Analysis of Paved Shoulder Width Requirements

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EXECUTIVE SUMMARY

The analysis of paved shoulder width requirements in this technical memorandum considered the current methodology used by the Texas Department of Transportation (TxDOT) to design flexible pavements. This methodology, as implemented in TxDOT's Flexible Pavement System (FPS) program, is based on modeling the pavement as a linear-elastic layered system, with each layer characterized by a modulus and a Poisson's ratio. This model assumes pavement layers that extend infinitely in the horizontal direction with applied loads acting within the layered system, i.e., no edge loading. In reality, roadways are of finite width. Thus, this project examined the variation of the predicted pavement response at different load offsets from the pavement edge to determine paved shoulder width requirements that minimize the effect of the edge boundary and maintain consistency with the interior loading assumption used in FPS. For flexible pavements designed using this program, it is important that this assumption be realized during the service life of the given pavement.

To analyze shoulder width requirements, this study used a 2-dimensional finite element program to predict the variation in pavement response as the load is positioned at different offsets from the pavement edge. This analysis covered a representative range of flexible pavements that included different material types and thicknesses. Based on the results obtained, the following findings are noted:

1. The predicted variation in surface deflections exhibits the most sensitivity over the range of load offsets from the edge compared to other performance-related pavement response parameters considered in the analysis. Based on predicted surface deflections, the minimum suggested paved shoulder width varies from 3 to 6 feet over the range of material types and layer thickness included in the evaluation. For the case where the subgrade is stiff, the predicted deflection drops to within 5 percent of the corresponding mid-lane value at an offset between 3 to 4 ft from the pavement edge. In contrast, the required offset is between 5 to 6 ft for a weak or soft subgrade. The analysis found the effect of edge loading to be not as severe on a stiff subgrade, where the predicted deflections more rapidly approach the corresponding deflections at the mid-lane position compared to the condition where the subgrade is weak.
2. Variations in pavement design, such as changing from a 1-course surface treatment (1-CST) to a hot-mix asphalt (HMA) surface, increasing the HMA or flexible base thickness, and using a stiffer base material on a weak or soft subgrade reduce the predicted deflections and subgrade vertical compressive strains in varying degrees. The results suggest that using higher quality materials or placing thicker layers will require minimum paved shoulder widths in the 2- to 5-ft range. Wider paved shoulders are indicated for higher class roadways designed for heavy truck traffic where the predicted pavement response under load must be kept at the levels necessary to achieve the design service life. Thus, realizing the interior loading condition assumed in pavement design becomes even more critical under high-volume, heavy truck traffic service conditions.
3. For the range of pavements considered in the analysis, the predicted subgrade vertical compressive strain reduces to within 5 percent of the corresponding mid-lane value at a 1-ft load offset from the pavement edge. Beyond this offset, there is minimal variation in the predicted subgrade compressive strains from the mid-lane value.
4. The predicted horizontal tensile stress at the bottom of a cement modified base and horizontal tensile strain at the bottom of a thick (6-inch) HMA surface increases as the

load moves away from the unpaved shoulder. Thus, the edge is not the critical location for these performance-related pavement response parameters.

5. The analysis also predicts that a thin (2-inch) HMA surface is primarily in compression under load, except at the pavement edge where the horizontal strain is tensile at the bottom of the material. In addition, the maximum shear stress at the bottom of this thin HMA surface is predicted when the load is at the pavement edge. These predictions of pavement response are consistent with the observed edge breaks on narrow thin-surfaced roads where the wheel loads track at the pavement edge, and could help explain why these failures develop.
6. The analysis also considered the effect of shoulder slope on the predicted pavement response under the applied wheel loads on the travel lane. This analysis assumed the shoulder as consisting of non-stabilized, loose material, placed on top of the subgrade adjacent to the travel lane. Everything else being the same, the analysis revealed minimal differences in predicted pavement response between a 1:3 and a 1:6 shoulder slope.
7. The analysis also resulted in a number of findings useful for developing pavement design guidelines applicable to roadways that serve energy development and production activities. The relevant findings are summarized below:
    a. The effect of the flexible base stiffness on the predicted surface deflections is not as significant as the effect of subgrade stiffness. The predicted deflections drop significantly with increase in subgrade stiffness. The predicted deflections also diminish with increase in base stiffness but the change is not as significant, and depends on the level of subgrade stiffness.
    b. The analysis suggests that a higher quality flexible base would be more effective at minimizing the development of pavement rutting due to repeated load repetitions when placed on a soft or weak subgrade than when founded on a stiff subgrade, where the predicted deflections are governed by the stiff subgrade.
    c. The analysis found that flexible base thickness has a greater effect on the predicted surface deflections under load compared to flexible base stiffness. For a pavement on a soft or weak subgrade, increasing the base thickness from 6 to 12 inches leads to larger reductions in the predicted surface deflections compared to the reductions achieved when a stiffer (100 vs. 40 ksi modulus) base material is used.
    d. Changing the surface material from a 1-course surface treatment to a 2-inch HMA significantly reduces the predicted deflections under load for the pavements considered in the analysis. However, in lieu of changing the surface material, another option to consider is to increase the flexible base thickness. The predicted surface deflections for the thicker flexible base (12 vs. 6 inches) were found to be comparable to the calculated deflections for the 2-inch HMA pavement.
    e. With respect to reducing the subgrade vertical compressive strain and the potential for pavement rutting, the results suggest that changing the flexible base thickness from 6 to 12 inches would be more effective than changing the surface material from a 1-CST to hot-mix asphalt.

In summary, TxDOT Districts currently place 2-ft shoulders as a minimum. Assuming 12-ft travel lanes, this practice translates to paved two-lane roadway widths of 28 ft. This study found that the predicted surface deflections govern the minimum paved shoulder width requirements. The results suggest that these requirements range from 4 ft for a pavement founded on a stiff subgrade, to 6 ft for a pavement founded on a weak or soft subgrade but built with higher quality or thicker surface or base layers. Assuming 12-ft travel lanes, these findings translate to minimum paved two-lane roadway widths ranging from 32 to 36 ft. These minimum requirements are based on structural pavement design considerations. Paved shoulders exceeding these requirements could further enhance roadway safety and protection against moisture infiltration.

The details of the analysis of paved shoulder width requirements are presented in the remainder of this technical memorandum.

INTRODUCTION

Many of the corridors impacted by oil/gas energy development and production activities are on narrow two-lane Farm-to-Market (FM) roads with paved widths of 18 to 20 ft. Considering that the distance between side-view mirrors ranges from10 to 10½ ft on heavy trucks used by the energy sector, the outside tires can be running right at the pavement edge or off the edge when trucks traveling in opposite directions pass each other on these narrow FM roadways. The unpaved shoulder offers little lateral support for this edge loading condition. This lack of lateral support coupled with the thin pavement structures typically found on these roads result in breakage of the pavement edge under repeated heavy load applications (see Figure 1). The loss of edge material becomes progressive and can lead to loss of the pavement if left uncorrected. Moreover, road safety is diminished as further narrowing of the paved width increases the risk of collisions between oncoming vehicles. Thus, engineers consider pavement widening when evaluating strategies for maintaining the serviceability of routes impacted by oil/gas energy development and production activities. This memorandum presents an analysis of paved shoulder width requirements to investigate just how much widening might be needed.

STUDY APPROACH

The analysis of paved shoulder width requirements considered the current methodology used by TxDOT to design flexible pavements. This methodology, as implemented in TxDOT's Flexible Pavement System program, is based on modeling the pavement as a linear-elastic layered system, with each layer characterized by a modulus and a Poisson's ratio. The modulus input for pavement design is representative of a value backcalculated from falling weight deflectometer (FWD) data as opposed to a value determined from laboratory tests on molded specimens. FPS models the pavement as a layered system resting on a semi-infinite rigid bottom with each layer above the rigid bottom having a finite thickness but extending infinitely in the horizontal direction. This model therefore assumes no edge loading condition, i.e., all loads are within this vast expanse of the layered system (an interior loading condition). In reality, roadways are of finite width. Thus, it is relevant to ask how wide the pavement should be to minimize the effect of a boundary such as the edge on the pavement response determined using layered elastic theory (LET).

Figure 1. Shoulder Exhibiting Signs of Degradation due to Traffic Loads.

To investigate this issue, the study used the finite element method (FEM) to analyze how the predicted pavement response varies with distance from the pavement edge. FEM is used to analyze edge and corner loads on concrete pavements, making it a suitable method to use for analyzing edge loading conditions on flexible pavements. Using FEM, the study modeled the pavement as a system of interconnected elements, with each element characterized by a modulus and a Poisson's ratio. Thus, the analysis considered different pavement layers or materials by specifying the appropriate moduli and Poisson's ratios. Figure 2 illustrates a finite element representation of a pavement system.

In the analysis, the surface load was represented by a dual-tire configuration. Given the moduli, Poisson's ratios, and thicknesses of the different layers, the study used the finite element method to predict deflections, strains, and stresses due to the applied loads. These quantities are generally referred to as the pavement response due to the surface load. Figure 3 illustrates specific pavement response parameters that are used in the FPS design program. The predicted surface deflection under load is used in FPS to compute a surface curvature index that is related to the loss in pavement serviceability with cumulative load applications. The horizontal tensile strain at the bottom of the asphalt layer, and the vertical compressive strain at the top of the subgrade are used in a mechanistic design check to guard against premature failure due to bottom-up fatigue cracking and pavement rutting, respectively.

