

Behavior of Stabilized Layers Under Repeated Loads

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ABSTRACT

An improved method of analysis for pavements with stabilized layers has been proposed. The method incorporates the bimodular properties (i.e., tensile modulus different than compressive modulus) of the stabilized layers and the stress-dependent behavior of granular and subgrade soils. The proposed method could be used to predict stresses, resilient strains, and deformations using a finite element representation of pavement structures. The proposed method is used to study the behavior of stabilized layers under repeated loads. Results of a limited number of split tension and flexure tests conducted on a cement-treated silty clay are presented to illustrate the bimodular behavior of the material and the influence of testing procedure and computation method on modulus values. On the basis of laboratory results it is proposed to characterize the stabilized layer in terms of its split tensile modulus, bimodular ratio, and split tensile strength. This method of characterization is incorporated in the analysis of the behavior of stabilized layers in pavements. Specifically, the influence of material characteristics on response prediction, and on fracture of stabilized layers under repeated loads, has been investigated.

Cement- and lime-stabilized layers are used in pavement structures to enhance their load-carrying capacity and improve their performance. Although shrinkage and fatigue are two common types of failure of stabilized layers, pumping and loss of foundation support are other modes of failure that could result in excessive stresses and deflections in the stabilized layer and thereby increase its rate of deterioration. Performance prediction of stabilized layers under repeated traffic loads is a soil-structure interaction problem in which the interaction between traffic loads, stabilized layer, and other soil layers in the pavement structure should be considered.

An improved method of analysis for determining the response of pavements with stabilized layers under repeated loads is presented. The proposed method uses the finite element technique to predict the stresses, strains, and deflections in the pavement section. The method incorporates the load-deformation characteristics of stabilized soils in tension and compression, the nonlinear stress-deformation behavior of granular and subgrade soils, and a failure criterion for these soils based on the Mohr-Coulomb theory. The proposed method is used to study the behavior of pavements with stabilized layers under repeated loads. Specifically, the analyses include the following:

1. The significance of materials characterization in the response of stabilized layers and
2. The fracture of stabilized layers overlying soft and stiff subgrades.

PROPOSED METHOD

The finite element method is used to determine the stresses and resilient deformations in a given pavement structure assuming axisymmetric, plane strain, or plane stress conditions. Stabilized materials in the pavement section are assumed to have bimodular properties (i.e., modulus in tension different than modulus in compression). Granular and subgrade soils

are assumed to have stress-dependent moduli. For granular soils (1), the resilient modulus (M_R) is expressed as

$$M_R = K\theta^n \quad (1)$$

where

$$\begin{aligned} \theta &= \sigma_1 + \sigma_2 + \sigma_3, \\ \sigma_1, \sigma_2, \text{ and } \sigma_3 &= \text{principal stresses, and} \\ K \text{ and } n &= \text{material constants.} \end{aligned}$$

For fine-grained soils, a typical representation of resilient modulus (M_R) as a function of repeated deviator stresses ($\sigma_1 - \sigma_3$) has been proposed by Figueroa (2) and is shown in Figure 1. Similar functions proposed by others (3,4) could be incorporated in the proposed method.

The nonlinear properties of the granular and subgrade layers and the bimodular properties of the stabilized layers are included by means of a successive iteration technique. On the first iteration the modulus in tension (E_t) of the stabilized layer is set equal to the modulus in compression (E_c), whereas the moduli of the subgrade and granular layers are set equal to an assumed initial value. On successive iterations the modulus in tension is substituted in directions of principal tension for elements in the stabilized layer. Elements in the subgrade and granular layers are assigned values depending on the stress state at the end of the previous iterative step. The principal stresses in the granular and subgrade layers are modified at the end of each iteration so that they do not exceed the strength of the material as defined by the Mohr-Coulomb envelope. The procedure for stress modification has been developed by Raad and Figueroa and is presented elsewhere (5). A reasonable degree of convergence is attained in three or four iterations; and constitutive relations, equilibrium equations, and kinematic and boundary conditions are essentially satisfied.

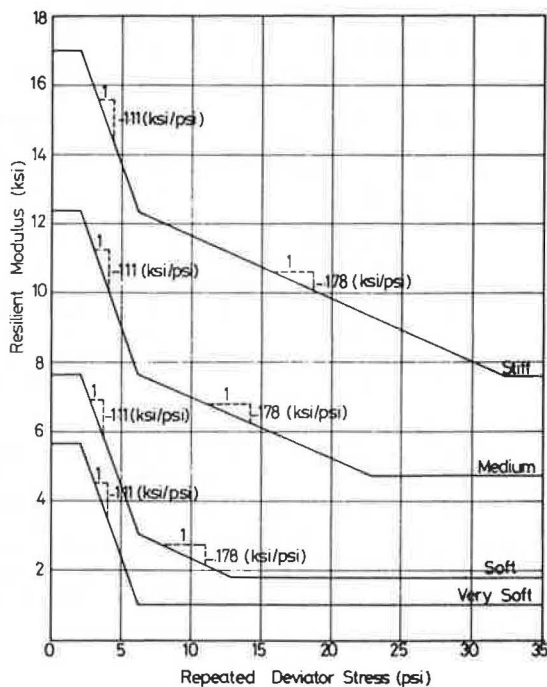


FIGURE 1 Resilient modulus of subgrade soils.

