Crack Propagation in Soil-Cement Bases Subjected to Repeated Wheel Loads

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Fatigue in the soil cement has been shown to be a controlling factor in the process of selecting thickness for pavements containing cement-stabilized layers. If the fatigue criteria obtained from laboratory tests do not include consideration of the number of repetitions associated with crack propagation, conservative pavement thicknesses might result. This paper shows how laboratory fatigue data on soil-cement specimens subjected to biaxial states of stress are used to estimate how many additional repetitions will produce crack propagation in the field. The test results are interpreted by using a fatigue model based on Griffith's failure criteria and a finite-element idealization of pavement systems containing a soil-cement layer. The analyses include the influences of (a) age, maximum stress level, and interface boundary condition between base and subgrade on the rate of crack propagation through a soil-cement base; (b) maximum stress level in the base on the number of repetitions needed to propagate the crack to the surface of the base; and (c) interface friction and the ability of the subgrade to accommodate tension stresses on fatigue fracture in the soil-cement base. The examples given show that permitting crack propagation to the surface rather than crack initiation will give considerably thinner design base courses.

In the thickness-selecting process for pavements containing cement-stabilized layers, fatigue cracking from repeated traffic loading has been considered by many (1, 2) as a major cause of damage. If laboratory fatigue criteria are used to select thickness, conservative pavement thicknesses might result; laboratory behavior may not necessarily reflect the number of repetitions required to propagate cracks once they have been initiated in a pavement structure (2).

Accordingly, it is the purpose of this paper to present the results of analyses to estimate the additional repetitions needed to produce crack propagation in the field. Laboratory fatigue data on soil-cement specimens subjected to biaxial states of stress were used. The test results are interpreted by means of a fatigue model based on Griffith's failure criterion (3) and a finite-element idealization of pavement systems containing a soil-cement layer. The Griffith theory (4) is used in this case to define a stress level (F) as a parameter proportional to the tensile stress at the tip of the most critically oriented flaw in the material. Mathematically,

$$F = (\sigma_1 - \sigma_3)^2/8(\sigma_1 + \sigma_3)T_i \quad (1)$$

for $\sigma_1 + 3\sigma_3 \geq 0$, or

$$F = -(\sigma_3/T_i) \quad (2)$$

for $\sigma_1 + 3\sigma_3 \leq 0$, where

- σ_1 = major principal stress,
- σ_3 = minor principal stress, and
- T_i = initial tensile strength of soil cement, the tensile strength before subjecting the material to repeated states of stress. (Compressive stresses are positive; tensile stresses are negative.)

The analyses include the influences of

1. Age, maximum stress level, and interface boundary condition between base and subgrade on the rate of crack propagation through a soil-cement base;
2. Maximum stress level in the soil-cement base on the additional number of repetitions to propagate the crack to the surface of the base, and
3. Interface friction and the ability of the subgrade to accommodate tensile stresses on fatigue fracture in the soil-cement base.

From these analyses, suggestions for permitting the use of laboratory fatigue tests in design are made.

METHOD OF ANALYSIS

The pavement is represented as a two-layer system as shown in Figure 1. The materials were assumed to be linearly elastic with bimodular properties; i.e., modulus in compression could be different from modulus in tension. The effect of interface friction on base cracking was simulated by introducing a thin layer of lubricant, which had large bulk and low shear moduli, between the base and the subgrade.

Criteria for cumulative damage and fatigue based on Griffith's theory (3, 5) were used to determine the decrease in tensile strength of the material when it was subjected to stresses of different magnitudes and to many repetitions. Fatigue failure would occur at a point in the base if the tensile strength were decreased from an initial value T_i to a value T such that

$$(\sigma_1 - \sigma_3)^2/8(\sigma_1 + \sigma_3) = T \quad (3)$$

for $\sigma_1 + 3\sigma_3 \geq 0$, or

$$\sigma_3 = -T \quad (4)$$

for $\sigma_1 + 3\sigma_3 \leq 0$, where σ_1 and σ_3 are the major and minor principal stresses, respectively.

