Three-Dimensional Finite Element Model for Analysis of Concrete Pavement Support

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A three-dimensional (3-D) finite element model for concrete pavements called 3DPAVE was developed to analyze the many complex and interacting factors that influence the support provided to a concrete pavement, including foundation support (subgrade k value); base thickness, stiffness, and interface bond and friction; slab curling and warping due to temperature and moisture gradients; dowel and aggregate interlock load transfer action at joints; and improved support with a widened lane, widened base, or tied concrete shoulder. The ABAQUS general-purpose finite element software was used to develop a powerful and versatile 3-D model for analysis of concrete pavements. The 3DPAVE model easily overcomes many of the inherent limitations of two-dimensional (2-D) finite element models that reduce the accuracy of the results obtained from 2-D models. The 3-D model was validated by comparison with deflections and strains measured under traffic loadings and temperature variations at the AASHO Road Test, the Arlington Road Test, and the Portland Cement Association's slab experiments. In every comparison with measured field data, 3DPAVE's calculated responses were found to be in good agreement with the measured responses and significantly closer to the measured responses than those calculated by 2-D programs. The development and validation of the 3DPAVE model are described.

Many pavement researchers have resorted to three-dimensional (3-D) finite element models as the best method of solving complicated structural analysis problems. Two-dimensional (2-D) finite element models have inherent limitations related to plate theory assumptions; thus, many interesting problems cannot be realistically modeled by 2-D finite element programs. Thanks to the development of finite element techniques and computer capabilities and speeds, well-developed versatile 3-D finite element packages are capable of modeling numerous complex mechanisms in engineering problems within tolerable computer run times. A realistic simulated pavement system may then be built in a computer model instead of in the field.

In the 1990s, the general-purpose 3-D finite element package ABAQUS gained popularity in simulating pavement problems concerning nonlinear subgrades, dynamic loading (*1*), and falling weight deflectometer tests (*2*). This paper presents a brief overview of ABAQUS, a summary of the sensitivity study of feasible element types in ABAQUS, a description of the development of a 3-D concrete pavement model with ABAQUS, and a variety of analyses conducted to validate the 3-D concrete pavement model (3DPAVE) by comparison with measured field data from the AASHO Road Test and other experiments.

OVERVIEW OF ABAQUS

ABAQUS has been used widely for stress/strain, fatigue, flow, and thermal analysis in many fields, such as structures, geotechnical engineering, hydrosystems, and materials. It is available in most research computer systems. Because it was not developed specifically for pavements, preparation of an input file requires understanding of the organization of ABAQUS and the conventions of finite element model building. The ABAQUS components used in 3DPAVE are ABAQUS/Standard, a general-purpose finite element program, and ABAQUS/Post, an interactive postprocessing program. A summary of the ABAQUS model input options, element library, materials library, analysis procedures, and postprocessing capabilities is provided elsewhere (*3*).

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FEASIBILITY STUDY OF ELEMENT TYPES

An appropriate element is essential to a good pavement model. It must be capable of simulating pavement behavior realistically and efficiently. Furthermore, ABAQUS provides a wide variety of elements potentially suitable for plate-type problems. A study of element performance is necessary to choose the most appropriate element to build a 3-D model for concrete pavement analysis.

The accuracy of finite element analysis is sensitive to mesh fineness. The mesh must be sufficiently fine, especially in the vicinity of the load, to achieve an acceptable level of accuracy. Different types of elements may require different degrees of mesh fineness to achieve the same accuracy.

2-D Elements

In the first stage of this development process, a 2-D model was developed in ABAQUS and compared with ILLI-SLAB and Westergaard's solutions, which are both based on plate theory. ABAQUS provides a wide variety of shell elements suitable for shell and plate problems. The 2-D element used in ILLI-SLAB and also in the popular general-purpose finite element code FINITE is a four-node rectangular element called RPB12. The rectangular shell elements in ABAQUS provide additional degrees of freedom for consideration of transverse shear, a capability generally considered unnecessary for thin plate modeling. A thin plate is defined as one with a length-to-thickness ratio greater than about 20. (Note that what in the structural analysis literature is called a "thin plate" is often called in the pavement literature a "medium-thick plate" but the definition is the same). Transverse shear may become a significant factor when the loaded area is small or when the slab does not satisfy the thin plate definition.

The maximum stress computed with ABAQUS using an eight-node rectangular element (S8R5) was found to agree well with that of ILLI-SLAB regardless of mesh fineness. This element is not, however, as efficient as ILLI-SLAB's element because it has almost three times as many nodes as the RPB12 element. However, in some cases in which pavement slabs are too thick to be modeled appropriately as thin plates, S8R5 will yield better results than ILLI-SLAB.

The ABAQUS four-node rectangular (S4R5) element did not agree well with the ILLI-SLAB result when a coarse mesh was used but converged to the ILLI-SLAB result with increasing mesh fineness. ABAQUS also provides a linear triangular element (STR135) that has properties similar to the RPB12 element and is efficient in modeling thin plates. The triangular element produces stress results close to those of ILLI-SLAB even with a coarse mesh. However, a triangular element is not as convenient as a rectangular element for modeling rectangular pavement slabs.