CHARACTERIZATION OF STABILIZED LAYERS

The use of advanced analytical techniques to predict the response of stabilized layers requires proper material characterization in order to obtain meaningful results. Stabilized layers are generally characterized using the flexure and split tension tests for the determination of elastic moduli and tensile strength. Analyses (6,7) indicate that elastic moduli and strength values could be different for the same material as a result of the bimodal behavior of stabilized soil as shown in Table 1. The

TABLE 1 Correlation Between E_s/E_t and T_f/T_s as a Function of the Bimodal Ratio E_c/E_t

E_c/E_t	E_s/E_t	T_f/T_s
1.0	0.90	1.56
2.0	1.35	1.67
5.0	2.06	1.71
10.0	2.38	1.78

Note: E_s = split tensile modulus, T_s = split tensile strength, T_f = flexural strength, E_c = compressive modulus, and E_t = tensile modulus.

same method of analysis would therefore yield different results depending on the input properties used for the stabilized layers. Moreover, the determination of the thickness of a stabilized layer required to carry a given traffic depends on the tensile strength used for the material if a stress criterion is chosen for design. In this case the tensile stress on the underside of the stabilized layer should be compared with the actual tensile strength of the material, which could be reasonably estimated from the split tension test according to Raad et al. (6).

A limited number of flexure and split tension tests were conducted on a cement-treated silty clay (CL, PI = 12, LL = 29) to study the difference be-

tween flexural and split tensile moduli and to investigate the bimodal behavior of the material. The cement content used was 11 percent. Cylindrical specimens 4 in. in diameter and 3 in. high and beam specimens 21 in. x 6 in. x 6 in. were prepared using a drop hammer compactor and modified AASHTO compaction energy. The specimens were wrapped in polyethylene sheets and cured in a humid room for 42 days at 73° F. The compaction characteristics of the material are shown in Figure 2. At the end of the curing period, 1-in.-long SR-4 strain gauges were glued to the top and bottom of the beam specimens in the middle one-third portion. Similar strain gauges were glued on both sides of the cylindrical specimens at the center to measure lateral tensile strains (Figure 3). In both the flexure and split tension tests the load was applied through a loading head at constant rate of displacement equal to 0.0120 in. per minute. The strain gauges were monitored continuously during loading. Vertical deflections at the center of beam specimens were also monitored using a 0.0001-in. dial gauge.

Flexural modulus values E_f and E_s based, respectively, on moment-curvature relations and deflection

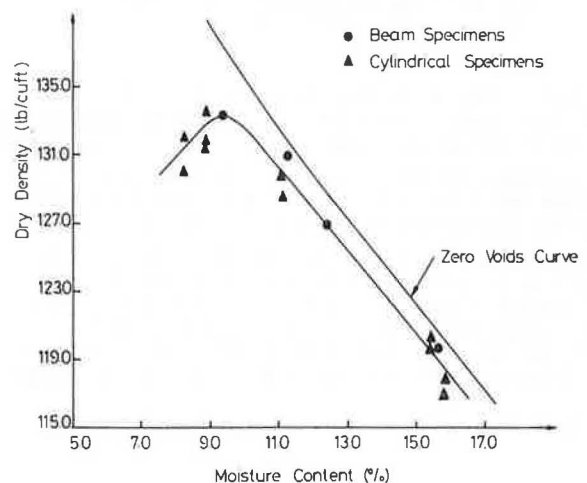


FIGURE 2 Compaction characteristics of cement-treated silty clay.

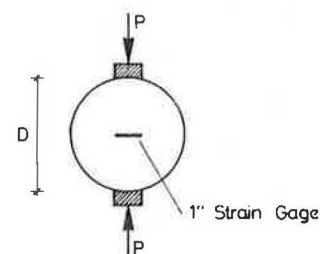
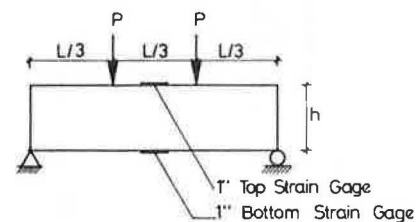


FIGURE 3 Representation of flexure and split tension tests.

at the center of the beam, were determined and compared with split tensile modulus (E_s). A summary of expressions for modulus values in the flexure and split tension tests is given in Table 2. The relationship for the split tensile modulus in terms of tensile strain (ϵ_t) at the center of the specimen has been derived using the finite element method of analysis, a Poisson's ratio equal to 0.20, and a bimodular representation of the stabilized material. The average error in this case does not exceed ± 9.0 percent for a bimodular ratio variation between 1 and 10.