Stresses were calculated in the soil-cement layer by using a finite-element procedure and assuming the applicability of a plane-strain condition. Bimodular material properties were included by using a successive approximation technique. The modulus in compression was used for all elements on the first iteration, but the modulus in tension was substituted for it in directions of principal tension on successive iterations. Three or four iterations were necessary to attain a reasonable degree of convergence. The influence of shrinkage cracks was included by considering the slab to have a finite length, L (2). A finite-element representation of the system is shown in Figure 2.

The procedure for determining crack propagation through the base followed this order:

1. The stress state in each element was calculated;

Figure 1. Representation of a pavement system.

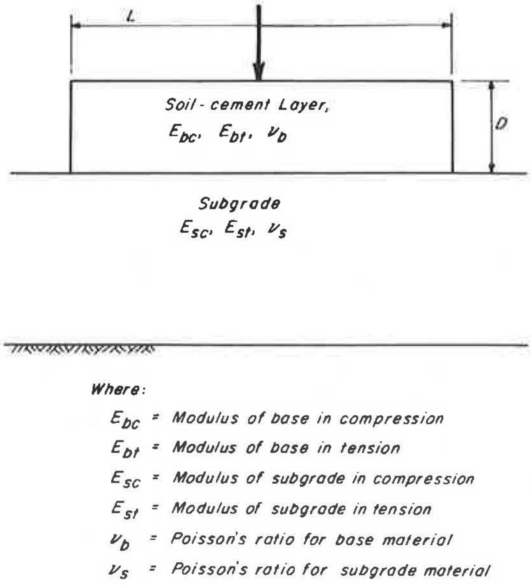


Figure 2. Finite-element representation.

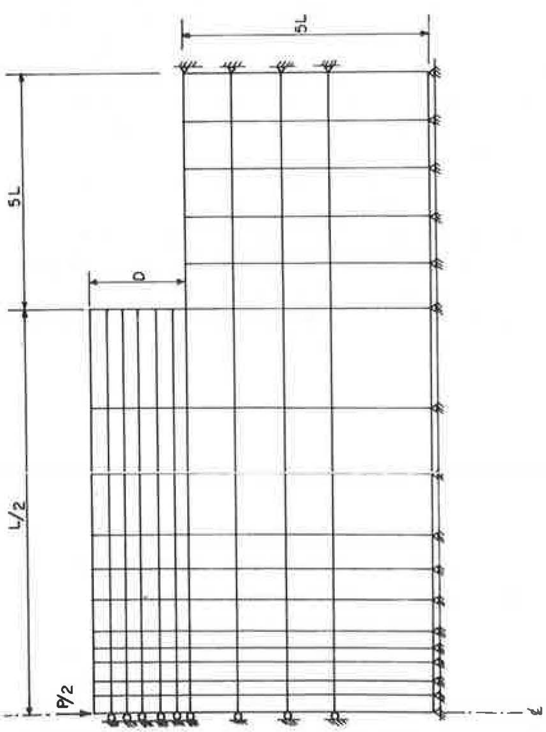


Table 1. Pavement systems analyzed.

Case No.	L/D	E_{bc}/E_{sc}	E_{bt}/E_{sc}	E_{st}/E_{sc}	ν_b	ν_s	Continuity Condition at Base-Subgrade Interface
1	10	100	100	1	0.15	0.48	Full
2	10	100	100	1	0.15	0.48	Frictionless
3	10	100	10	10^{-7}	0.15	0.48	Full
4	10	100	10	10^{-7}	0.15	0.48	Frictionless
5	10	100	10	1	0.15	0.48	Full

2. The number of repetitions required to crack the most critically stressed element was determined;
3. The fractured element was taken out of the system and a new stress field determined; and
4. The number of additional repetitions to crack a new, most critically stressed element was estimated.

This procedure was repeated until the crack propagated to the surface of the base.

For a given pavement system, the analyses provided an estimate of the number of repetitions required to initiate cracking at the bottom of the base, N_1, and the total number of repetitions required for the crack to propagate to the slab surface (including N_1), N_T, as a function of the stress level at the bottom of the base. Table 1 provides a summary of the systems analyzed.

