Evaluation of a Dual-Load Nondestructive Testing System To Better Discriminate Near-Surface Layer Moduli

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Theoretical analyses were conducted to illustrate the inability of the existing single-load falling weight deflectometer (FWD) to discriminate among near-surface layer moduli of flexible pavement systems. Comprehensive analyses were also conducted to show that this deficiency can be overcome by using a dual-load FWD when the loads are spaced sufficiently apart to induce a concave downward curvature in the pavement surface between the loads (transverse deflection basin). The analyses showed that the asphalt concrete modulus is strongly, and almost uniquely, related to the curvature of this transverse deflection basin, whereas the base course modulus is strongly, and almost uniquely, related to the shape of the longitudinal deflection basin. This strong correspondence was shown to hold true for a broad range of pavement geometries and layer moduli. Stress and deformation analyses were conducted to show that the dual-load system works because the shape of the transverse deflection basin is most strongly influenced by the bending moments induced within the asphalt concrete layer between the loads, and by the relatively large changes in vertical compression that are induced in the asphalt concrete layer within this zone. Neither of these effects is observed in the base course, which explains the lack of influence of the base course on the shape of the transverse deflection basin. Finally, an analysis was conducted to select load radii and spacing, and deflection sensor positions that optimize the capabilities of a dual-load system to discriminate among near-surface layer moduli. It was shown that a set of relatively simple equations can be developed to determine (backcalculate) pavement layer moduli obtained from surface deflection measurements using the dual-load system proposed.

Nondestructive testing is now a commonly accepted method for pavement structural evaluation. The surface deflections produced under a load are routinely used for determining pavement layer moduli in analysis and design. Of the numerous devices that have been developed for this purpose, the falling weight deflectometer (FWD) is probably the most widely used. Its advantages include simplicity, capability to use variable loads, and the claim that the loading induced by the instrument closely simulates a moving wheel load. However, several disadvantages are also associated with the instrument.

Ruth et al. (*1*) and Badu-Tweneboah et al. (*2*) showed that the deflection basin resulting from the single-load FWD did not allow for accurate discrimination of different pavement layer moduli, particularly the moduli of near-surface layers. They also showed that deflections resulting from a dual-load system such as the dynaflect allowed for better discrimination of near-surface layer moduli when appropriate deflection measurements were obtained. They used a modified sensor configuration that defines deflection basins in both the longitudinal and transverse directions. However, the relatively small and fixed load levels used by the dynaflect system are a distinct disadvantage, particularly when determining effective layer moduli, which may depend on the load level used. In addition, the semirigid, noncircular loads are hard to model with existing analysis programs and prevent measurements from being obtained directly under the load.

These observations imply, however, that a superior system can and should be designed to provide optimal discrimination for each layer. A dual-load FWD would have these capabilities. The two loads would result in improved discrimination of pavement layer moduli while maintaining the advantage of using variable load levels similar to design wheel loads.

OBJECTIVES

The work reported in this paper was part of a comprehensive study conducted for the Florida Department of Transportation. The objectives were as follows:

1. To determine whether a dual-load nondestructive testing system provides for better discrimination of near-surface layer moduli than the existing single-load FWD;
2. To identify a dual-load system configuration (load radii and spacing, and deflection sensor positions) that optimizes the capabilities of the dual-load system to discriminate among near-surface layer moduli;
3. To develop analysis procedures (backcalculation) to determine layer moduli using surface deflection measurements that would be obtained from the dual-load system configured.

All three objectives were met, but this paper deals primarily with the first two objectives. The development of relationships for modulus prediction and their integration into a computer program was a study in itself and was considered beyond the scope of this paper. The specific objectives of this paper are as follows:

1. To illustrate the inability of the existing single-load FWD to discriminate among the near-surface layer moduli of flexible pavement systems (asphalt concrete, base, and subbase);

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2. To show that this deficiency can be overcome by using a dual-load FWD where the loads are spaced sufficiently apart to induce a concave downward curvature in the pavement surface between the loads;
3. To show why the dual-load system is more effective in isolating the effects of the asphalt concrete from the effects of the base course on the surface deflections;
4. To show that the improved discrimination of the dual-load system holds true for a broad range of pavement geometries and pavement layer moduli; and
5. To present the analyses and rationale used to select the dual-load system configuration (load radii and spacing, and deflection sensor positions) that optimizes the capabilities of the dual-load system to discriminate among near-surface layer moduli.