TABLE 2 Expressions for Modulus Values Determined in the Flexure Test and Split Tension Test

Flexure Test	Split Tension Test
$E_f = (23/648)(PL^3/dl)$	$E_s = (P/t\Delta)(\nu + 0.2732)$
$E_f = (PL/3I)[h/(\epsilon_c + \epsilon_t)]$	$E_s = (1.65)(P/\pi R t \epsilon_t)$

Note: P = applied load; L = length of beam specimen; d = deflection at center of beam specimen; I = moment of inertia of beam cross section; ϵ_c = compressive strain at top of beam specimen; ϵ_t = tensile strain at bottom of beam specimen or at center of cylindrical specimen; Δ = lateral deformation across diameter of cylindrical specimen; ν = Poisson's ratio; R, t = radius and thickness, respectively, of cylindrical specimens; and h = depth of beam specimen.

The variation of E_f , \bar{E}_f , and E_s with compaction moisture content is shown in Figure 4. Although the trend of variation with compaction moisture content is similar, values of E_f , \bar{E}_f , and E_s for specimens having the same dry density and compaction moisture content are different (Figure 5). Values of E_s are on the average 1.25 times greater than those of \bar{E}_f but could be as much as 6 times greater than E_f .

Bimodular behavior was investigated by comparing the compressive strain (ϵ_c) and tensile strain (ϵ_t) at the top and bottom of beam specimens in the flexure test. The bimodular ratio is expressed as

$$E_c/E_t = (\epsilon_t/\epsilon_c)^2 \quad (2)$$

The bimodular ratio appears to reach a maximum value at optimum compaction moisture content (Figure 4d). Moreover, the bimodular ratio is stress dependent as shown in Figure 6. It attained values between 0.80 and 6.0. Similar observations concerning bimodular behavior of stabilized soils using flexure, direct tension, and direct compression tests show that stabilized soils exhibit bimodular ratios in the range of 1 to 10 (8,9).

Bimodular behavior could be incorporated in the analysis of pavements by using compressive and tensile moduli that correspond to the level of tensile and compressive stresses or strains in the stabilized layer. Modulus values corresponding to a stress level equal to 50 percent of the modulus of rupture in the flexure test could be used in this case.

Although the compressive modulus (E_c) and the tensile modulus (E_t) could be used to characterize a stabilized layer, an alternative approach would be to use the split tensile modulus (E_s) and the bimodular ratio E_c/E_t . If the values of E_s and E_c/E_t are known, the values of E_c and E_t are estimated from the relationship between E_c/E_t and E_s/E_t , shown in Table 1, and are then used in the analysis of the stabilized layer.

BEHAVIOR UNDER REPEATED LOADS

The behavior of pavements with stabilized layers under repeated loads has been investigated using the proposed method. Specifically, the influence of load-deformation characteristics on response and the fracture of stabilized layers under repeated loads have been studied. In all these cases the material properties used to characterize the stabilized layer include the elastic modulus (E_b), the bimodular ratio (E_c/E_t), and Poisson's ratio. E_b corresponds either to the split tensile modulus or to the flexural modulus derived from moment-curvature relations in the flexure beam test. An axisymmetric loading condition is assumed in the analyses.

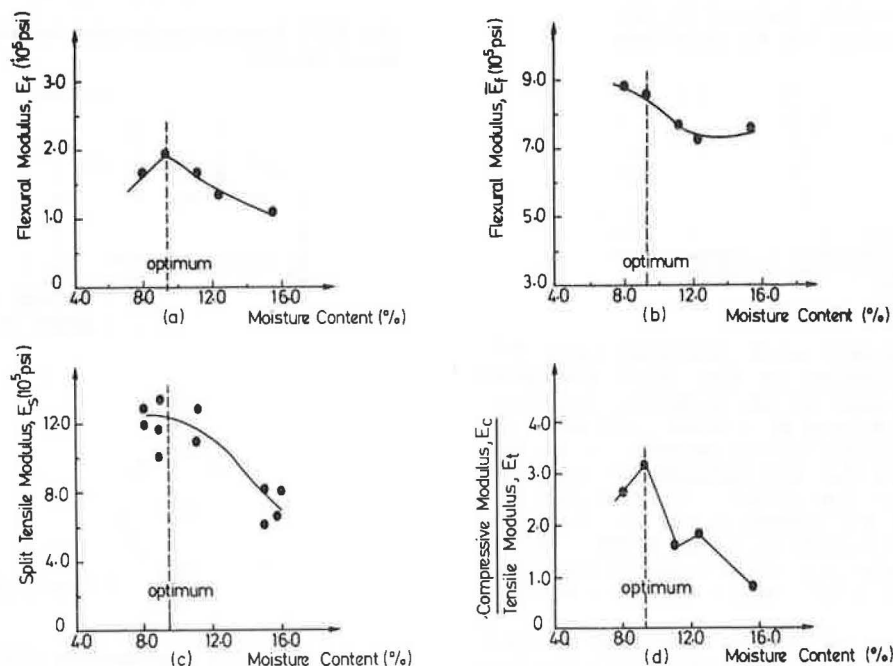


FIGURE 4 Variation of E_f , \bar{E}_f , E_s , and E_c/E_t at 50 percent stress level with compaction moisture content.