3-D Elements

The objectives of this portion of the feasibility study were to select the most appropriate element for a 3-D pavement model and to identify the mesh fineness and other criteria for achieving acceptable accuracy. The 3-D solution should agree with the 2-D solution for slabs that satisfy the thin plate definition. The 3-D solution should also agree with Westergaard's equations, within the range of load sizes for which Westergaard's equations are applicable, for slabs that satisfy the thin plate definition.

Three sets of analyses were conducted in the 3-D element feasibility study. A slab resting on a Winkler foundation was run and compared with Westergaard's interior and edge loading equations. Another set of comparisons dealt with a simply supported rectangular slab with a large distributed load. The results were compared with an analytical solution to investigate the mesh effect. It should be pointed out that both analytical solutions only serve as benchmarks, instead of exact solutions, because these equations are all based on plate theory, which ignores slab compressibility and shear deformation.

Several candidate brick elements were considered. The first one selected was C3D8, which is a linear interpolation element with a node at each corner of a brick. The support is modeled with the FOUNDATION option that requires as input a spring coefficient (e.g., *k* value). After several runs with various mesh designs, it was concluded that the C3D8 linear element does not compare well with Westergaard's solution. Even when a single pavement layer was meshed up to four layers of bricks elements with aspect ratio 1:1:1, the results did not show significant improvement. Therefore, the C3D8 element was ruled out in later comparisons.

The next category of brick elements considered was quadratic elements, which have a node at each corner and also a node at the midpoint of each edge. According to the *ABAQUS Example Problems Manual* (*4*)," quadratic elements perform well even with a coarse mesh. There are many types of quadratic elements provided in the ABAQUS element library. According to finite element theory (*5–7*), some 3-D elements may lock when the major deformation mode is bending, which usually happens in transversely loaded plate problems. Reduced integration elements should be used to remedy this problem. Thus, only two quadratic elements, C3D20 and C3D20R (the latter with reduced integration), were considered further.

C3D20R converged to Westergaard's analytical solution for stress better than the C3D20 element did in a finer mesh. The two elements gave almost the same deflections for various meshes. The calculated vertical compressibility of the concrete slab in these examples was about 5×10^{-5} in. (1.3×10^{-3} mm), or $\epsilon_{zz} = 0.01$, which is less than 0.7 percent of deflection. This justifies one of the hypotheses for thin plate theory that transverse compressibility (ϵ_{zz}) of the plate is negligible in some cases.

However, the vertical shear stresses are significant compared with the maximum stresses, about 15 percent of the maximum tensile stresses. This shows that the assumption of neglecting transverse shear in thin plate theory is not appropriate in some cases. The following observations were made based on the sensitivity analysis results:

- High shear stresses only occur in the vicinity of the loaded area. Most of the plate has no significant transverse stresses. Westergaard mentioned this problem and developed an equation based on special theory to take the shear deformation near a small loaded area into account.
- Load size plays a key role. Although the length-to-thickness ratio of the plate analyzed was 50, which satisfies the thin plate criterion, a small load may still violate plate theory in the vicinity of the loaded area. When the load is distributed over a large area, transverse shear should be negligible as assumed in thin plate theory.

Performance of 3-D Elements Versus 2-D Elements

Another issue in developing a 3-D model is how 3-D results compare with 2-D results. They are not expected to match in all cases because some plate responses are neglected in 2-D model formulation. Agreement of 2-D and 3-D models can only be expected when the plate is sufficiently thin, the load size is sufficiently large, the meshes meet requirements for accuracy, and the problem is restricted to the type for which 2-D models apply.

Interior Loading Case

To compare the 2-D and 3-D elements for various meshes and loading sizes, a series of runs was made using different elements and changing the loading area, while holding the load magnitude, slab size, thickness, modulus, Poisson's ratio, and subgrade *k* constant. The interior and edge stresses and deflections were computed using Westergaard's equations, ILLI-SLAB and FINITE (2-D models), 2-D elements in ABAQUS (STR13, S4R, and S8R), and the 3-D brick element in ABAQUS (C3D20R).

Westergaard's interior stress equation predicts lower stresses than the finite element results at small load sizes and predicts higher stresses than the finite element results at large load sizes. The latter trend supports the statement that Westergaard's equations apply only when the loaded area is small in comparison with the radius of relative stiffness (*7*). However, the transverse shear effect may become significant when the loaded area approaches a point load. Consequently, Westergaard's interior stress equation agrees with the 3-D model within an intermediate range of load area size. Research on load size effects on 2-D finite element results has shown the same conclusion (*8*).

Interior stress results were similar for nearly all of the 2-D and 3-D element types over a wide range of load sizes. The exception was the ABAQUS 2-D S4R element, which was expected to agree more closely with the 3-D results than the other elements because it takes into account transverse shear.