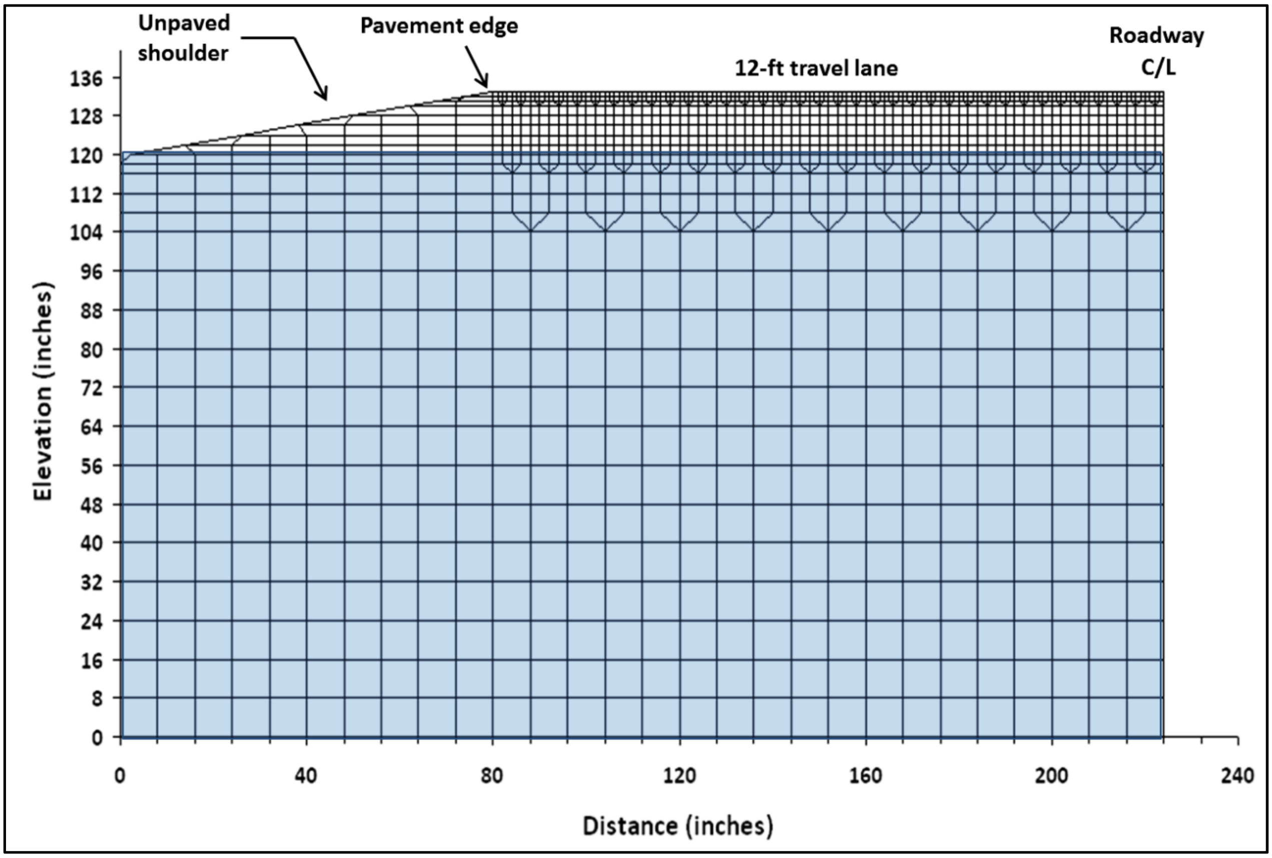

Figure 2. Example Finite Element Mesh Used in Edge Load Analysis.

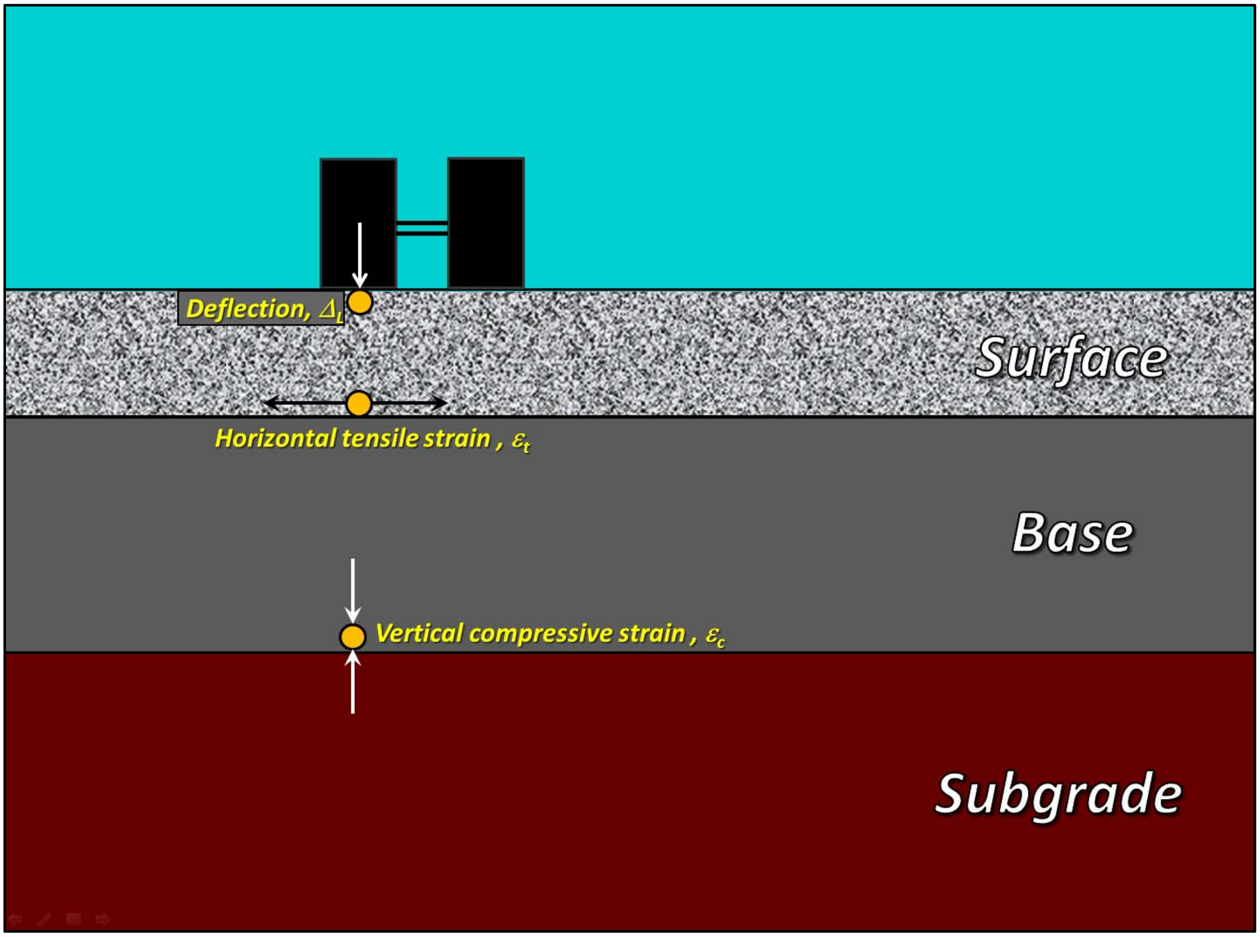

Figure 3. Pavement Response Parameters Used in FPS Design Program.

Using FEM, this study evaluated how pavement response under the applied load varies with distance from the pavement edge. This analysis was done at different offsets of the dual-tire load from the pavement edge as illustrated in Figure 4. Specifically, the load position was varied at 1-ft increments, up to a distance of 6 ft from the edge, which corresponds to the middle of the 12-ft travel lane used in the analysis. This location was also taken as the interior position in the analysis. The predicted pavement response at the different offsets was then compared to the corresponding response at the middle of the travel lane to evaluate the distance from the edge at which the predicted pavement response approximates the interior loading condition for the given pavement. This evaluation covered a representative range of flexible pavements. Results from this evaluation are presented shortly in this memorandum. In the following, a comparison between the finite element method and multi-layered elastic theory is presented to verify the reasonableness of the proposed analysis approach.

