# STRUCTURAL DESIGN OF COMPOSITE CONCRETE PAVEMENTS

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A rational design procedure was developed for composite concrete pavements based on fatigue damage considerations. The structural analysis of the composite system was perfomed using a finite element computer model developed at the University of Illinois. A curve was also developed using field data and a fatigue damage program to relate pavement cracking index to the fatigue damage value. This curve was developed to calibrate the procedure to actual field cracking conditions. It is an aid to the designer in selecting a fatigue damage value to use in the design of the pavement section for any allowable level of cracking. The example designs indicate that the composite pavement can be constructed at reasonable thicknesses with a potential reduction in total cement content.

A composite concrete pavement is a monolithically cast two layer portland cement concrete pavement. The lower layer is a low strength concrete that is capped with a high strength wearing surface. The two layers cast monolithically provides a full bond between the layers allowing the system to be considered a composite structure.

Currently, a considerable interest in composite pavements exists because of economic, energy, and material availability advantages. However, there is little information available on the design and performance of composite concrete pavements. Thus, new design procedures are greatly needed since many projects are being initiated employing this type of construction.

This paper presents a rational design procedure based on fundamental fatigue damage considerations. A finite element (F.E.) analysis was used to model the composite concrete slab on a dense liquid subgrade. The computed stresses from the F.E. program have been found to agree closely with stresses computed from measured strain at the AASHTO Road test.

The design procedure developed was compared to existing empirical approaches, and a design example is presented for illustration. A sensitivity analysis of the design variables was conducted to show the effect of changes in the design parameters on required slab thickness.

## Design Considerations

Design of a composite concrete pavement requires the consideration of truck traffic volume and weight, climate and foundation support, similar to the design of conventional concrete pavements. Pavement components requiring detailed design include the following for plain jointed composite concrete pavement:

1. Slab materials and dimensions
   a. Surface layer strength, elasticity, durability, and thickness.
   b. Lower layer strength, elasticity, durability, and thickness.
2. Subbase materials and thickness
3. Joints
   a. Transverse joint spacing, load transfer, and configuration.
   b. Longitudinal joint configuration and tie bar spacing.
4. Subsurface drainage

Each of these components and their interactions have an influence on the performance of the pavement system.

The major types of distress occurring in plain jointed concrete pavement as determined from extensive field studies are joint faulting and transverse cracking (Ref. 7). Darter (Ref. 3) lists traffic, slab thickness, foundation support, subbase, and joint spacing as the primary factors affecting slab cracking. Packard (Ref. 4) states that truck traffic volume, subbase, and joint spacing in a given climate have the most influence on the faulting of undoweled concrete pavements. The items common to both the lists are traffic volume, slab thickness, subbase, and joint spacing. The interaction of these parameters has a definite effect on the total pavement system especially in terms of cracking and faulting of the slabs. For example, the Michigan and Minnesota road tests showed that joint spacings of longer than 15 to 20 ft. had significantly greater amounts of cracking. These and other in-service projects show that joint spacing has a dramatic effect on the amount of transverse cracking of the slabs.

All factors discussed thus far have an important role in the structural design of the conventional plain jointed concrete pavement. They should also be taken into account in the design of composite concrete pavements. The effects of these parameters on the

composite pavement system are basically the same as their effects on the conventional system because the basic materials properties are the same. However, there is a large reduction in the flexural strength and the modulus of elasticity of the low strength concrete base layer. These differences are significant in affecting the stresses caused by the truck traffic and the resulting fatigue damage to the slab. Also, an additional factor to be considered in the design of composite concrete pavements is the shear stress at the layer interface.

Because of these differences, the design of composite concrete pavement cannot be based on conventional design procedures.

## Structural Analysis of Composite Concrete Pavement

### Finite Element Analysis Model

In order to perform the stress analysis of the composite concrete pavement system, it was necessary to find a model that was capable of handling a two layer system with variable material properties, and a method for analyzing the interface condition of shear transfer (bond). Such a model was found in the modified Kentucky finite element program. The original program was developed by Huang (Ref. 5), but was modified by Tabatabaie, at the University of Illinois, to analyze a two layer system.

The two layer system modeled by the program is supported by a dense liquid subgrade. The degree of composite response is a function of the shear transfer or bond between the two layers. In the modified Kentucky program, the degree of response can be set at either zero or one hundred percent (i.e. full bond).

In order to determine the stresses in the two layer system, an equivalent layer based on the transformed-section concept is used to determine the neutral axis of the composite system. The neutral axis of the composite system can be found using the first moment of the equivalent area of the transformed cross section. The equation is as follows:

$$D_2 = \frac{\frac{t_1 + t_2}{2} \cdot t_1}{t_1 + \frac{t_2 E_2}{E_1}} \qquad (1)$$

where $D_2$ is the vertical distance from the midplane of the lower layer to the neutral axis of the combined cross section, $t_1$ is the thickness of the surface layer, $t_2$ is the thickness of the lower layer, $E_2$ is the elastic modulus of the lower layer, and $E_1$ is the elastic modulus of the surface layer.

The computed stresses from the finite element program for a one layer system have been found to agree closely with the stresses computed from measured strains at the AASHO Road Test (Refs. 6, 7). The required inputs are the elastic modulus for the surface and lower concrete layer, the thickness of each layer, bond between the layers, Poisson's ratio for each layer, the modulus of subgrade reaction, and axle load magnitude and location. A typical slab with the grid system used in the analysis is shown in Figure 1 for an 18-kip single axle load.

The critical stress used in the analysis is the longitudinal edge stress at the bottom of the slab under the axle load. The location of this critical stress position is discussed thoroughly by Darter (Ref. 7), and has been shown to be critical by both measured field data from the AASHO Road Test (Ref. 6) and theoretical analyses by Huang (Ref. 5). The critical edge stress causes transverse cracking of the slab which is a major structural distress in plain jointed concrete pavements.

