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Suitability of Using the Falling Weight Deflectometer in Determining Deteriorated Areas in Jointed Rigid Pavements

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ABSTRACT

In this study the suitability of using the falling weight deflectometer (FWD) to determine deteriorated areas in rigid pavements was investigated. The FWD deflection basins of a few hypothetical concrete pavements of three types of deficiency conditions were calculated by using the finite-element analysis computer program WESLIQUID. These computed deflection basins were then compared with the deflection basin of a reference pavement that was in good condition. The three types of deficiency conditions studied were pavements with (a) weak subgrades, (b) voids in the subgrade beneath the concrete slab, and (c) deteriorated concrete slabs. Two FWD loading positions were considered: loading at the center of a pavement slab, and loading near the joint of the slabs. The results of the study indicate that the three different types of concrete pavement distress give three distinctly different FWD deflection basin shapes. The distinction among these three types of FWD deflection basins can be more easily understood by considering the differences between the FWD deflection of the pavement considered and that of a standard pavement of the same dimension that is loaded at the same position ($D-D_s$). The type and extent of the pavement distress could be determined from the shape and the magnitude of the $D-D_s$ plot. The results of the study also indicate that the effects of the joint are insignificant when the applied FWD load is far away from the joint.

In recent years the falling weight deflectometer (FWD) has been used by many state highway agencies in the evaluation of the performance of rigid and flexible pavements. The FWD test system consists of a loading system, a series of six or seven deflection sensors, and an automatic data recording system. The test system measures the deflection basin caused by a dynamic load on the pavement structure. The test load is applied by a weight dropped from a specified height to a circular loading plate. The falling weight load simulates to some degree the dynamic vehicular load on the pavement structure. The FWD test configuration is variable in terms of the radius of the loading plate, the magnitude of the applied load (by changing the drop height), and the positions of the deflection sensors. Currently, there are still no commonly accepted standard test configurations. Further study is needed to determine the most appropriate test configurations as well as the most effective use of the FWD in pavement evaluation.

One of the main functions of a pavement structure is to protect the subgrade from excessive deformation under the expected vehicular loads. As a pavement deteriorates with use, the deflection of the pavement under the same load increases. Although the magnitude of the maximum pavement deflection caused by an FWD load can indicate the degree of pavement deterioration, it is believed that the deflection basin can give indications of the type of structural deficiency encountered. Deterioration in a concrete pavement may be caused by (a) problems in the concrete material, such as delamination and cracking, caused by the use of poor quality materials or improper design and construction; (b) a weak subgrade, caused by a high water level or freezing and thawing; or (c) voids in the subgrade beneath the concrete slab, caused by the pumping action of water. It is envisioned that the deflection basins of the concrete pavement obtained from the FWD tests can be used to identify these three types of deficiency and to determine the extent of the deteriorated areas. An accurate determination of the type and extent of deterioration in concrete pavements will facilitate the proper selection of maintenance or rehabilitation methods on these pavements.

In this study the FWD deflection basins of a few hypothetical concrete pavements of various conditions were computed by using a finite-element analysis computer program. The theoretically computed FWD deflection basins were then evaluated to determine if they could be used to identify the type and extent of distress in concrete pavements. The three major types of pavement deterioration considered in this study were (a) poor concrete pavement materials, (b) weak subgrades, and (c) voids in the subgrade beneath the pavement slabs. Two FWD loading positions were considered in this study: loading at the center of a pavement slab, and loading near the joint of the slabs. The results from this theoretical study will provide an assessment of the usefulness of the FWD and a theoretical basis for further field testing and verification.