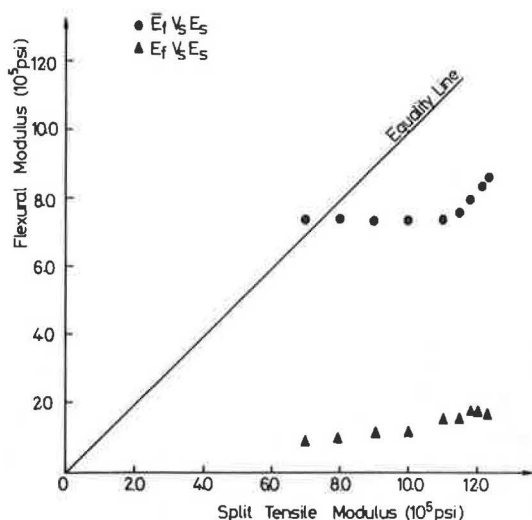


FIGURE 5 Comparison of E_f , \bar{E}_f , and E_s for cement-treated silty clay.

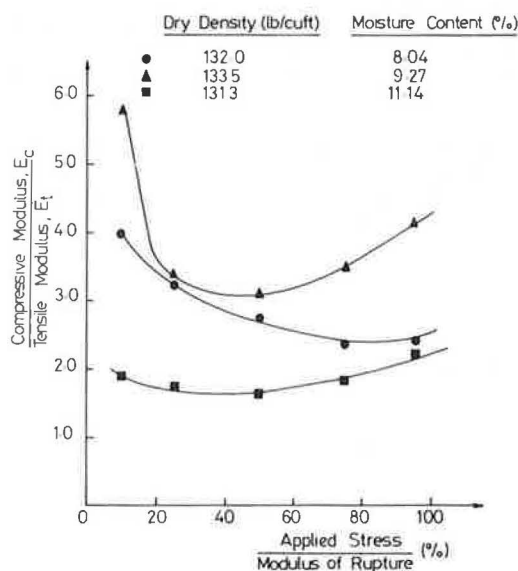


FIGURE 6 Variation of bimodular ratio with applied stress level.

Influence of Material Characteristics

The pavement section analyzed is shown in Figure 7. Two cases are considered (Table 3). In the first case the stabilized layer is assumed to be linearly elastic with a bimodular ratio equal to 1. No failure criterion is used for granular and subgrade soils. In the second case the stabilized layer is assumed to have the same elastic modulus as in Case 1, but a bimodular ratio equal to 10 and a Mohr-Coulomb failure criterion are used for the granular and subgrade layers.

Results of analysis indicate that an increase of bimodular ratio of from 1 to 10 would increase the tensile strains on the underside of the stabilized layer by 38 percent but would decrease the tensile stresses by 45 percent as shown in Figure 8. Moreover, the use of the Mohr-Coulomb failure model in the proposed approach would result in a "no tension" zone in the granular subbase. The lateral stresses predicted using the higher bimodular ratio and fail-

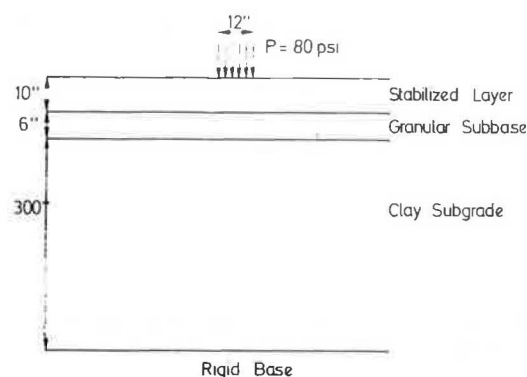


FIGURE 7 Pavement section analyzed for response prediction.

TABLE 3 Material Properties Used in Response Prediction Under Applied Load

Case	Stabilized Layer	Granular Subbase	Subgrade
1	$E_b = 1.0 \times 10^6$ psi $E_c/E_t = 1$ $\nu = 0.20$	$K = 7000$ $n = 0.35$ $\nu = 0.35$	Soft (Figure 1) $\nu = 0.47$
2	$E_b = 1.0 \times 10^6$ psi $E_c/E_t = 10$ $\nu = 0.20$	$K = 7000$ $n = 0.35$ $\phi = 32$ degrees, $C = 0.0$ $\nu = 0.35$	Soft (Figure 1) $\phi = 0.0$ degree $C = 7.0$ psi $\nu = 0.47$

Note: E_b = modulus of stabilized layer, E_c/E_t = bimodular ratio, ν = Poisson's ratio, C and ϕ are cohesion and angle of friction determined from Mohr-Coulomb envelope, K and n are defined in Equation 1.