RESULTS

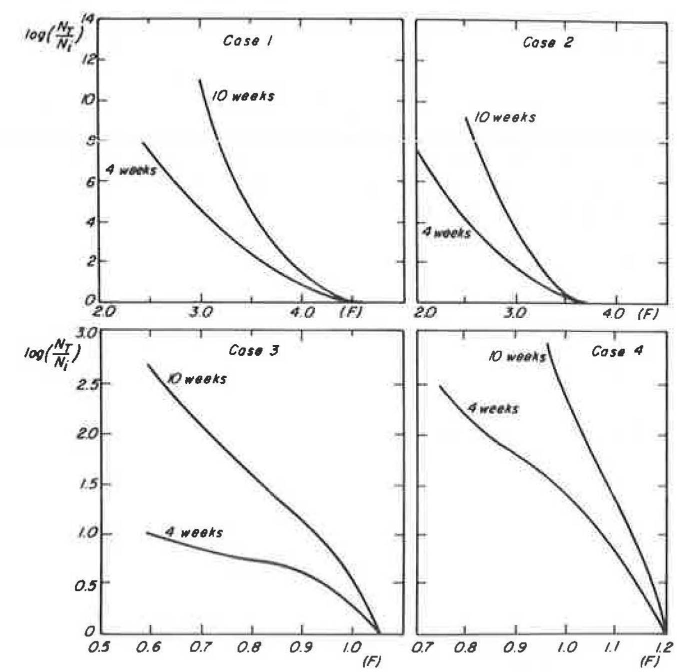
Rate of Crack Propagation

For a base of thickness D, the rate of base crack propagation from repeated loads is defined by $D/(N_T - N_1)$ and is a function of maximum applied stress level, material properties of base and subgrade, age of base, and interface conditions between base and subgrade. For a given maximum stress level and base thickness, the larger the value of log (N_T/N_1), the slower the rate of crack propagation.

Results of the analyses of cases 1-4 for the influence of age, stress level, and interface conditions are plotted in Figure 3, and the following conclusions on the rate of crack propagation are drawn.

1. It decreases as curing age increases (cases 1-4).

Figure 3. Rate of crack propagation as a function of maximum stress level.



N_T = Number of repetitions required to initiate and propagate crack from bottom to surface of base
N_i = Number of repetitions required to initiate cracking at bottom of base
F = Maximum stress level

2. It increases as the applied load magnitude increases (cases 1-4).

3. For a subgrade material with a tension modulus equal to its compression modulus and for a given stress level at the bottom of the slab, it increases as interface friction decreases (cases 1 and 2).

4. It decreases for a given stress level at the bottom of the slab as interface friction decreases (cases 3 and 4) if the subgrade material cannot take tension.

Initiation and Propagation of Cracks

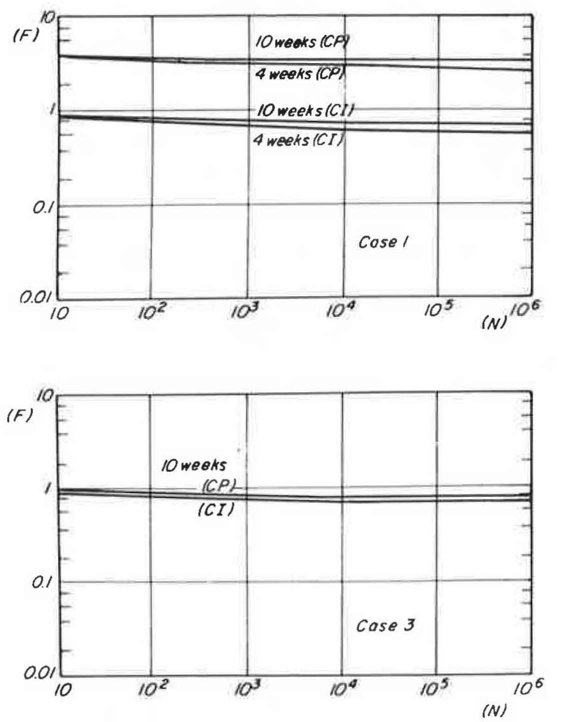
The influence of the stress level F on both N_I and N_T is shown in Figure 4. Results for the five cases and for two ages of the soil cement are summarized in Table 2. Analysis of this information leads to these conclusions: Conservative thicknesses of base slabs result if crack initiation is used as a criterion for design (Figure 4); the degree of conservatism will be greater if the base and subgrade have the same modulus in tension and in compression (Figure 4); and stresses larger than those associated with simple bending at the bottom of the slab are required for complete fracture under statically applied loads, because of the support provided by the subgrade (Table 2).