### Evaluation of the Composite Concrete Pavement System

An analysis of slab stress was conducted considering the factors and ranges shown in Table 1. The elastic moduli, subgrade reaction, and slab length values were chosen since they are considered representative of the values found in the materials and used in design practice. The values of the thicknesses for the surface layer ($h_1$) were selected for two reasons: (1) the lower limit is based on construction limits, and (2) the upper bound approaches a standard pavement thickness above which the pavement system need not be designed as a composite pavement. The thicknesses of the low strength concrete layer were selected to give a reasonable range of combined thicknesses thought to be suitable for any range of traffic loads. An example factorial of the tensile edge stresses from the analysis are shown in Table 2.

The table shows the critical tensile edge stresses in psi, at the bottom of the slab, produced by an eighteen kip single axle load. A review of the data showed that the surface layer thickness did not influence the tensile stress developed when the total combined thickness was the same: As shown in Figure 2, for a total thickness of 8 inches the same tensile stress of approximately 233 psi is obtained if the $h_1$ = 2 ins. and $h_2$ = 6 ins., or if $h_1$ = 4 ins. and $h_2$ = 4 ins. This effect was always shown when the surface layer thickness was less than the base layer thickness. However, when the surface layer thickness exceeded the base layer thickness a small stress reduction was noticed as compared to the same case where the surface layer was thinner than the base course. The reduction was usually on the order of three percent. Therefore, the total combined thickness of concrete layers has been established as the major criteria in the design analysis.

The importance of a good bond between the layer materials was also found to have a great influence on the tensile stress as shown in Figure 3.

Presently, there are two major approaches for designing concrete pavements. These are the serviceability/performance and fatigue damage methods. The serviceability/performance model is based on extensive data collected at the AASHO Road Test. To use this approach in the design of the composite pavement, a large test facility would have to be constructed to collect the extensive performance data. This is the major reason the serviceability approach cannot be used at this time for composite concrete pavement design. Thus, the fatigue damage appoach is used in this design procedure.

Fatigue damage methods currently in use are those of the Portland Cement Association and the Corps of Engineers. Recent development of a more comprehensive fatigue damage design approach has been accomplished at the University of Illinois for the Federal Highway Administration (Refs. 7, 8) for plain jointed concrete pavements.

Fatigue damage analysis is used to prevent slab cracking under repeated loads. The basic parameters considered in the fatigue damage design are (1) properties of the concrete (fatigue and strength), (2) the foundation support, and (3) type and amount of truck traffic loads anticipated. The loading of concrete slabs produces a flexural (tension) stress at the bottom of the slab. The highest stress occurring when the load is situated at mid-slab near the edge (within 6 ins.).

It has been shown in many studies that plain PCC beams experience fatigue failure when subjected to repetitive flexural stresses. The fact that the composite pavement consists of a low strength concrete

and a normal strength concrete does not pose a problem when considering a fatigue analysis. The fatigue analysis is performed using the stress developed in the low strength concrete layer and the flexural strength of that layer. Low strength concrete performs similarly to regular concrete mixes in fatigue when the ratio of stress to strength (R) value is used for the comparison (Ref. 9). Thus, fatigue stress/strength ratio versus load application curves previously developed for standard PCC can be used.

In order to conduct a fatigue damage analysis, a fatigue curve must be selected. In developing the Zero-Maintenance design, Darter has plotted an R vs. cycles to failure curve for 140 tests from three different studies (Ref. 9, 10, 11). A least square regression curve representing a probability of failure of 50 percent was derived. The fatigue curve used in this design procedure is the same as the Zero-Maintenance design curve, representing a probability of failure of 24 percent. The equation of the curve is

$$\text{Log}_{10}N_d = 16.61 - 17.61\ (R) \qquad (2)$$

where $N_d$ is the load applications to failure used in design and R is the ratio of flexural stress to strength (ASTM C 76).

It is recommended that the MR used in design be a value representing a confidence level of 85 percent to account for the variability in strength of the concrete. Knowing the standard deviation of the MR tests, the MR used in design can be calculated using the following equation:

$$MR_d = MR - S.D. \times 1.03 \qquad (3)$$

where $MR_d$ is the MR used in the design to compute the stress/strength ratio, MR is the average modulus of rupture for the selected time period, SD is the standard deviation of MR, and 1.03 is the normal deviate for the 85 percent confidence level.

The structural analysis section of the paper presented the response of the composite pavement system to an 18 kip single axle load producing an edge load condition (Table 2). From this analysis, it was possible to evaluate the flexural stress produced for many combinations of E-values, k-values and thicknesses. Based upon these values, a graphical solution was prepared as shown in Figure 4 to determine the stress produced for a single axle load. The stress produced by axle loadings other than the 18 kip single axle were determined by using a ratio of the axle load to the 18 kip load since the structural system is linearly elastic. For example, if an 18 kip axle load produced a stress of 300 psi, a 20 kip axle load would produce a stress of (20/18) x 300 psi = 333 psi.

Figure 5 shows the graph for determining the stress produced by a tandem axle load. The tandem axle graph was developed in the same manner as the 18 kip single axle graph. For loads other than the 36 kip tandem, the ratio of the axle load to the 36 kip axle load was used as the multiplier.

## Fatigue Damage Computation

Fatigue damage occurs from heavy repeated truck traffic that could result in cracking of the slabs. The damage model used is Miner's accumulative damage model. This model is represented by the equation

$$\text{Damage} = \sum_{i=1}^{i=m} \frac{n_i}{N_i} \qquad (4)$$

where

Damage = accumulated fatigue damage over the design period occuring at the slab edge

$n_i$ = number of applied axle loads of the $i^{th}$ magnitude

$N_i$ = number of axle load applications of the $i^{th}$ magnitude to failure (determined from the fatigue curve)

i = counter for magnitude of axle load (single and tandem)

m = total number of single and tandem axle load groups

The value $n_i$ is computed from the traffic data specified using the following expression:

$$n_i = (ADT)(365)(DP)(T)(DF)(LD)(A)(P)(EL)(CON) \qquad (5)$$

where

ADT = average annual daily traffic over the design period in vehicles per day

365 = constant converting vehicles/day to vehicles/year

DP = design period in years

T = percent of ADT that is trucks expressed as a decimal (i.e., 0.20)

DF = directional factor to convert two-way ADT into one-way ADT, usually 0.50

LD = lane distribution factor the percent trucks in the design lane in one direction expressed as a decimal

A = mean number of axles per truck

P = percent axles in the $i^{th}$ load group

EL = percent axles causing edge load condition (see Figure 4)

CON = 1 for single axles and 2 for tandem axles

$N_i$ is computed from the PCC fatigue expression, Eq. 2. First, the slab edge stress must be found using the graphs shown in Figures 6 and 7 for single and tandem axles, respectively. The design flexural strength of the low strength concrete must also be determined as explained in Eq. 3. Once these values have been determined the value of $N_i$ can be calculated.

