

# Non-Linear Dynamic Analysis of Concrete Pavements

**Sameh Zaghoul**  
Graduate Student  
School of Civil Engineering  
Purdue University  
West Lafayette, Indiana

**Professor Thomas White**  
School of Civil Engineering  
Purdue University  
West Lafayette, Indiana

## 1. Introduction

The conventional analysis method for rigid pavement is usually based on a closed-form solution for an infinitely long pavement subjected to static loads [Zaman, et al., 1990]. The fact that rigid pavements have finite slab dimensions and are subjected to moving loads make the predicted pavement response under the closed-form assumptions inappropriate. Finite element methods (FEM) can be used to better model concrete pavements. A number of studies of concrete pavements have been conducted using FEM [FHWA, 1989]. However, most of these studies assume that the concrete slab is a thin or thick plate resting on a Winkler, dense liquid, or elastic solid foundation. Also, static loading conditions are assumed. Table 1 summarizes assumptions associated with these applications of FEM.

In a recent study at the University of Oklahoma, rigid pavements were modeled as a thick, linear elastic plate on a viscoelastic foundation represented by a system of discrete linear springs and dashpots in parallel at the nodal points [Zaman, et al., 1990]. Moving loads were considered. Although an improvement, the assumptions associated with this model do not accurately represent

concrete pavements.

Purdue University conducted a study funded by the Indiana Department of Transportation (INDOT) and the Federal Highway Administration (FHWA) to evaluate the damage effect of overloaded trucks on the Indiana highway network. A three-dimensional dynamic finite element method (3D-DFEM) [ABAQUS, 1989a] was used to analyze both asphalt and concrete pavements. The concrete pavement was modeled as three-dimensional slabs resting on a layered foundation. The linear and non-linear material properties of the different layers; concrete slab, subbase and subgrade; were represented. Truck loads moving at different speeds were applied and the pavement elastic and plastic responses were predicted. Prior to application, the 3D-DFEM was verified for static and dynamic analysis of pavements. The pavement static response predicted by the 3D-DFEM was compared with that predicted using Westergaard's equations [Westergaard, 1926] for similar conditions and no significant difference was found. Also, a comparison was made between the 3D-DFEM predictions and actual pavement deflections measured under moving trucks [Okamoto and Packard, 1989]. The predicted pavement deflections were found to agree with the

measured deflections. These static and dynamic verification studies showed that the 3D-DFEM can be used, with confidence, to predict actual pavement response from moving loads.

## **2. Features of the Finite Element Model**

### **2.1. Introduction**

The finite element method is a numerical method for solving problems with complicated geometries, loading, and material properties. In general, analytical solutions for these types of problems are impossible [Logan, 1986]. Jointed reinforced concrete pavements (JRCP) have two types of joints: longitudinal and transverse joints. A load transfer device (dowel bar) is commonly used to transfer loads across the transverse joints, while tie bars are commonly used to tie two adjacent slabs together. The combination of JRCP geometry, static or dynamic loading, boundaries, and layer interaction results in a complicated problem. There are two general approaches associated with finite element methods: force (flexible method) and displacement (stiffness method). The stiffness method is the most commonly used and is the basis of the ABAQUS theoretical formulation. In this method nodal displacements are unknown. Equations are developed that represent the nodal displacements based on the equations of equilibrium and a relation between forces and displacements. Virtual work, direct equilibrium and weighted residuals are commonly used to relate nodal forces to nodal displacements [Logan, 1986].

### **2.2 Model Geometry**

A jointed reinforced concrete pavement (JRCP) cross section consists of a concrete slab with limited dimensions. It is commonly supported by a subbase course and a subgrade resting on top of a deep foundation. The typical jointed concrete highway slab length ranges from 18 to 36 feet, with a width of 12 feet. A subbase provides improved support, erosion control and a facility for draining the pavement. It may be unstabilized or stabilized. The deep foundation type is site specific and can range from bed rock to a soft clay. The deep foundation may start a few feet under the pavement surface or may start much deeper.

The first step in finite element analysis is to create the finite element mesh (FEM). Three factors control the FEM geometry:

1. Pavement geometry, which controls the general size of the FEM.
2. Load configuration, such as distance between wheels and axles.
3. Degree of detail, i.e., locations where pavement response parameters will be predicted.

The spacing of the FEM has to be small enough to allow detailed analysis of the pavement section. However, a fine mesh results in a large number of nodes and elements which requires large computer capacity and/or results in long computing time. On the other hand, a coarse FEM requiring lower computer capacity and/or shorter computing time does not allow detailed analysis. A

compromise to this problem is to use more than one mesh size to model the pavement section. A coarse FEM can be used to model the general pavement section and a finer FEM can be used where a higher level of detail is desired. Figure 1 shows one of the mesh configurations used in this study. The spacing in the traffic direction,  $y$ , is constant, 18", while the spacing in the transverse direction,  $x$ , is varied. For areas which are close to the loading points, greater detail was desired, therefore a mesh was used with a 6 inch spacing. For the area located between the loads, the need for detail is not as great; therefore, a mesh was used with a 24 inch spacing. A mesh with 24 inch spacing was also used to model the shoulder. The subgrade is modeled as a set of layers. The number of layers depends on the degree of detail required in predicting the pavement response in the vertical direction. In the example shown in Figure 1, the subgrade is modeled as a set of five layers, while the concrete slab and the subbase coarse are modeled as single layers. This FEM has 8,567 nodes and 7,616 three-dimensional, eight node solid (continuum) stress/displacement elements. The reduced integration method was used for this type of element to provide more accurate results and reduce the time of computation [ABAQUS, 1989b]. This number of nodes and elements was used to ensure reasonable representation of the problem.

Adhesion between layers was considered as a function of friction and normal pressure on the layers, Mohr-Coulomb Theory. A full contact between slabs and the subbase is assumed as an initial condition. When loads

are applied, the contact conditions depend on the deformed shapes of the slabs and the subbase. The contact condition at the end of any load application is used as an initial condition for the next load application.

### 2.3. Boundary Condition

The boundary conditions for the finite element model are important and have a significant influence on the predicted response. Therefore, boundary conditions similar to those of actual pavements need to be considered. The rigid pavement cross section could have one of the three geometries shown in Figure 2. At the slab edge, two forces exist: vertical friction between the pavement edge and the adjacent soil ( $F$ ) and lateral passive pressure of the adjacent soil ( $P$ ). The friction force,  $F$ , depends on the relative movement, coefficient of friction and gap between the pavement and the adjacent soil as well as the lateral passive earth pressure. Lateral earth pressure,  $P$ , depends on the soil type and weight of the soil wedge expected to affect the pavement. For the configuration "a" in Figure 2, the soil wedge is small; therefore, both forces,  $F$  and  $P$ , can be neglected. In this case the pavement edge can be assumed to be free to move in both directions, lateral and vertical. For the configurations "b" and "c" in Figure 2, both forces exist and cannot be neglected. In the 3D-DFEM analysis, both  $F$  and  $P$  were considered.