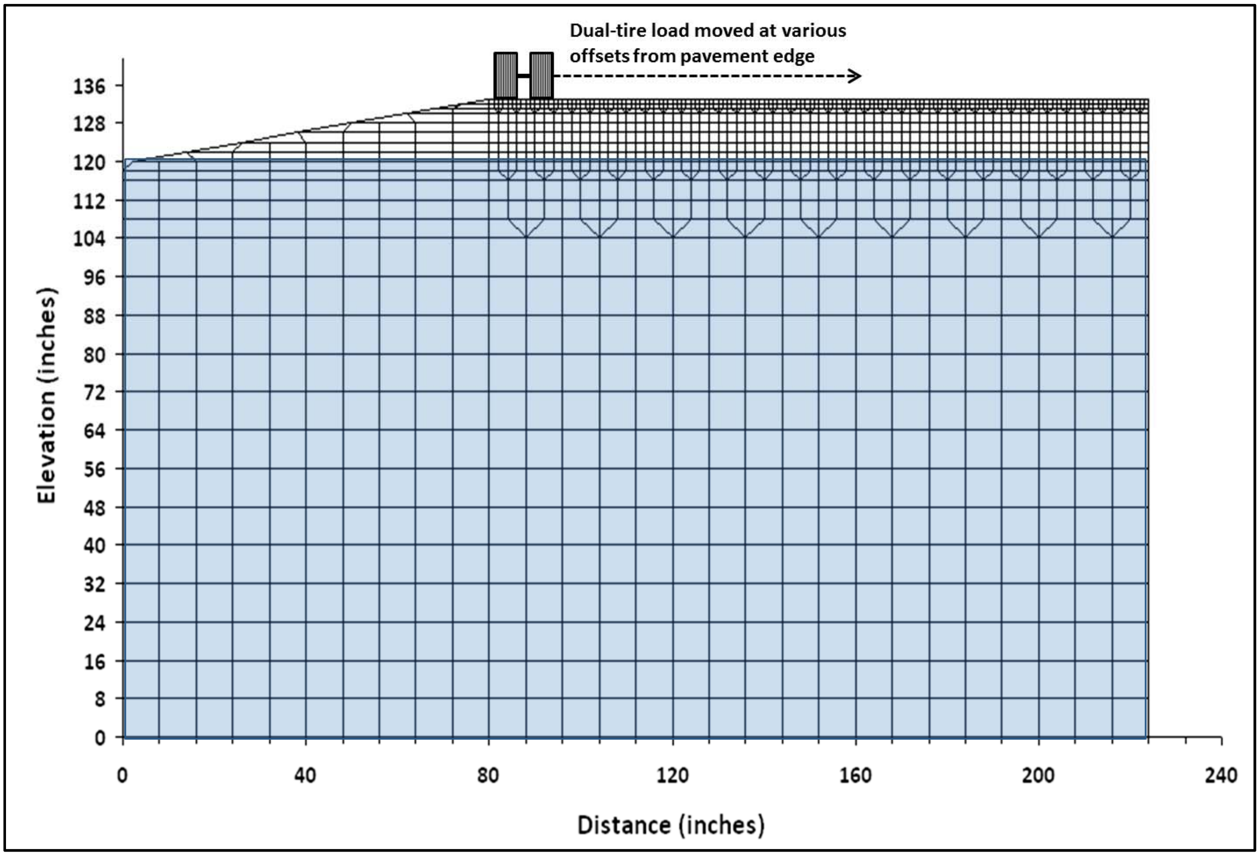

Figure 4. Load Position Varied from Edge to Interior of Travel Lane in the Analysis.

COMPARISON OF FEM AND LAYERED ELASTIC THEORY

Prior to running the edge load analysis, the study compared FEM and layered elastic theory to check the effect of differences in the assumptions used on the predicted pavement response due to surface loads. With respect to the finite element method, a plane strain assumption was made to permit a simpler two-dimensional (2D) analysis in lieu of a 3D analysis. The plane strain condition is typically applicable to the analysis of dams, tunnels, pavements, and other geotechnical structures, where the dimension of the structure in one direction is very large in comparison with the dimension of the structure in the other two directions. This condition is found in the pavement structure of a typical travel lane, where the longitudinal or traffic direction is very much larger than the dimensions of the pavement cross-section. Under a plane strain condition, the applied forces are assumed to act in the plane of the cross-section, perpendicular to the large dimension and do not vary along that direction. Thus, for a structure where plane strain can reasonably be assumed, the analysis is done on a finite slice of the structure.

Recognizing that simplifying assumptions used in any analysis can affect its outcome, the study compared the finite element method with layered elastic theory, which is the basis of the current TxDOT flexible pavement design method. Specifically, the study compared predicted pavement response parameters underneath the applied surface loads for the same pavement. Given that layered elastic theory assumes semi-infinite pavement layers, the finite element analysis positioned the dual-tire loads at the middle of the travel lane to represent an interior loading condition. The finite element pavement model used in this analysis is shown in Figure 2, with the pavement materials characterized as given in Table 1.

Table 1. Pavement Structure Used in Comparing FEM and Layered Elastic Theory.

Material	Thickness (inches)	Modulus (ksi)	Poisson's Ratio
Chip seal	1	200	0.40
Flexible base (FB)	6	40	0.40
Cement modified base	6	150	0.25
Subgrade	120	5	0.40
Shoulder*	Varies according to 1:6 slope	15	0.40

*Included only in FEM analysis

Note that layered elastic theory cannot be used to model the pavement shoulder since each material is assumed to be homogenous and semi-infinite in the horizontal extent. This difference between the FEM and LET pavement models would certainly affect the predictions and thus, the comparisons of predicted pavement response. Nevertheless, for consistency, the decision was made to model the pavement shoulder in this comparison given that the FEM pavement model for the edge load analysis includes this material.

Figure 5 shows the variation of the predicted deflections with depth under a 16,000 lb dual wheel load (8000 lb per tire). (This load represents the Average Tenth Heaviest Wheel Load (ATHWLD)used by TxDOT for somefor some pavement thickness design calculations). It is observed that the FEM deflections are consistently higher than the LET predicted deflections but that the trends in the deflections are similar. The predicted deflections from both methods decrease with depth and the signs of the deflections are the same, i.e., the vertical deflections are all positive indicating that the deflections under load are in the downward direction. The differences in deflection magnitudes are attributed to the differences between the analysis methods. LET assumes semi-infinite layers that are homogenous and continuous. On the other hand, the FEM analysis assumes finite layers that are each discretized into finite elements to represent the continuum.

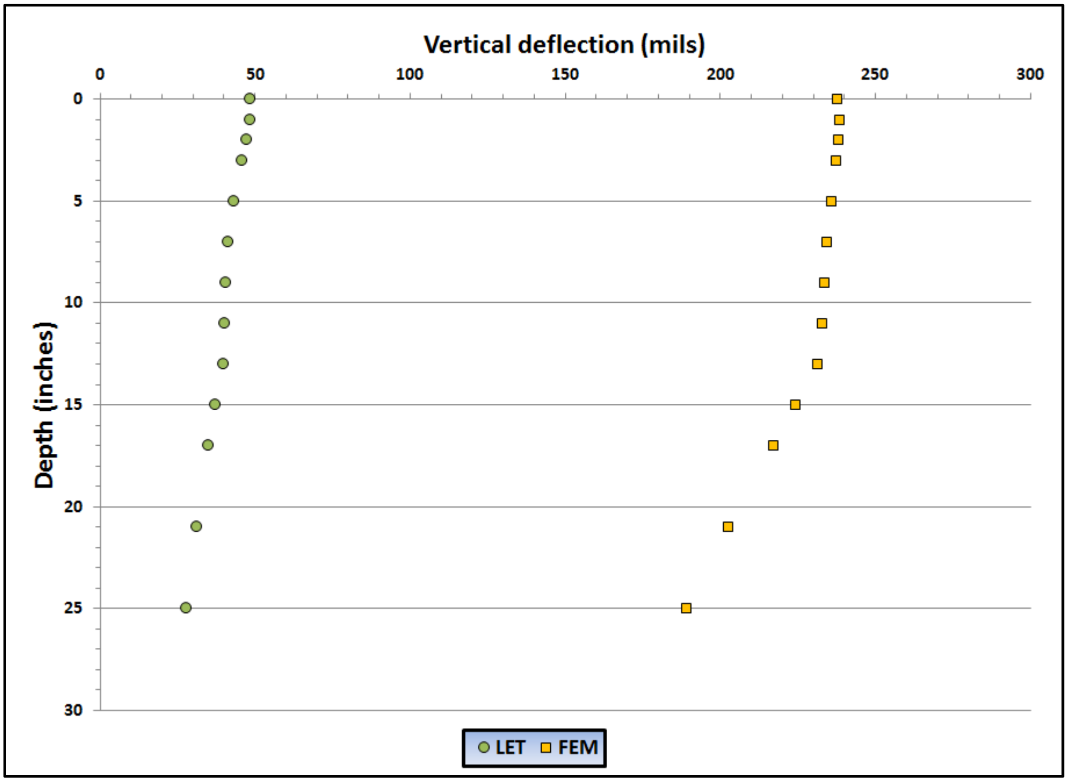

Figure 5. Predicted Variation of Vertical Deflections with Depth.

Figure 6 compares the predicted vertical stresses with depth, while Figure 7 compares the predicted horizontal stresses. The following observations are made:

1. The predicted vertical stresses within the chip seal and flexible base layers are comparable. However, the predicted vertical stresses significantly differ within the cement modified base (CMB) and subgrade layers, where the predicted FEM vertical stresses are higher in magnitude than the corresponding LET predictions. However, the trends in the predicted vertical stresses are similar, and the predictions from both methods all have the same sign, i.e., compressive vertical stresses are predicted.
2. The predicted horizontal stresses within the chip seal are significantly different but the differences diminish with depth into the flexible base layer. Within these layers, the predicted FEM horizontal stresses are higher in magnitude (more compressive) than the corresponding LET predictions. The predicted FEM horizontal stresses are significantly higher in magnitude at the mid- and near-bottom positions within the CMB layer, with both methods predicting positive (tensile) horizontal stresses.
3. The predicted horizontal stresses within the subgrade are much lower in magnitude compared to the other layers. The predicted horizontal stresses from both methods are all compressive, with the FEM predictions being comparable to the LET predictions.