SCOPE

Only flexible pavement systems were considered in this study. All analyses were conducted using the elastic layer computer program BISAR (*3*). Therefore, the layer moduli being considered for determination are effective layer moduli for response prediction using elastic layer analysis. The evaluations reported here are based on analyses performed on a range of pavement geometries and layer moduli typically encountered in North America. The range of pavement geometries were identified using the Strategic Highway Research Program general pavement sections data base. A broad range of pavement layer moduli was selected.

EVALUATION OF EXISTING FWD

An evaluation of the deflection basins for a typical pavement structure clearly illustrates the inability of the existing single-load FWD to discriminate among the near-surface layer moduli of flexible pavement systems (asphalt concrete, base, and subbase). Figures 1 and 2 show that for a typical pavement structure (6-in. asphalt concrete, 10-in. base course, 10-in. subbase, and semi-infinite subgrade), changes in the asphalt concrete modulus affect the same portion of the deflection basin as changes in the base course modulus. Therefore, two different combinations of asphalt concrete and base course moduli may result in the same deflection basin. Figure 3 shows that reducing the base course modulus for a specific pavement structure by one-third has roughly the same effect on the deflection basin as does reducing the asphalt concrete modulus by one-half. It would be difficult to reliably determine the correct moduli of these near-surface layers on the basis of the measured surface deflections from the single-load FWD. One could attempt to use an asphalt concrete-temperature relationship to bound the problem, but temperature relationships are extremely rough at best because the modulus of the asphalt concrete will depend heavily on many other factors, including the degree of age-hardening and the characteristics of the specific mixture.

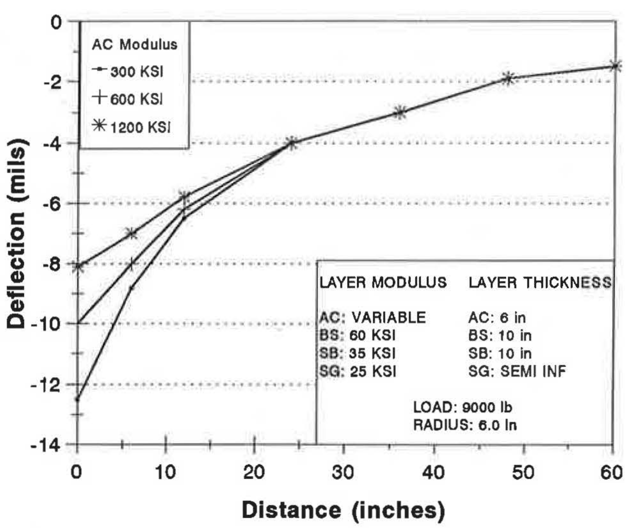

FIGURE 1 Effect of changes in the asphalt concrete modulus on predicted deflections for a single-load system.

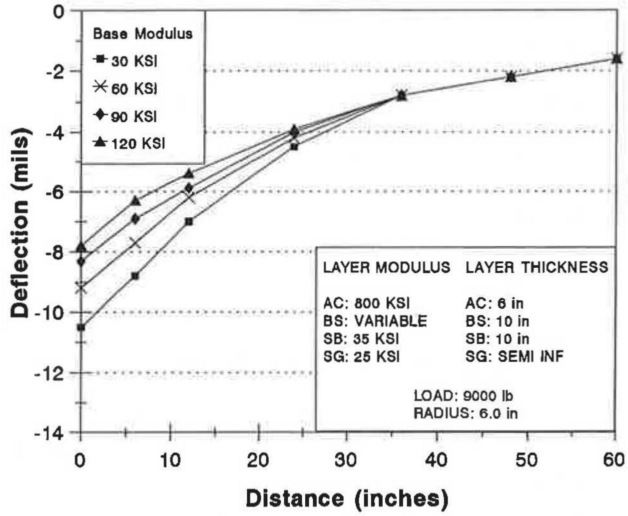

FIGURE 2 Effect of changes in the base course modulus on predicted deflections for a single-load system.

