. (*10*) and estimates of rut life using the Shell equation (*11*) were obtained. This was done (a) to assess the impact of spring thaw weakening on long-term pavement performance and (b) to compare the performance of different pavement structures.

The standard load used in the analysis was a single tire, single axle load of 20,000 lb. In addition, dual tire, single axle loads of 20,000 lb and dual tire, tandem axle loads of 34,000 lb were analyzed. Surface deflections and subgrade vertical strain were obtained for 20 percent and 100 percent of the total load for each load configuration for each hypothetical pavement cross section to develop load-deflection and load-strain relationships at each analysis time in the spring. The deflection and strain from the summer reference condition were then compared with the spring load-deflection or load-strain response at each analysis time in spring. Using this procedure the spring pavement response was identified in terms of the allowable spring load, which was the load that corresponded to the summer deflection or strain parameter level. The critical parameter at each analysis time in the spring was the response parameter that resulted in the greatest reduction in allowable load. This is shown schematically in Figure 1.

Asphalt tensile strain has been used as a pavement response parameter since it has been correlated with asphalt concrete fatigue failures in both the laboratory and field (*10*). In addition to obtaining primary response parameters (strains and deflections), estimates of remaining life for the hypothetical pavement cross sections were made to compare the pavement performance in summer and spring as well as that of different pavement sections. The equation for remaining fatigue life

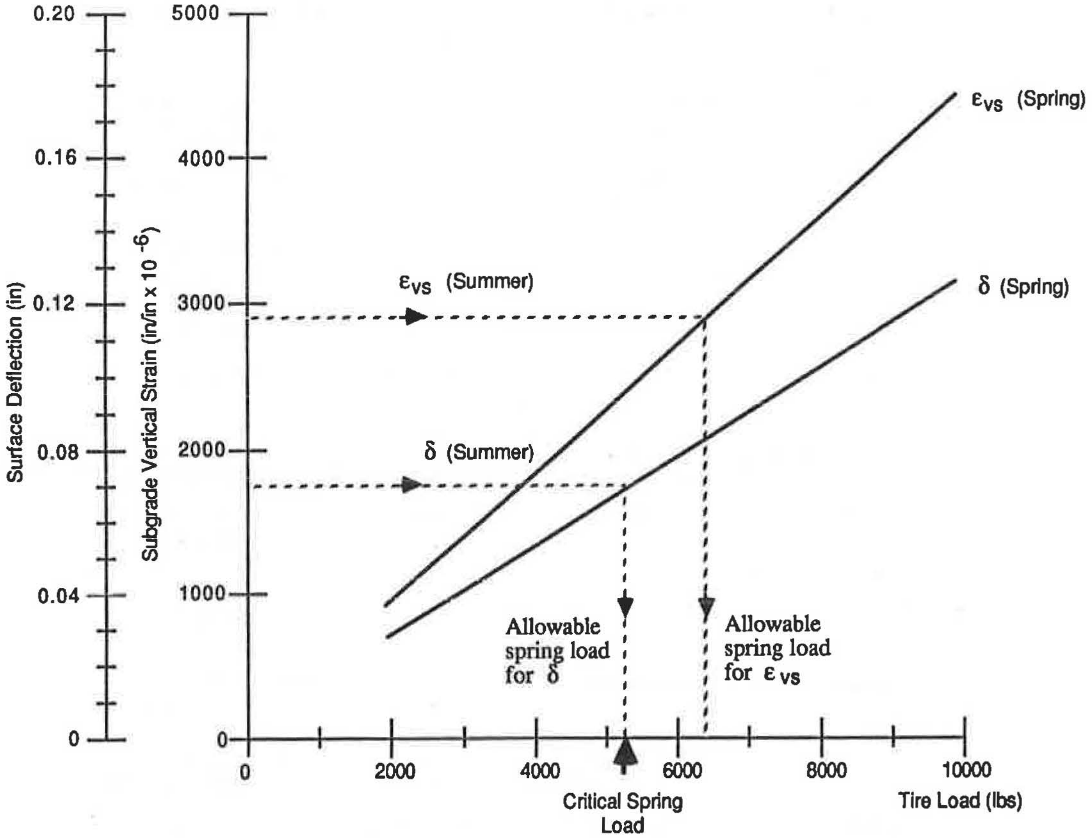

FIGURE 1 Selection of allowable spring load levels for deflection and subgrade vertical strain.

used for this study, developed by Finn et al. (*10*), is the following:

$$\log N_f = 15.947 - 3.291 \log (\varepsilon_t/10^{-6}) - 0.854 \log (E^*/10^3)$$

where

N_f = the number of load applications of constant stress to cause the initiation of fatigue cracking,
ε_t = the initial tensile strain for the applied stress, and
E^* = the complex modulus, in psi.