DESCRIPTION OF STUDY

Modeling of Concrete Pavements

The finite-element analysis computer program WESLIQUID, developed by the U.S. Army Corps of Engineers Waterways Experiment Station (1), was used to perform the computations. The WESLIQUID program models a concrete pavement slab as an assemblage of rectangular plate bending elements, and models the subgrade as a dense liquid by means of a series of linear elastic springs. It has the capability to model subgrade voids, slab boundaries, and joint conditions. Subgrade voids are modeled as gaps between the concrete slabs and the springs. Load transfers across a joint are modeled by means of shear and moment efficiencies. The efficiency of shear transfer is the ratio of vertical deflection along the joint between the unloaded (or less loaded) slab and the more heavily loaded slab. It is an effective way of modeling load transfer through dowel bars or aggregate interlocks at the joints. The efficiency of moment transfer is defined as the ratio between the actual moment and the full moment, which is determined by assuming that the rotations on both sides of the joints are the same. When a joint has a load transfer device such as a dowel or tiebar, which can resist a degree of bending moment, some moment transfer across a joint will be possible. However, in this study a moment transfer efficiency of zero was assumed in all analyses.

Modeling of FWD Loads

One of the higher FWD drops used by the Florida Department of Transportation (DOT) was used as the FWD load in the analyses in this study. This specific FWD drop produced a pressure of 217 psi (1500 kPa) on an 11.8 in. (300 mm) diameter load plate (2), with a total equivalent static load of 23.8 kips (106 kN). The FWD load was modeled as a static load of 23.8 kips applied uniformly over a 10.5 x 10.5-in. (266 x 266-mm) square area that resulted in a uniform pressure of 217 psi. The circular load plate was approximated by a square of the same area as required by the finite-element program.

Modeling of Distress Conditions

The three types of structural deficiency in concrete pavement as described earlier were considered in the analyses. Pavements with deterioration in the concrete slab were modeled as having a reduced stiffness (elastic modulus) in the concrete material. Pavements with a weak subgrade were modeled as having a reduced subgrade stiffness. Pavements with pumping problems and voids in the subgrade beneath the concrete slabs were modeled as having gaps of certain heights between the concrete slab and the spring support at the locations of the voids. These conditions are shown in Figure 1.

Research Approach

The deflection basins of a reference concrete pavement under an FWD load of 23.8 kips (106 kN) were computed for center load and joint load conditions. The reference concrete pavement used in the analyses represented a typical plain jointed concrete pavement of good condition. The concrete material was assumed to have an elastic modulus (E) of 4×10^6 psi (27.6 GPa), and a Poisson's ratio (μ) of 0.2. The subgrade stiffness was assumed to be 400 lb/in.^{3} (pci) (1.09×10^8 N/m^3), and there were no voids in the subgrade. The concrete slabs had a uniform thickness of 9 in. (229 mm), a length of 20 ft (6.1 m), and a width of 12 ft (3.7 m). When the center load was considered, a three-slab system was used in the analysis. When the joint load was considered, a two-slab system was used. These two cases are illustrated in Figures 2 and 3, respectively. Slabs farther away from the load do not have significant effects on the response of the pavement, and thus do not have to be considered in the analysis.

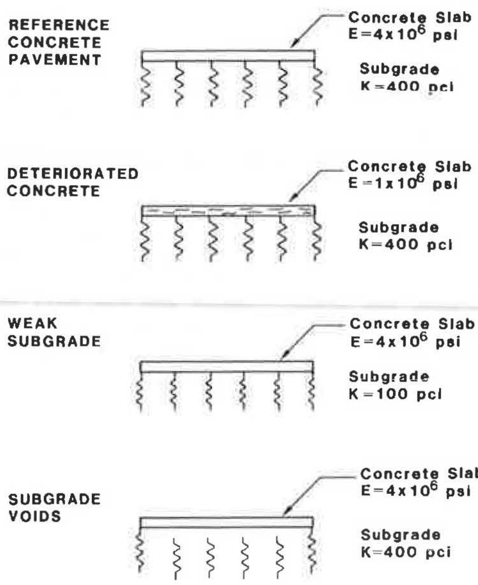


FIGURE 1 Modeling of distress conditions in concrete pavement.