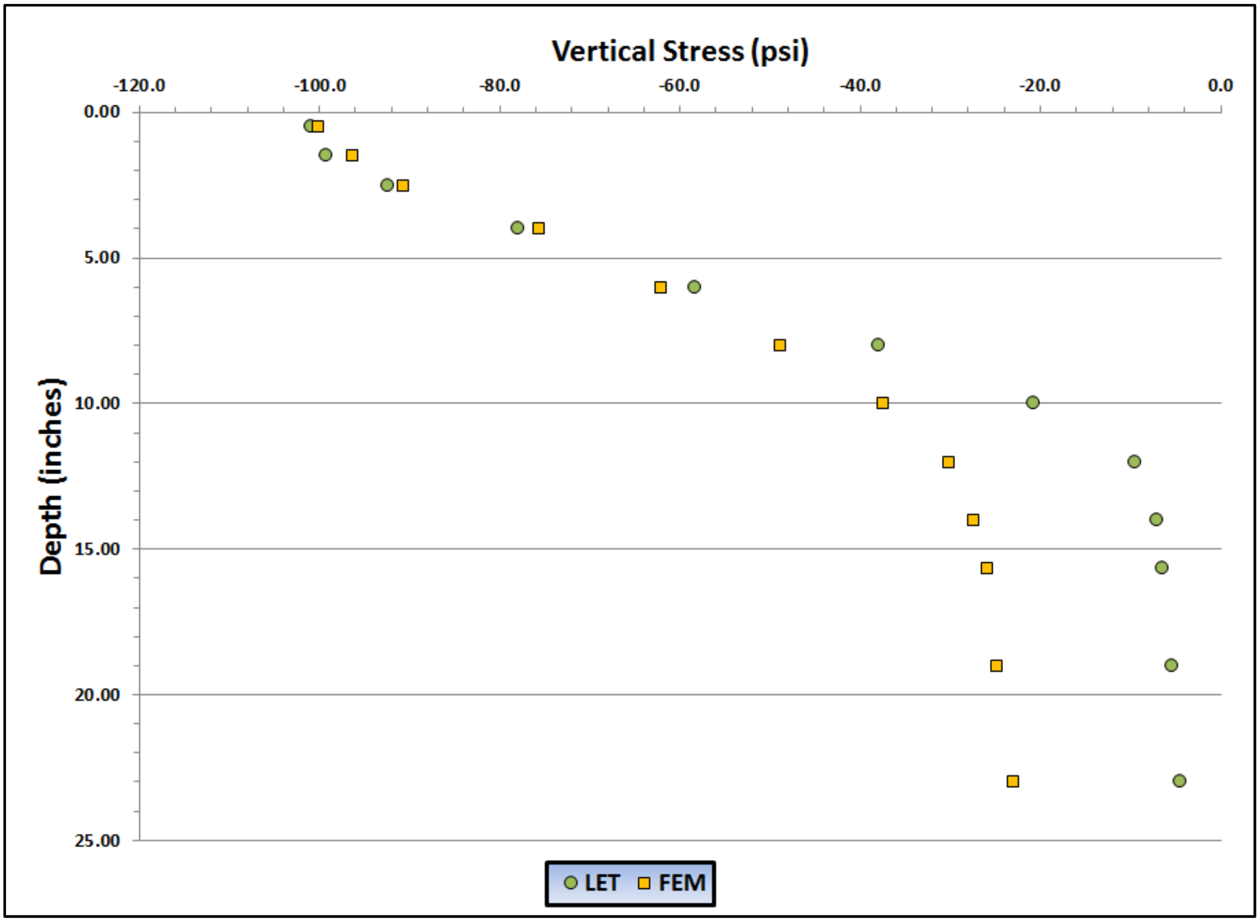

Figure 6. Predicted Variation of Vertical Stresses with Depth.

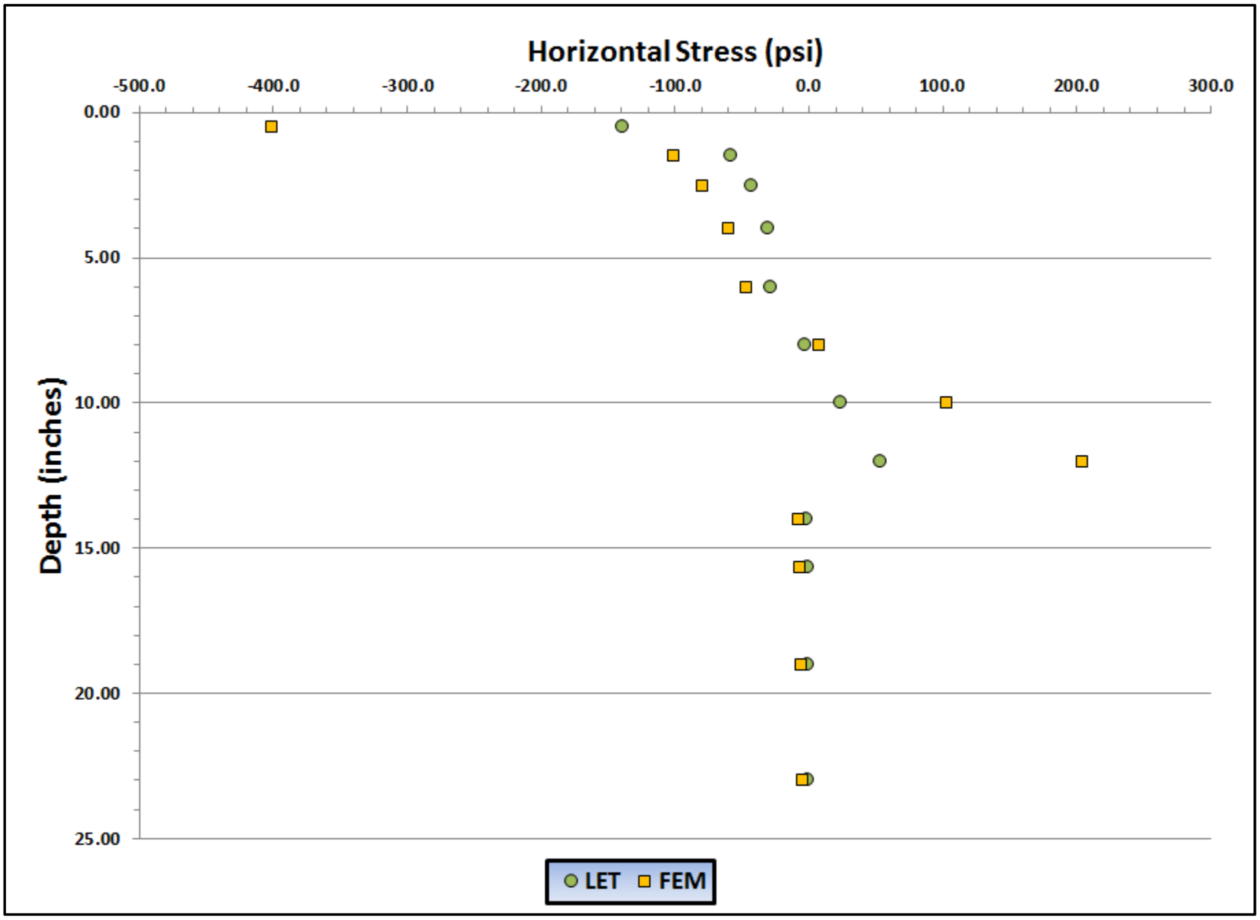

Figure 7. Predicted Variation of Horizontal Stresses with Depth.

In summary, the comparisons revealed several significant differences in the magnitudes of predicted pavement response parameters between the finite element and layered elastic analyses. However, the trends in the predicted pavement response from both methods were found to be similar. Given that the proposed approach for establishing guidelines on paved shoulder width requirements is to examine the predicted variation in pavement response at different load offsets from the pavement, the decision was made to proceed with a 2D finite element analysis to accomplish this objective. Representative results from this relative comparison of the predicted response at different load offsets to the corresponding response at the interior load position are presented in the next section.

RESULTS FROM EDGE LOAD ANALYSIS

Using FEM, an edge load analysis was performed following the approach presented previously. This analysis covered a range of flexible pavements that included the pavement structure given in Table 1, and two levels of shoulder slope, 1:3 and 1:6. The analysis assumed the shoulder as consisting of non-stabilized, relatively loose material, placed on top of the subgrade adjacent to the travel lane.

Figure 8 illustrates the predicted surface deflections under a 16-kip dual-tire load at various load offsets from the pavement edge. These results are for the pavement structure given in Table 1, except that a 1:3 shoulder slope was included in the analysis. Figure 8 shows that the differences in predicted surface deflections between a 1:3 and a 1:6 shoulder slope are minimal. Similar results were observed from examination of the predictions for other pavement response parameters. Consequently, only the results for a 1:6 shoulder slope are given in the remainder of this technical memorandum.

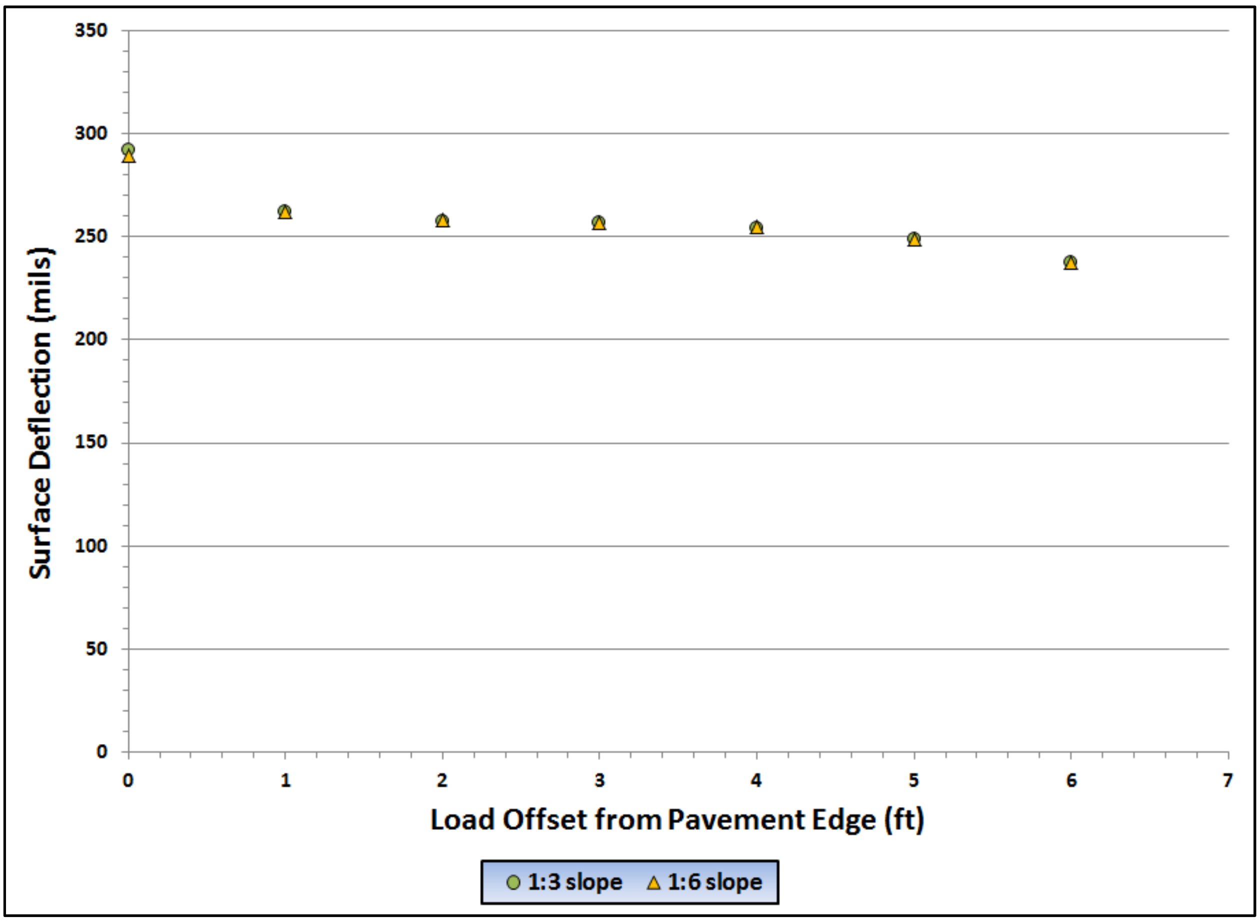

Figure 8. Predicted Variation in Surface Deflections for 2 Levels of Shoulder Slope.