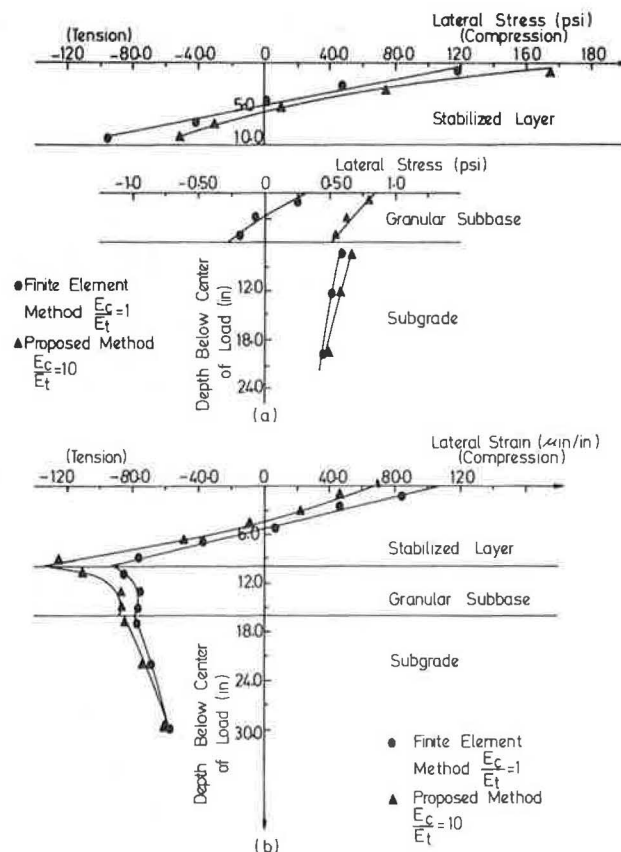


FIGURE 8 Influence of material characterization on response.

TABLE 4 Cases Studied in Fracture Analysis of Stabilized Layers

Case	Modulus of Stabilized Layer (E_b) in psi	Subgrade Stiffness	Bimodular Ratio (E_c/E_t)	Split Tensile Strength (T_s) in psi	Thickness of Stabilized Layer (h) in in.
1	3.0×10^6	Soft (Figure 1)	1 5 10	150 300	4 6 8 12 16
2	3.0×10^6	Stiff (Figure 1)	1 5 10	150 300	4 6 8 12 16
3	3.0×10^5	Soft (Figure 1)	1 5 10	50 100	4 6 8 12 16
4	3.0×10^5	Stiff (Figure 1)	1 5 10	50 100	4 6 8 12 16

ure criterion are higher but decrease with depth of the granular subbase, as shown in Figure 8.

Fracture Behavior of Stabilized Layers

The fracture behavior of two-layer systems consisting of a stabilized layer overlying a clay subgrade has been analyzed under an applied circular load that has a 12-in. diameter and a uniform surface pressure. Fracture behavior under long-term loading (i.e., 10^6 repetitions) and short-term loading (i.e., 1 repetition) has been considered. A mechanistic model for strength and fatigue based on the Griffith failure theory (10) has been used in the analysis.

For fracture behavior under long-term loading, the stress state in each element of the stabilized layer was determined and the number of repetitions required to crack the most critically stressed element was estimated. The fractured element was taken out of the system and a new stress field was determined. The number of additional repetitions required to crack a new most critically stressed element was

estimated. This process was continued until the crack had propagated to the surface of the layer.

For fracture behavior under short-term loading, the load needed to crack the most critically stressed element was calculated. The fractured element was taken out and a new stress field was found. The additional load increment required to crack the next most critically stressed element was calculated. This was repeated until complete fracture of the stabilized layer had occurred.

For a given pavement system, the analysis provided a relationship between the thickness of the stabilized layer and the magnitude of load required to induce fracture. Table 4 gives a summary of the cases analyzed. In all these cases the subgrade was considered to be a layer 300 in. thick resting on a rigid base. The analyses performed lead to the following conclusions:

1. The load required to fracture the stabilized layer (i.e., ultimate load capacity) under long-term loading (10^6 repetitions) and short-term loading (1 repetition) increases with increase in layer stiffness, layer thickness, and subgrade stiffness