### 2.4. Longitudinal and Transverse Joints

Two types of joints are considered: longitudinal and transverse joints, which are parallel and perpendicular,

respectively, to the traffic direction. Openings in the range of 3/8" to 3/4" was considered for both types of joints [Yoder and Witczak, 1975]. Longitudinal and transverse joints were modeled using gap elements in which the initial joint opening is specified. Depending on the deformed shape of the slabs after the load is applied, the slabs might come in contact and friction develop.

Tie bars are used across the longitudinal joints in some cases to tie two slabs together or to tie concrete shoulders to the traffic lane slabs. For transverse joints, a load transfer device (dowel bar) is commonly used to insure positive load transfer between slabs. Both types of bars were modeled as rebars located at the mid thickness of the slab. For dowel bars, the bond stress at one side was assumed to be zero to allow a relative horizontal movement between the slabs.

## 2.5. Material Properties

Westergaard analysis, as well as most of the existing FEM's, assumes that the paving materials are linear elastic. In this analysis paving materials were divided into four groups: concrete, granular materials, clays and asphalt aggregate mixtures. The actual material behavior for each group was considered.

The concrete behavior was divided into three stages: elastic, elastic-plastic and after-failure stages. Figure 3 shows the stress-strain curve used to model concrete. If the concrete slab is subjected to a stress level less than its yield stress, it will behave as an elastic material. When the stress level exceeds the yield stress of the concrete, micro

cracking will develop and the behavior is elastic-plastic until the stress reaches the failure limit. At that point a macro crack will develop and the after-failure stage will start [ABAQUS, 1989a].

Granular materials, subbase course and subgrade in some cases, were modeled using the extended Drucker-Prager model [Drucker and Prager, 1952 and ABAQUS, 1989b]. This model assumes that the material will behave as an elastic material for low stress levels. When the stress level reaches a certain limit, yield stress, the material will start to behave as an elastic-plastic material. In Figure 4 the assumed stress-strain curve for a granular material is shown.

The extended Cam-Clay model [Schofield et al., 1968, Parry, 1972 and ABAQUS, 1989b] was used to model clays. This model uses a strain rate decomposition in which the rate of deformation of the clay is decomposed additively into an elastic and a plastic part. Figure 5 shows the assumed soil response in pure compression.

Asphalt mixtures, for subbase and shoulders, are modeled as visco-elastic materials. The time dependent properties are represented by instantaneous and long term shear moduli [ABAQUS, 1989b].

Other material characteristics required in the analysis include modulus of elasticity, Poisson's ratio, damping coefficient and bulk density.

## 3. Loading Cycles

The 3D-DFEM was used to simulate truck loads moving at highway speeds. At speeds less than 20 mph a

truncated sawtooth load function is used while a step load function is used for speeds greater than 20 mph. Figure 6 shows the truncated sawtooth load cycle used in the analysis. The load cycle begins with a load magnitude equal to zero at time  $T_0$ . After time  $T_0$ , the load is increased linearly to a maximum value at time  $T_1$ . The load magnitude remains constant between time  $T_1$  and time  $T_2$ . After time  $T_2$  the load is decreased linearly to zero at time  $T_3$ . The length of time from  $T_0$  to  $T_1$ ,  $T_1$  to  $T_2$  and  $T_2$  to  $T_3$  are functions of speed and the length of the contact area between the truck tire and pavement surface. The length of the contact area or tire print was calculated by assuming the area to be a combination of a central rectangular with semicircles at the ends, as shown in Figure 6 [Yoder and Witczak, 1975].

$$L = \sqrt{\frac{A}{0.5226}}$$

Where,  $L$  = Length of the tire print, inches.

$A$  = contact area, square inches.

In the step function load cycle  $T_0 = T_1$  and  $T_2 = T_3$ .

Load cycle application in the 3D-DFEM analysis considers that no load is applied at a point,  $n$ , on a pavement prior to time  $T_0$ . After  $T_0$  the load cycle is applied at point  $n$  and to subsequent points at increments of time equivalent to the distance between the axles.

Times  $T_0, \dots, T_3$  were calculated as follows:

$$T_i = j \frac{L}{V}$$

Where,  $L$  = Length of the tire print, inches

$V$  = Speed, inch/second

$i = 0, 1, 2$  and  $3$ , respectively

$j = 0.0, 0.3, 0.7$  and  $1.0$ , respectively for  $V$   
 $< 20$  mph

$= 0.0, 0.0, 1.0$  and  $1.0$ , respectively for  $V$   
 $> 20$  mph

In initial studies an 18-kip single axle with dual wheels was assumed.

#### 4. Finite Element Model Verification

The 3D-DFEM was verified for static analysis as well as for dynamic analysis.

##### **4.1. Static Analysis Verifications**

A design of experiment (DOE) was set up to check whether the 3D-DFEM pavement response predictions agree with those calculated using Westergaard's equations [Westergaard, 1926] under the same conditions of linear elastic material properties and static loads. Three factors were included in the DOE: slab thickness, subgrade type and load position. Three levels of slab thickness, 6, 10 and 14 inches and two levels of subgrade type, sand and clay, were included in the analysis. Assuming a static loading condition and linear elastic material properties, surface deflections from three loading positions, center, edge and corner, were predicted using the 3D-DFEM. Also, for the same cross sections and loads, the surface deflections were calculated using Westergaard's equations. An analysis of variance (ANOVA) was made of the results to test whether or not there is a significant difference between the

deflections predicted using the 3D-DFEM and those calculated from Westergaard's equations for different cross section/load position combinations. Also, the ANOVA was examined to find out if the correlation between the 3D-DFEM predictions and Westergaard's results is limited to certain cross sections and load positions or if it could be generalized for a range of cross sections and load positions. Three factors were included in the ANOVA: deflections predicted using the 3D-DFEM (SF), deflections calculated using Westergaard's equations (STH) and a factor representing the pavement cross section/load position combination (PTYPE). STH was considered as the dependent variable, while SF and PTYPE were the independent variables. The interaction term, SF\*PTYPE, was included in the analysis to check if the correlation between STH and SF depends on the cross section/load position or not. It was found that there is a very high linear correlation between SF and STH ( $R^2 = 97.7\%$ ). The interaction term, SF\*PTYPE, was found to be insignificant, which means that the correlation between STH and SF does not depend on cross section/load position. The results of the ANOVA as well as different factor levels included in the analysis are shown in Figure 7.