The determination of the $n_i$ and $N_i$ values permits the computation of the fatigue damage over the design period. The calculation is an iterative process using various thicknesses, concrete properties, and subgrade support values in order to achieve a low enough total damage to last the design period.

## Selection of Limiting Fatigue Damage Value

Theoretically, Miner's hypothesis states that when the accumulative damage value reaches 1.0 the concrete should fracture in fatigue. However, due to the variability of the material strengths and many other differences between the loading of beams in the laboratory and slabs in the field, this is not the case. In order to determine a realistic limiting fatigue damage value to use in the design procedure, a fatigue analysis using the expression shown in Eq. 3 was used on many in-service pavements. (All data for this analysis was obtained by Darter and Barenberg for the Zero-Maintenance design project (Ref. 3).) The cracking index of these pavement sections was measured. From the analysis on the sections having 12 to 20 ft. joint spacing, the curve shown in Figure 6 was developed. The data used for the curve were

from plain jointed concrete pavements. The damage values are considered valid for use in the composite pavement design procedure since fatigue is based on the ratio of stress to strength. This curve essentially represents a calibration of the fatigue damage design models.

The designer, with the use of this curve, can select a limiting design damage value to limit the cracking of the pavement section, or once the fatigue damage value is computed for a given design, the cracking index over the design period can be estimated.

It is recommended that low cracking index values be used for high traffic volume pavements to provide high reliability. A much higher cracking index can be tolerated on low traffic volume roads. Recommended damage values for high, medium, and low traffic volume roads are $10^{-4}$ (ADT > 20,000), $10^{-2}$ (2000 < ADT < 20,000), and 1.0 (ADT < 2,000), respectively.

## Design Application and Sensitivity Analysis

A design example for a two lane rural highway has been developed. The design inputs were selected from available data. The low strength concrete properties were obtained from data compiled by the Florida DOT presented in Ref. 1. The design inputs are shown in Table 3. The axle load distribution is shown in Table 4.

The design procedure is an iterative process which involved selecting a thickness, determining a stress from the design chart (based on the design properties), and computing the total accumulative damage over its design life for the given thickness. If the computed damage value is considerably less than or greater than the recommended or selected value, the thickness must be altered accordingly and another damage value computed. The fatigue damage calculation for an 8.5 inch thick slab is shown in Table 5. This trial resulted in a damage value of $1.83 \times 10^{-2}$ which is close enough to the recommended value of $1 \times 10^{-2}$ for a medium traffic volume pavement.

### Other Design Parameters

The joint spacing of the composite pavement is recommended to be 12 ft. to 20 ft., but preferably no more than 15 ft. The design charts and cracking index curve have been based on slabs of 12-20 ft. Using slab lengths in excess of this will produce higher stresses (due to temperature and moisture gradients) and more cracking will result.

Load transfer devices such as dowel bars should be used for very heavy truck traffic. Faulting index nomographs have been developed by Parkard (Ref. 4) which may be used to indicate if load transfer is needed.

### Sensitivity Analysis

A sensitivity analysis was conducted to illustrate the effect of changes in several of the design parameters on the required slab thickness. The analysis was performed for the rural two lane highway design example. The average conditions are those design inputs shown in Table 3. The analysis was performed by changing one parameter at a time leaving all others constant.

The first parameter considered is the mean 28 day modulus of rupture ($\overline{MR}$). $\overline{MR}$ was varied from 150 to 400 psi. As the MR is decreased from 400 to 150 psi, the slab thickness required to maintain the same fatigue damage value increases from 8 to 14 ins. This is shown in Figure 7. Also shown in the figure is the variation of $E_2$, elastic modulus of the base concrete, since its variation is dependent on the MR. The E-MR relation was taken from Econocrete report No. 1 (Ref. 1). The coefficient of variation of the MR was also altered from a value of 10 percent (good quality control) to 30 percent (poor quality control). The resulting change in required slab thickness was 2 ins. (Figure 8). Thus, quality control does have a large impact on the thickness design. Therefore, the low strength concrete or econocrete used as the lower layer material must have good quality control.

The foundation conditions were changed by varying the k-value from 50 to 500 pci. The resulting change in required slab thickness, as shown in Figure 9, is 2.5 ins.

The elastic modulus of the surface concrete was varied from 4 to 10 x $10^6$ psi. This resulted in a change of required thickness of 9.5 to 8 ins., as shown in Figure 10.

The last design input varied was $\overline{D}$, mean distance from the slab edge to the outside of truck dual tires. This variable effects the percent of trucks causing the edge load condition. D was varied from 0 to 30 ins.; this change produced a reduction in slab thickness of 1 in. (Figure 11). This same idea was used on a paving project in North Dakota. An extra wide slab was placed, and the edge strip was painted 2 ft. in from the slab edge.

The 8.5 in. design for this rural highway is expected to have a cracking index of 4 ft/1000 $ft^2$ after 20 years of service, as determined from Figure 6. The thickness can be altered and another fatigue damage value calculated, and the cracking index can then be estimated from Figure 8. Considering a range of thicknesses from 7 to 10 ins., the concurrent change in cracking index was from a value of 35 ft/1000 $ft^2$ to 0, as shown in Figure 12. Thus the pavement thickness can be altered depending on the amount of cracking that can be tolerated for the specific pavement being designed. The consequence of providing too thin a slab is obvious from Figure 12.