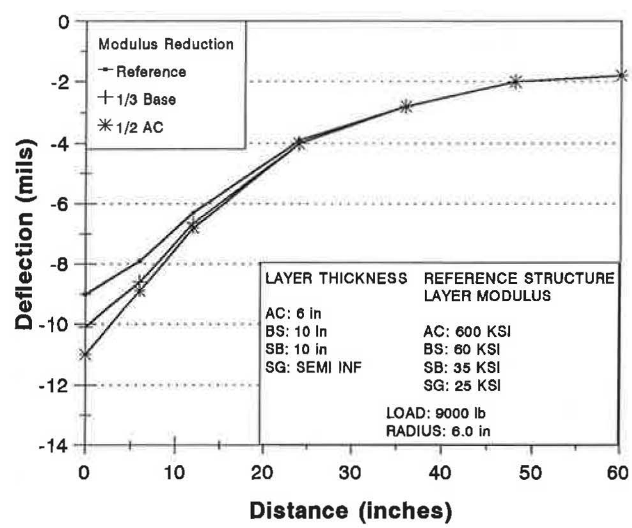

FIGURE 3 Deflection basins caused by reducing the asphalt concrete or base course modulus for single-load system.

Although the results in this example are specific to the pavement structure used (i.e., the effect of changing the layer moduli on the deflection basin will be different for different pavement structures), they are fairly representative of what occurs for the range of pavement structures typically encountered (asphalt concrete from 3 to 9 in.; base course from 8 to 16 in.). The problem of discriminating near-surface layer moduli using the single-load FWD becomes more difficult for asphalt concrete layers thinner than the 6-in. layer used in the example.

EVALUATION OF DUAL-LOAD SYSTEMS

An evaluation of the transverse and longitudinal deflection basins for a dual-load system on the same pavement structure mentioned previously (see Figure 1) clearly illustrates the superiority of the dual-load system in independently isolating the effects of the asphalt concrete modulus and the base course modulus on the surface deflections. Figure 4 shows a plan view of the dual-load system. A load spacing of 40 in. was chosen for the analysis. The effects of varying the asphalt concrete modulus and the base course modulus on the transverse deflection basin are shown in Figures 5 and 6. Figure 5 clearly shows that the asphalt concrete modulus is strongly reflected in the shape of the transverse deflection basin of the dual-load system. As the asphalt concrete modulus varies from 300,000 psi to 1,200,000 psi, the deflection underneath the loads changes significantly, whereas the deflection immediately between the two loads remains constant. On the other hand, Figure 6 shows that the base course modulus has a relatively small influence on the shape of the transverse deflection basin. As the base course modulus varies from 30,000 psi to 120,000 psi the deflection change is relatively uniform at all points along the deflection basin. Therefore, the shape of the transverse deflection basin appears to provide a clear way to discriminate between the effects of the asphalt concrete modulus and the base course modulus. Later in this paper it will be shown that the strong relationship between the asphalt concrete modulus and the shape of the transverse deflection basin for a dual-load system was found to hold true for a broad range of pavement geometries and layer moduli.

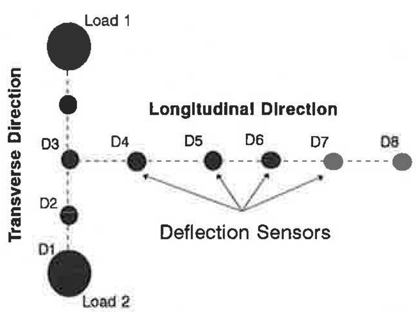

FIGURE 4 Plan view of the dual-load system.

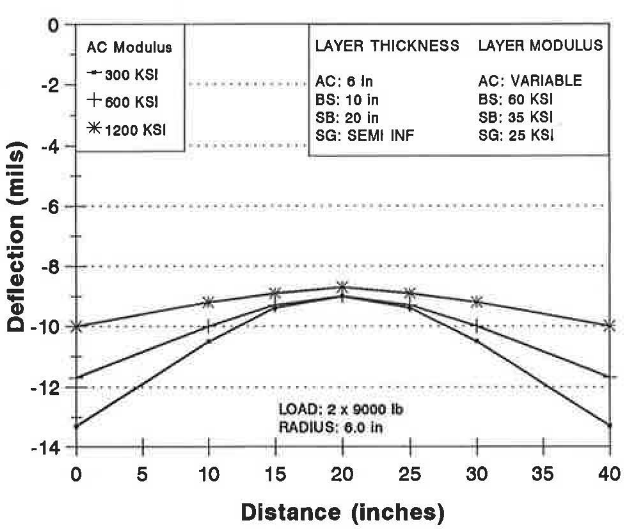

FIGURE 5 Effect of changes in asphalt concrete modulus on transverse deflection basin for dual-load system: 40-in. spacing.