It should be noted that ANOVA was used in this analysis to test if there is a linear correlation between the predictions of the 3D-DFEM and Westergaard's equations predictions for different treatments (cross section/load position combinations). In this type of analysis, if there is a constant difference between the two method predictions and this difference is the same (constant) for all treatments,

the linear correlation between the two method predictions will not be affected. The meaning of this constant difference is that one of the two models needs to be calibrated and a constant shift to the results is required (not data transformation). However, this was not the case between the 3D-DFEM and Westergaard results. The magnitude of pavement deflections for different treatments predicted with both methods are very close and no model calibration or data shift were found necessary.

#### 4.2. Dynamic Analysis Verification

To evaluate the dynamic analysis capabilities of the 3D-DFEM, it was decided to compare its predictions with pavement deflections measured under moving trucks. In a study by the Portland Cement Association (PCA) [Okamoto and Packard, 1989], a field testing program was conducted at six sites, three of these sites were located in Wisconsin and the other three in Pennsylvania. The surface deflection was measured at these sites under single and tandem axles moving at creep speed, 2 mph. The three pavement sections located in Wisconsin were incorporated in the verification study. Finite element meshes were created to match these cross sections and reasonable material properties were assumed. Moving axle loads similar to those used in the field test were considered in the analysis and the total surface deflection from these loads was predicted using the 3D-DFEM. Table 2 shows the measured and predicted deflections. A simple regression analysis between the measured and predicted deflection was done to test how well the predict deflections match the measured ones. The

result of this regression analysis is shown in Figure 8. As can be seen from this figure, the predicted deflections were found to agree very well with the measured deflections ( $R^2 = 99.64\%$ ).

### **5. Sensitivity Analysis**

The verification studies, static and dynamic, were extremely successful in demonstrating the capabilities of the 3D-DFEM. With this background, a sensitivity analysis was conducted to investigate the effect on pavement responses of load parameters, such as speed and axle load magnitude, and cross section parameters, such as slab thickness and dowel bars. One advantage of the 3D-DFEM is the capability of simulating actual truck loads and paving material properties. Therefore, the predicted pavement response is expected to be very close to that occurring in the field. Another advantage of the 3D-DFEM is the capability to predict certain parameters, which no other analysis procedure can do. For example, most of the available analysis procedures can predict the elastic deflection at the subgrade surface. The 3D-DFEM not only predicts the elastic pavement response, but also the plastic (permanent) response. Permanent (plastic) deflection is strongly related to pavement performance.

#### **5.1 Effect of Moving Load Speed**

Previous studies [Idelin et al., 1991] showed that the effect of static loads is more severe than that of moving loads. To investigate the effect of speed on concrete pavement response, a single 18-kip single axle load (SAL)

moving at a creep speed (1.75 mph), slow speed (10 mph) and relatively high speed (30 mph), respectively, was considered. The pavement section in the analysis consisted of a 10" concrete slab, 4" granular subbase and sandy subgrade. A 6 foot tied concrete shoulder having the same cross section was assumed. The predicted horizontal tensile strain and total surface deflection from these loads are shown in Figure 9. Pavement response decreased significantly with an increase in speed from 1.75 mph to 10 mph as compared to that with an increase in speed from 10 mph to 30 mph. The total tensile strain and the surface deflection at 10 mph are 75% and 60% lower, respectively, of those at 1.75 mph. This reduction in the pavement response demonstrates the significance of the speed effect. The speed effect on concrete pavement response is ignored by most of the available analysis procedures.

#### **5.2 Effect of Load Position**

Concrete slabs have limited dimensions. When a load is applied at the center of the slab, the slab distributes the load. When a load is applied at the edge of the slab (close to a transverse joint) only a part of the slab carries the load. Therefore, response (such as deflection) to edge loads is expected to be higher than that to interior loads. To evaluate the effect of load positions on rigid pavement response an 18-kip single axle load (SAL) moving at a speed of 1.75 mph was applied on a 10" undoweled concrete pavement resting directly on a sandy subgrade. The pavement section was assumed to have a 6 feet wide asphalt shoulder, 4" asphalt surface and 10" granular base

course. The load was applied at two positions, center and edge of the slab. The horizontal tensile stress as well as the vertical deflection of the slab is presented in Figure 10 for the center and edge loads. The edge loading increases the vertical deflection and corresponding tensile stress compared to interior loading by 45% and 40%, respectively. The same pavement section was analyzed using Westergaard's equations for interior and edge static loads. The edge load was found to increase the pavement response by similar ratios.

### 5.3 Effect of Subbase Course

One of the purposes of using a subbase course underneath rigid pavements is to provide improved support to the concrete slabs. An 8" undoweled concrete pavement resting on a 4" granular subbase course on the top of a sandy silt subgrade was loaded at the edge with an 18-kip SAL moving at a speed of 1.75 mph. The pavement section was assumed to have a 6 foot untied concrete shoulder with the same section as the traffic lanes. Vertical deflection of this pavement was predicted using the 3D-DFEM and compared with the case of the pavement resting directly on the sandy silt subgrade. These results are shown in Figure 11. The 4" granular subbase course reduces the maximum vertical deflection by 45%.

Joint efficiency for these two sections was calculated as follows:

$$\xi = \frac{2\Delta_1}{\Delta_1 + \Delta_2} * 100$$

Where,

$\xi$  = joint efficiency

$\Delta_1$  = deflection of the second slab edge

$\Delta_2$  = deflection of the first slab edge (where the load is applied)

The relative aggregate interlock joint efficiency using the 4" granular subbase increased from 55% to 66%. This effect is a result of the improved support provided by the subbase.

### 5.4 Effect of Dowel Bars

When a load is applied at one side of an undoweled transverse joint (edge load), a part of this load is transferred to the next slab by aggregate interlock. A load transfer device (dowel bar) is commonly used to insure positive load transfer. In Figure 12, the effect of dowel bars on pavement deflection is shown. Two similar concrete pavements consist of an 8" concrete slab rested directly on sandy subgrade were loaded with an 18-kip SAL moving at speed of 1.75 mph. One pavement cross section was analyzed with no dowel bars and the other assumed to have 1.25" diameter dowel bars with 12" dowel spacing. The joint efficiency of the transverse joint increased from 54% for the no dowel case to 66% with dowels. Also, the maximum vertical deflection was reduced by 20% with dowels. The minimal increase in joint efficiency may be contributed to by the sandy subgrade.