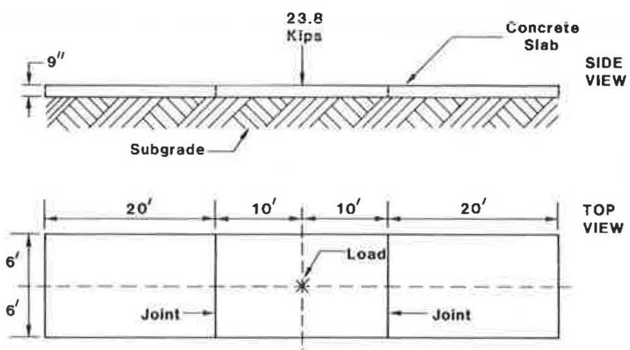


FIGURE 2 Three-slab system for analysis of center load.

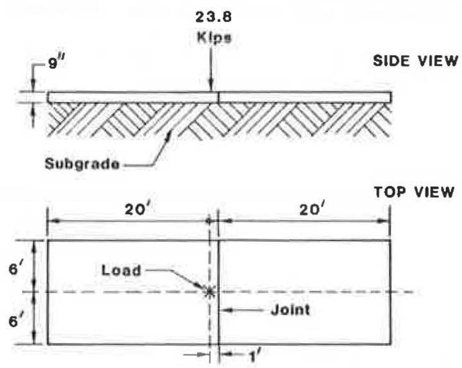


FIGURE 3 Two-slab system for analysis of joint load.

Computations were then made for the deflection basins of a few hypothetical deteriorated concrete pavements under the same FWD load (23.8 kips) at the same two positions (center and joint loads). The same dimensions (9 in. x 12 ft x 20 ft) of slabs were used. The computed deflection basins of these pavements were then compared with the deflection basins of the reference pavement.

RESULTS OF THE STUDY

Effects of Subgrade Stiffness and Joint Shear Transfer

The results of the analyses indicated that the FWD deflection basin would generally shift downward, while remaining in roughly the same shape, as the subgrade stiffness was reduced. The effects of subgrade stiffness on the computed FWD deflection basins of a concrete pavement loaded at the center of the slab are shown in Figures 4 and 5. Figure 4 shows the deflection plots along the longitudinal (or horizontal) line through the point of load, and

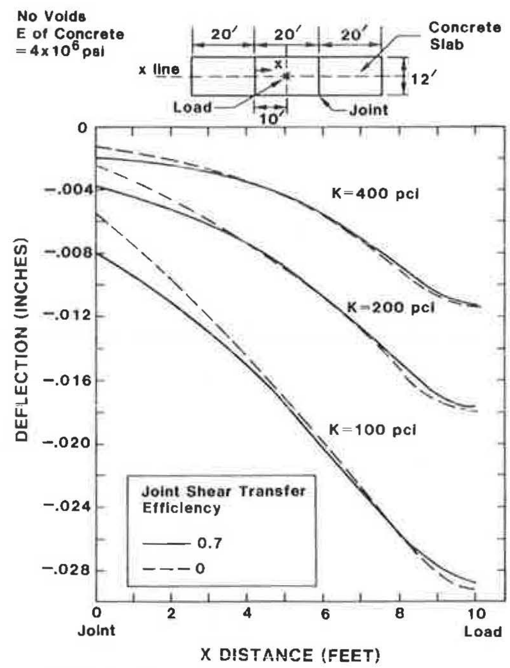


FIGURE 4 Effect of subgrade stiffness on computed longitudinal FWD deflection basins of a concrete pavement loaded at the center.