Interior deflections for all element types converge as the load size increases, but Westergaard's deflection solution diverges from the finite element solutions as the load size increases. In the range of small load sizes, the finite element deflection results form two groups: one group consists of the ABAQUS element types that consider transverse shear, and the other group consists of the ILLI-SLAB, FINITE, and ABAQUS STR13 element types that ignore transverse shear.

These results indicate that 2-D elements are capable of good agreement with 3-D results for interior stress over a wide range of load sizes, but a discrepancy exists over a wide range of load sizes between the interior deflections computed using 2-D elements and those computed using 3-D elements.

Edge Loading Case

Another set of sensitivity runs was conducted for edge loading, using load sizes from 9 to 36 in. (229 to 914 mm) square, and all of the other parameters the same except for the slab size, which was a constant 10 by 20 ft (3 by 6 m). The edge stresses and deflections were computed using Westergaard's equations, ILLI-SLAB and FINITE (2-D models), 2-D elements in ABAQUS (STR13 and S8R), and the 3-D brick element in ABAQUS (C3D20R).

The edge stress results indicate that Westergaard's edge solution agrees with the 3-D finite element solution until the load size becomes larger than about 20 in. (508 mm) square. The RPB12 element (used in ILLI-SLAB and FINITE) predicts somewhat higher edge stresses than do the shell and solid elements in ABAQUS. This discrepancy narrows as the load size becomes larger. Thus, it might be explained by the transverse shear effect in edge loading being slightly more significant than in the interior loading situation. Further investigation of this is needed. Although STRI3 is a thin shell element like RPB12, the geometry and different formulation (e.g., using 6 degrees of freedom instead of 3 degrees of freedom in RPB12) might explain the gap between the STRI3 and ILLI-SLAB edge stress curves. However, the gap is less than 5 percent even under very concentrated loading.

Westergaard's edge deflection solution diverges dramatically from all of the finite element solutions as the load size increases. The edge deflections computed with ABAQUS using the 2-D S8R element and the 3-D C3D20R element are higher than the edge deflections computed with ILLI-SLAB, FINITE, and the STR13 element over the full range of load sizes examined. The gap narrows with increasing load size.

The edge loading results using the 3-D model agree with the 2-D model results for slabs that could be considered thin plates, that is, having length-to-thickness ratio of 20 or less. However, in analysis of thicker and smaller slabs that did not satisfy the definition of a thin plate, discrepancies between the 3-D and 2-D results became more significant. The edge loading comparison may be summarized as follows:

- The performance of various element types in edge loading is similar to that in interior loading.
- Thin plate elements produce either higher or lower stresses than solid elements. Transverse shear effects might be responsible for these discrepancies.
- Westergaard's edge stress and deflection solutions are best suited for small loads.
- Good agreement between the 3-D and 2-D models is achieved for edge deflection and stress results when the slab is a thin plate (i.e., when the length-to-thickness ratio is more than 20.) Below this limit progressively greater discrepancies exist.

Element Proportions

In finite element analysis, a balance must be achieved between accuracy of results and efficiency of computation. The mesh must be sufficiently fine to yield results with an acceptable level of accuracy. However, computer storage space and CPU time increase with mesh fineness. In 3-D analysis with solid elements, not only the horizontal fineness of the mesh but also its vertical fineness may be important to the accuracy of results. An examination of the sensitivity of solid element size was conducted to assess its significance. Instead of placing a plate on a foundation, a simply supported plate under interior loading is considered, because the responses of a simply supported plate are more sensitive to changes in the analysis parameters than a plate resting on a foundation. The load was applied over a large area to eliminate the effect of transverse shear caused by concentrated loading.

Compared with the exact solution derived by thin plate theory, the maximum stress calculated with the solid element model yielded less than 2 percent discrepancy even with the coarse mesh ($2a/h = 2$). The mesh becomes more plate-like as this ratio increases. Therefore, the model will lose accuracy if it is meshed with a plate-like solid. For highway pavements, the $2a/h$ ratio rarely exceeds 1 under normal truck wheel loads if the model is meshed no larger than the load size. Hence, the mesh fineness will generally be satisfactory from the standpoint of accuracy if the element aspect ratio $2a/h$ is less than 2. For larger loaded areas it may be necessary to divide the loaded area into multiple elements.

Limitations of 2-D Models and Motivation for 3-D Model Development

The previous comparison of 2-D and 3-D element types demonstrates that it is possible, with careful element selection and mesh definition, to achieve good agreement between 2-D and 3-D models, for the limited range of problems that 2-D models are able to solve. The performance comparison is necessarily limited to those types of problems. The motivation for developing 3DPAVE was that many aspects of concrete pavement behavior cannot be realistically modeled in two dimensions. Among the aspects considered important to this study are the following:

- Curling or warping of a slab off a base layer: In 2-D models the slab and base always have the same curvature, and though the layers may be unbonded horizontally, the slab and base can never be any distance apart at any node.
- Direct modeling of nonlinear or unequal temperature, or both, or moisture gradients in the slab and base: A 2-D element is by its nature incapable of modeling a nonlinear gradient within a single pavement layer. The 2-D models such as ILLI-SLAB are also incapable of modeling unequal gradients in the slab and base. Although ILLI-SLAB allows different slab and base gradients as input, the program converts these into a single linear gradient through the full slab and base thickness. Some 2-D methods represent a nonlinear gradient by an equivalent linear gradient or add the stresses due to linear and nonlinear components of the total nonlinear gradient. A direct and more realistic analysis of the effects of nonlinear gradients through the slab or base, or both, requires a 3-D model.
- Widened base, widened lane, and mismatched joints and cracks: In 2-D models the horizontal boundaries of the slab and base must coincide. 3-D modeling permits analysis of more realistic

geometries in which the slab and base have mismatched edges, joints, and cracks.