Figure 13 compares the PCA conventional concrete thickness design with the three designs for the composite pavement. As shown in the figure for this specific example, both the Florida DOT (Larsen) (Ref. 1), and the PCA's preliminary 1975 procedure (Packard) (Ref. 8) require slightly thicker composite pavements than the new procedure (Kohn and Darter). It should be noted that both the Florida and PCI procedures are preliminary methods. The new procedure differs from the conventional pavement by 3 ins. for the high volume road to 1.5 ins. for the low volume traffic road. The thicknesses shown for the Florida and PCA procedures are based on a 3 in. surface course. The total thicknesses in these two methods can be decreased by increasing the surface course thickness. It was found in this study, however, that the surface course thickness did not decrease the stress in the lower course until the surface course was thicker than the base.

## Horizontal Shear Stress Analysis

As previously mentioned, the shear at the interface of the two materials should be considered. In order to evaluate the horizontal shearing stress at the interface of the composite system, an elastic layer computer program and transformed section beam analyses were employed. In the elastic layer analysis, a 9-kip circular load was used modeling a tire imprint with 70 psi pressure. Table 6 summarizes the results of the computer runs which show a maximum shear of only 48 psi. The maximum horizontal shear stress at the interface of materials was found at the edge of the loaded circular area. It should be noted

that this result is for an interior load condition. The shear stress for the edge will be about 50% higher.

A second analysis used the transformed section analysis for a beam 24 inches wide with a center point loading of 9 kips. The sections were transformed to a beam of material type 1 using the ratio of $E_2/E_1$. The shear stresses were calculated just above and below the interface using the equation

$$\tau = \frac{VQ}{Ib} \quad (6)$$

where

$\tau$ = horizontal shear stress
V = vertical shear force
Q = Statical moment of area above layer considered with respect to the neutral axis
I = moment of inertia
b = width of section considered

These results are shown in Table 7. It should be noted that the stress at section 2-2 is correct in terms of material 1. This method, using only a 24 inch wide beam, represents an extreme condition, and it is very doubtful if the maximum shear of 176 psi will ever occur in an actual pavement.

In the composite pavement system, the two layers of concrete are both placed in a plastic state. To ensure bonding of the interface, the surface of the concrete may be roughened prior to placing the high strength concrete. Also, vibrators may be introduced through the high strength layer and slightly penetrate the low strength material. Thus, the interface should attain a shear strength equal to the low strength material, which should be on the order of 12 to 28 percent of its strength. Regular paving concrete has a shear strength ranging from approximately 700 to 1700 psi, which translates into 12-28% of a typical compressive strength of 6000 psi. This gives a shear strength of a lean concrete at 240-560 psi, if the compressive strength is 2000 psi.

Based on these calculations, it appears that the shear stress at the interface of materials is significantly less than the shear strength of the econocrete material. Thus for purposes of design, it is recommended that a 3 inch surface be used.

## Conclusions

1. The design method developed is practical, based upon a fundamental approach, and gives reasonable results for slab thickness requirements. Sensitivity analysis shows that changes in the various inputs provide reasonable changes in the required slab thickness.

2. The cracking index versus fatigue damage relationship provides designers some guidelines on selecting appropriate thicknesses for different types of pavements and provides some verification of the design approach.

3. The design procedures developed give the designer much freedom to consider many variations in composite concrete pavement design.

4. Required total composite concrete slab thickness is about 1 to 3 ins. greater than required for conventional concrete slabs. The following shows the general sensitivity of the design procedure:

| Parameter and Range | Range of Required Total Slab Thickness |
|---|---|
| Traffic Level low to high volume | 7 to 13 ins. |
| Mean 28 day flexural strength 400 to 150 psi | 8 to 14 ins. |
| Quality control of the concrete good to poor | 8.5 to 10.5 ins. |
| Foundation support poor to excellent | 9.5 to 7 ins. |

5. The major design component of the composite concrete pavement is total slab thickness ($H_t$). Results showed that any combination of surface and base layer thicknesses which resulted in the same total thickness produced the same critical stress. Thus, the output of the design procedure is the required $H_t$. The thickness of $h_1$ should be selected as a minimum value depending on construction constraints (3 ins. recommended).

6. The composite concrete slab must be placed monolithically to ensure a full bonding between lower and surface concrete mixes. Any reduction in the bond would result in higher critical stress in the lower layer.

7. A test program should be initiated to build and carefully monitor the performance of composite pavement. The results from recent experimental pavement projects can be incorporated into such a study.

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Table 1. Composite pavement parameters.

| Parameter | Range of Values |
|---|---|
| $h_1$ = thickness of normal strength surface concrete | 2, 4, 6 inches |
| $h_2$ = thickness of low strength base layer concrete | 4, 6, 8, 10 inches |
| $H_t$ = total combined thickness $h_1 + h_2$ | 6, 8, 10, 12, 14, 16 inches |
| $E_1$ = elastic modulus of the surface layer | 4, 5, 6 x $10^6$ psi |
| $E_2$ = elastic modulus of the base layer | 1, 2, 3, 4 x $10^6$ psi |
| k = modulus of subgrade reaction | 50, 100, 200, 500 pci |
| L = slab length | 10, 15, 20, 25 feet |
| C = composite action factor (bond between the layers) | 0, 100 percent |
| $\mu$ = Poisson's ratio, $\mu_1$ | .15 |
| $\mu_2$ | .28 |

Table 2. Edge stress in psi produced by 18 kip single axle load computed by finite element program (slab length = 15 ft., k = 50 pci).