The effect of dowel bar diameter on surface deflection for the same pavement section and speed of loading is shown in Figure 13. One pavement was assumed to have dowels with 1" diameter and 12" spacing, while a

second pavement was assumed to have dowels with 1.4" diameter and 12" spacing. Although the capacity of the 1.4" dowel is higher than that of the 1" diameter dowels, no significant reduction of surface deflection or improvement of joint efficiency is shown. The reason of this is that the 1" diameter dowels have adequate load transfer capacity.

In Figure 14 the effect of dowel bar spacing is shown for the same pavement section and speed of loading. Two similar pavement sections, 8" slab resting on a silt subgrade, was loaded with an 18-kip SAL moving at a speed of 1.75 mph. Both pavement sections were assumed to have 1" diameter dowels. The dowels were spaced 6" apart in one cross section and 20" apart in the other. The joint efficiency was found to increase from 58%, in case of 20" spacing, to 68%, in case of 6" spacing.

The effect of dowel bar length on the surface deflection of the same pavement section and speed of loading is presented in Figure 15. Both pavement sections were assumed to have 1" diameter dowels. An analysis was made for dowel bar lengths of 44" and 88". As can be seen from Figure 16 there is no change in surface deflection for the two dowel bar lengths. This result agrees with previous work done by Friberg 1938 in which it was found that dowel embedment length should be about 8 times the dowel diameter, i.e. 8" embedment length for a 1" diameter dowel.

A stiff subbase course reduces rigid pavement deflections. At the joint, the additional support reduces the differences in deflection from one side of the joint to the other. The effect is an apparent increase in joint efficiency.

An 18-kip SAL moving at a speed of 1.75 mph was applied on an 8" undoweled concrete pavement rested directly on a sandy subgrade. The joint efficiency was found to be 54%. Using a 4" granular subbase course increases the joint efficiency to 63%. Using one inch diameter dowels spaced at 12" without the subbase increases the joint efficiency to 66%. Using both dowels and subbase increases the joint efficiency to 73% (see Figures 12 and 16). Therefore, using a subbase course and dowels can significantly increase joint load transfer efficiency.

### 5.5 Effect of Joint Width

To study the effect of joint width on surface deflection a joint efficiency analysis was made of an 8" undoweled concrete pavement resting on a 4" granular subbase course on a sandy subgrade. The pavement was loaded with an 18-kip SAL moving at a speed of 1.75 mph. Three joint widths were considered in the analysis, 0.25", 0.375" and 1.0". As can be seen from Figure 17, the pavement deflection decreases when the joint width decreases. The relationship between the joint opening and the joint efficiency is presented in Figure 18.

### 5.6 Effect of Axle Loads and Slab Thickness

A non-linear dynamic analysis was conducted to investigate the effect of axle load magnitude and slab thickness on pavement deflection. In this analysis the pavement structure was modeled as a set of layers, concrete slab, subbase course and subgrade. The material behavior of each layer is dependent on the stress level which it is

subjected to. If the stress level is lower than the yield stress of the layer material, the layer will behave as an elastic material. If the stress level is higher than the yield stress, the layer will behave as an elastic-plastic material. In other words, some plastic (permanent) deformation will be developed. In Figure 19 the effect of axle load magnitude and slab thickness on surface deflection are shown. A range of slab thicknesses resting on a 4" granular subbase course was analyzed with a number of single axle loads moving at a speed of 1.75 mph. Each curve in Figure 19 represents a slab thickness. As expected, for low load levels the surface deflection was found to increase as the axle load increases and to decrease as the slab thickness increases. For the range of loads shown in Figure 19 the yield stress of the pavement structure materials was not exceeded and therefore, the pavement response is in the linear elastic range. To show the elastic-plastic behavior of the pavement structure, an 18-kip SAL and a 60-kip SAL were repetitively applied on two pavement sections, 8" and 14" concrete slabs on a 4" granular subbase and clay subgrade. Both loads were applied at a speed of 1.75 mph. The pavement response to these loads are shown in Figure 20. As can be seen from this figure the pavement deflection from the 18-kip SAL is constant with repetition of load. Obviously, the 18-kip SAL did not develop stress levels higher than the yield stress of the pavement layers and therefore the pavement behaved as an elastic structure. For the 60-kip SAL, the pavement deflection increased from the repetition of loads. This indicates the stress level developed by the 60-kip SAL was higher than the yield stress of one

or more of the pavement structure layers or the subgrade, i.e., plastic deformation is developed in one or more of the pavement layers. Plastic deformation of each layer shown in Figure 21 indicates significant accumulation of permanent deformation in the subgrade.

## **6. Summary and Conclusions**

Analysis of rigid pavements based on or derived from Westergaard's equations assumes linear elastic material properties and static loading conditions. Also, it is assumed that the concrete slab has an infinitely long dimension. Studies that have been conducted of rigid pavements using the finite element method (FEM) assume that the concrete slab is a thin or thick plate resting on a Winkler, dense liquid, or elastic solid foundation. Also, static loading conditions are assumed. In either case these assumptions lead to inaccurate predictions of rigid pavement response.

In this paper a three-dimensional dynamic finite element model (3D-DFEM) was used to analyze rigid pavements subjected to moving loads. The linear and non-linear material properties of the different layers were included and the elastic and plastic pavement response were predicted. Two studies were conducted to verify the 3D-DFEM predictions; static, linear elastic and dynamic, non-linear analyses. In the static, linear elastic verification study, the 3D-DFEM predictions were compared with Westergaard analysis, assuming static loads and linear elastic material properties. A high linear correlation was found between the results obtained by the 3D-DFEM and

Westergaard analysis for a wide range of load and pavement geometry. To verify the dynamic, non-linear analysis capabilities of the 3D-DFEM, the 3D-DFEM predictions were compared with field measured pavement deflection. A high linear correlation between the measured and the predicted pavement deflection was found.

The effect of vehicle speed was found to be significant. The maximum surface deflection was reduced by 60% when the speed increased from 1.75 mph to 10 mph.

Subbase courses were found to have a significant effect on pavement deflection and load transfer between slabs. The maximum surface deflection was reduced by 45% with the use of a 4" subbase. Also, the joint efficiency was increased by 11%. A 20% reduction in the maximum vertical deflection and 12% increase in joint efficiency was realized with the use of 1.25" diameter dowels with 12" dowel spacing. It was found that the capacity of 1" diameter dowels is adequate for an 18-kip single axle load moving at speed of 1.75 mph. An analysis of dowel bar lengths commonly used indicated satisfactory performance. Also, Joint width was found to have a significant effect on joint efficiency.