- Friction coefficients and horizontal and vertical bond strengths: These interface characteristics can be directly and realistically modeled in 3-D. In 2-D models, layer interfaces can only be bonded or unbonded.
- Thicker pavement and base cross sections: Transverse shear stress is significant for thicker cross sections but cannot be considered in analytical solutions (e.g., Westergaard) based on medium-thick plate theory or in most of the available 2-D programs.
- Layer compressibility: 3-D modeling permits direct definition of the compressibility of the slab and base layers. In 2-D plate models all layers above the subgrade are incompressible.

In addition to these capabilities, a 3-D model developed within a powerful and versatile finite element package such as ABAQUS provides the potential to model a wide variety of other pavement behaviors that would be of interest to other research efforts. Some of these are

- Dynamic loading,
- Viscoelastic behavior,
- Temperature-dependent properties,
- No tension in unbound materials,
- Explicit modeling of steel reinforcement (for JRCP and CRCP),
- Variable joint width and variable load transfer in doweled or undoweled joints,
- Stress-dependent response of unbound materials, and
- Concrete behavior beyond the elastic range, including inelastic response, cracking failure, and behavior after cracking.

DEVELOPMENT OF 3DPAVE MODEL

The 3DPAVE model was developed by first developing a 2-D model, to gain experience with the many options and commands of ABAQUS, and then upgrading the 2-D model to a 3-D model. Each step in the development process involved many challenges in model input, element properties, execution problems, results checking, and so forth.

3-D Solid Element (Brick Element)

On the basis of the element study presented earlier, C3D20R was selected as the standard element for this model. However, the C3D20R element had difficulty converging to a solution when contact problems were modeled. Because it is important to be able to model the mechanisms of contact and loss of contact when a slab curls on top of a stiff base, the C3D27R element was used in place of the C3D20R element. C3D27R is a variable node element, similar to C3D20R but with extra nodes on faces that are contact surfaces.

By using the quadratic elements C3D20R and C3D27R it is possible to model a bilinear temperature gradient through the slab, using the nodes at the top, middle, and bottom of the element. More nonlinear temperature distributions may be modeled with multiple layers of C3D27R elements. However, modeling a slab with multiple layers instead of a single layer dramatically increases the computer run time. Thus, unless the stress distribution through the slab depth is a major concern, a single-layer mesh is considered adequate for calculation of curling stresses at the top and bottom of the slab.

Interface Element

To investigate the effects of separation between layers, interface friction, and bonding, the interface should be modeled. ABAQUS provides many interface elements for surface contact problems. The INTER9 element is an interface element that can be used with the C3D27R element. Detailed interface responses (e.g., vertical contact stress or separation, and horizontal stress or slip) may be calculated when this element is used in the model. Further studies of complex behavior under loading, such as crack growth, are also available in the options associated with this element.

The interface element can be either no thickness, which is the case when two layers are in contact, or can have a thickness equal to the distance between two layers of nodes to simulate an initial gap. Analyses involving separation between layers, such as curling or erosion problems, require several iterations to converge to a solution.

Subgrade Modeling

Dense liquid foundations and elastic solid foundations can easily be modeled in ABAQUS. For a dense liquid foundation, a keyword FOUNDATION is available for all solid, shell, and membrane elements to provide spring support under elements. However, introducing interface elements between the slab and subgrade hinders the use of the dense liquid foundation because FOUNDATION is not compatible with interface elements. Hence, when the FOUNDATION option is used, a membrane element should be used below the interface element so that the dense liquid foundation can be modeled under the interface element. The stiffness and thickness of the extra membrane layer is minimal to eliminate its effect on slab stresses. To investigate the error caused by this membrane layer, the results from two models were compared with no curling, one model with brick elements directly resting on the foundation, and another model incorporating the interface and membrane elements between the slab and the foundation. The differences in maximum stresses and deflections were all less than 0.05 percent.

To model the subgrade as an elastic solid foundation, layers of brick elements may be used to a depth at which the foundation deflection is assumed to be negligible. This requires the determination of the depth to which deflection is expected, and it takes much more computer storage space and execution time to complete one run because of the number of elements. An alternative that addresses both of these drawbacks is to use infinite elements, a new feature in ABAQUS.