| L, ft. | $H_1$, in. | $H_2$, in. | $E_2 \times 10^6$ psi | $E_1 \times 10^6$ psi | K pci | 15' | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | 2 | | | | 4 | | | | 6 | | | |
| | | | | | | 4 | 6 | 8 | 10 | 4 | 6 | 8 | 10 | 4 | 6 | 8 | 10 |
| 50 | 4 | 1 | | | | 340 | 220 | 155 | 118 | 220 | 155 | 118 | 92 | 155 | 118 | 92 | 74 |
| | | 2 | | | | 431 | 270 | 186 | 142 | 270 | 186 | 142 | 107 | 186 | 142 | 107 | 86 |
| | | 3 | | | | 495 | 307 | 210 | 158 | 307 | 210 | 158 | 119 | 210 | 158 | 119 | 97 |
| | | 4 | | | | 550 | 337 | 230 | 171 | 337 | 230 | 171 | 129 | 230 | 171 | 129 | 102 |
| | 5 | 1 | | | | 340 | 216 | 152 | 115 | 216 | 152 | 115 | 90 | 152 | 115 | 90 | 72 |
| | | 2 | | | | 420 | 261 | 180 | 137 | 261 | 180 | 137 | 103 | 180 | 137 | 103 | 83 |
| | | 3 | | | | 485 | 295 | 205 | 150 | 295 | 205 | 150 | 113 | 205 | 150 | 113 | 91 |
| | | 4 | | | | 525 | 324 | 220 | 164 | 324 | 220 | 164 | 122 | 220 | 164 | 122 | 97 |
| | 6 | 1 | | | | 325 | 207 | 147 | 112 | 207 | 147 | 112 | 87 | 147 | 112 | 87 | 71 |
| | | 2 | | | | 415 | 256 | 178 | 133 | 256 | 178 | 133 | 100 | 178 | 133 | 100 | 81 |
| | | 3 | | | | 465 | 287 | 197 | 146 | 287 | 197 | 146 | 111 | 197 | 146 | 111 | 89 |
| | | 4 | | | | 515 | 313 | 211 | 157 | 313 | 211 | 157 | 118 | 211 | 157 | 118 | 93 |

Composite Action = 100% Temperature Gradient = 0°F/in.

Table 3. Summary of design parameters for rural highway.

| PARAMETER | VALUE |
|---|---|
| 1. Elastic Modulus of Surface Concrete $E_1$ | $6 \times 10^6$ psi |
| 2. Elastic Modulus of Base Concrete $E_2$ | $1 \times 10^6$ psi |
| 3. Design Modulus of Rupture (Base Concrete) $MR_d$ | 336 psi |
| 4. Modulus of Subgrade Reaction K | 100 pci |
| 5. Design Period | 20 years |
| 6. Average ADT over Design Period | 6000 veh./day |
| 7. Percent of ADT which is Trucks | 13% |
| 8. Percent Trucks in Design Lane | 100% |
| 9. Directional Distribution | 50% |
| 10. Mean Axles per Truck | 2.14 axles/truck |
| 11. Mean Distance from Slab $\overline{D}$ | 11.0 ins. |
| 12. Percent of Trucks Causing Edge Load Condition | 32% |
| 13. Axle Load Distribution | Table 5.6 |

Table 4. Rural two lane highway axle load distribution.

| Axle Load Group (kips) | Design Axle Load Distribution (percent) |
|---|---|
| Single Axles | |
| 0-3 | 21.20 |
| 3-7 | 15.84 |
| 7-8 | 6.41 |
| 8-12 | 16.17 |
| 12-16 | 3.27 |
| 16-18 | 1.81 |
| 18-20 | 0.24 |
| 20-22 | 0.03 |
| 22-24 | 0.02 |
| 24-26 | 0.02 |
| Tandem Axles | |
| 0-6 | 0.36 |
| 6-12 | 8.69 |
| 12-18 | 5.21 |
| 18-24 | 5.56 |
| 24-30 | 9.59 |
| 30-32 | 4.43 |
| 32-34 | 0.22 |
| 34-36 | 0.74 |
| 36-38 | 0.12 |
| 38-40 | 0.04 |
| 40-42 | 0.01 |
| 42-44 | 0.01 |
| 44-46 | 0.01 |
| TOTAL | 100.00 |

Table 5. Composite concrete pavement design worksheet.

Project: Rural Two Lane Highway

Single Axle Load

| Axle Load Kips | Stress Psi | Stress Ratio R | Expected Repetitions $n_i$ | Allowable Repetitions $N_d$ | Fatigue Damage $n_i/N_d$ |
|---|---|---|---|---|---|
| 3 | 27 | .08 | 494,440 | $1.59 \times 10^{15}$ | $3.11 \times 10^{-10}$ |
| 7 | 61 | .18 | 369,430 | $2.75 \times 10^{13}$ | $1.34 \times 10^{-8}$ |
| 8 | 71 | .21 | 149,498 | $8.16 \times 10^{12}$ | $1.83 \times 10^{-8}$ |
| 12 | 104 | .31 | 377,127 | $1.40 \times 10^{11}$ | $2.69 \times 10^{-6}$ |
| 16 | 141 | .42 | 76,264 | $1.64 \times 10^{9}$ | $4.65 \times 10^{-5}$ |
| 18 | 158 | .47 | 42,213 | $2.15 \times 10^{8}$ | $1.96 \times 10^{-4}$ |
| 20 | 175 | .52 | 5,600 | $2.84 \times 10^{7}$ | $1.97 \times 10^{-4}$ |
| 22 | 192 | .57 | 700 | $3.74 \times 10^{6}$ | $1.87 \times 10^{-4}$ |
| 24 | 212 | .63 | 466 | $3.28 \times 10^{5}$ | $1.42 \times 10^{-3}$ |
| 26 | 232 | .69 | 466 | $2.88 \times 10^{4}$ | $1.62 \times 10^{-2}$ |
| | | | | Single Axle Subtotal | $1.82 \times 10^{-2}$ |

Trial Thickness: 8.5 inches  Elastic Modulus $E_1$: $6 \times 10^6$ psi

MR Design: 336 psi  Elastic Modulus $E_2$: $1 \times 10^6$ psi

K Design: 100 pci

Table 5. Composite concrete pavement design worksheet (continued).