The axle load magnitude was found to have a significant effect on pavement deflection. For low load levels, the relation between load magnitude and pavement deflection was found to be linear. When the load level exceeds a certain limit the relation between the load and slab thickness was found to be non-linear. Also, at high load levels the subgrade was found to behave as an elastic-plastic material and significant plastic (permanent)

deformation could accumulate in the subgrade. This plastic deformation accumulated with load repetitions and indicates the mechanisms by which pavement damage develops from repetitive heavy loads. Also, higher quality of pavement layers should be achieved to prevent severe damage to pavements.

## 7. References

1. "ABAQUS, Finite Element Computer Program," Version 4.9, Hibbitt, Karlsson and Sorensen, Inc., 1989a.
2. "ABAQUS, Finite Element Computer Program," Theory Manual, Version 4.9, Hibbitt, Karlsson and Sorensen, Inc., 1989b.
3. "ABAQUS, Finite Element Computer Program," User Manual, Version 4.9, Hibbitt, Karlsson and Sorensen, Inc., 1989c.
4. Derucher, K. and Korfiatis, G., "Materials for Civil and Highway Engineers," Second Edition, Prentice Hall, New Jersey, 1988.
5. Drucker, D. C., and W. Prager, "Soil Mechanics and Plastic Analysis or Limit Design," Quarterly of Applied Mathematics, Vol. 10, pp. 157-165, 1952.
6. Federal Highway Administration, "Rigid Pavement Analysis and Design," FHWA-RD-88-068, Virginia, June 1989.
7. Friberg, B., "Design of Dowels in Transverse Joints of Concrete Pavements," Proceeding, Highway Research Board, 1938.
8. Idelin, M., Bhatti, M. and Stoner, J., "Nonlinear Response of Rigid Concrete Pavements to Simulated Vehicle Loads, Midwest Transportation Center, Iowa, May 1991.
9. George, K. P., "Resilient Testing of Soils Using Gyrotory Testing Machine," Transportation Research Board, 71 st Annual Meeting, Washington, D.C., January 12-16, 1992.
10. Kim, D. and Stokoe, K. H., "Characterization of Resilient Modulus of Compacted Subgrade Soils Using Resonant Column and Torsional Shear Test," Transportation Research Board, 71 st Annual Meeting, Washington, D.C., January 12-16, 1992.
11. Logan, D., "A First Course in the Finite Element Method," PWS-KENT Co., 1986.
12. Okamoto, P. and Packard, R., "Effect of High Tire Pressures on Concrete Pavement Performance," Proceedings, 4th International Conference on Concrete Pavement Design and Rehabilitation, Purdue University, April 1989.
13. O'Reilly, M. and Brown, S., "Cyclic Loading of Soils: from theory to design," Van Nostrand Reinhold, New York, 1991.

14. Parry, R. H., Editor, "Stress-Strain Behavior of Soils," G. T. Foulis and Co., Henley, England, 1972.
15. Schofield, A., and C. P. Worth, "Critical State Soil Mechanics," McGraw Hill, New York, 1968.
16. Westergaard, H. M., "Stresses in Concrete Pavements Computed by Theoretical Analysis," Public Roads, April 1926.
17. Wood, D., "Soil Behaviour and Critical State Soil Mechanics," Cambridge University Press, 1990.
18. Yoder, E. J. and Witzak, M. W., "Principles of Pavement Design," Second Edition, Hohn Wiley and Sons, Inc., 1975
19. Zaman, M., Taheri, M. and Alvappillai, A., "Dynamic Response of a Thick Plate on Viscoelastic Foundation to Moving Loads," International Journal for Numerical and Analytical Methods in Geomechanics, Vol. 15, 627-647, 1991.

Table 1 Assumptions of the Existing FEM's for Rigid Pavements [FHWA, 1989]

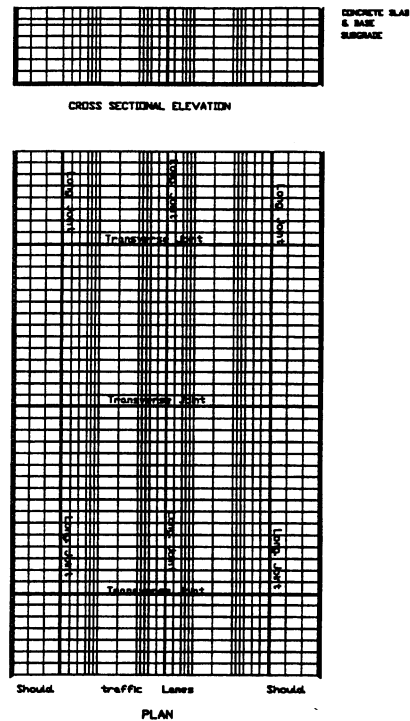
| FEM       | Slab Model  | Subgrade | Load   | Concrete       |
|-----------|-------------|----------|--------|----------------|
| ILLI-SLAB | Thick Plate | Winkler  | Static | Linear Elastic |
| JSLAB     | Thick Plate | Spring   | Static | Linear Elastic |
| Wesliquid | Thick Plate | Winkler  | Static | Linear Elastic |
| Weslayer  | Thick Plate | Elastic  | Static | Linear Elastic |
| JCS-1     | Thick Plate | Elastic  | Static | Linear Elastic |
| RISC      | Thick Plate | Winkler  | Static | Linear Elastic |
| CMS       | Thick Plate | Elastic  | Static | Linear Elastic |

Table 2 Measured and Predicted Pavement Deflections

| Axle Configuration | Axle Load | Slab Thickness | Base Thickness | Measured Deflection | Predicted Deflection |
|--------------------|-----------|----------------|----------------|---------------------|----------------------|
| Single             | 18kip     | 9"             | 6"             | 0.007               | 0.0076               |
| Single             | 18kip     | 8"             | 6"             | 0.009               | 0.0086               |
| Single             | 18kip     | 9"             | 6"             | 0.0085              | 0.0081               |
| Single             | 18kip     | 9"             | 6"             | 0.00817             | 0.00793              |
| Tandem             | 34kip     | 9"             | 6"             | 0.016               | 0.0173               |
| Tandem             | 34kip     | 8"             | 6"             | 0.018               | 0.019                |
| Tandem             | 34kip     | 9"             | 6"             | 0.0165              | 0.0162               |
| Tandem             | 34kip     | 9"             | 6"             | 0.01663             | 0.01773              |