The form of this equation indicates that fatigue is a function of resilient stiffness (M_r) and maximum asphalt tensile strain, ε_t. In this analysis the asphalt concrete resilient modulus varied in spring and summer because of the variation in average pavement temperature at these times. Because asphalt tensile strain response was obtained to predict fatigue, it seemed more defensible to compare fatigue life in spring and summer than asphalt tensile strain directly. Therefore, allowable loads for asphalt tensile strain were actually based on fatigue life computed using the Finn equation with AC M_r values of 300 and 1200 ksi for summer and spring, respectively, as follows:

$$\log \frac{\varepsilon_{t\ \mathrm{su}}}{\varepsilon_{t\ \mathrm{sp}}} = \frac{0.854}{3.291}\left(\log \frac{M_{r\ \mathrm{sp}}}{M_{r\ \mathrm{su}}}\right)$$

The relationship of spring and summer fatigue life and asphalt tensile strain is shown in Figure 2.

RESULTS

The results described in this section are for a single tire, single axle loading. Results for other load configurations assumed for the analyses are presented later.

The results suggested that the 2-in. thick and 4-in. thick pavements modeled responded quite differently when spring and summer responses were compared. The majority of 2-in. pavements developed asphalt tensile strains that resulted in significant reductions in fatigue life by the time thawing had reached the bottom of the base course. Allowable loads were reduced up to 89 percent for all 2-in.-thick pavements, with an average reduction of 50 percent. The greatest load reductions were obtained for the pavements modeled with base materials with summer M_r values of 50 ksi (the stronger base material used for the study).

When thawing proceeded into the subgrade, asphalt tensile strains in all 2-in. AC pavements increased further. The average allowable spring load for asphalt tensile strain at this time was 47 percent of the maximum load, with allowable loads ranging from 0 to 84 percent for fatigue. Asphalt tensile strain was the critical parameter for the majority of the 2-in. pavements modeled for the study at early subgrade thawing. However, thin pavements (2 in. AC) with summer base M_r values of 25 ksi that were modeled with reductions in subgrade modulus of 75 to 90 percent at early subgrade thawing resulted in the greatest reductions in allowable loads from increases in subgrade vertical strain rather than asphalt tensile strain and fatigue.

At total thaw, AC tensile strain was the critical parameter for 42 of the 48 thin pavements analyzed. At this time, asphalt tensile strain and fatigue life were relatively unchanged compared with early subgrade thawing, whereas subgrade vertical strains decreased an average of 19 percent for these pavements. The change in allowable loads during the spring thaw period obtained from the analyses for deflection, asphalt tensile strain, and subgrade vertical strain for one of the 2-in. pavement cases is shown in Figure 3.

By comparison, the 4-in.-thick pavements modeled did not develop strains or deflections resulting in a reduction in allow-

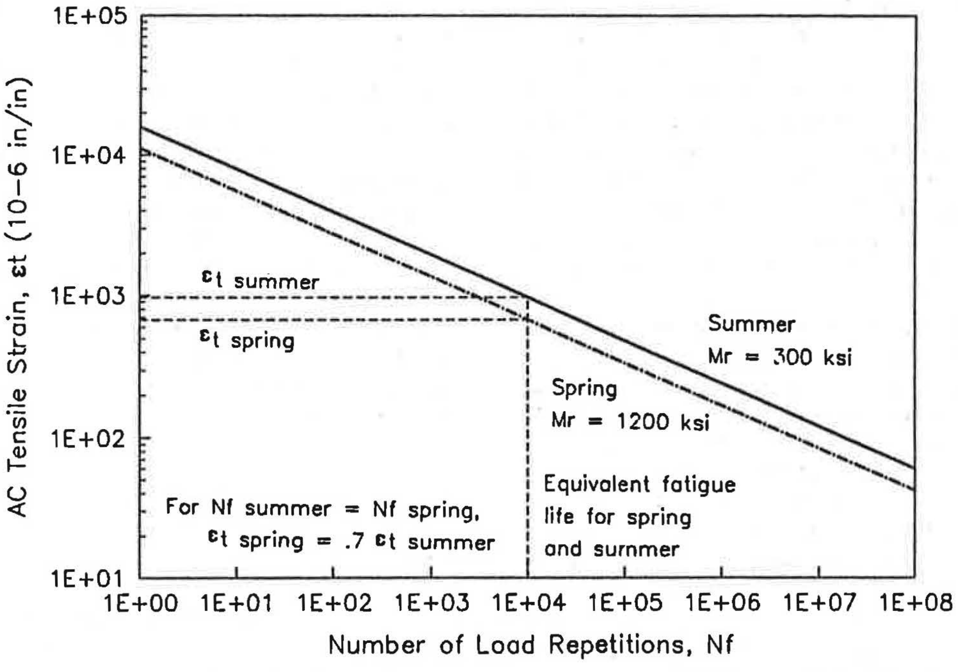

FIGURE 2 Comparison of spring and summer fatigue life using the fatigue model by Finn et al. (*10*).