Project: Rural Two Lane Highway

Tandem Axle Load

| Axle Load Kips | Stress Psi | Stress Ratio R | Expected Repetitions $n_i$ | Allowable Repetitions $N_d$ | Fatigue Damage $n_i/N_d$ |
|---|---|---|---|---|---|
| 6 | 24 | .07 | 16,792 | $2.38 \times 10^{15}$ | $7.06 \times 10^{-12}$ |
| 12 | 47 | .14 | 405,347 | $1.40 \times 10^{14}$ | $2.90 \times 10^{-9}$ |
| 18 | 71 | .21 | 243,022 | $8.16 \times 10^{12}$ | $2.98 \times 10^{-8}$ |
| 24 | 94 | .28 | 259,348 | $4.78 \times 10^{11}$ | $5.43 \times 10^{-7}$ |
| 30 | 118 | .35 | 447,328 | $2.79 \times 10^{10}$ | $1.60 \times 10^{-5}$ |
| 32 | 124 | .37 | 206,638 | $1.24 \times 10^{10}$ | $1.66 \times 10^{-5}$ |
| 34 | 134 | .40 | 10,261 | $3.68 \times 10^{9}$ | $2.79 \times 10^{-6}$ |
| 36 | 142 | .42 | 34,517 | $1.64 \times 10^{9}$ | $2.10 \times 10^{-5}$ |
| 38 | 148 | .44 | 5,597 | $7.27 \times 10^{8}$ | $7.70 \times 10^{-6}$ |
| 40 | 158 | .47 | 1,865 | $2.15 \times 10^{8}$ | $8.67 \times 10^{-6}$ |
| 42 | 165 | .49 | 467 | $9.57 \times 10^{7}$ | $4.88 \times 10^{-6}$ |
| 44 | 171 | .51 | 467 | $4.26 \times 10^{7}$ | $1.10 \times 10^{-5}$ |
| 46 | 181 | .54 | 467 | $1.26 \times 10^{7}$ | $3.71 \times 10^{-5}$ |
| | | | | Tandem Axle Subtotal | $1.26 \times 10^{-4}$ |
| | | | | Single Axle Subtotal | $1.82 \times 10^{-2}$ |
| | | | | Total Fatigue Damage | $1.83 \times 10^{-2}$ |

Table 6. ELASTIC LAYER PROGRAM

| PROBLEM | $H_1$ in | $H_2$ in | $E_1 \times 10^6$ psi | $E_2 \times 10^6$ psi | $E_3$ psi | $T_{max}$ @ interface |
|---|---|---|---|---|---|---|
| 1 | 2 | 4 | 5 | 2 | 3000 | 48 psi |
| 2 | 2 | 8 | 5 | 2 | 3000 | 29 psi |
| 3 | 2 | 8 | 5 | 2 | 6000 | 29 psi |
| 4 | 2 | 8 | 6 | 1 | 3000 | 29 psi |
| 5 | 2 | 8 | 5 | 3 | 3000 | 28 psi |
| 6 | 4 | 6 | 5 | 2 | 3000 | 26 psi |
| 7 | 4 | 10 | 5 | 2 | 3000 | 20 psi |
| 8 | 4 | 10 | 5 | 2 | 6000 | 20 psi |
| 9 | 4 | 10 | 6 | 1 | 3000 | 17 psi |
| 10 | 4 | 10 | 5 | 3 | 3000 | 21 psi |

$H_1$ = Thickness of High Strength Concrete
$H_2$ = Thickness of Low Strength Concrete
$E_1$ = Modulus of Elasticity of layer 1
$E_2$ = Modulus of Elasticity of layer 2
$E_3$ = Modulus of Elasticity of subgrade

Table 7.
Transformed section (Section transformed to material of $E_1$)
Simply supported beam (24" wide)

| PROBLEM | $H_1$ in | $H_2$ in | $E_1 \times 10^6$ | $E_2 \times 10^6$ | b | "nb" | $\tau$ - interface, psi 1-1 | 2-2 |
|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 4 | 5 | 1 | 24 | 4.8 | 25.1 | 125.4 |
| 2 | 2 | 4 | 5 | 2 | 24 | 9.6 | 46.0 | 115.0 |
| 3 | 2 | 8 | 5 | 2 | 24 | 9.6 | 23.8 | 59.5 |
| 4 | 2 | 8 | 6 | 1 | 24 | 4.0 | 27.0 | 162.0 |
| 5 | 4 | 6 | 5 | 2 | 24 | 9.6 | 70.4 | 176.0 |
| 6 | 4 | 10 | 5 | 2 | 24 | 9.6 | 22.0 | 54.0 |

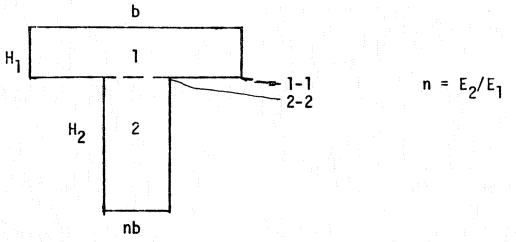


Figure 1. Finite element slab layout for single axle load.

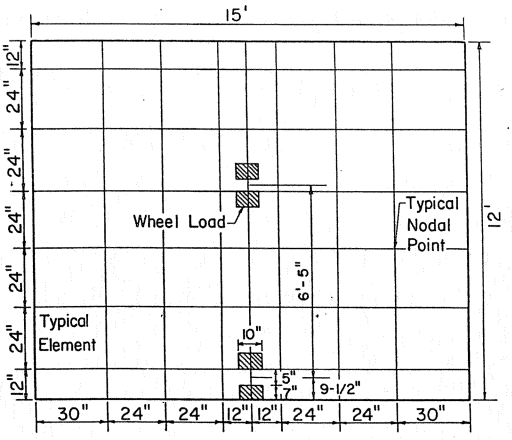


Figure 2. Interaction of thicknesses $h_1$ and $h_2$.