\* All deflections in inches

Figure 1 Finite Element Mesh Configuration



FINITE ELEMENT MESH FOR RIGID PAVEMENT

Figure 2 Rigid Pavement Cross Sections

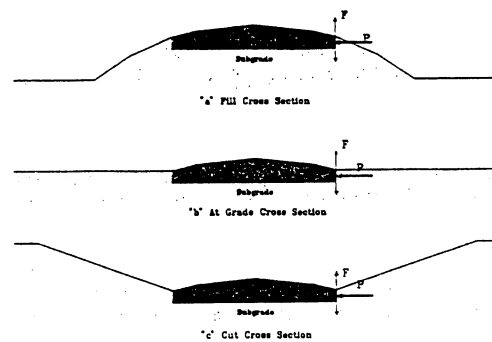


Figure 3 Behavior of Concretes  
[ABAQUS, 1989c]

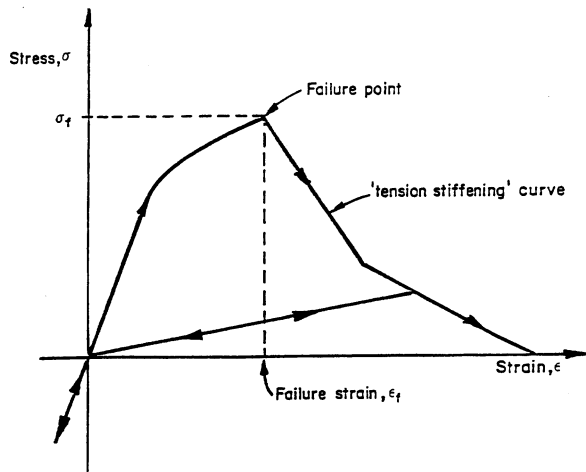


Figure 4 Behavior of Granular Materials  
(Drucker-Prager Model) [ABAQUS, 1989c]

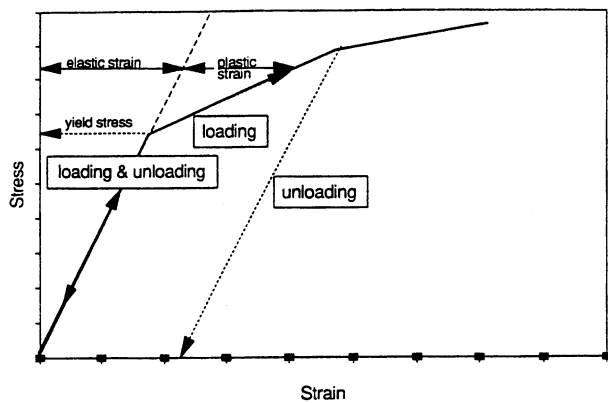


Figure 5 Cam-Clay Model for Cohesive Soils [Wood, 1991]

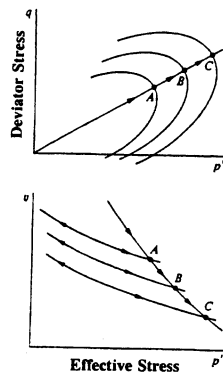


Figure 6 Applied Loading Cycle

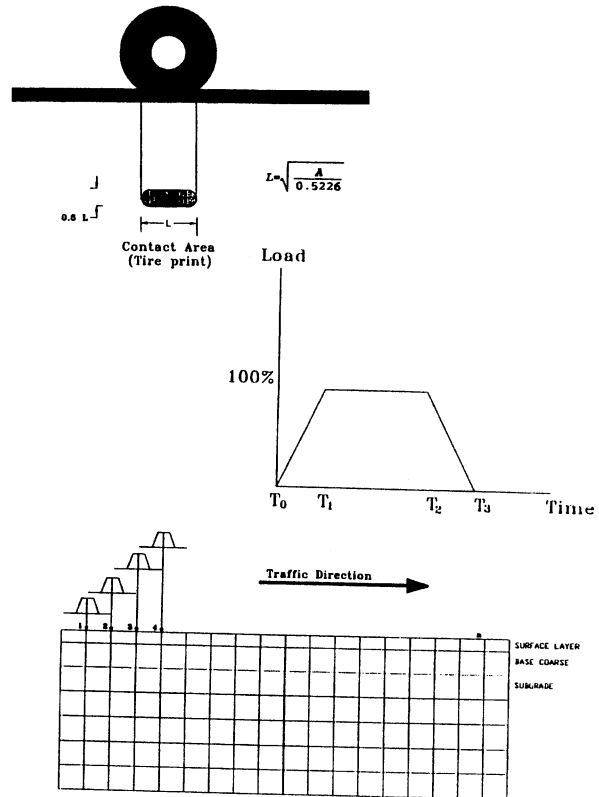


Figure 7 Static Analysis Verification

| SLAB THICKNESS | SUBGRA TYPE | LOAD POSITION |      |          |
|----------------|-------------|---------------|------|----------|
|                |             | CORNER        | EDGE | INTERIOR |
| 6              | SAND        |               |      |          |
|                | CLAY        |               |      |          |
| 10             | SAND        |               |      |          |
|                | CLAY        |               |      |          |
| 14             | SAND        |               |      |          |
|                | CLAY        |               |      |          |

| The SAS System                  |    |                |              |           |        |
|---------------------------------|----|----------------|--------------|-----------|--------|
| General Linear Models Procedure |    |                |              |           |        |
| Dependent Variable: STH         |    |                |              |           |        |
| Source                          | DF | Sum of Squares | Mean Square  | F Value   | Pr > F |
| Model                           | 10 | 1064944.4601   | 106494.4460  | 30.57     | 0.0001 |
| Error                           | 7  | 24382.8016     | 3483.2574    |           |        |
| Corrected Total                 | 17 | 1089327.2616   |              |           |        |
| R-Square                        |    | C.V.           | Root MSE     | STM Mean  |        |
| 0.977617                        |    | 25.72966       | 59.019127    | 229.38167 |        |
| Source                          | DF | Type I SS      | Mean Square  | F Value   | Pr > F |
| SF                              | 1  | 924904.93363   | 924904.93363 | 265.53    | 0.0001 |
| PTYPE                           | 4  | 138903.75286   | 34725.93822  | 9.97      | 0.0051 |
| SF*PTYPE                        | 5  | 1135.77357     | 227.15471    | 0.07      | 0.9958 |