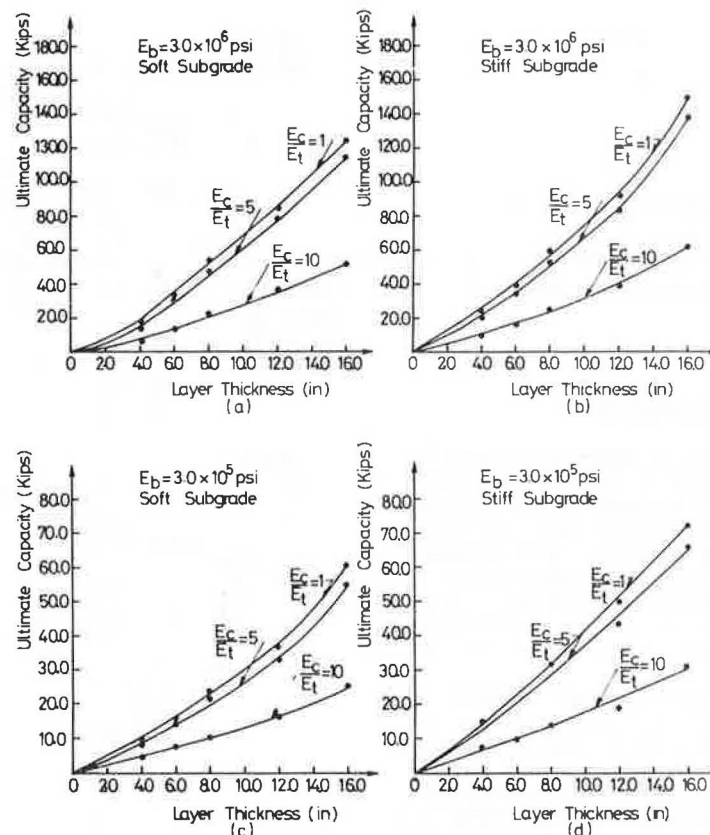


FIGURE 9 Repeated load required to fracture stabilized layer after 10^6 repetitions.

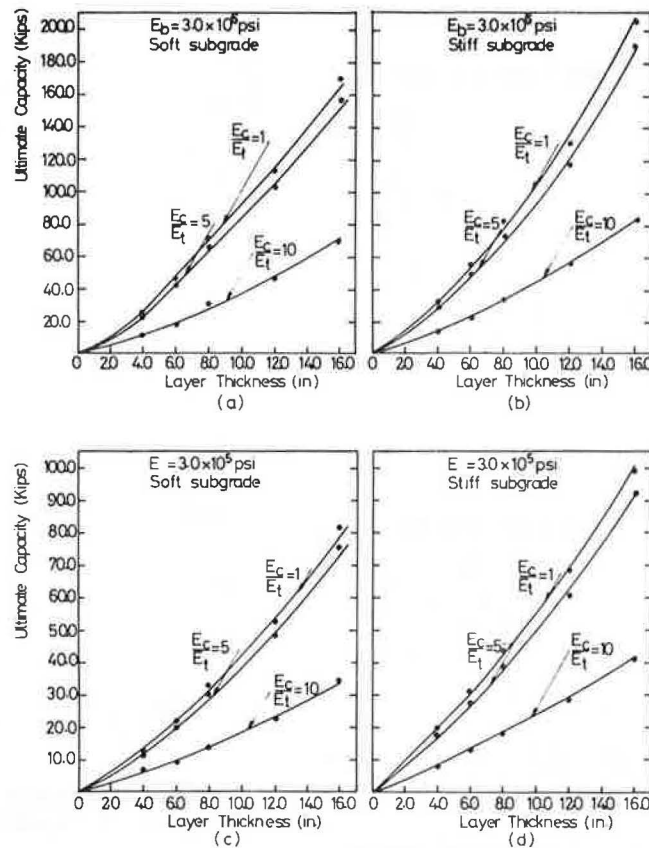


FIGURE 10 Ultimate load required to fracture stabilized layer after 1 repetition.

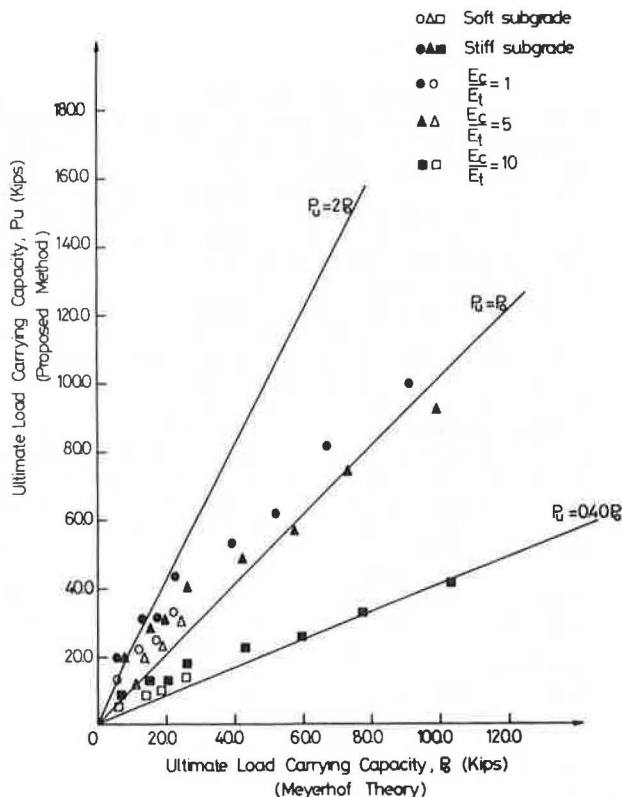


FIGURE 11 Comparison of load capacity predicted by proposed method and by Meyerhof theory.

but decreases with increase in bimodular ratio (Figures 9 and 10). The decrease is more pronounced for bimodular ratios greater than 5. Reducing the tensile strength of the stabilized layer by 50 percent leads in general to a reduction of layer capacity in the range of from 45 to 50 percent. Results shown in Figures 9 and 10 correspond to tensile strength of 300 psi ($E_b = 3.0 \times 10^6$ psi) and 100 psi ($E_b = 3.0 \times 10^5$ psi).