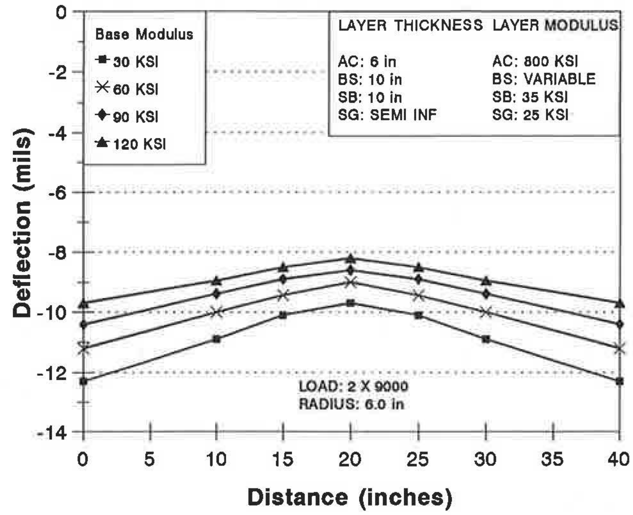

FIGURE 6 Effect of changes in base course modulus on transverse deflection basin for dual-load system: 40-in. spacing.

An evaluation of the longitudinal deflection basins shown in Figures 7 and 8 clearly demonstrates that the base course modulus is strongly reflected in the shape of the longitudinal deflection basin, whereas the asphalt concrete modulus has a relatively small effect on the longitudinal deflections. Figure 7 shows that there is almost no change in the longitudinal deflection basin as the asphalt concrete modulus varies from 300,000 psi to 1,200,000 psi. Figure 8 shows that the deflections near the transverse centerline between the two loads decrease as the base course modulus varies from 30,000 psi to 120,000 psi. The figure also shows that the deflections beyond 30 in. away from the loads remain relatively constant as the base course modulus changes. Therefore, the shape of the longitudinal deflection basin appears to provide a clear way to discriminate between the effects of the asphalt concrete modulus and the base course modulus. Later in this paper it will be shown that the relationship between the base course modulus and the shape of the longitudinal deflection basin for a dual-load system was found to hold true for a broad range of pavement geometries and layer moduli.

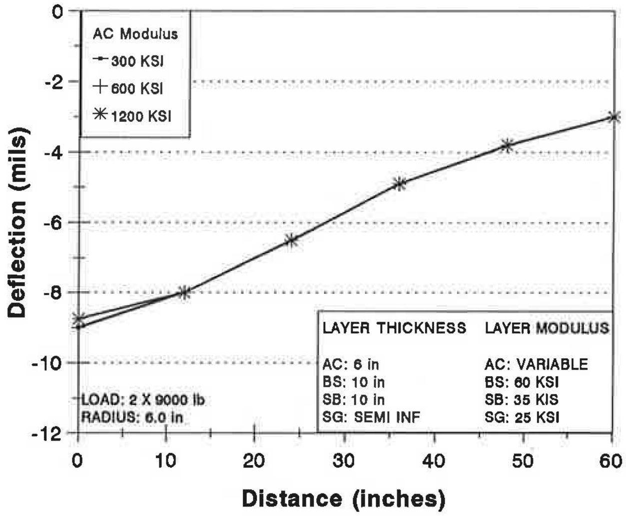

FIGURE 7 Effect of changes in asphalt concrete modulus on longitudinal deflection basin for dual-load system: 40-in. spacing.

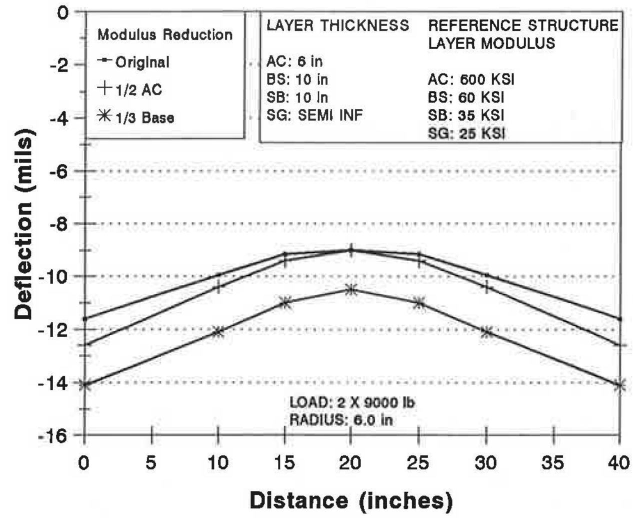

FIGURE 9 Transverse deflection basin caused by reducing asphalt concrete or base course modulus for dual-load system: 40-in. spacing.