Figure 8 Dynamic Analysis Verification

|                                                                          |              |                       |             |                       |           |   |
|--------------------------------------------------------------------------|--------------|-----------------------|-------------|-----------------------|-----------|---|
| The SAS System                                                           |              |                       |             |                       |           | 7 |
| General Linear Models Procedure                                          |              |                       |             |                       |           |   |
| Number of observations in data set = 8                                   |              |                       |             |                       |           |   |
| The SAS System                                                           |              |                       |             |                       |           | 8 |
| General Linear Models Procedure                                          |              |                       |             |                       |           |   |
| Dependent Variable: MEASURED                                             |              |                       |             |                       |           |   |
| Source                                                                   | DF           | Sum of Squares        | Mean Square | F Value               | Pr > F    |   |
| Model                                                                    | 1            | 0.00139947            | 0.00139947  | 1947.78               | 0.0001    |   |
| Error                                                                    | 7            | 0.00000503            | 0.00000072  |                       |           |   |
| Uncorrected Total                                                        | 8            | 0.00140450            |             |                       |           |   |
| R-Square                                                                 |              | C.V.                  |             | Root MSE              | MEAS Mean |   |
| 0.996419                                                                 |              | 6.781121              |             | 0.0008476             | 0.0125000 |   |
| NOTE: No intercept term is used: R-square is not corrected for the mean. |              |                       |             |                       |           |   |
| Source                                                                   | DF           | Type I SS             | Mean Square | F Value               | Pr > F    |   |
| PREDICTED                                                                | 1            | 0.00139947            | 0.00139947  | 1947.78               | 0.0001    |   |
| Source                                                                   | DF           | Type III SS           | Mean Square | F Value               | Pr > F    |   |
| PREDICTED                                                                | 1            | 0.00139947            | 0.00139947  | 1947.78               | 0.0001    |   |
| Parameter                                                                | Estimate     | T for H0: Parameter=0 | Pr >  T     | Std Error of Estimate |           |   |
| PREDICTED                                                                | 0.9613819643 | 44.13                 | 0.0001      | 0.02178541            |           |   |

Figure 9 Effect of Speed on Pavement Response

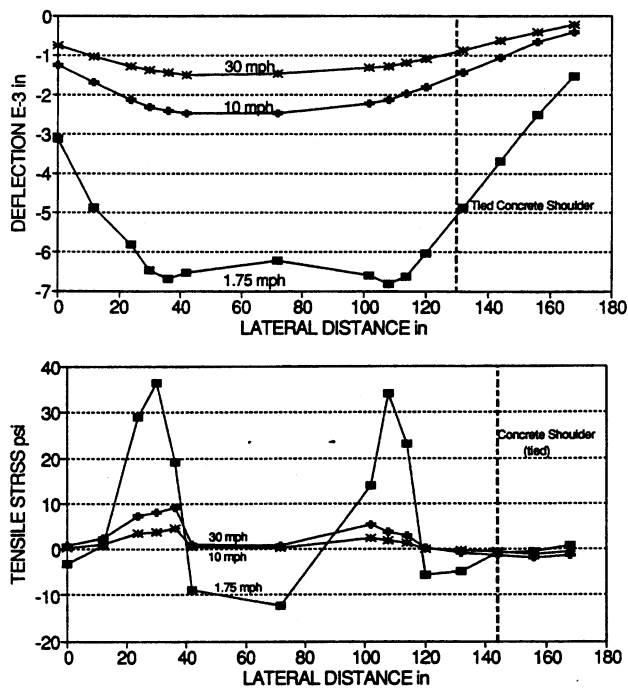


Figure 10 Effect of Load Position on Pavement response

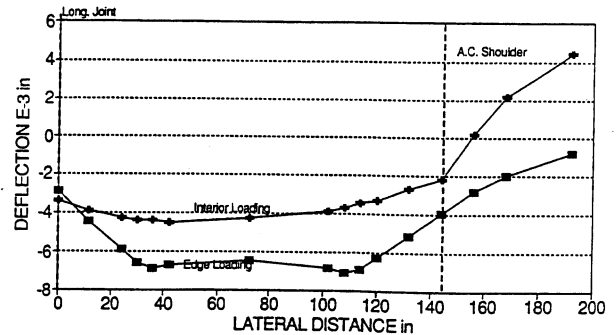
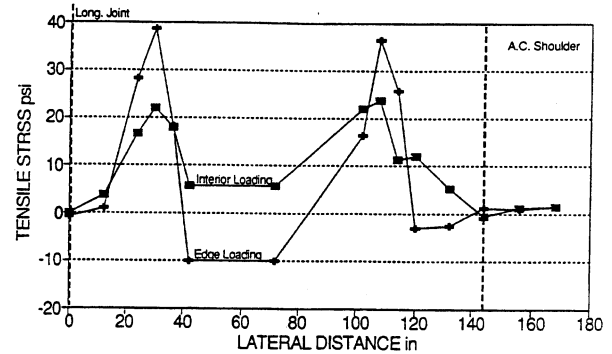


Figure 11 Effect of Subbase on Surface Deflection

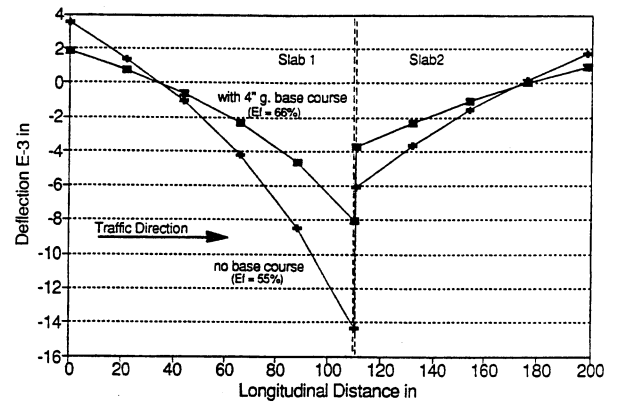


Figure 12 Effect of Dowel Bars on Surface Deflection (No Subbase Course)