Bonding and Friction

In ABAQUS version 5.2, new options named DEBONDING and BOND SURFACE have been added for advanced modeling of contact problems. Users may specify debonding criteria or debonding mechanisms as parameters of the keyword DEBONDING. Separation between layers may also be modeled with DEBONDING. Two fatal problems with these new options were found during the model development. Because of these difficulties, alternative methods were developed to consider vertical and horizontal interface stresses together.

Vertical bonding may be specified without vertical separation, or a vertical bond strength may be specified. With the latter option, the layers are allowed to separate when the vertical interface stress exceeds the specified bond strength. If two layers are vertically bonded, the output file will print the vertical stresses at each node. If separation occurs, the vertical interface stress is zero and the gap size will be reported in the output file.

Friction (horizontal bonding) may be modeled using a variety of parameters provided by ABAQUS. One option is full bond, which is equivalent to a friction coefficient approaching infinity. Another option is classical Coulomb friction with an optional limit on the shear stress. Some relative motion (elastic slip) is permitted when the interface is still sticking. Permitting a large amount of relative motion during sticking makes convergence of the solution more rapid, at the expense of local solution accuracy. Permitting only a small amount of relative sliding motion better simulates behavior in which no slip is permitted in the sticking state, but requires more iterations to converge. A variable degree of bonding may be modeled by specifying the ultimate bonding stress that can be carried by the bond in the field. After a load is applied, some region may remain bonded, whereas bond breaks at those nodes whose calculated interfacial shear stresses exceeds the ultimate bond stress.

The situation with no bonding but accounting for friction at the interface may be achieved by specifying a realistic friction coefficient. The last situation is fully unbonded and no friction considered. This case may be modeled by setting the friction coefficient and vertical bond strength to zero.

Dowel Bars and Aggregate Interlock

Dowel bars are modeled in 3DPAVE with beam elements. Unlike the dowel models available in 2-D programs, the use of beam elements in ABAQUS eliminates the need to assign bending stiffness and shear stiffness values to the dowels elements. Instead, only physical properties (i.e., steel elastic modulus, bar diameter, and dowel spacing) are needed. When dowel bars are modeled in 3DPAVE with beam elements, the results agree with those obtained from ILLI-SLAB with a high dowel-concrete interaction factor (high load transfer). An option is available in ABAQUS to allow the dowel bars to slip relative to the slab.

Aggregate interlock is modeled in a straightforward manner by formulating the joints connecting slabs by shear springs. Finding the spring stiffness that represents the load transfer provided by aggregate interlock has been a subject of research (*9*). For the same shear interlock stiffness, ABAQUS and ILLI-SLAB yielded close values of load transfer efficiency and maximum slab stresses.

A schematic illustration of the 3DPAVE model is shown in Figure 1. More detailed information on its development is provided elsewhere (*10*).

VALIDATION OF 3DPAVE

Validation of the new model was the next and most important step of its development. Validation was done by comparison with full-scale field test data.

AASHO Road Test

The comparison between 3DPAVE and AASHO Road Test measurements was made with the data measured on the main loops. The main loop test was set up to measure the edge deflections and strains under moving truck loads. These data are valuable because the measured location was fixed at the midslab edge, whereas Loop 1 measurements were located at various positions and only the maximum strain data reported.

Stress Validation

According to the AASHO Road Test vehicle specifications (*11*), air pressure in the tires was maintained to ensure that the contact pressure was uniform for all test vehicles and axle loads. Thus, in the 3DPAVE model validation runs, contact pressure was held constant and load size was varied with varying axle load magnitudes. Finite element meshes were adjusted to match the tire prints that changed as axle loadings changed. Also, meshes were refined when the plate thickness was less than the smallest element width.

The primary subgrade *k* value test conducted at the AASHO Road Test was for the elastic *k*, which was obtained from measurements of the elastic deformation of the subgrade (not including permanent deformation) under a 30-in.-diameter (762-mm) plate after a 15-sec loading. The mean elastic *k* value for springtime conditions was 86 psi/in. (23 kPa/mm) (*12*). However, it is reasonable to expect that a higher *k* value is required to match the deflections and stresses measured on the main loops under wheel loads moving at 30 mph (48 km/hr). Simulation of single-axle and tandem-axle loads on the main loops showed that the stresses computed from measured field-