The study also investigated the effect of the modulus or stiffness of the flexible base and subgrade materials. This investigation used the pavement structure given in Table 1 except that additional finite element runs were made to consider the effect of a stiffer flexible base and a stiffer subgrade as shown in Table 2. Figure 9 compares the predicted surface deflections for the four conditions identified in Table 2.

Table 2. Flexible Base and Subgrade Moduli Used to Examine Effect of Material Quality.

Condition	FB Stiffness (ksi)	Subgrade Stiffness (ksi)
Stiff Base-Stiff Subgrade (SBSS)	100	15
Stiff Base-Weak Subgrade (SBWS)	100	5
Weak Base-Stiff Subgrade (WBSS)	40	15
Weak Base-Weak Subgrade (WBWS)	40	5

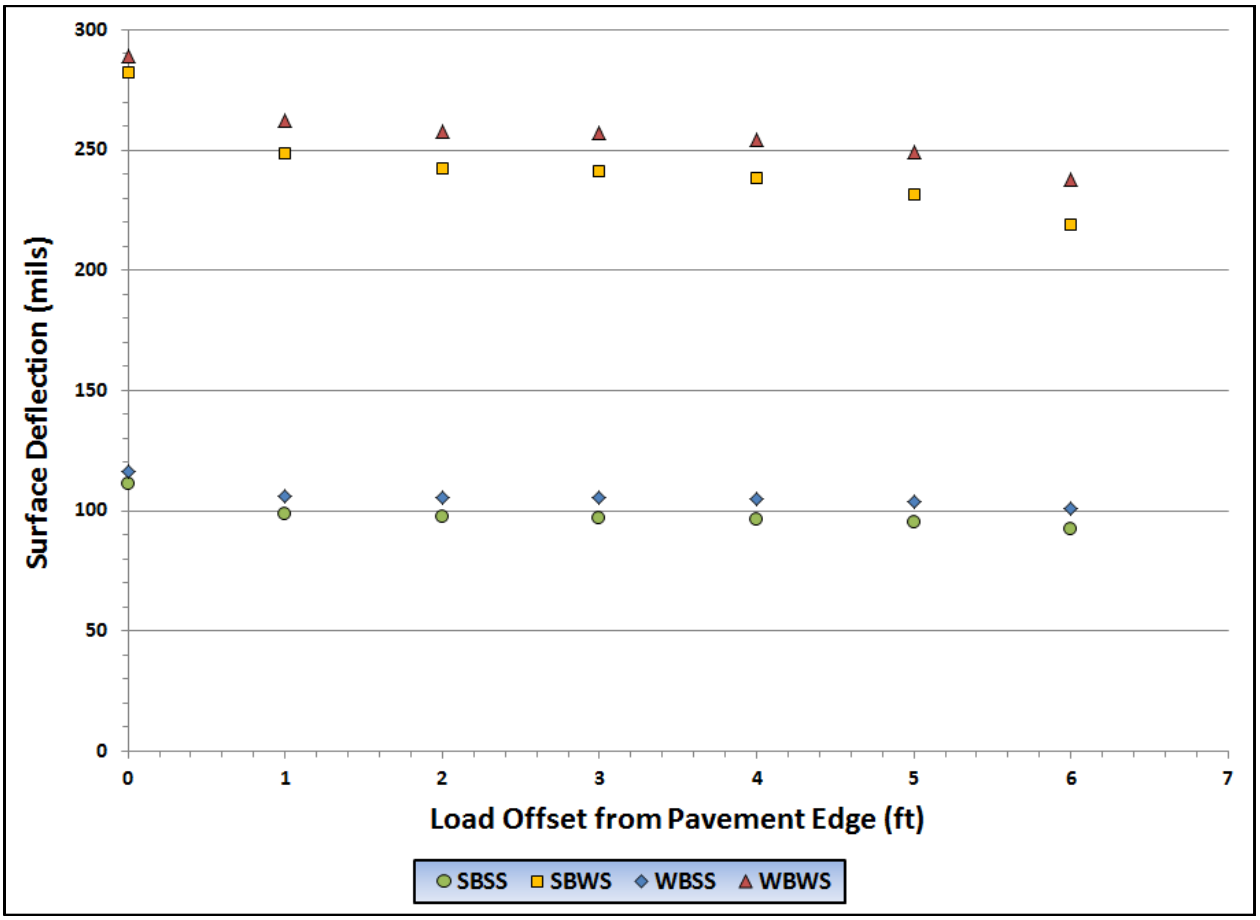

Figure 9. Effects of FB and Subgrade Moduli on Predicted Surface Deflections.

The following observations are noted from the results presented in Figure 9:

1. The effect of the flexible base stiffness on the predicted surface deflections is not as significant as the effect of subgrade stiffness. The predicted deflections drop significantly with increase in subgrade stiffness. The predicted deflections also diminish with increase in base stiffness but the change is not as significant compared to the effect of subgrade stiffness.
2. The effect of edge loading is not as severe on a stiff subgrade, and the predicted deflections for this condition more rapidly approach the corresponding deflections at the

mid-lane position compared to the weak subgrade. Figure 10 illustrates this observation, where the ratio of the deflection at a given offset to the deflection at the mid-lane position is plotted according to the level of subgrade stiffness. For a stiff subgrade, Figure 10 shows that the deflection drops to within 10 percent of the mid-lane value at an offset of 1-ft from the pavement edge. In contrast, the required offset is 4 ft for a weak or soft subgrade.

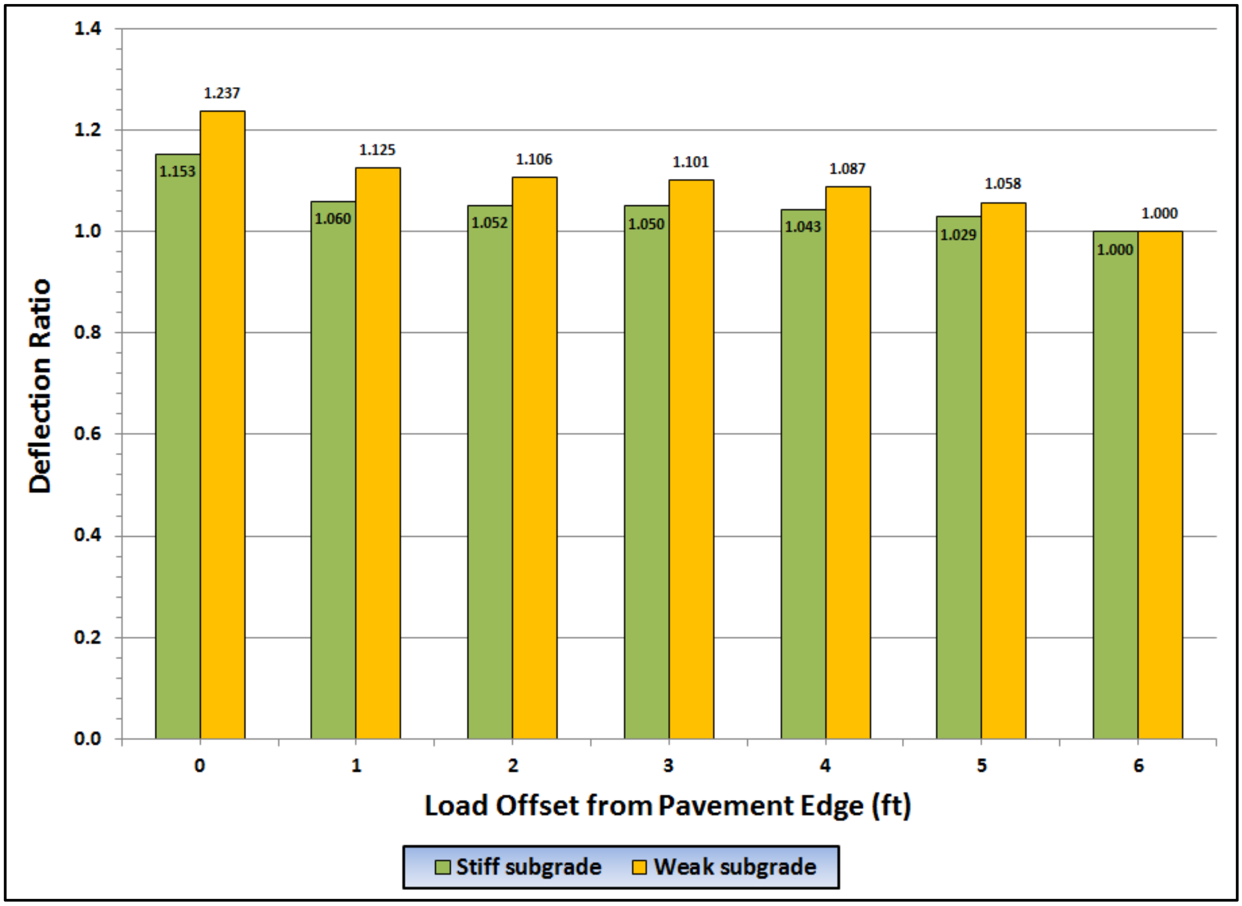

Figure 10. Predicted Surface Deflection Ratios at Two Levels of Subgrade Stiffness.