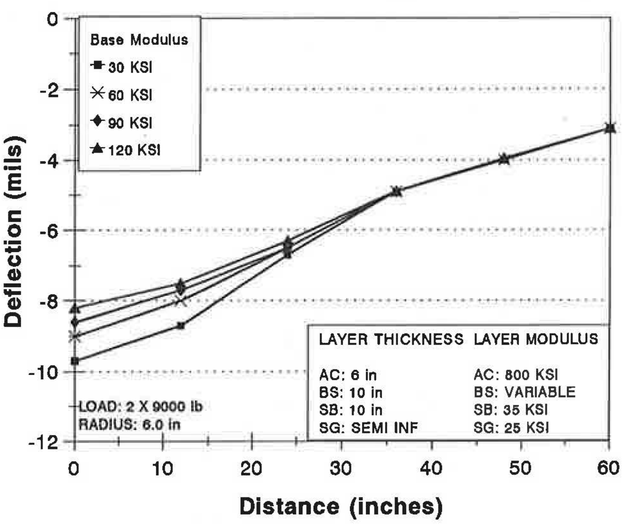

FIGURE 8 Effect of changes in base course modulus on longitudinal deflection basin for dual-load system: 40-in. spacing.

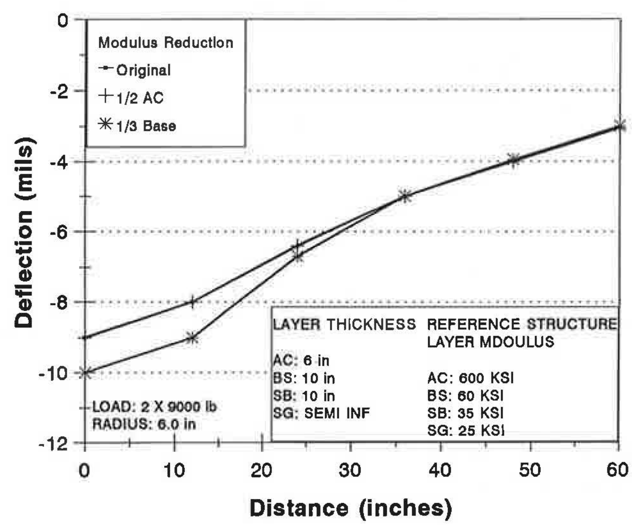

FIGURE 10 Longitudinal deflection basin caused by reducing the asphalt concrete modulus or base course modulus for dual-load system: 40-in. spacing.

In sharp contrast to the single-load FWD, Figures 9 and 10 show that two different combinations of asphalt concrete and base course moduli will not result in the same deflection basins for a dual-load system. Whereas for the single-load FWD, reducing the base course modulus by one-third had roughly the same effect on the deflection basin as reducing the asphalt concrete modulus by one-half (see Figure 3), the same modulus changes resulted in distinctly different changes in the transverse and longitudinal deflection basins for the dual-load system. Figure 9 shows that reducing the asphalt concrete modulus by one-half increased the deflections only under the load, whereas a reduction in base course modulus of one-third increased the transverse deflections uniformly. Figure 10 shows that only the reduction in base course modulus affected the longitudinal deflection basin.

ANALYSIS OF PAVEMENT RESPONSE INDUCED BY DUAL-LOAD SYSTEM

Stress and deformation analyses were conducted on a typical pavement structure to determine why the dual-load system works so well in isolating the independent effects of the asphalt concrete modulus and the base course modulus. An understanding of the system would allow configuration of a system that optimizes the capabilities to discriminate among the effects of near surface layer moduli. Deflection measurements obtained from such a system would optimize our chances of determining near-surface layer moduli accurately and reliably.

An evaluation of the stresses and deformations induced along a transverse cross-section of a typical pavement subjected to a dual-load system demonstrates why the system works. Figure 11 shows that when the loads are spaced 40-in. apart, the surface deformations between the loads result in a concave downward deflection basin. As shown in the figure, this results in significant bending moments in the asphalt concrete layer between loads. Basic mechanics demonstrates that the curvature resulting from these bending moments depends on the stiffness (modulus and thickness) of the asphalt concrete layer. Figure 11 also shows that the bending moments induced in the base course are negligible so that the stiffness of the base course should have a negligible influence on the curvature of the surface, which agrees with the findings presented previously.