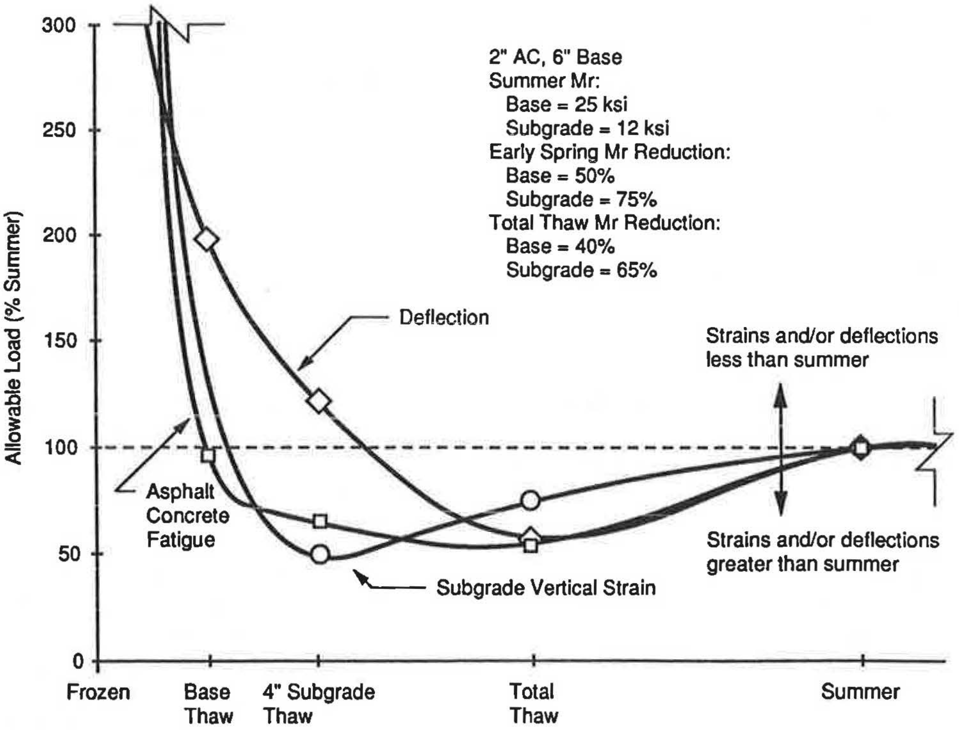

FIGURE 3 Allowable load versus time for a 2-in. asphalt concrete pavement.

able loads when thawing reached the bottom of the base material. It was not until some thawing of the subgrade material occurred that strains in excess of the summer levels were obtained. Not all of the 4-in.-thick pavements resulted in increased strains at this time. Those that did, however, resulted in the greatest calculated reductions in load-carrying capacity as a result of increased subgrade vertical strain leading to rut development. Allowable spring loads obtained at 4 in. of subgrade thawing ranged from 29 to 100 percent.

At the time of total thawing all 4-in.-thick pavements experienced a reduction in maximum subgrade vertical strain relative to the time of early subgrade thawing. This reduction ranged from 9 to 49 percent for the pavements that required some load reductions, with an average decrease in subgrade vertical strain of 25 percent since early subgrade thawing. The change in pavement response during spring thawing expressed in allowable load for one of the 4-in. pavements analyzed is shown in Figure 4. The results for allowable loads for all pavements modeled for the three analysis times in spring can be found elsewhere (*7*).

Many agencies have deflection testing capabilities that may be used for identifying the critical spring thaw period. It was found that, with the exception of the most severely weakened pavements, reductions in load-carrying capacity occurred before the time that deflections reached or exceeded summer levels. Figure 5 shows the deflection at the time of base thaw versus the allowable load for fatigue for all 2-in. pavements modeled. Deflections for 2-in.-thick pavements with accelerated fatigue consumption at base thaw (load reductions up to 89 percent were required for these pavements) ranged from 37 to 100 percent of summer deflection levels.

When thawing had advanced 4 in. into the subgrade, 2-in. pavements that experienced some reduction in load-carrying capacity due to fatigue or subgrade vertical strain (calculated load reductions up to 100 percent were obtained) had deflections that ranged from 66 to 279 percent of summer deflection levels, with the majority of these pavements resulting in deflections that were still less than in summer. Similar findings were reported by Stubstad and Connor (*2*) on actual pavements in Alaska and in Minnesota (*4*). These results were based on deflection measurements obtained during thawing using the Falling Weight Deflectometer (FWD).

The earliest time that calculated spring response for 4-in. pavements resulted in the need for load reductions due to deflection was at 4 in. of subgrade thawing. Deflections at this time for the 4-in. pavements that needed some level of load reductions because of fatigue or subgrade vertical strain ranged from 55 to 144 percent of summer levels.

As a result of the accumulation of strain in the weakened unbound materials with time in spring, all pavements resulted in calculated deflections equal to or greater than summer levels at total thaw in this analysis. For 4-in. AC pavements where subgrade vertical strain produced the greatest reduction in allowable load, a relationship between the allowable load needed to maintain subgrade vertical strains at their summer levels and deflection was obtained from a linear regression of the data from the analyses at total thaw. The relationship is the following:

$$P_{\varepsilon_{vs}} = 0.17 + 0.90\,(\delta_{\text{summer}}/\delta_{\text{total thaw}})$$

where

$P_{\varepsilon_{vs}}$ = the allowable load for subgrade vertical strain,
δ_{summer} = the deflection for the summer reference condition,
$\delta_{\text{total thaw}}$ = the deflection at total thaw.