By comparing the results obtained for cases 3 and 5, the influence of the ability of the subgrade to withstand tensile stresses can be obtained. In addition, the influence of different soil-cement properties in tension and compression, as well as the influence of interface conditions (cases 3 and 4), can also be ascertained (cases 1 and 5). Results are shown in Figures 5 and 6.

In these studies we had to recognize the influence of different stresses resulting from the different conditions; for example, for the comparison shown in Figures 5 and 6, the magnitude of the applied load was expressed in terms of the stress level it produced when applied to case 1.

From the study of these figures, it can be concluded that, for a given load, fewer repetitions are needed to initiate and propagate cracking if the subgrade ability to carry tensile stresses decreases (Figures 5a and 6b) and to initiate and propagate cracking if the interface between base and subgrade is frictionless (Figures 5b and 6a). It is essential to use the correct modulus in tension and in compression for the subgrade and base materials. Higher values of stress level will be obtained for a given applied load if the moduli in tension of the base and subgrade are assumed to be equal to their moduli in compression (Figure 5a). This would require thicker base sections to resist a given number of repetitions of a specified load before crack initiation.

Figure 4. Influence of maximum stress level on initiation and propagation of cracks through the soil-cement base.

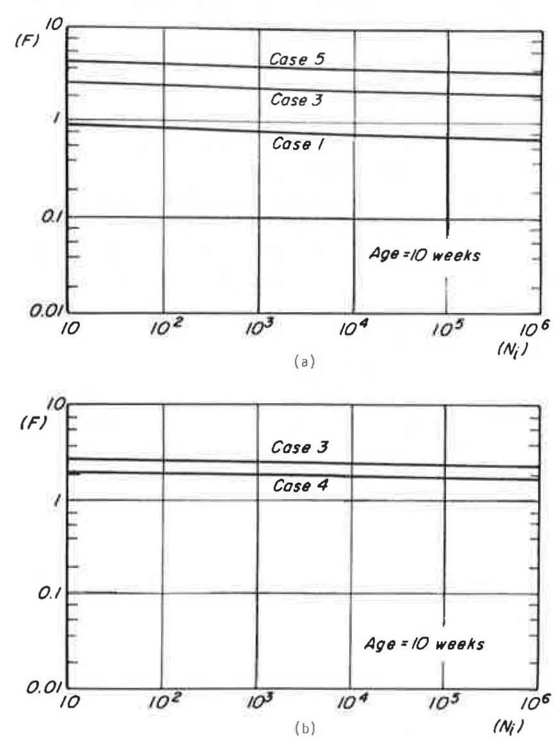


F = Maximum stress level
N = Number of repetions (N_i or N_T)
CI = Crack initiation
CP = Crack propagation

Table 2. Stress levels required to initiate cracking and to completely fracture the soil-cement base.