An evaluation of the vertical compressive stress distribution in the asphalt concrete and the base course layers shows that the effect of the base course modulus on the shape of the surface deflection basin should be negligible compared to the effect of the asphalt concrete modulus. Figures 12 and 13 show vertical stress distributions at different depths along the transverse cross-section of the pavement for base moduli of 30,000 psi and 60,000 psi, respectively. In both cases, the transverse stress distribution within the base layer is relatively uniform compared with the stress distribution within the asphalt concrete layer. Note that it is the variation in stresses that results in changes in the shape of the deflection basin. Changes in the base modulus will result in changes in total deflections, but the stress distributions imply that these changes should be uniform. Once again, this agrees with the findings presented earlier.

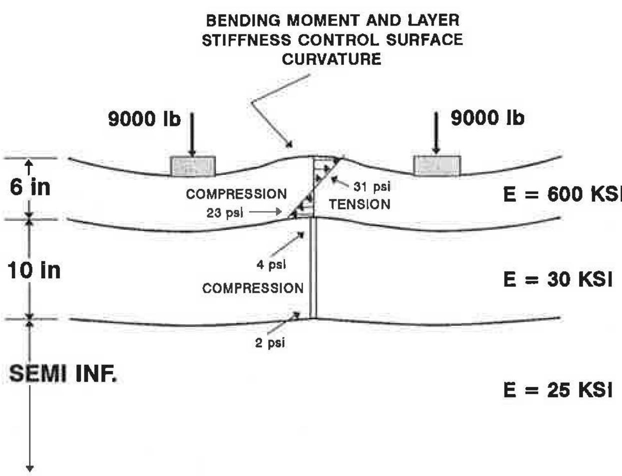

FIGURE 11 Stresses and deformations induced by a dual-load system.

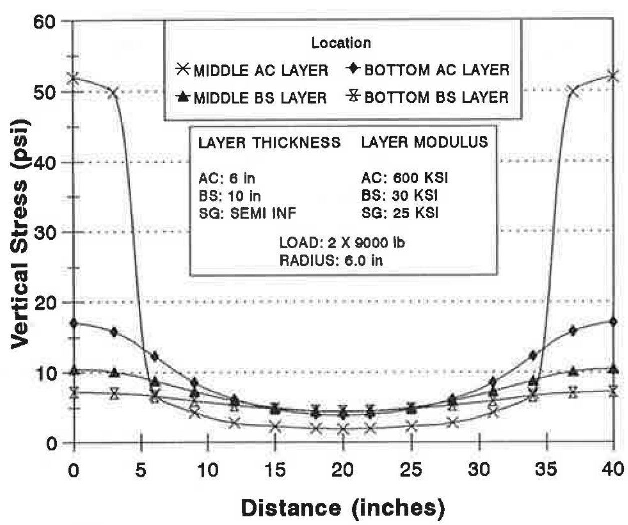

FIGURE 12 Vertical stress distributions induced by a dual-load system: 40-in. spacing, low-modulus base.

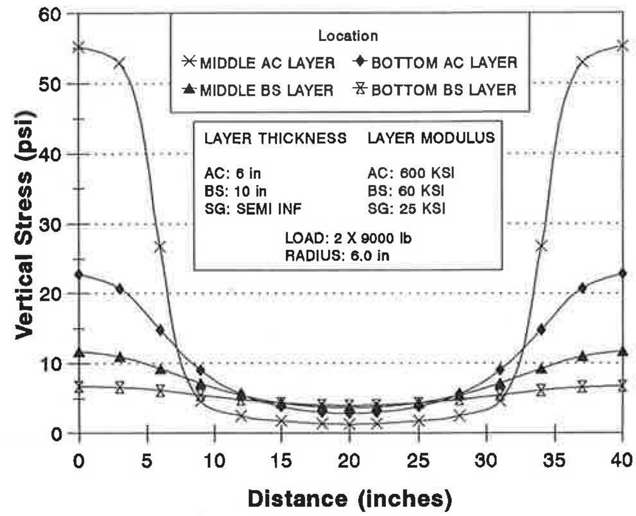

FIGURE 13 Vertical stress distributions induced by a dual-load system: 40-in. spacing, high modulus base.

DETERMINATION OF OPTIMAL LOAD-SPACING AND LOAD RADIUS

The analyses presented previously clearly indicate that the asphalt concrete modulus is and should be strongly related to the shape of the transverse deflection basin for a dual-load system. This implies that load spacings, which produce sharper (rather than flatter) concave downward transverse deflection basins between the loads, will optimize the system's capability to discriminate among the effects of the near-surface layer moduli. This will allow for more accurate and reliable determination of these moduli. Furthermore, the system's deflection sensors must be positioned to define both the transverse and longitudinal deflection basins accurately enough to detect the independent changes caused by the different pavement layers.