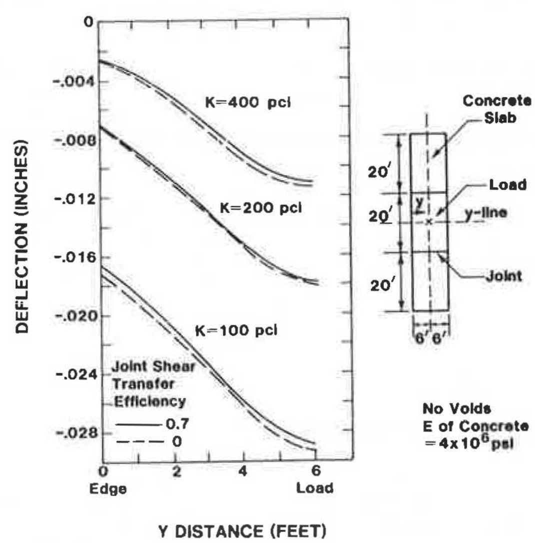


FIGURE 5 Effect of subgrade stiffness on computed transverse FWD deflection basins of a concrete pavement loaded at the center.

Figure 5 shows the deflection plots along the transverse (or vertical) line through the point of load.

Figures 6 and 7 show the effects of subgrade stiffness on the computed longitudinal and transverse FWD deflection basins of a concrete pavement loaded at a position 1 ft (305 mm) from the middle of the joint. The same trend can be observed here. As the subgrade stiffness was reduced from 400 to 100 pci (1.09 x 10^8 to 2.73 x 10^7 N/m^3), the FWD deflection basin shifted downward, while remaining in roughly the same shape.

Two joint shear transfer efficiencies were used in the analyses: 0.7 and 0. A joint shear transfer efficiency of 0.7 models the behavior of a good joint, across which a large portion of shear forces can be transferred. A joint shear transfer efficiency of 0 models a joint across which no shear forces can be transferred. The results of the analyses indicate that when the applied load is far away from the joint, the effects of joint shear transfer become insignificant. As seen in Figures 4 and 5, in the case of loading at the center of the slab, the FWD deflection basins computed from the use of a shear efficiency of 0.7 are not much different from ones that use a shear efficiency of 0. When the applied load is near the joint, the effects of the joint become significant. As shown in Figures 6 and 7, in the case of loading near the joint, the FWD deflection basins computed from the use of a shear efficiency of 0.7 are significantly different from ones that use a shear efficiency of 0.

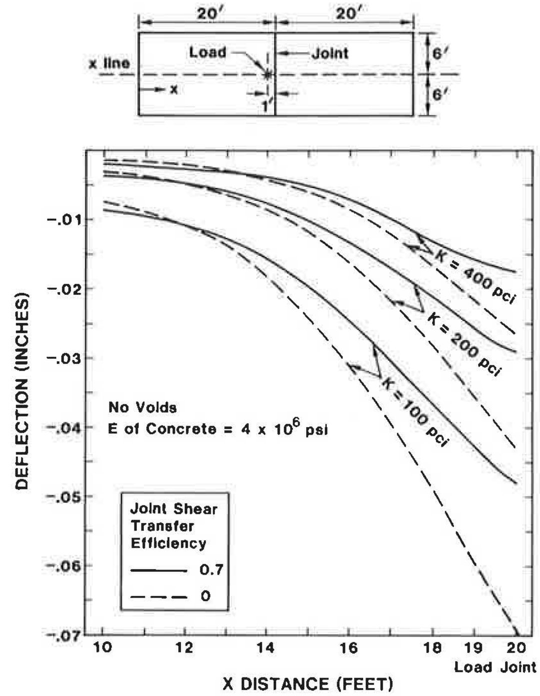


FIGURE 6 Effect of subgrade modulus on computed longitudinal FWD deflection basins of a concrete pavement loaded at the joint.