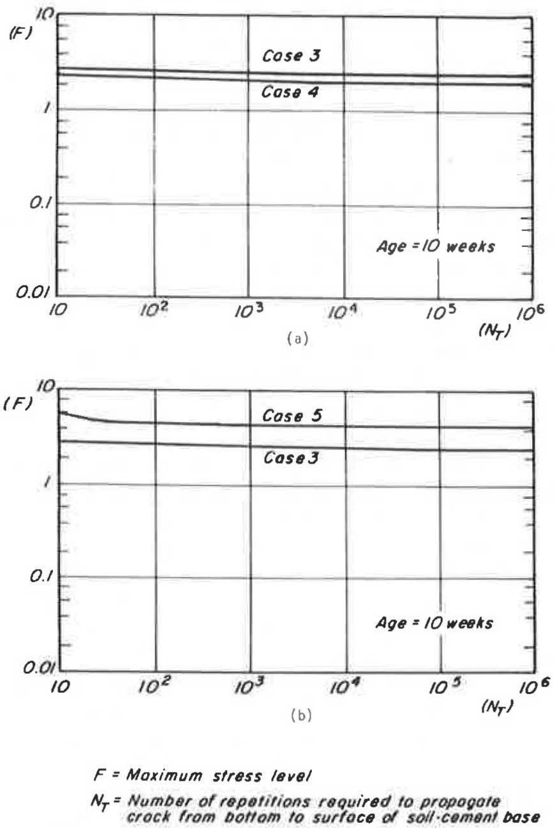
Case No.	Static Loading: Crack Initiation	Static Loading: Complete Fracture	At 10^6 Repetitions, Age, 4 Weeks: Crack Initiation	At 10^6 Repetitions, Age, 4 Weeks: Complete Fracture	At 10^6 Repetitions, Age, 10 Weeks: Crack Initiation	At 10^6 Repetitions, Age, 10 Weeks: Crack Propagation
1	1	4.60	0.58	2.70	0.73	3.35
2	1	3.73	0.58	2.17	0.73	2.75
3	1	1.06	0.58	0.62	0.73	0.78
4	1	1.20	0.58	0.69	0.73	0.87
5	1	1.09	0.58	0.64	0.73	0.81

Figure 5. Crack initiation under a given repeated load.



F = Maximum stress level
N_i = Number of repetitions required to initiate cracking at bottom of soil-cement base

Figure 6. Crack propagation under a given repeated load.



DESIGN CONSIDERATIONS

This study has demonstrated that the thicknesses selected by the procedure based on crack initiation in the soil-cement base are conservative and that consideration of crack propagation to the surface may provide more reasonable estimates. To do this, however, soil-cement properties, subgrade characteristics, and interface continuity must be correctly assessed.

Mitchell, Dzwilewski, and Monismith (2) used multilayer elastic theory to develop charts that would permit estimation of the tensile stresses in the interior and at the edges of a soil-cement base for a specific combination of wheel load, base, and subgrade properties. An example of these charts is shown in Figure 7.

Raad (3) suggested a simplified procedure to calculate the tensile stresses in the base that takes the base and subgrade properties and interface conditions between the base and subgrade into account. The tensile stresses (interior or edge) can be written as

$$\sigma = \sigma_M(\alpha_1 \cdot \alpha_2 \cdot \alpha_3) \quad (5)$$

where σ_M is the interior or edge stress value (2) and α_1, α_2, and α_3 are as summarized below.

Design Variables	α_1	α_2	α_3
E_{bc}/E_{bt}			
1	1.0	—	—
10	0.20	—	—
Interface			
Fully continuous	—	1.0	—
Frictionless	—	1.20	—
Subgrade			
Carries tension	—	—	1.0
Carries no tension	—	—	1.60

Figure 7. Relationship between tensile stress and base thickness for various aircraft loads.

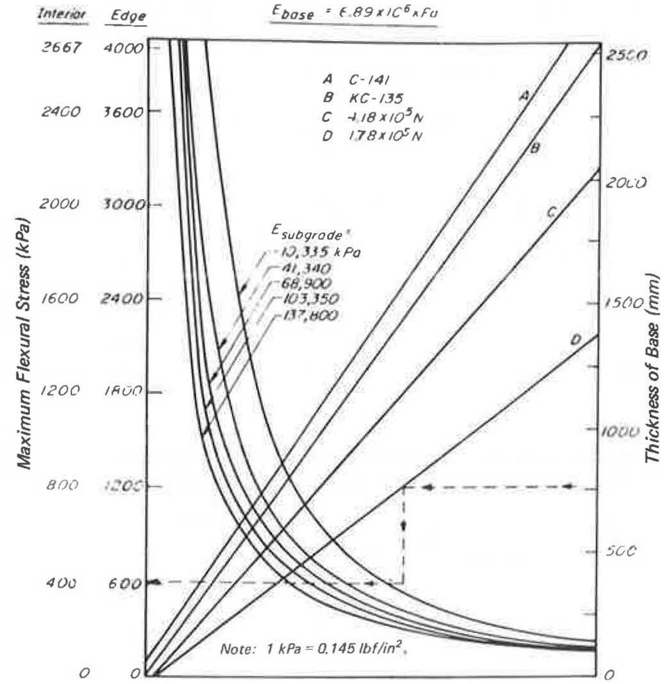


Table 3. k values for 10^6 repetitions and E_{bc}/E_{sc} = 100.