2. The load-carrying capacity under short-term loading (i.e., 1 repetition) (P_u) predicted using the proposed method could be greater or smaller than the ultimate capacity (P_o) predicted using Meyerhof theory (11) depending essentially on the bimodular ratio of the stabilized layer. For $E_c/E_t = 1$, P_u could approach $2 P_o$, whereas for $E_c/E_t = 10$, P_u could be as low as $0.40 P_o$ as shown in Figure 11. Meyerhof theory tends to overestimate the ultimate capacity (P_u) for bimodular ratios greater than 5 and underestimates P_u for bimodular ratios smaller than 5. The modulus of subgrade reaction (k_s) assumed in the Meyerhof analysis was 50 psi per inch for the soft subgrade and 450 psi per inch for the stiff subgrade.

3. Experimental data presented by Suddath and Thompson (12) for ultimate capacity of lime-stabilized layers fall in the range of predicted values using the proposed method (Figure 12).

4. Comparison between load capacity under short-term and long-term loading associated with crack initiation on the underside of the stabilized layer and crack propagation to its surface is shown in Figures 13 and 14.

Results demonstrate that contrary to some current practice, which assumes that cracking of the base

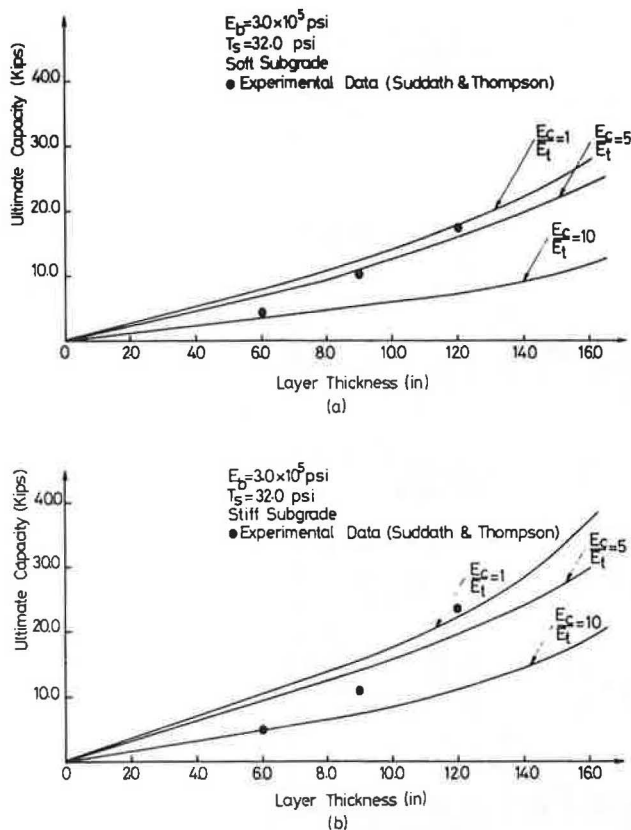


FIGURE 12 Comparison of predicted and measured ultimate capacity.

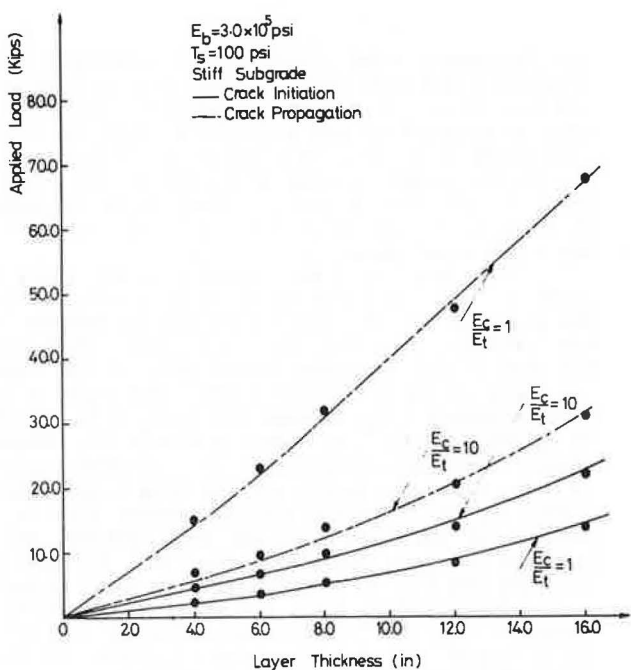


FIGURE 13 Load capacity in terms of crack initiation and propagation after 10^6 repetitions.

propagates quickly to the surface of the stabilized layer (13), the load required for crack propagation could be substantially greater than that needed for crack initiation, especially for layers with low bimodular ratios. A similar conclusion can be reached by comparing the load required to fracture