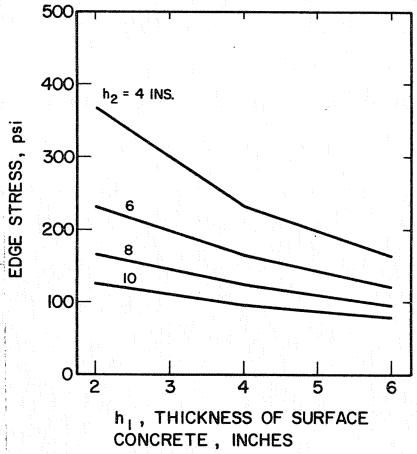

Figure 3. Comparison of edge stresses when either there is 0 or 100 percent bond between the concrete layers.

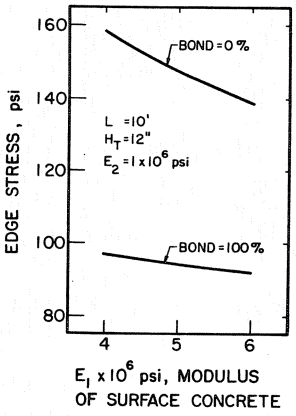


Figure 4. Composite concrete pavement edge stress for single axle load nomograph.

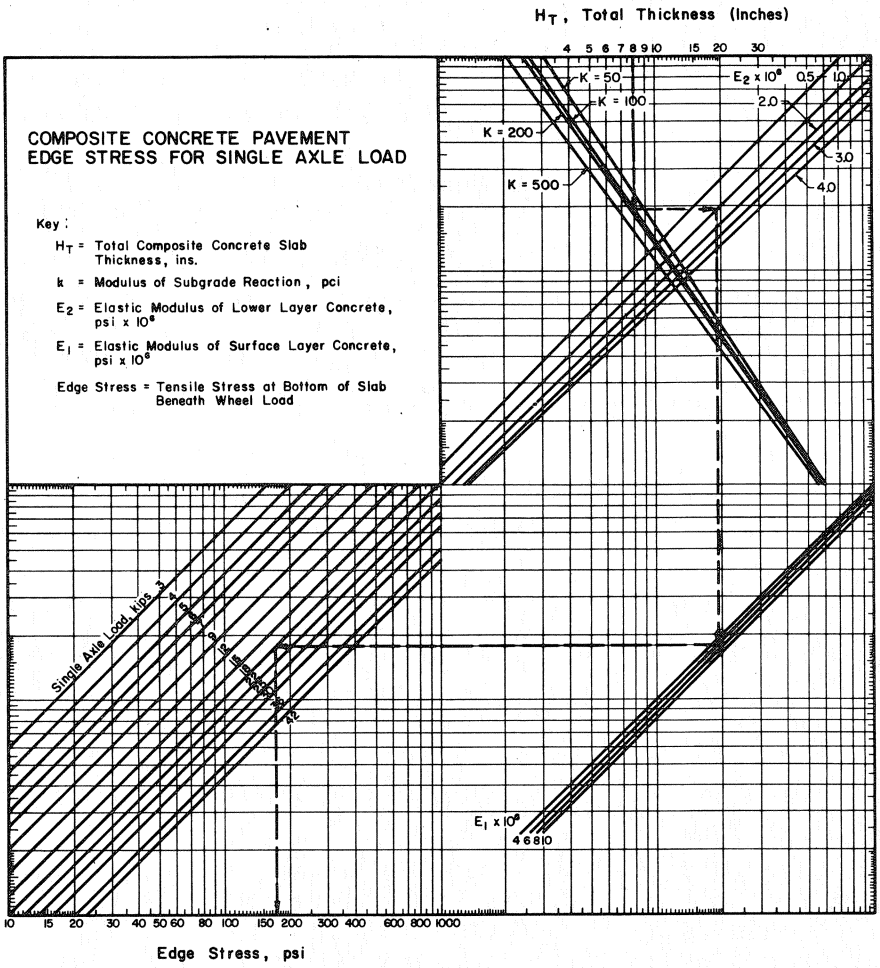

Figure 5. Composite concrete pavement edge stress for tandem axle load nomograph.

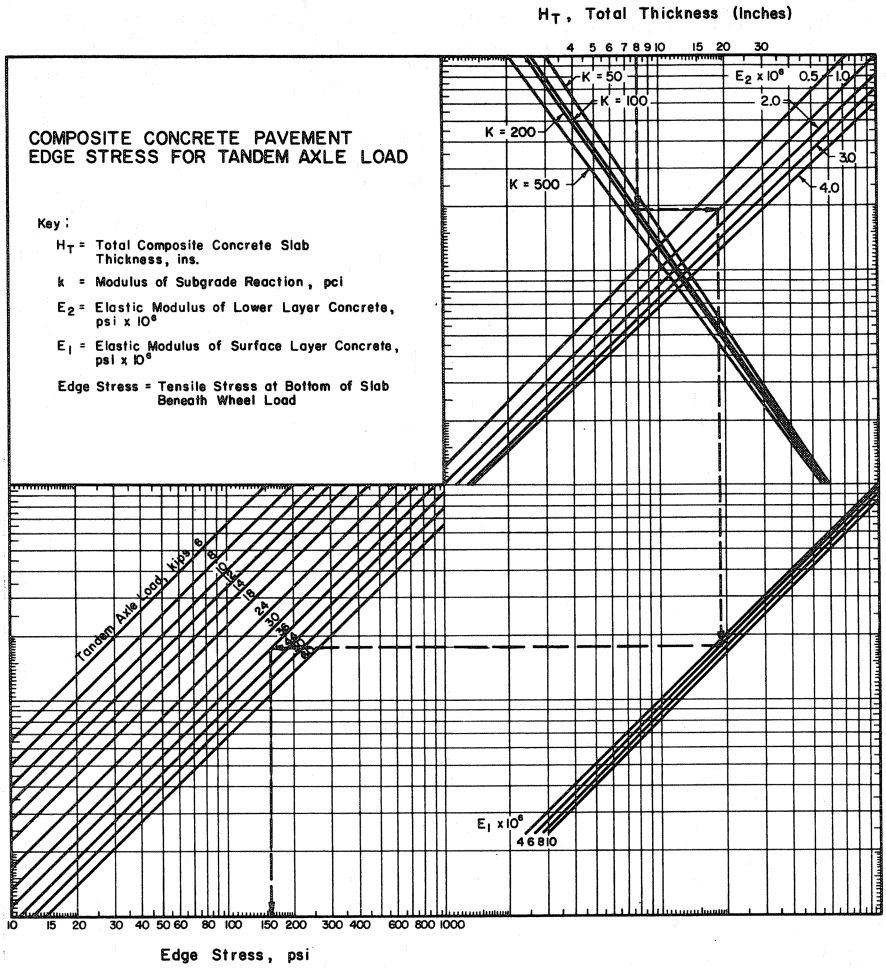


Figure 6. Cracking index vs. computed fatigue damage developed for in-service pavements.