	Subgrade Carries Tension		Subgrade Carries No Tension	
E_{bc}/E_{bt}	Frictional Interface	Nonfrictional Interface	Frictional Interface	Nonfrictional Interface
1	3.35	2.75	3.20	3.55
10	0.81	0.78	0.78	0.87

Moreover, the value of σ should not exceed an allowable value kT, where T is tensile strength and k is the crack propagation factor (determined by finite-element analysis).

The allowable stress, kT, can then be selected so that cracking either will initiate on the underside of the base or will propagate to the surface of the base at the desired number of stress applications (design life).

Values for k associated with crack propagation to the surface of the base are shown in Table 3. These values apply to a cement-stabilized material 10 weeks old (curing age) or older. If crack initiation is used as the design criterion, a value of k equal to 0.73 is appropriate for materials of this age.

To illustrate the procedure a design example will be presented for a pavement to carry 10^6 repetitions of a KC-135 aircraft. The table below (1 kPa = 0.145 lbf/in²) contains a summary of the requisite soil-cement and subgrade characteristics, where the flexural strength of soil cement is 1780 kPa (258 lbf/in²) and tensile strength is 990 kPa (144 lbf/in²).

Material State	Elastic Properties (kPa)
Base	
In compression, E_{bc}	6.89×10^6
In tension, E_{bt}	1.38×10^6
Subgrade	
In compression, E_{sc}	6.89×10^4

Calculation of α is done with

$$\alpha_1 = 0.64,$$
$$\alpha_2 = 1.20 \text{ (frictionless interface)},$$
$$\alpha_3 = 1.60 \text{ (subgrade carries no tension)}, \text{ and}$$
$$\alpha_1 \cdot \alpha_2 \cdot \alpha_3 = 0.24 \times 1.20 \times 1.60 = 1.23.$$

Calculation of k is done, using a crack propagation criterion, with

$$k = 2.36 \text{ (interpolation from Table 3)},$$
$$\sigma_M(\alpha_1\alpha_2\alpha_3) = kT,$$
$$\sigma_M = kT/\alpha_1\alpha_2\alpha_3 = \text{allowable edge or interior tensile stress to be used in the chart shown in Figure 7, and}$$
$$\sigma_M = [2.36(0.5 \times 1980)]/1.23 = 1900 \text{ kPa } (276 \text{ lbf/in}^2)$$

and, using a crack initiation criterion, with

$$k = 0.73, \text{ and}$$
$$\sigma_M = [0.73(0.5 \times 1980)]/1.23 = 593 \text{ kPa } (86 \text{ lbf/in}^2).$$

Resulting thicknesses are summarized below (1 mm = 0.039 in):

Thickness	Stress Used for Design: Edge Stress (mm)	Stress Used for Design: Interior Stress (mm)
Suggested method (crack propagation)	457	380
Suggested method (crack initiation)	1140	812
50 percent flexural strength criterion	710	558

In this table thicknesses obtained by using the procedure suggested by Mitchell, Dzwilewski, and Monismith (2) are also shown. Note that these values lie between those obtained by using the procedure reported here.

SUMMARY

In this paper a design procedure permitting incorporation of crack propagation in the thickness-selecting process for cement-stabilized bases has been briefly outlined. This procedure makes use of a fatigue criterion that is based on a theory of fracture originally proposed by Griffith (4).

The data presented indicate that crack initiation and propagation rate are determined by base and subgrade properties, interface friction, and load magnitude. The simplified design procedure presented here incorporates these variables.

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Abridgment

Clay Mineral Weathering Controls on Lime and Cement Stabilization of Southwestern Ontario Clay Borrow

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This paper describes the significant role of clay mineral weathering in the upper 3 m of a clay crust in the compaction and stabilization characteristics of borrow materials extracted from different levels of the crust. The main mineralogical control is an increase in smectite (swelling clay) content toward the surface that is caused by oxidation weathering of unstable chlorites in the original soil.

MATERIALS AND METHODS

The soil samples were taken from a 2.5-m trench dug