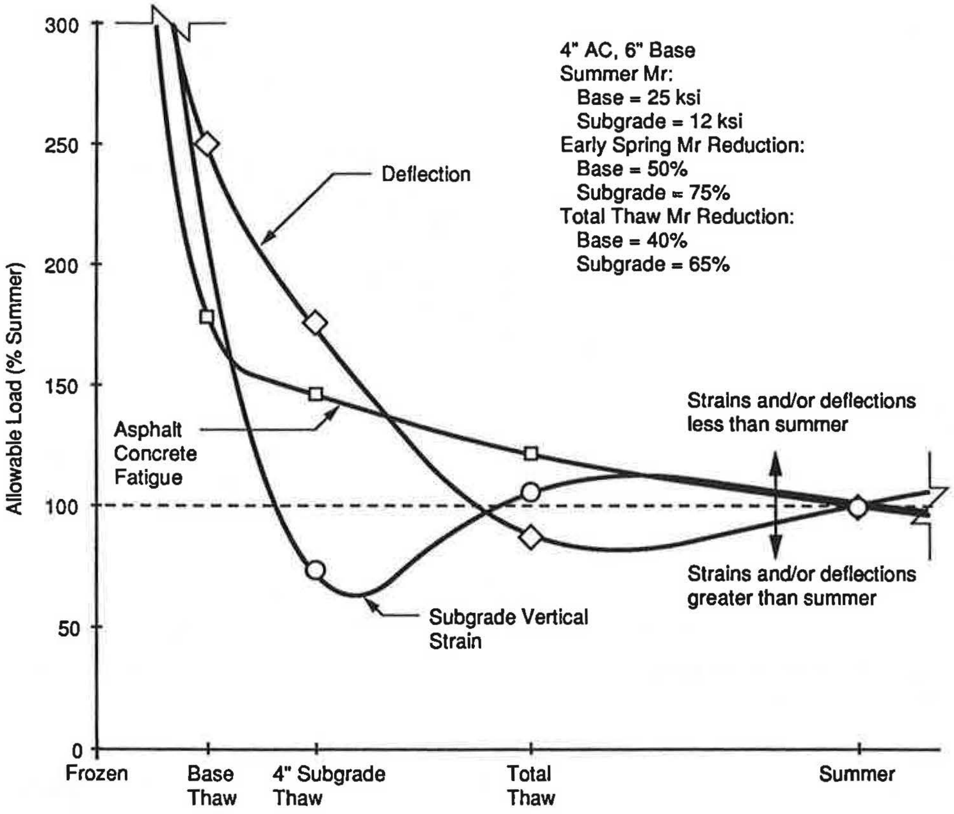

FIGURE 4 Allowable load versus time for a 4-in. asphalt concrete pavement.

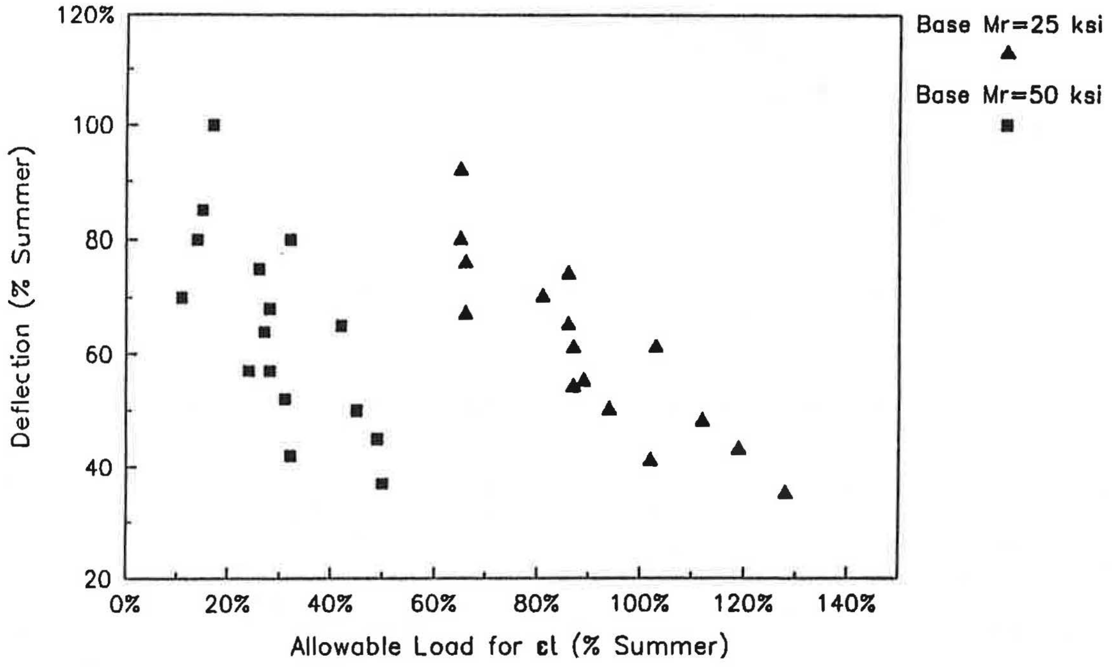

FIGURE 5 Deflection versus allowable load for asphalt tensile strain at base thaw, 2-in. AC.