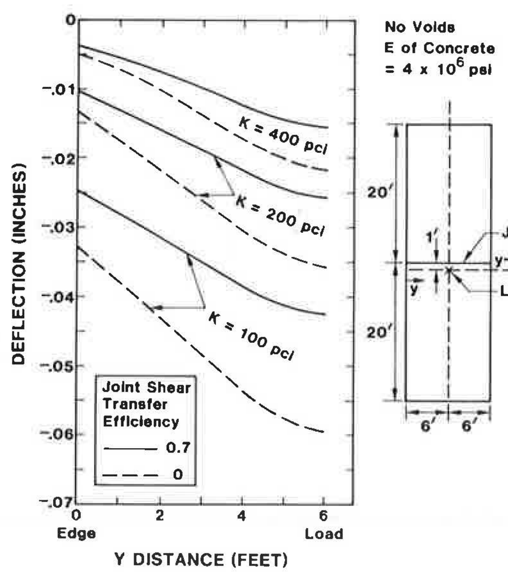


FIGURE 7 Effect of subgrade modulus on computed transverse FWD deflection basins of a concrete pavement loaded at the joint.

Effects of Subgrade Void Size

The effects of subgrade void size on the computed FWD deflection basins are presented in this section. Subgrade voids of a uniform depth of 0.75 in. (19 mm) and of various square areas were placed at the positions of the applied FWD load; deflection basins were computed by using a joint shear transfer efficiency of 0.7. The elastic modulus of the concrete was 4 x 10^6 psi (27.6 GPa) and the subgrade stiffness was 400 pci (1.09 x 10^8 N/m^3).

Figures 8 and 9 show the effects of subgrade void size on the computed longitudinal and transverse FWD deflection basins of a concrete pavement loaded at the center of the slab. It can be noted that the magnitude of the maximum deflection increases as the size of subgrade void increases. When compared with the deflection basin of the reference pavement that has no subgrade voids, it is noted that the more significant increase in deflection occurs at and near the locations of the voids.

Figures 10 and 11 show the effects of subgrade void size on the computed longitudinal and transverse FWD deflection basins of a concrete pavement loaded at a position 1 ft (305 mm) from the middle

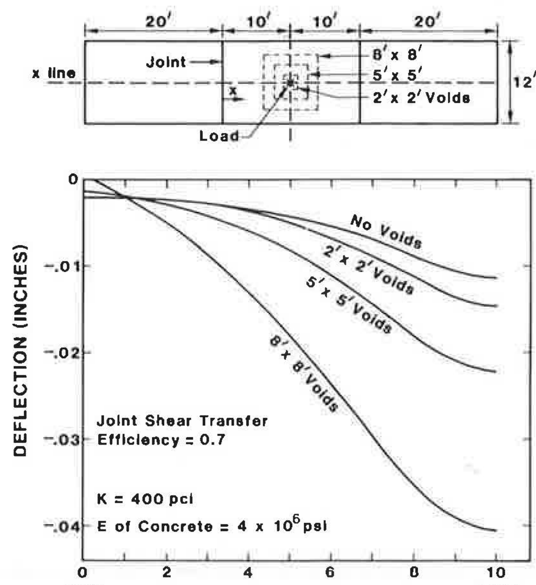


FIGURE 8 Effect of subgrade void size on computed longitudinal FWD deflection basins of a concrete pavement loaded at the center.

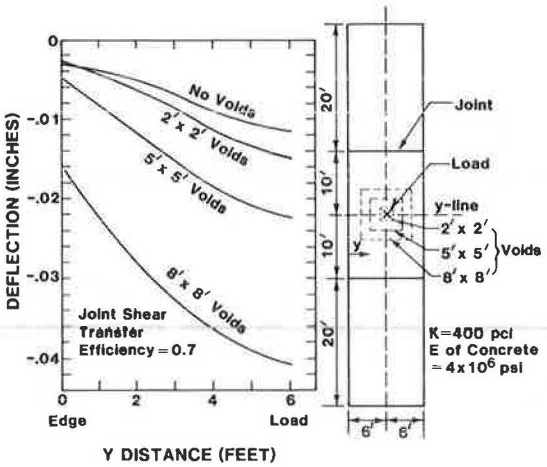


FIGURE 9 Effect of subgrade void size on computed transverse FWD deflection basins of a concrete pavement loaded at the center.