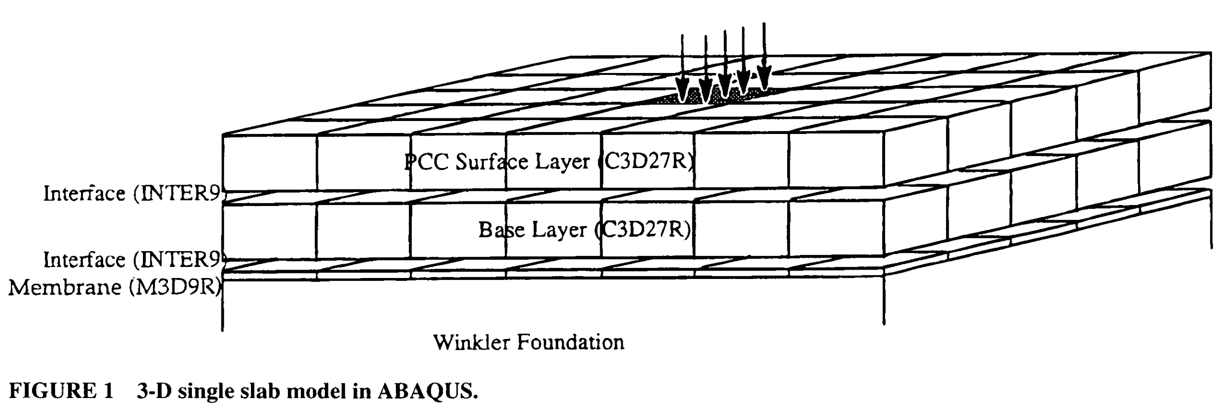


FIGURE 1 3-D single slab model in ABAQUS.

measured strains matched closely with those computed by the 3DPAVE model when the subgrade k value was selected as 170 psi/in. (46 kPa/mm), which is about double the measured plate load k_E. AASHO Road Test stresses calculated from measured strains are compared with stresses computed using 3DPAVE in Figure 2.

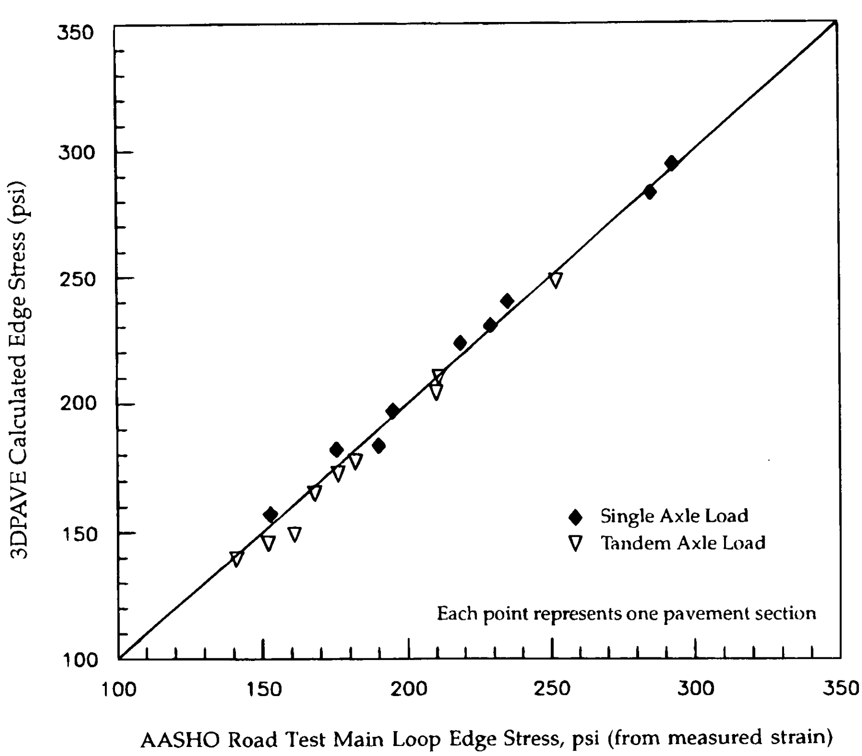
k Value Traffic Speed

At the AASHO Road Test, deflections and strains were measured for a range of truck speeds from creep speed to 60 mph (97 km/hr). An equation to compute the reduction factor for deflection and strain measured on the main loops for any speed between 2 and 60 mph (3.2 and 97 km/hr) was provided (*12*). Because the main loop tests were conducted at a speed of 30 mph (48 km/hr), the strains and deflections measured at the speed may be used in the empirical equation (*12*) to estimate the deflections and strains at creep speed. These results were used to develop a relationship for the AASHO Road Test main loop experiment between k value and speed. 3DPAVE was run to analyze the axle loads on the main loop slabs using a range of k values, and the stresses and deflections obtained were used to calculate reductions factors from the creep speed deflections and strains. These reduction factors were used to determine the speed corresponding to each input k value. For example, the estimated k value for creep speed loading is about 75 psi/in. (20 kPa/mm), which is close to the elastic k value of 86 psi/in. (23 kPa/mm) obtained by plate load tests on the subgrade.

Crack Initiation Location at AASHO Road Test

Crack development locations were recorded at the AASHO Road Test. Cracks in thin slab sections [3.5 and 5 in. (89 and 127 mm)] were first observed along the wheelpath, starting at the transverse joint. In thick slabs (6.5 to 12.5 in.), cracks most often developed from the edge at midslab.