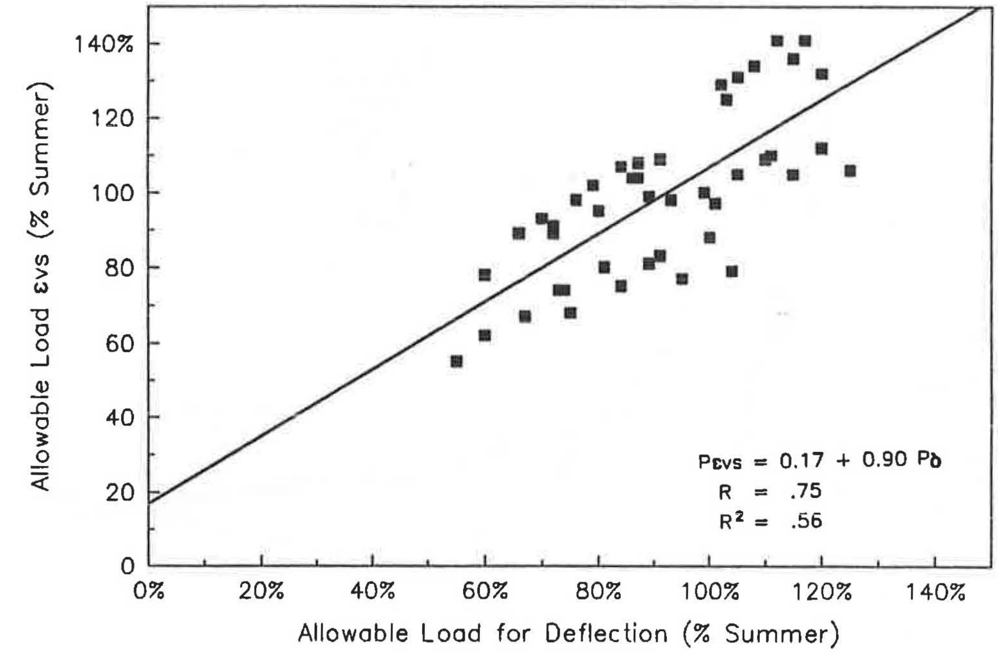

FIGURE 6 Allowable load for subgrade vertical strain versus allowable load for deflection at total thaw, 4-in. AC.

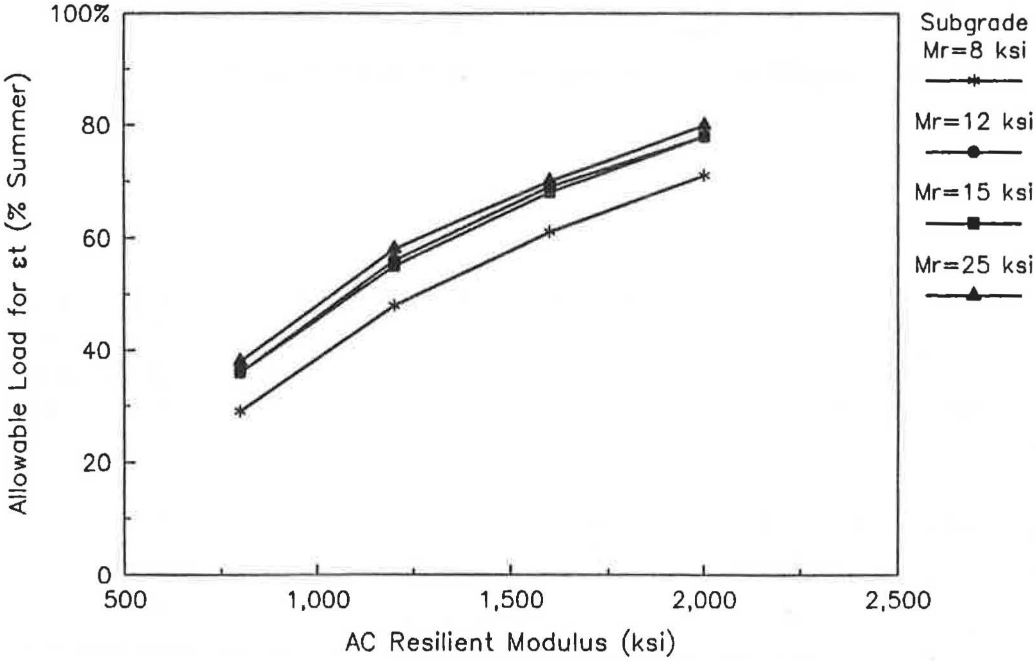

FIGURE 7 Allowable load for asphalt tensile strain versus spring AC M_r at total thaw.