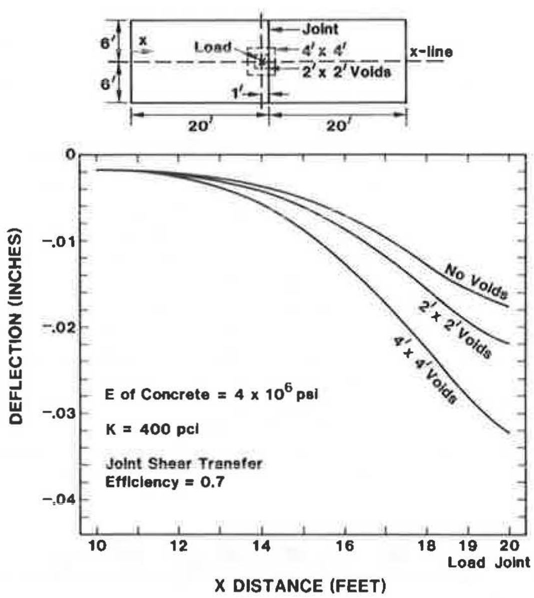


FIGURE 10 Effect of subgrade void size on computed longitudinal FWD deflection basins of a concrete pavement loaded at the joint.

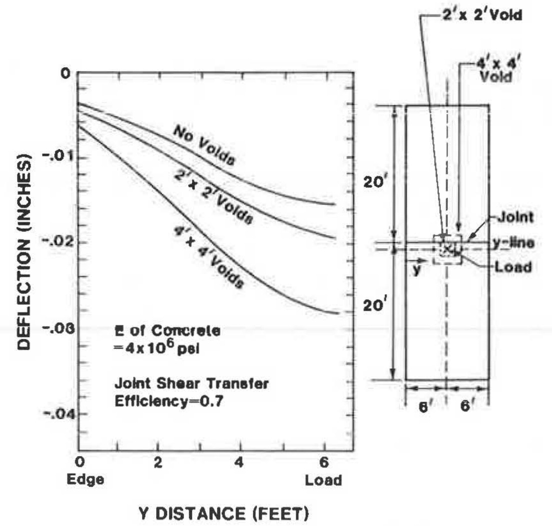


FIGURE 11 Effect of subgrade void size of computed transverse FWD deflection basins of a concrete pavement loaded at the joint.

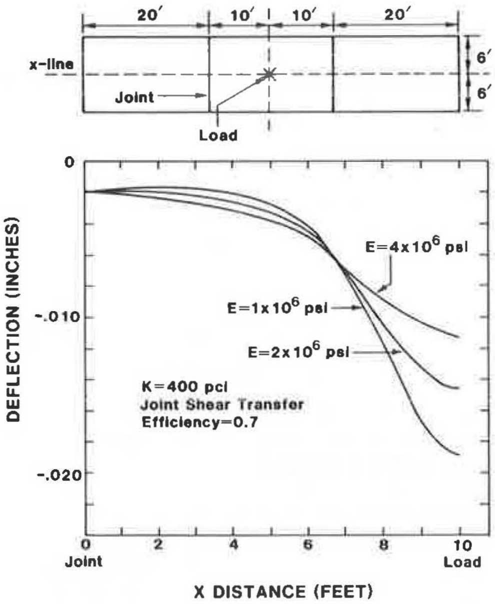


FIGURE 12 Effect of elastic modulus of concrete on computed longitudinal FWD deflection basins of a concrete pavement loaded at the center.

of the joint. The same trend can be noted here. The more significant increase in deflection, when compared with the deflection basin of the reference pavement, occurs at and near the locations of the voids.