Figure 11 illustrates the effect of flexible base stiffness on the vertical compressive strain at the top of the subgrade. FPS uses the subgrade compressive strain to run a mechanistic design check and guard against excessive pavement rutting due to repeated load repetitions for the specified design period. Figure 11 indicates that the effect of base stiffness depends on the level of subgrade stiffness. A stiffer base is more effective at minimizing the development of pavement rutting due to repeated load repetitions when placed on a soft or weak subgrade than when founded on a stiff subgrade. Compared to the variation in the predicted surface deflections under a weak or soft subgrade, Figure 11 also shows that the predicted subgrade compressive strain approximates the value at the mid-lane position at an offset of 1-ft from the pavement edge. Beyond this offset, there is minimal variation in the predicted subgrade compressive strains from the mid-lane value.

Figure 12 shows the predicted variation of the tensile stress near the bottom of the CMB layer at different load offsets from the pavement edge. The effect of subgrade stiffness is very significant with much lower tensile stresses predicted in the CMB layer when it overlies a stiff subgrade. In comparison, the effect of flexible base stiffness is minimal. Figure 12 also shows that the predicted CMB tensile stress increases as the load moves away from the shoulder. This observation might seem counter-intuitive at first. However, the increased tensile stress results from greater bending action within the CMB layer as the load moves away from the shoulder where there is less restraint. Since the critical tensile stresses occur in the interior of the travel lane, Figure 12 indicates that paved shoulder width requirements will not be governed by the tensile stress within the CMB layer for the pavements analyzed.

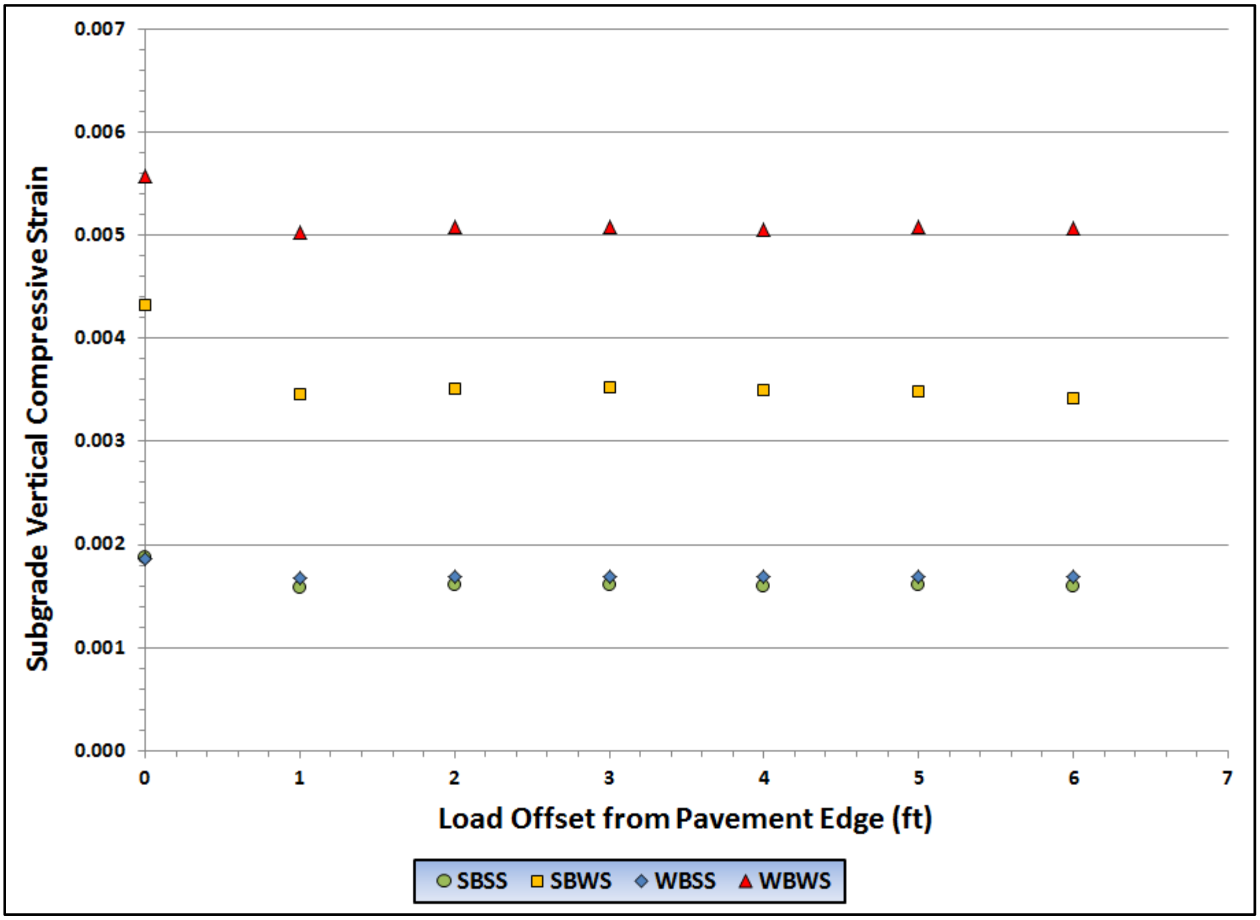

Figure 11. Effect of FB and Subgrade Moduli on Predicted Subgrade Compressive Strain.

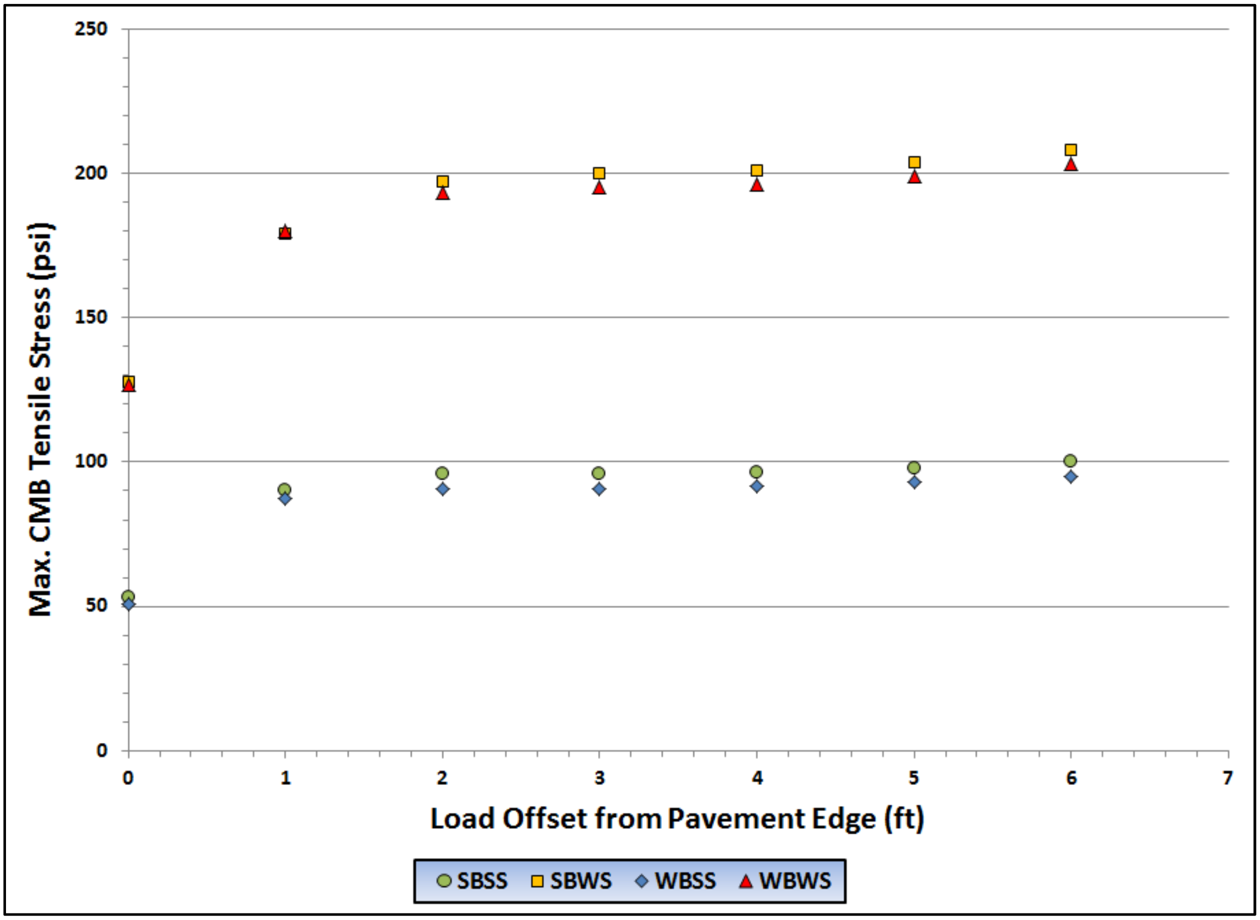

Figure 12. Predicted Variation in CMB Tensile Stress with Load Offset and Subgrade Stiffness.