The data points for the 4-in. pavements and the relationship obtained are shown in Figure 6. By comparison, the 2-in. pavements modeled resulted in the greatest calculated reductions in allowable loads at total thaw because of continued accelerated fatigue consumption. No useful correlation of allowable loads for fatigue and deflection at total thaw was found from the calculated response obtained for the 2-in. pavements.

Only one value of asphalt resilient modulus was assumed for the surface layer in the analysis. Because asphalt tensile strain was the critical parameter for thin pavements, the sensitivity of asphalt tensile strain to AC M_r was considered. A 2-in. pavement with a 6-in. base layer was selected as a reference case to consider the sensitivity of the results for different AC M_r values. The reduction in base resilient modulus assumed for the reference case was 50 and 40 percent for early and late thawing, respectively. The corresponding reduction in subgrade resilient modulus assumed was 75 and 65 percent. Summer AC M_r values selected for the sensitivity analysis ranged from 200 to 500 ksi. The corresponding spring M_r

values were four times the summer M_r values, as in the preceding portion of the analysis. The variation in allowable load for fatigue at total thaw (which was the critical parameter for these pavements) versus AC M_r is shown in Figure 7. A 42 percent variation in allowable load for fatigue resulted for the range of AC M_r investigated for the different subgrade cases. The effect of the variation in AC M_r on allowable loads for deflection and subgrade vertical strain was substantially less. The maximum variation in allowable spring loads for deflection and maximum subgrade vertical strain was 9 and 17 percent, respectively.

MULTIPLE LOAD CONFIGURATIONS

Heavy vehicles typically are configured with both single and tandem axles. Single axles are typically found on the steering axle on Class 8 heavy vehicles, and tandem axles often support the drive axle and the payload portion of the vehicle. In light of this, both axle configurations were included in the analysis.

The analyses for dual tires on single axles and dual tires on tandem axles were performed when thawing had proceeded 4 in. into the subgrade, because this was when allowable loads reached critical levels for all hypothetical pavements that required some load reductions for the single tire, single axle load case. It was found that for dual tire load configurations subgrade vertical strain was always the parameter that resulted in the greatest reduction in allowable load at this time. In the case of the single tire loads discussed previously, fatigue life (and asphalt tensile strain) was the critical parameter for the majority of 2-in. AC pavements.

Allowable loads for dual tire, single axle and dual tire, tandem axle loads were very close to the allowable loads for the same pavement structures loaded with single tire, single axle loads. The difference in allowable loads for the three load cases for a given pavement structure ranged from 0 to 11 percent. It was also found that the maximum subgrade vertical strain and maximum deflections for both dual tire cases always occurred between the tires during spring.

A comparison of the absolute value of maximum subgrade vertical strains when thawing was 4 in. into the subgrade showed that strains were consistently less for multiple load configurations compared with single tire loads. Figure 8 shows remaining rut life in a 2-in. AC pavement with a 6-in. base for the three load cases studied at early subgrade thawing. It can be seen that the calculated remaining rut life when spring thaw conditions prevailed was several times greater for dual tire loads for all cases of subgrade moduli included in the study.

EVALUATING THE BENEFITS OF APPLYING SPRING LOAD RESTRICTIONS

The results obtained from the analyses indicated that load restrictions up to 100 percent were required to maintain pavement performance during spring thawing at summer levels for the hypothetical pavement cross sections selected for the study. Current load restriction practices in the United States and Canada (*1*) indicate that agencies are currently imposing load restrictions that reduce allowable loads to 50 to 80 percent of the legal maximum loads. It is believed that the discrepancy in the allowable loads applied in practice and the allowable loads found for the hypothetical pavements is due to the fact that agencies do not intend to restrict pavements to the extent required to maintain summer performance levels. It is more likely that the objective in applying spring load restrictions is to reduce the need for major rehabilitation and/or to prolong serviceable life.

Based on these observations the calculated response from all of the analyses for fatigue and subgrade vertical strain was merged into two figures to evaluate the benefits of applying different levels of spring load restrictions for the hypothetical pavements. The remaining life for rutting was calculated for