The key to obtaining sharper deflection basins for optimal discrimination among the surface layer moduli is to position the loads sufficiently far apart to cause significant bending moments in the region immediately between the loads. If the loads are too close, such that strong interactions develop between the loads, these moments may never develop or the entire surface between the two loads may be in a state of horizontal compression. On the other hand, if the loads are spaced too far apart, the loads may act independently of each other, which would essentially result in two single-load systems. In either case, the advantages of the dual-load system would be lost.

Given that the shape of the transverse deflection basin would be influenced not only by the load spacing, but also by the pavement geometry and layer moduli, a comprehensive analysis was conducted to determine an optimal load spacing that would result in appropriate deflection basins for a broad range of pavement structures. The values shown in Table 1 were considered in the analysis.

The following constraints limited the ranges of acceptable load radii and spacings:

- The load levels used for testing should be representative of the load levels attained in the field. The load level chosen will govern the radii used to obtain average pressures similar to the ones obtained in the field.
- The center-to-center spacing of the loads should be kept as close as possible to make the construction of a dual-load system possible. A spacing greater than 40 in. was considered impractical.

Assuming 9,000 lbs per load, the resulting average stress under each load would be as follows:

- 179 psi for a 4.0 in. radius,
- 114 psi for a 5.0 in. radius, and
- 79.5 psi for a 6.0 in. radius.

These ranges were considered to be acceptable in pressures, such that radii less than 4.0 in. or greater than 6.0 in. were not considered for evaluation.

Elastic layer analyses were conducted for the range of pavement structures listed in Table 1, using load spacings of 20, 30, and 40 in. and load radii of 4 and 6 in. Typical results of the analyses are shown in Figures 14 and 15, which show transverse deflection basins for a 4-in. and 8-in. asphalt concrete pavement, respectively. Both figures indicate that load radius had little effect on the shape of the deflection basin. Figure 14 shows that for the thinner pavement section, all three load spacings resulted in fairly sharp transverse deflection basins, which would allow for accurate discrimination among near-surface layer moduli. This was typical for the thinner (lower stiffness) sections investigated, and indicated that there was no advantage of using one load spacing over another.

For the thicker (higher stiffness) sections investigated, it was found that wider load spacings were required to obtain deflection basins with reasonably sharp curvatures. A typical example is shown in Figure 15, which shows that the 40-in. spacing offers a slight advantage over the 30-in. spacing and a significant advantage over the 20-in. spacing in producing measurable deflection differences along the transverse axis.

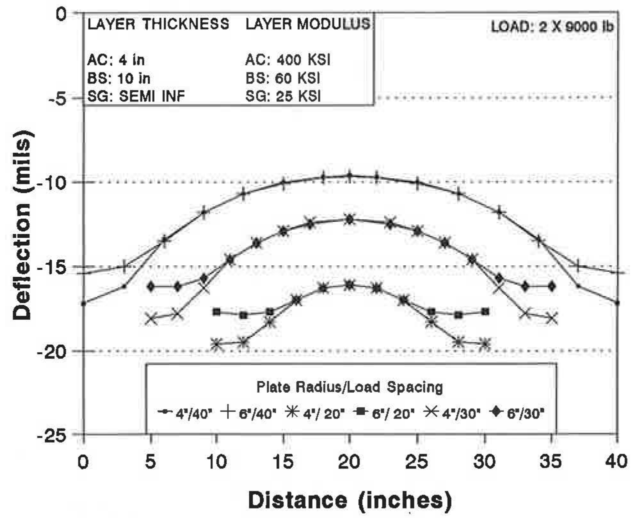

FIGURE 14 Comparison of transverse deflection basins induced by different load-spacing and radii on 4-in. pavement section.

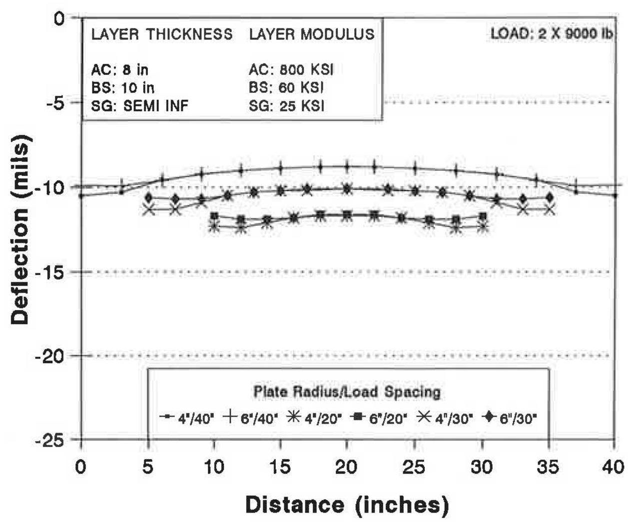

FIGURE 15 Comparison of transverse deflection basins induced by different load spacing and radii on 8-in. pavement section.