Effects of Elastic Modulus of Concrete

Pavements with deterioration in the concrete slab were modeled as having a reduced elastic modulus in the concrete material. The effects of reduced elastic modulus of concrete on the computed FWD deflection basins are presented in this section.

Figures 12 and 13 show the effects of elastic modulus of concrete on the computed longitudinal and transverse deflection basins of a concrete pavement loaded at the center of the slab. A subgrade stiffness of 400 pci (1.09 x 10^8 N/m^3) and a joint shear transfer efficiency of 0.7 were used to model pavement behavior. It can be noted that the magnitude of the maximum deflection increases as the elastic modulus of the concrete pavement material decreases. When compared with the deflection basin of the reference pavement, note that the more significant increase in pavement deflection (with the decrease in elastic modulus of concrete) occurs only at and near the applied load. At more than a certain distance [about 3 ft (0.9 m) in this case] away from the load, the change in elastic modulus of concrete has little effect on pavement deflection.

Use of FWD Deflection Basins

It is clear from the results presented in the previous section that the three different types of structural deficiency in concrete pavements give three distinctly different FWD deflection basin

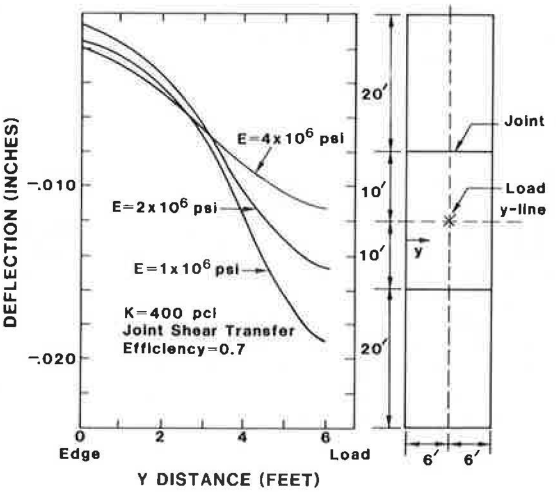
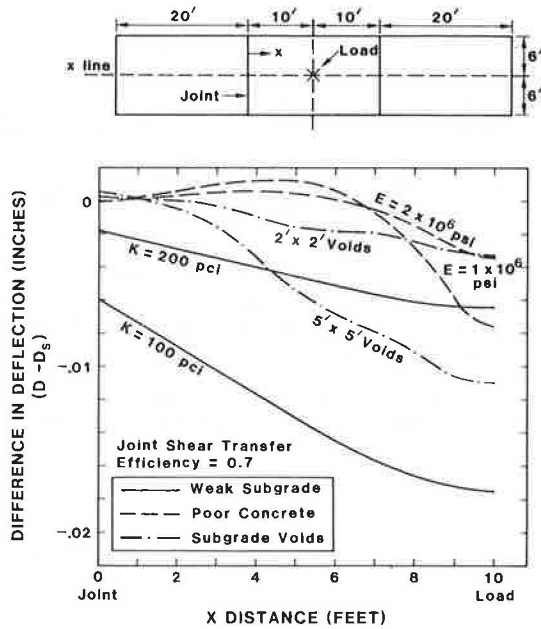


FIGURE 13 Effect of elastic modulus of concrete on computed transverse FWD deflection basins of a concrete pavement loaded at the center.

shapes. Although the shape of the FWD deflection basin appears to be related to the type of distress, the magnitude of the FWD deflection appears to be related to the severity of the distress conditions. When compared with the FWD deflection basin of a reference concrete pavement of good condition, the deflection basin of a concrete pavement with a weak subgrade is relatively higher in magnitude while having roughly the same shape. The FWD deflection basin of a concrete pavement with voids in the subgrade reveals relatively higher deflections at and near the location of the voids. The FWD deflection basin of a pavement with deterioration in the concrete slab reveals relatively higher deflections at and near the position of the FWD load.