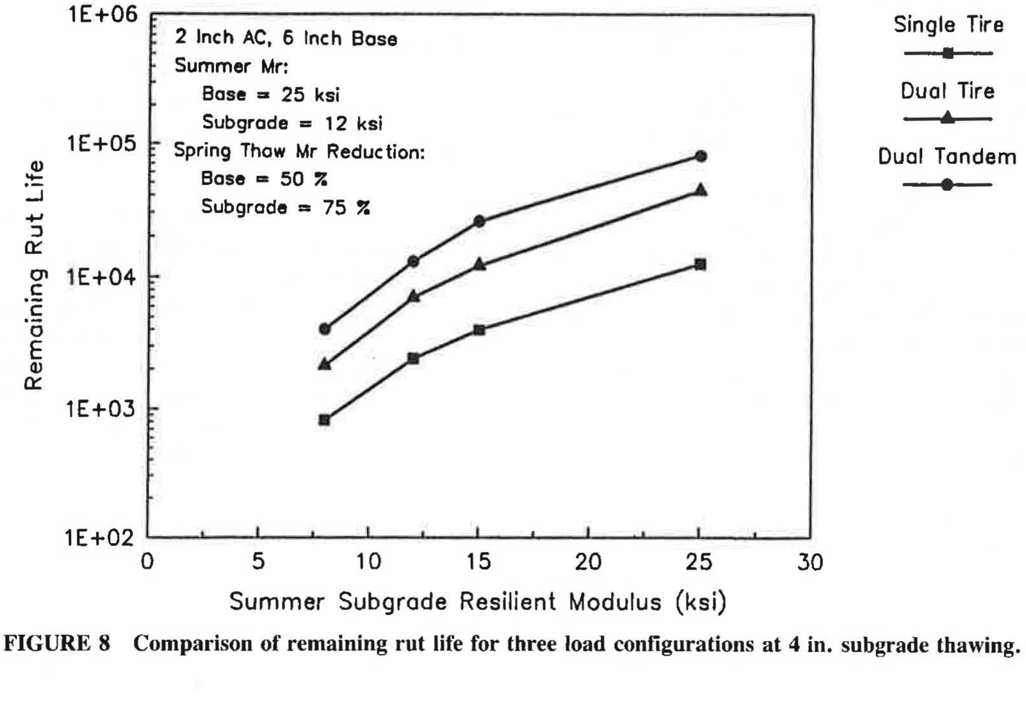

FIGURE 8 **Comparison of remaining rut life for three load configurations at 4 in. subgrade thawing.**

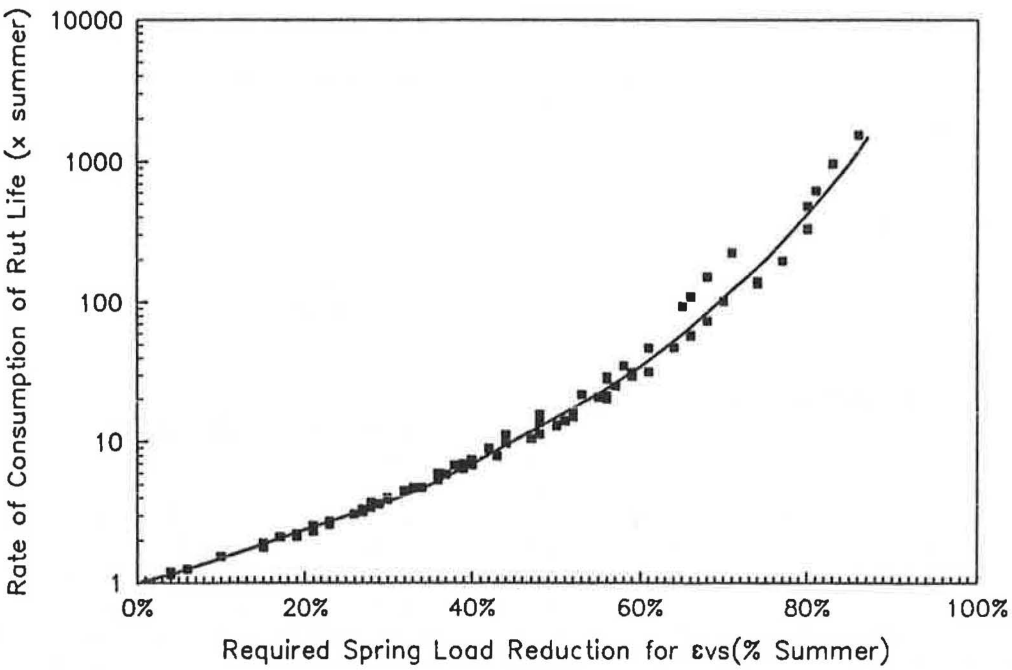

FIGURE 9 Rate of consumption of rutting life (relative to summer) versus required spring load reduction for subgrade vertical strain.

all pavement sections analyzed at 4 in. of subgrade thawing using the Shell equation (*11*). Figure 9 shows the rate of consumption of remaining rut life in spring compared with summer consumption as a function of the load reduction level required to maintain summer rutting levels. The benefits of applying some amount of load restrictions can be obtained from this figure for the pavements that require load restrictions based on subgrade vertical strains, which in this analysis was primarily the 4-in. AC pavements. For example, if an analysis of spring conditions suggested that the allowable spring load should be reduced to 40 percent of the legal maximum load to maintain summer conditions, the figure shows that the rut life consumption for this case with no load reduction would be about 7½ times as great as in summer. However, if a load restriction of 20 percent was applied, a load reduction of (40 − 20) or 20 percent would still be required. The rate of consumption of rut life for a required load reduction of 20 percent according to the figure is about 2½ times the summer consumption. Although this is clearly in excess of summer consumption, a considerable benefit has been realized by applying some level of spring load restriction.

Figure 10 presents the rate of consumption of remaining fatigue life as a function of load reduction for fatigue. This figure is used in the same way as the previous figure presented for rut life consumption; however, it should be used for pavements where asphalt tensile strain is the critical pavement response parameter during spring thawing, which typically was the case for the 2-in.-thick pavements analyzed.