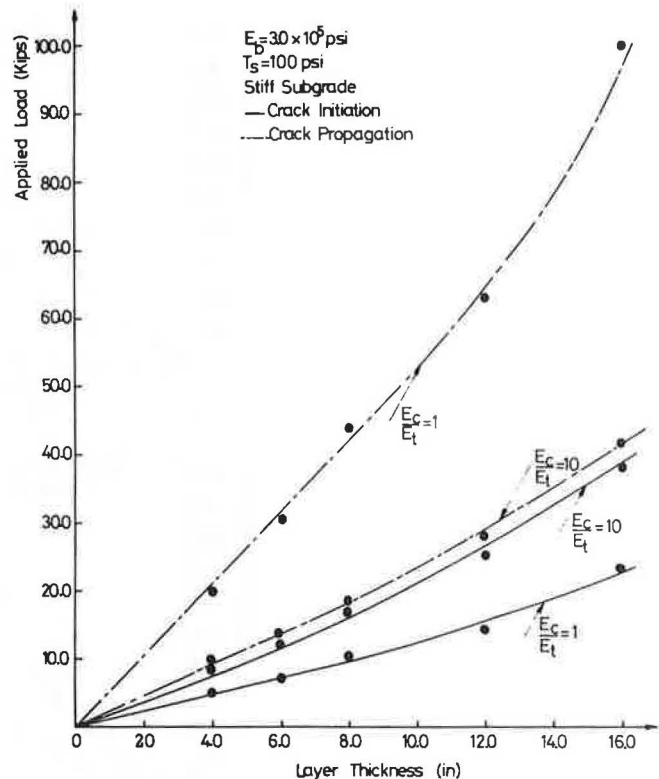


FIGURE 14 Load capacity in terms of crack initiation and propagation after 1 repetition.

the stabilized layer using Meyerhof theory with that required to induce a tensile stress at its interior (14) equal to the tensile strength, as shown in Figure 15.

SUMMARY AND CONCLUSIONS

An improved method of analysis for pavements with stabilized layers has been proposed. The method incorporates the bimodular properties (i.e., tensile modulus different than compressive modulus) of the stabilized layer and the stress-dependent behavior of granular and subgrade soils. The proposed method could be used to predict stresses, resilient strains, and deformations using a finite element representation of the pavement structure.

The proposed method has been used to study the behavior of stabilized layers under repeated loads. A limited number of split tension and flexure tests conducted on a cement-treated silty clay show that the material exhibits bimodular behavior and that modulus values computed for similar specimens are generally different and depend on testing procedure and method of computation. On the basis of laboratory results, it has been proposed to characterize the stabilized layer in terms of its split tensile modulus, bimodular ratio, and split tensile strength. This method of characterization was incorporated in the analysis to study the behavior of stabilized layers in pavements. Specifically, the influence of material characteristics on response prediction and the fracture of stabilized layers under repeated loads have been investigated.

Results of the analyses show that an increase in bimodular ratio tends to increase the tensile strains and decrease the tensile stresses on the underside of the stabilized layer. Fracture of stabilized layers, on the other hand, depends on stiffness, strength, and bimodular properties of stabilized material and on stiffness of underlying

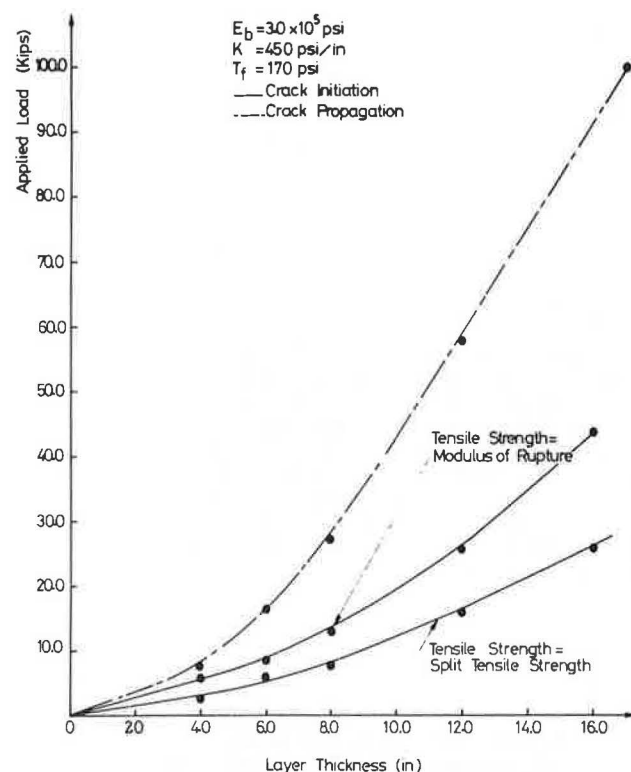


FIGURE 15 Load capacity in terms of crack initiation and propagation using Westergaard approach and Meyerhof theory.

subgrade. Agreement between predicted ultimate capacity using the proposed method and Meyerhof theory depends essentially on the bimodular ratio of the stabilized layer. Reasonable agreement between predicted capacity and experimental data has been attained within the common range of bimodular ratios of stabilized soils (i.e., E_c/E_t between 1 and 10). Results also indicate that loads associated with fracture of the stabilized layer could be substantially greater than those required for crack initiation on its underside.

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