To verify crack initiation in thin and thick slabs with 3DPAVE, two pavements with slab thicknesses of 4 and 12 in. (102 and 305 mm) were modeled with loads applied at various positions. Examination of the principal stress contours from 3DPAVE confirms that in thin slabs the highest stress occurs at the bottom of the slabs when the wheel load is at the joint. The critical loading position for thicker



PCC E = 6.25 million psi [43063 MPa]
PCC μ = 0.28
k = 170 psi/in [46 kPa/mm]
Speed = 30 mph [48 km/hr]
Axle load range = 12 to 48 kips [53 to 214 kN]
Slab thickness range = 6.5 to 11 inches [165 to 279 mm]
1 psi = 6.89 kPa
3DPAVE/AASHO stress ratio range is from 0.93 to 1.03
Mean 3DPAVE/AASHO stress ratio is 1.00
R^2 = 0.99
n = 18

FIGURE 2 3DPAVE calculated stresses versus AASHO Road Test stresses from measured strains.

slabs [6.5 in. (165 mm) and greater] is midslab loading. The highest stress is located at the bottom of the slab at the longitudinal edge, which is also where transverse cracks initiated.

PCA Tests on Cement-Treated Bases

The Portland Cement Association conducted tests in the 1950s to investigate the responses of pavements with cement-treated bases (*13*). Many designs were constructed and tested in the laboratory. Among the sections for which data are available, fully bonded sections were analyzed with 3DPAVE because no detailed information was provided in the report for the other sections with various interface treatments.

Comparisons were made for both interior loading and free edge loading conditions. Because edge loading deflections of slabs with bonded bases were only available in "edge with ledge" sections [i.e., the base extended 1 ft (0.3 m) beyond the edge of the slab], a widened base was modeled in 3DPAVE. This is easily accomplished by constructing the two layers with brick elements and then removing a row of brick elements from the edge of the slab layer.

In addition to 3DPAVE, the analysis was also performed with ILLI-SLAB and the Westergaard equations. Figure 3 shows the deflection comparisons for interior loading. For the 3DPAVE and ILLI-SLAB analyses, the *k* value used for each section was the value measured by the PCA in plate load tests on the subgrade at that location. For the computation using Westergaard's equation, the *k* value used was the value measured by the PCA in plate load tests on the cement-treated base at that location. 3DPAVE model and ILLI-SLAB predict interior deflections very well for the 5-in. (127 mm) slab sections on 6-in. (152 mm) and 9-in. (229 mm) cement-treated bases. Some scattered results are observed for 7-in. (178 mm) slabs (7B6,7B9). In general, every analysis method predicted fairly well for interior loading conditions.

For edge loading conditions, the 3-D model results match the measured deflections much better than the other conventional analyses, as shown in Figure 4. Again, for the 3DPAVE and ILLI-SLAB analyses, the *k* value used for each section was the value measured by the PCA in plate load tests on the subgrade at that location. For the computation using Westergaard's equation, the *k* value used was the value measured by the PCA in plate load tests on the cement-treated base at that location. Significant gaps between both the ILLI-SLAB and Westergaard results and the measured test data and 3DPAVE results illustrate the improved capability of the 3-D model. Because Westergaard's solution and ILLI-SLAB are not capable of considering a widened base, they tend to overpredict deflections. The 3DPAVE successfully reproduced the PCA pavement test results with widened bases.

Arlington Road Test

Data from the Arlington Road Test provide curling stresses computed from measured strains (*14*). These field results were compared with 3DPAVE analysis results as well as results obtained using ILLI-SLAB.

Longitudinal edge stresses in the Arlington Road Test slabs were computed from measured strains during periods of maximum thermal gradients for several days in 1934. For this comparison, a linear temperature distribution was assumed in the 3-D finite element model and no wheel loading was applied. The stresses computed from the measured strains for the 6- and 9-in. (152- and 229-mm) slabs and the computed finite element edge stresses are compared in Figure 5.

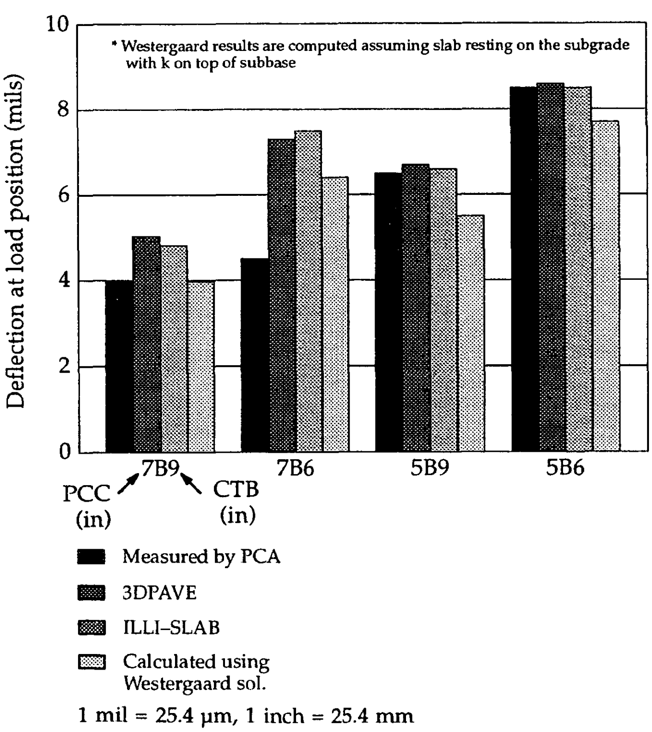


FIGURE 3 PCA data versus computed results for interior loading.