Figure 13 shows the effect of flexible base thickness on the predicted surface deflections under load. This figure shows that flexible base thickness has a greater effect on the predicted deflections compared to flexible base stiffness. For a pavement on a soft or weak subgrade, increasing the base thickness from 6 to 12 inches leads to larger reductions in the predicted surface deflections compared to the reductions achieved when a stiffer (100 vs. 40 ksi modulus) material is used. It is observed from Figure 13 that, with a 12-inch flexible base, the predicted deflection at a 1-ft load offset from the pavement edge approximates the corresponding deflection at the mid-lane position for the same pavement with a thinner 6-inch base. Compared to the mid-lane deflection for a pavement design with a stiffer 6-inch flexible base, a pavement design with a less stiff (40 ksi modulus) 12-inch base gives about the same deflection at a 4-ft load offset from the pavement edge.

The above comparisons bring out the structural benefit of placing a thicker flexible base in terms of reducing the predicted surface deflection under load. However, in terms of determining paved shoulder width requirements, the comparisons between deflections at various load offsets must be made for the given design instead of between different pavement designs. On this note, Figure 14 shows the ratios of deflections at different load offsets to the corresponding mid-lane deflections. The following observations are noted from this figure:

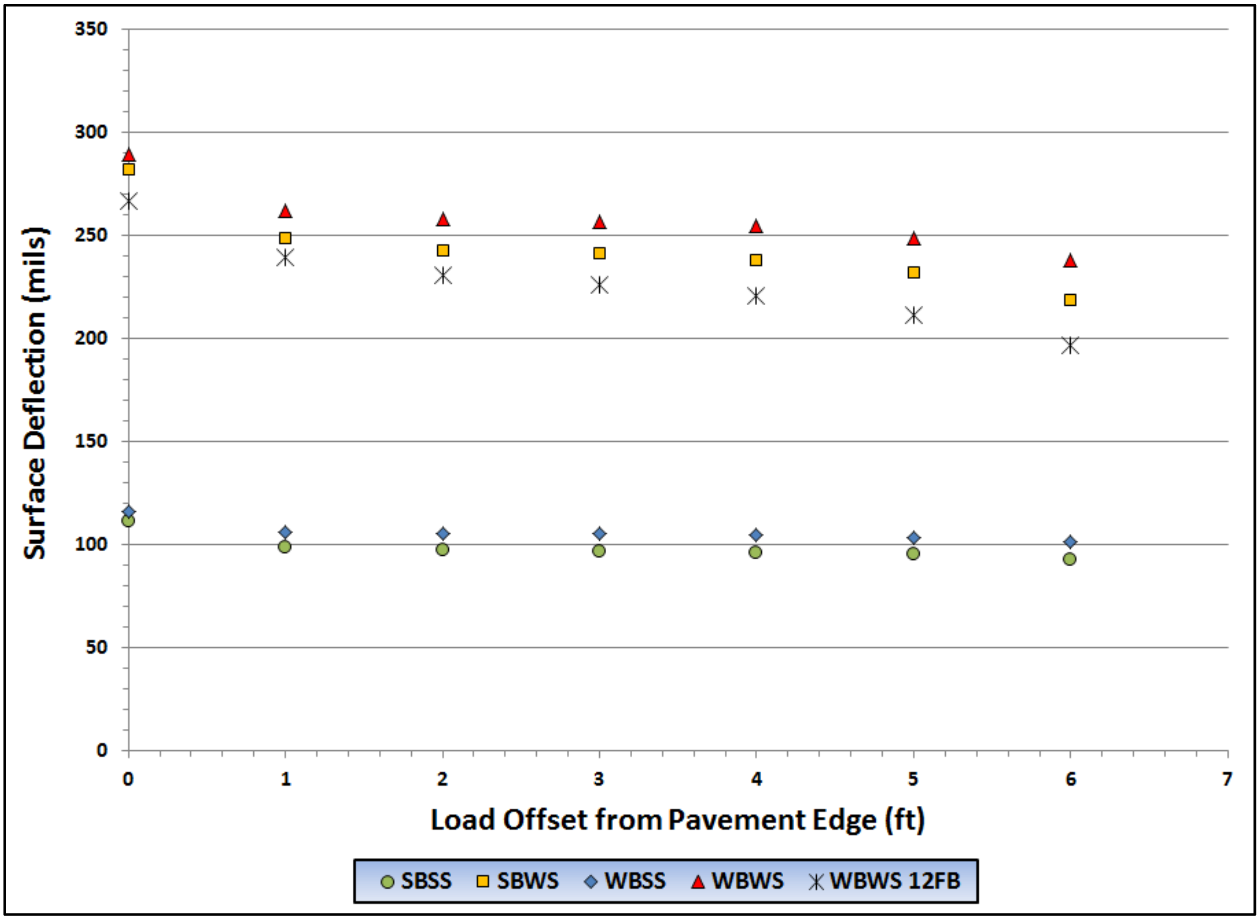

Figure 13. Effect of Flexible Base Thickness on Predicted Surface Deflections.

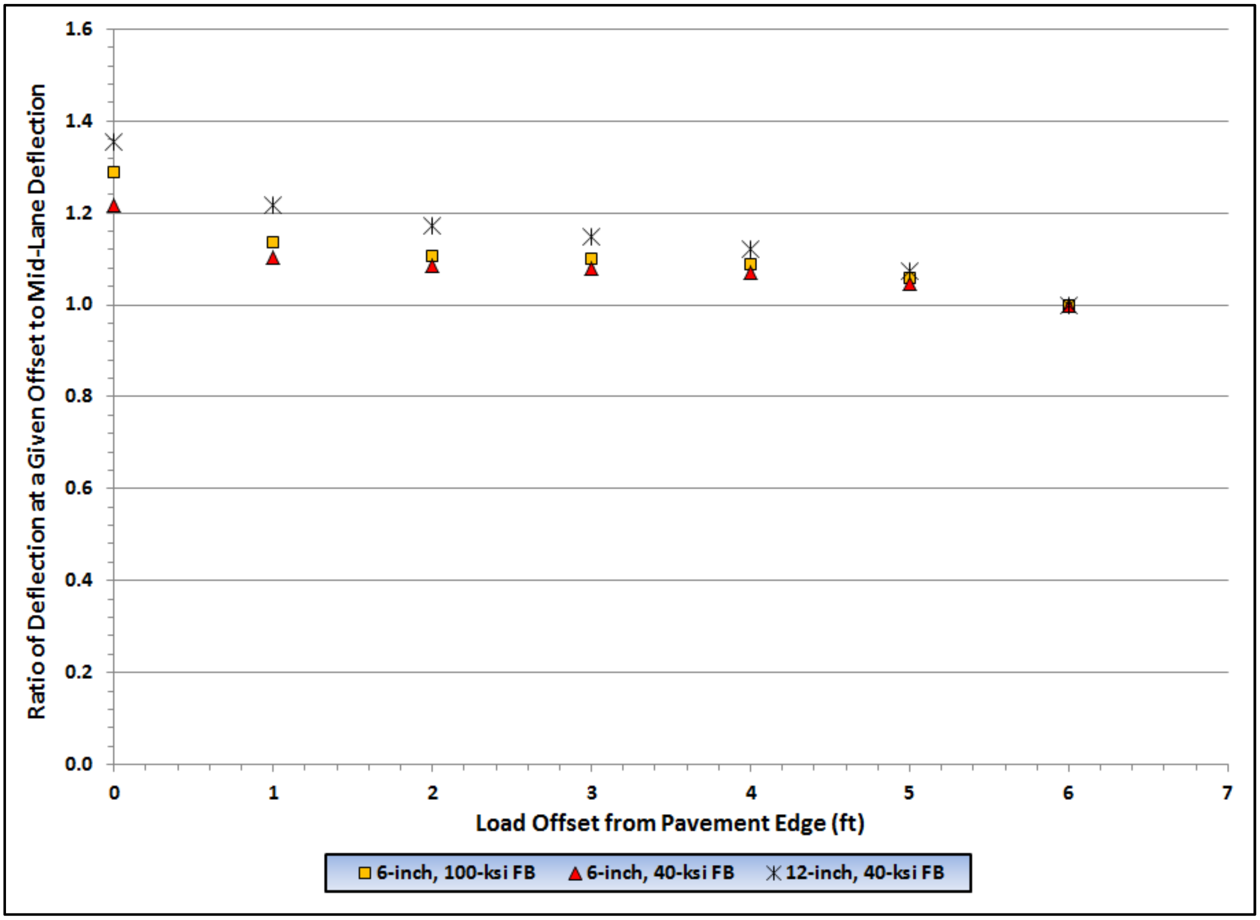

Figure 14. Deflection Ratios for Three Pavement Designs of Varying Base Thickness and Base Stiffness.

1. The deflection ratios for a 40-ksi and a 100-ksi 6-inch flexible base are comparable, with the relative differences between deflections decreasing to about 10 percent of the corresponding mid-lane values at a 2-ft load offset from the pavement edge.
2. With respect to a pavement design with a 40-ksi, 12-inch flexible base, the relative differences between deflections reduce to about 10 percent of the corresponding mid-lane value at a 5-ft load offset from the pavement edge. At this offset, the relative differences between deflections are at or within 10 percent of the corresponding mid-lane values for the three pavement designs shown in Figure 14.

The above results suggest 2- to 5-ft paved shoulders from the edge of a 12-ft wide travel lane based on predicted surface deflections. Note that the required shoulder width is higher for the 12-inch, 40-ksi pavement design. This observation might seem counter-intuitive at first glance until one considers the predicted mid-lane deflections for the three pavement designs. From Figure 13, these deflections are 197, 219, and 238 mils, respectively, for the 12-inch, 40 ksi; the 6-inch, 100 ksi; and the 6-inch, 40 ksi pavement designs. In practice, these designs may correspond to different levels of predicted service life. To maintain deflections under load at or close to a particular design value, the results suggest that a wider paved shoulder is needed for a design where a lower limiting value of deflection must be met.