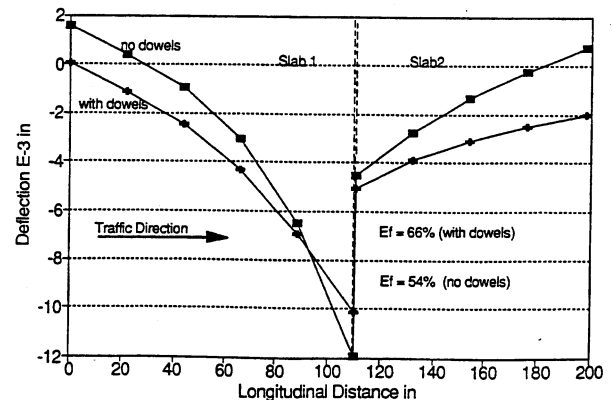


Figure 13 Effect of Dowel Bars Diameter on Surface Deflection

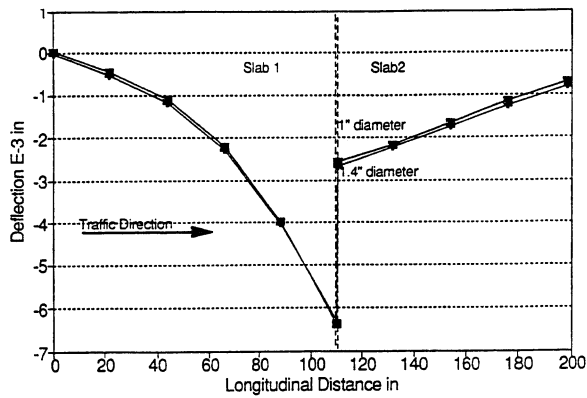


Figure 14 Effect of Dowel Bars Spacing on Surface Deflection

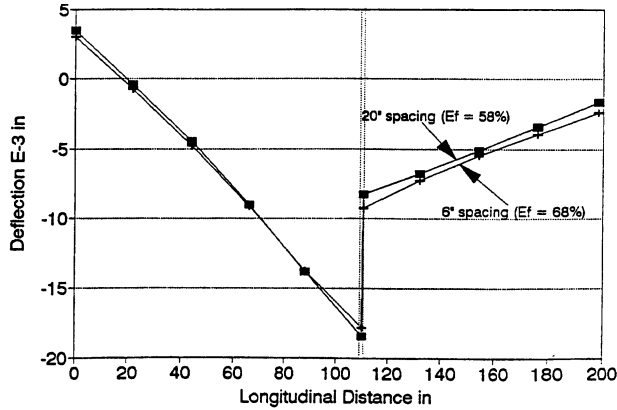


Figure 15 Effect of Dowel Bars Length on Surface Deflection

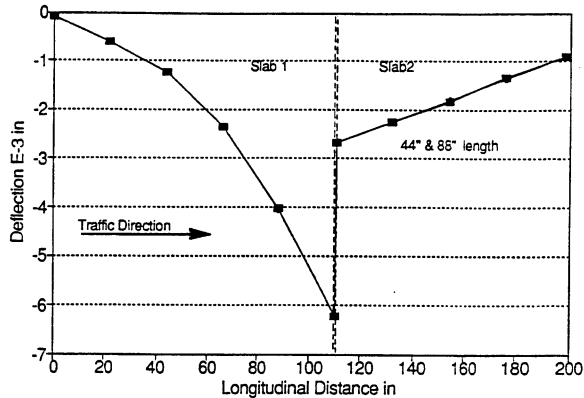


Figure 16 Effect of Dowel Bars on Surface Deflection (4\"/>

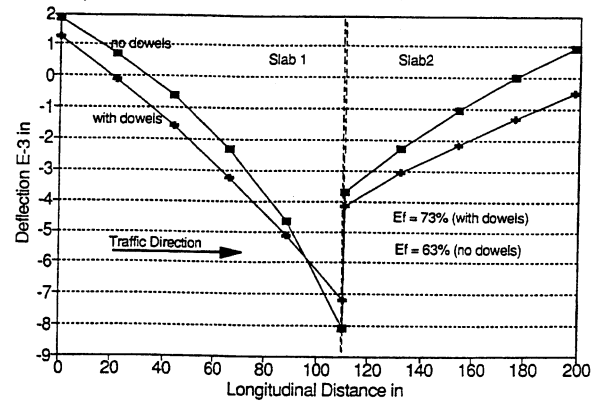


Figure 17 Effect of Joint Width on Surface Deflection

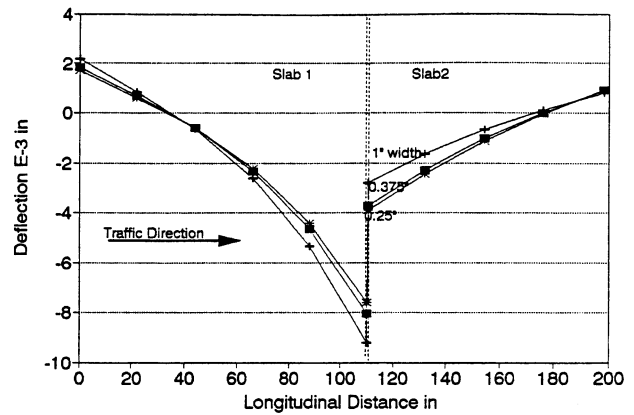


Figure 18 Effect of Joint Width on Load Transfer Efficiency

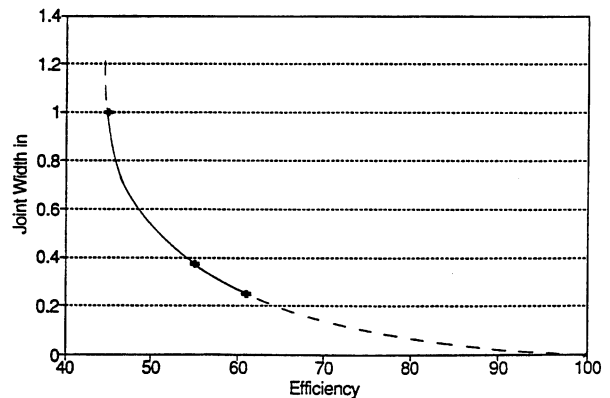


Figure 19 Effect of Axle Load and Slab Thickness on Surface Deflection (Single Axle Configuration)

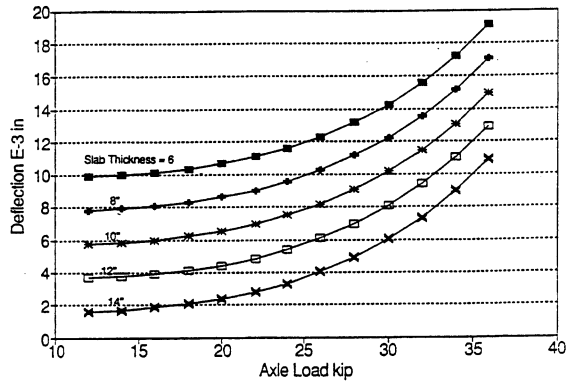


Figure 20 Effect of Load Repetitions on Surface Deflection

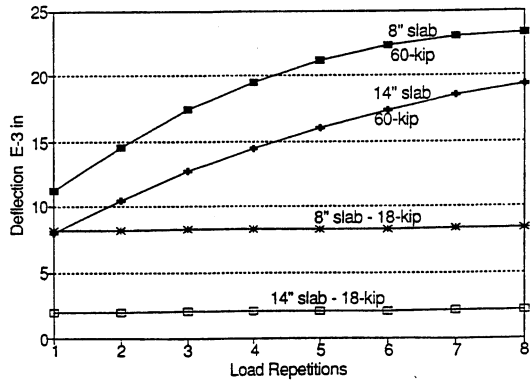


Figure 21 Effect of Load Repetitions on permanent Deformation