CONCLUSIONS

The results obtained in this study suggest that single tire, single axle loads result in the greatest reduction in allowable spring loads compared with that in summer, as well as largest absolute values of strains and deflections. Therefore, the following conclusions are based on this load case. Further, it would appear to be reasonable to suggest that an agency might use this load case as a basis for formulating load restriction policies as most Class 8 heavy vehicles have steering axles that are configured with single tires.

The conclusions drawn from this study are the following:

1. Some thin pavements (2 in. AC) required load reductions at the time of base thaw to maintain the pavement at its summer response level.
2. All pavements that required some load reductions had reduced load-carrying capacity by the time of early subgrade thawing, and allowable loads were usually at their lowest levels at this time.
3. Four-inch pavements modeled typically experienced critical conditions as a result of maximum subgrade vertical strain during thawing.
4. Two-inch AC pavements resulted in load reductions at early subgrade thawing, usually because of asphalt tensile strain, but for many cases subgrade vertical strain was the critical parameter. At the end of thawing, however, asphalt tensile strain was the critical parameter for nearly all thin pavements analyzed.
5. A correlation was found between allowable loads for subgrade vertical strain and deflection for 4-in. AC pavements at the end of thawing.
6. In general it was found that deflections relative to summer were not a reliable indicator of the need for load restrictions during spring thawing. The results on the hypothetical pavements suggested that using summer deflection levels as a basis for when to apply load restrictions would generally be unconservative and would not result in the optimal use of spring load restrictions.
7. The most severe conditions with respect to fatigue and subgrade vertical strain occurred in the pavements analyzed during early thawing when deflections were less than summer levels.

Actual pavements will have their own unique material properties and relative changes in resilient response between sum-

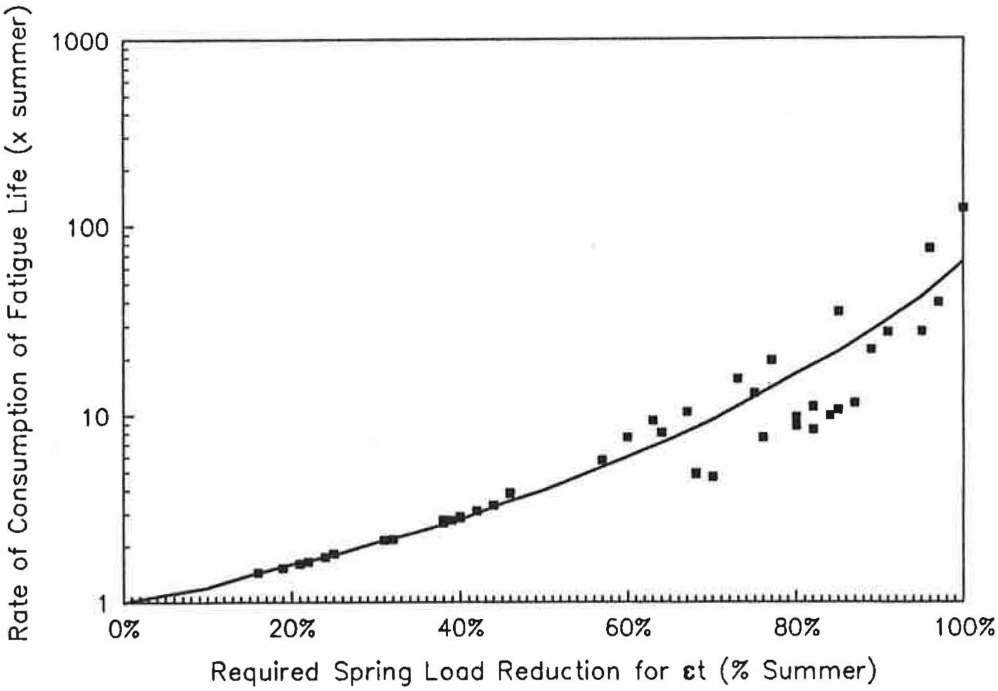

FIGURE 10 Rate of consumption of fatigue life (relative to summer) versus required spring load reduction for asphalt tensile strain.

mer and spring thawing. Further, the response of these pavements will vary from year to year because of variations in prevailing climatic conditions during the freezing and thawing period. The choices for layer thicknesses and resilient properties were intended to represent a broad range of resilient behavior that would be encountered in "real" pavements. If this has been accomplished, then the conclusions presented may be useful to individuals making decisions about the timing and magnitude of spring load restrictions. The assumptions made with respect to the change in resilient stiffness of materials from summer to spring conditions require further field testing and verification. This is clearly an area of further research.

In conclusion, it is important to recognize the need to rely on the judgment of experienced personnel in the decision-making process regarding the application of spring load restrictions. Site-specific topography, groundwater conditions, drainage, and annual variations in winter and spring climatic conditions result in considerable variation in the response of unbound materials underlying pavements. Observations by experienced individuals of the range of response of pavement sections that are particularly susceptible to damage during spring thawing should continue to be weighed heavily when making decisions regarding the application of spring load restrictions. It is intended that the research reported in this paper be used to enhance and not replace this experience.

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