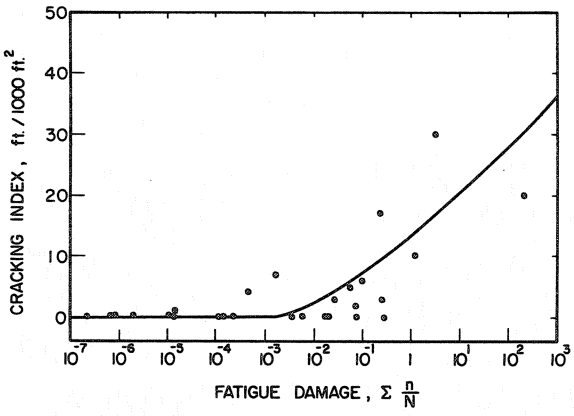


Figure 7. Effect of MR and $E_2$ on required design thickness.

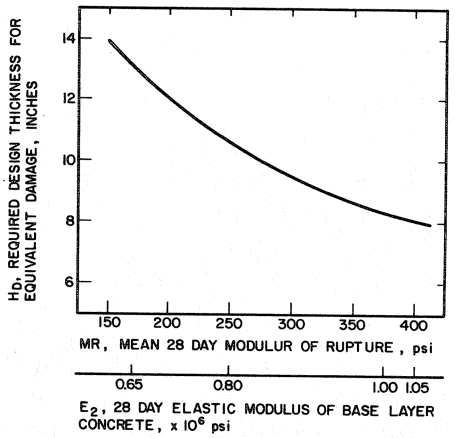

Figure 8. Effect of the coefficient of variation of the modulus of rupture on the required design thickness.

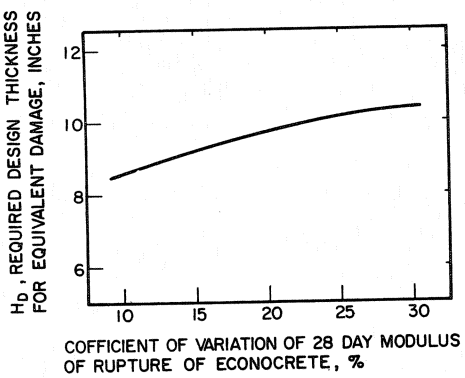


Figure 9. Effect of $E_2$ on required design thickness.

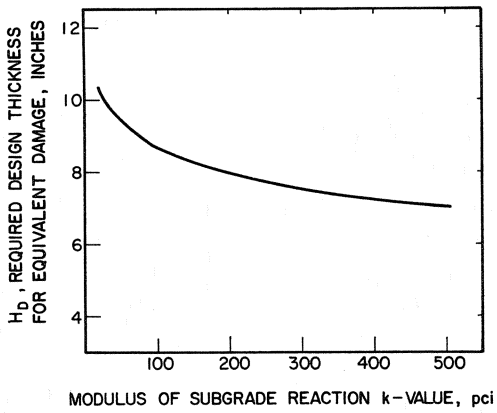


Figure 10. Effect of $E_2$ on required design thickness.

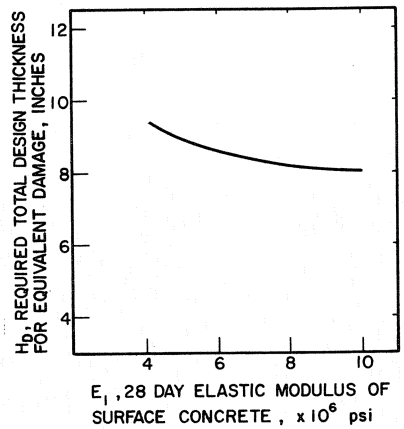


Figure 11. Effect of $\bar{D}$ on required design thickness.

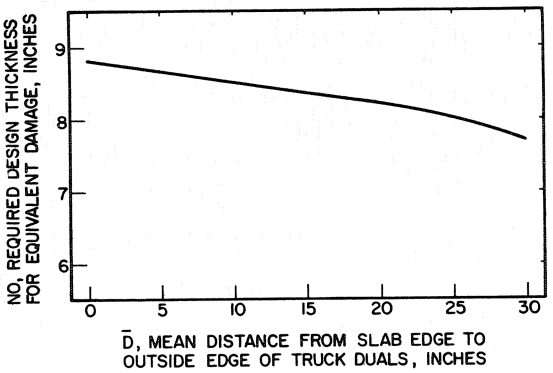


Figure 12. Effect of total thickness on expected cracking.

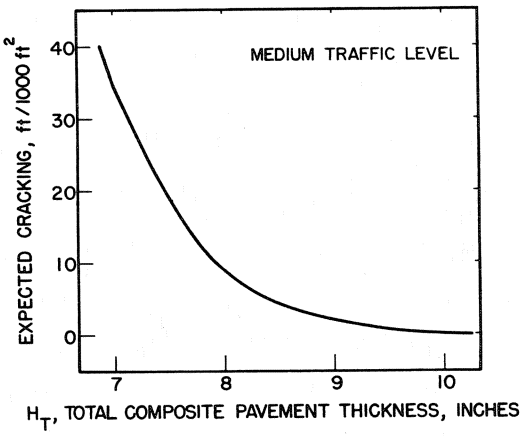


Figure 13. Comparison of design thicknesses of three composite pavements with conventional pavement thickness.