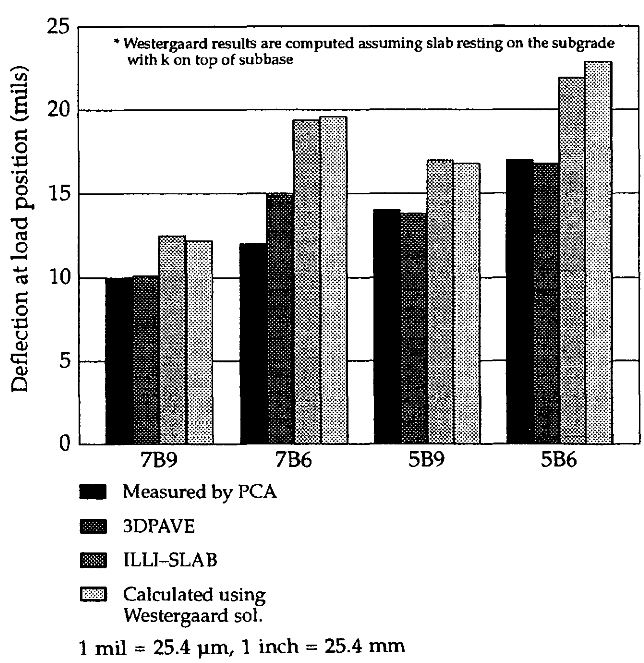
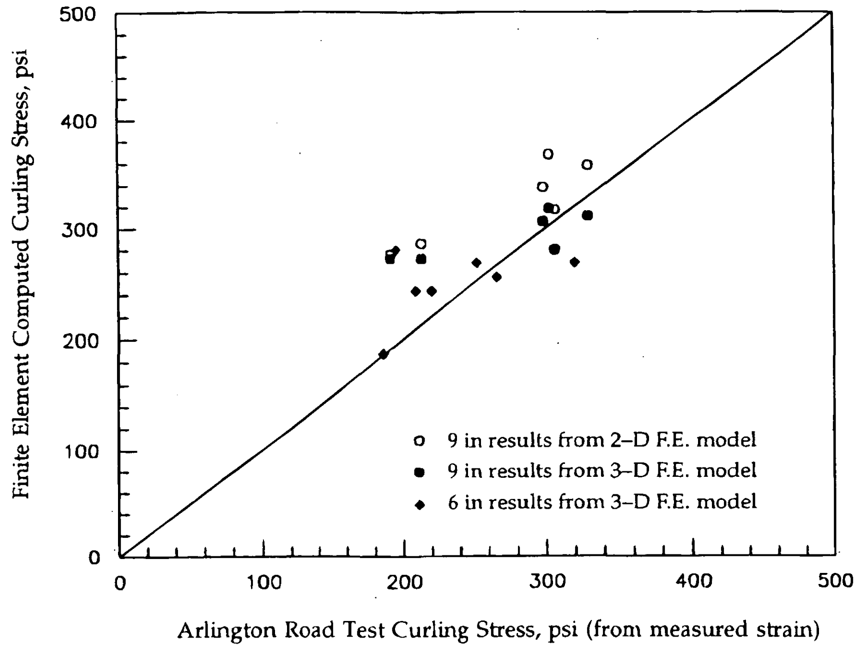


FIGURE 4 PCA data versus computed results for edge loading.



PCC E = 5 million psi [34450 MPa]
PCC μ = 0.15
PCC α = 5 x 10^{-6}/°F [2.78 x 10^{-6}/°C]
PCC γ = 144 lb/ft^3 [3295 k N/m^3]
k = 200 psi/in [54 kPa/mm]
1 in = 25.4 mm
1 psi = 6.89 kPa

FIGURE 5 Curling stresses in Arlington Road Test slabs, computed from measured strain and from 2-D (ILLI-SLAB) and 3-D (3DPAVE) finite element models.

As noted in research by Darter and Barenberg (*15*), the curling stresses computed by the 2-D finite element program are higher than the stresses computed from measured strains. This is demonstrated in Figure 5 by the 2-D results all being above the equality line. However, the stresses computed using 3DPAVE not only generally agree with the measured stresses but also are distributed on both sides of the line. These results provide additional evidence that the 3DPAVE model has been properly built to handle temperature curling and demonstrates its predictive capability.

CONCLUSIONS

3DPAVE, a 3-D finite element model for concrete pavements was developed to analyze the complex and interacting factors that influence the support provided to a concrete pavement, including the following:

- Foundation support (subgrade *k* value);
- Base thickness, stiffness, and interface bond or friction;
- Slab curling and warping due to temperature and moisture gradients;
- Dowel and aggregate interlock load transfer action at joints; and
- Improved support with a widened lane, widened base, or tied concrete shoulder.

The ABAQUS general-purpose finite element software was used to develop a powerful and versatile 3-D model for analysis of concrete pavements. The 3DPAVE model outperformed the 2-D model and Westergaard's solutions for a variety of problems.

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