Based on these analyses, and the fact that spacings greater than 40 in. were considered impractical, a spacing of 40 in. was selected for the optimal system configuration. A load radius of 6 in. was selected for further evaluation. However, any load radius from 4 to 6 in. may be considered acceptable, because the radius of the load was found to have little influ-

TABLE 1 Pavement Layer Thickness and Moduli Considered for Analysis

Layer	Moduli (ksi)	Thicknesses (in)
Asphalt Concrete	200, 400, 600, 800, 1200	4, 6, 8, 12
Base Course	20, 40, 60, 80, 120	5, 10, 20
Subbase	**	5, 10, 15
Subgrade	5, 15, 25, 50	semi-infinite

**The subbase modulus was varied between the subgrade modulus and the base modulus (i.e. it was never allowed to be greater than the base modulus or less than the subgrade modulus).

ence on the shape of the deflection basins. A 6-in. radius would allow for larger loads to be used without overstressing and possibly damaging the surface layer during testing.

EVALUATION OF THE DUAL-LOAD SYSTEM CONFIGURATION

An evaluation of the deflection basins resulting from the dual-load system configured previously (40-in. load spacing, 6-in. radius loads) was conducted for the range in pavement structures and layer moduli generally encountered in North America. These analyses showed that the relationships between the shape of the transverse deflection basin and the asphalt concrete modulus, and between the shape of the longitudinal deflection basin and the base course modulus, held true for almost all pavement structures investigated.

Elastic layer analyses were conducted using BISAR to determine the transverse and longitudinal deflection basins resulting from the dual-load system configured previously for every combination of the layer thicknesses and of layer moduli shown in Table 1. An analysis was conducted to determine whether there was a strong correspondence between the shape of the transverse deflection basin and the asphalt concrete modulus. The difference in deflections between the point immediately underneath the load (D1) and the point immediately between the loads (D3) was used as the parameter to represent the shape of the transverse deflection basin. The following relationship was found for a typical pavement structure (6-in. asphalt concrete, 10-in. base, 10-in. subbase, semi-infinite subgrade).

$$EAC = e^{[7.22 - 0.55(D1 - D3)]} \quad R^2 = 84.4 \text{ percent} \qquad (1)$$

where

EAC = asphalt concrete modulus (ksi),
$D1$ = surface deflection directly under one of the loads ($\times 10^{-3}$ in.),
$D3$ = surface deflection exactly between the two loads ($\times 10^{-3}$ in.).

Similarly, the base course modulus was found to be related to the shape of the longitudinal deflection basin for the range of pavement structures investigated. The relationship involved interactions with the subbase and subgrade moduli, such that a simple correlation as shown in Equation 1 could not be obtained.

It should be emphasized that Equation 1 is not intended to predict asphalt concrete modulus directly but only to show the strong correlation between the asphalt concrete and the shape of the transverse deflection basin as would be measured by the dual-load system. Predictive equations for all layer moduli, which account for the effects of layer thicknesses and interactions among layer moduli, were developed successfully based these analyses. However, presentation and development of these equations is beyond the scope of this paper.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions were reached on the basis of the results of the analyses presented in this paper:

1. A dual-load nondestructive testing system provides for better discrimination of near-surface layer moduli than the existing single-load FWD.
2. The dual-load system works because the shape of the transverse deflection basin induced between the two loads is most strongly influenced by the bending moments induced within the asphalt concrete layer between the loads and by the relatively large changes in vertical compression which are induced in the asphalt concrete layer between the loads.
3. A dual-load spacing of 40 in. was found to provide for optimal discrimination of near-surface layer moduli for the broad range of pavement geometries and layer moduli generally encountered in North America.
4. Because of the relatively strong and direct correlations between different layer moduli and surface deflections for a dual-load system, it appears that a set of relatively simple regression equations can be developed to determine layer moduli.

It is recommended that the dual-load system configured in this paper be constructed and implemented for field testing.

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