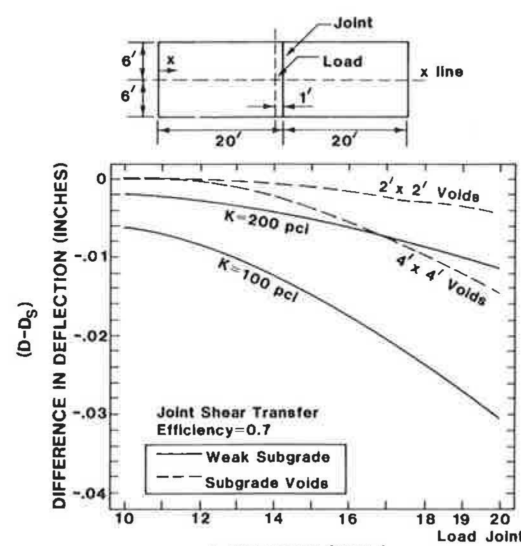
The distinction among these three types of FWD deflection basins can be more easily seen by considering the differences between the FWD deflection of the pavement considered (D) and that of a standard pavement (D_s) of the same dimension, loaded at the same position. Figure 14 shows the plots of these differences in deflection ($D-D_s$) for the computed longitudinal FWD deflection of a concrete pavement loaded at the center. For the three types of concrete pavement deficiency, three distinctly different families of $D-D_s$ plots can be observed. The $D-D_s$ plot for the weak subgrade condition is nearly linear, and slopes downward toward the position of the FWD load. The $D-D_s$ plot for the pavement with subgrade voids is approximately equal to zero at some distance away from the location of the voids, and curves downward sharply at and near the location of the voids. The $D-D_s$ plot for the deteriorated concrete condition is approximately equal to zero at some distance away from the FWD load, turns slightly upward as it moves toward the load, and then curves downward sharply as it approaches the load. An increase in the deterioration condition is indicated by an increase in the magnitude of the $D-D_s$ plot.

Figure 15 shows the $D-D_s$ plots for the longitudinal FWD deflection of a concrete pavement loaded at the joint. The two pavement deficiency types shown in this figure are the weak subgrade condition and the subgrade voids condition. Similar trends are observed here. The $D-D_s$ plot for the weak subgrade condition slopes downward toward the position of the FWD load in a nearly linear fashion. The $D-D_s$ plot for the condition of the subgrade voids is approximately equal to zero at some distance away from the location of the voids, and curves downward sharply at and near the location of the voids.



NOTE: D - Deflection of the pavement system considered
D_s - Deflection of the standard pavement system (E = 4 x 10^6 psi, K = 400 pci)

FIGURE 14 Difference in computed longitudinal FWD deflection of a concrete pavement loaded at the center.



NOTE:
D ——Deflection of the Pavement System Considered
D_s ——Deflection of the Standard Pavement System (E=4x10 psi, K=400 pci)

FIGURE 15 Difference in computed longitudinal FWD deflection of a concrete pavement loaded at the joint.

In order to use the FWD deflection basins effectively for determining deteriorated areas in rigid pavement, the FWD deflection basin of a reference pavement of known properties must be obtained first. The type and the extent of the pavement distress can then be determined from the shape and magnitude of the $D-D_s$ plot.

CONCLUSIONS

The results of this analytical study indicate that the deflection basins measured by the FWD could be used to determine the type and severity of structural deficiency distress in a jointed rigid pavement. The effective use of these FWD deflection basins would require comparing them with the FWD deflection basin of a reference pavement of the same dimension and loaded at the same position. The results of the study also indicate that the effects of the joint are insignificant when the FWD load is applied at some distance away from the joint. The results of this study provide some guidelines for further field testing and verification of the FWD method.

The effects of temperature differentials between the top and bottom of the concrete slab were not considered in this study. The conclusions thus only apply to the condition when the temperature differential is zero.

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