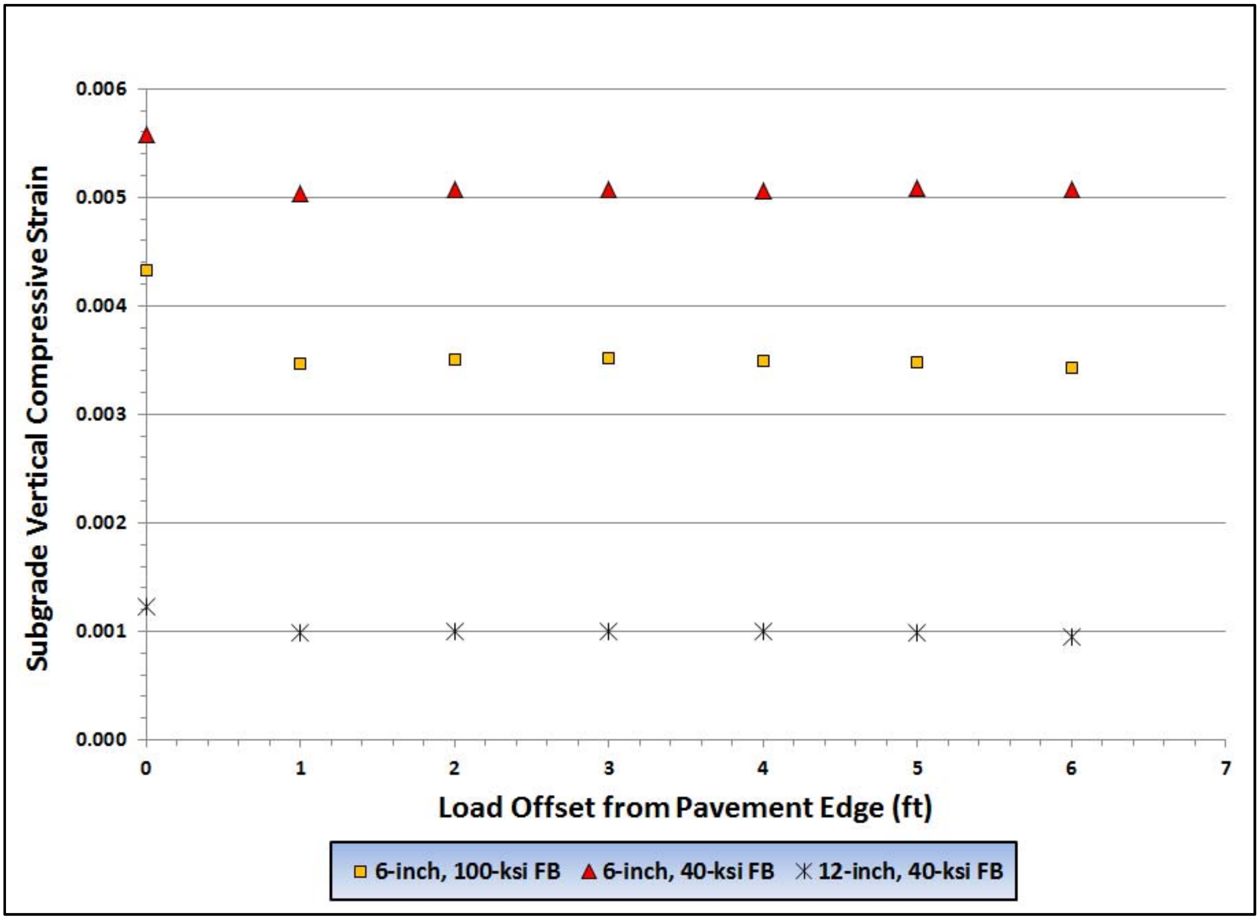

Figure 15. Predicted Subgrade Compressive Strains for Three Pavement Designs of Varying Base Thickness and Base Stiffness.

Figure 15 shows the predicted vertical compressive strains near the top of the subgrade for the three pavement designs presented previously. This figure indicates that increasing the thickness of a 40-ksi flexible base from 6 to 12 inches is more effective at reducing the subgrade compressive strain compared to keeping the same 6-inch base thickness but using a stiffer (100-ksi modulus) material on top of a weak or soft subgrade. Note that the 12-inch flexible base design yields lower predicted subgrade vertical compressive strains than the corresponding predicted values for a stiff subgrade shown in Figure 11. For each pavement design, Figure 15 also shows that the predicted subgrade compressive strain approximates the value at the mid-lane position at an offset of 1-ft from the pavement edge. Beyond this offset, there is minimal variation in the predicted subgrade compressive strains from the corresponding mid-lane values. Thus, it appears that predicted surface deflections have more bearing on paved shoulder width requirements than the predicted subgrade compressive strains.

Figure 16 shows the predicted tensile stresses near the bottom of the CMB layer. Similar to the results presented in Figure 12, the CMB tensile stress for the 12-inch thick flexible base design is predicted to increase with distance from the pavement edge. This particular design is also more effective at reducing the tensile stress in the CMB layer relative to the other two designs considered in these comparisons.

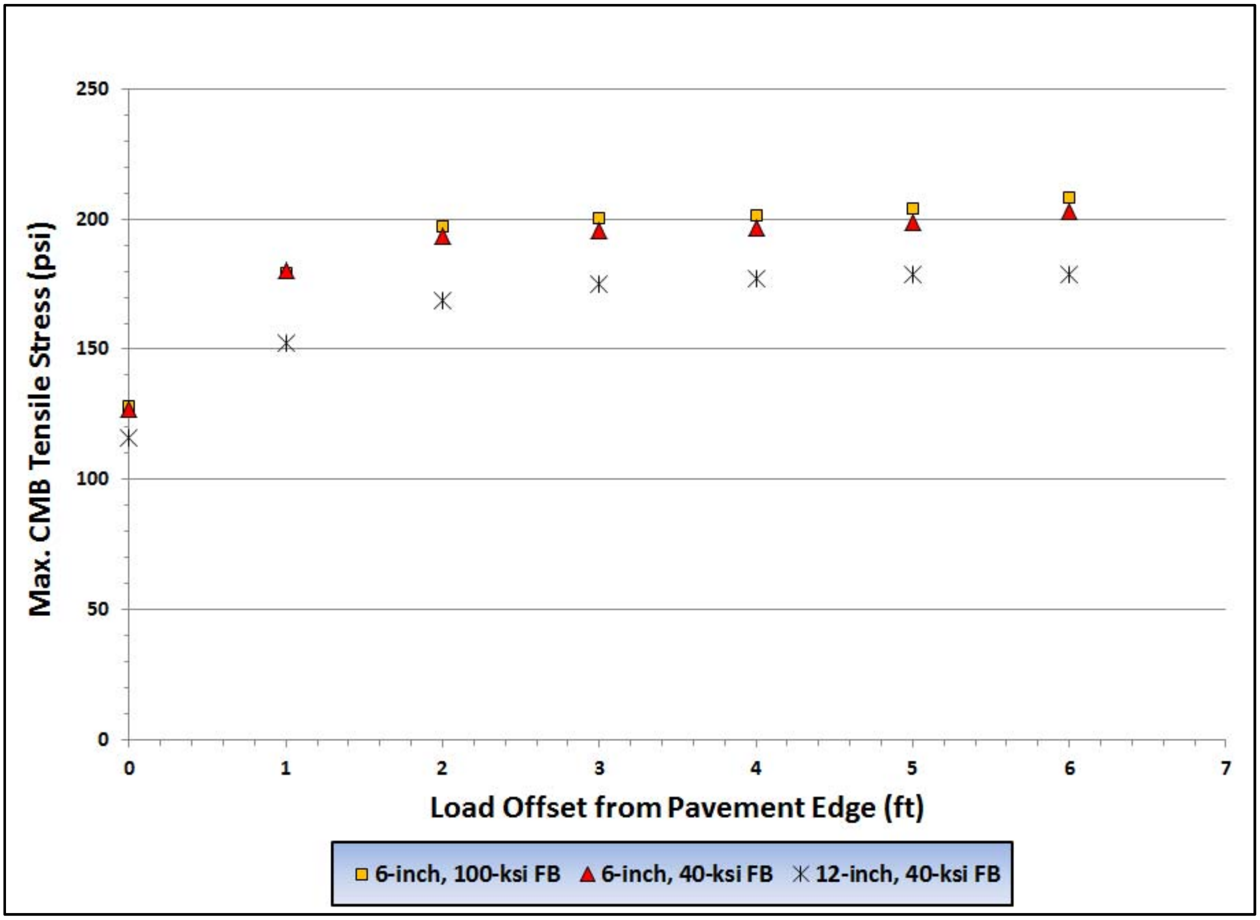

Figure 16. Predicted CMB Tensile Stresses for Three Pavement Designs of Varying Base Thickness and Base Stiffness.

Figure 17 shows the effect of changing the surface material from a 1-course surface treatment (1CST) with a modulus of 200 ksi to a 2-inch hot-mix asphalt (HMA) layer with a 500-ksi modulus. Making this change significantly reduces the predicted deflections under load as shown in the figure. It is observed that the predicted deflection at a 1-ft load offset on top of the HMA layer approximates the predicted surface deflection at the mid-lane position of the pavement with the 1-course surface treatment. Figure 17 also indicates that, in lieu of changing the surface material, one can consider changing the thickness of the flexible base from 6 to 12 inches. The predicted surface deflections for this design are comparable to the corresponding deflections computed for the 2-inch HMA pavement.

Figure 18 compares the deflection ratios between the three pavement designs identified in Figure 17. The deflection ratios are comparable between the 2-inch HMA and 12-inch flexible base designs, with the relative differences between deflections decreasing to within 10 percent of the corresponding mid-lane values at a 5-ft load offset from the pavement edge. Thus, Figure 18 suggests that the 2-inch HMA pavement will need a 5-ft wide paved shoulder, similar to the earlier result found for the 12-inch thick flexible base design.

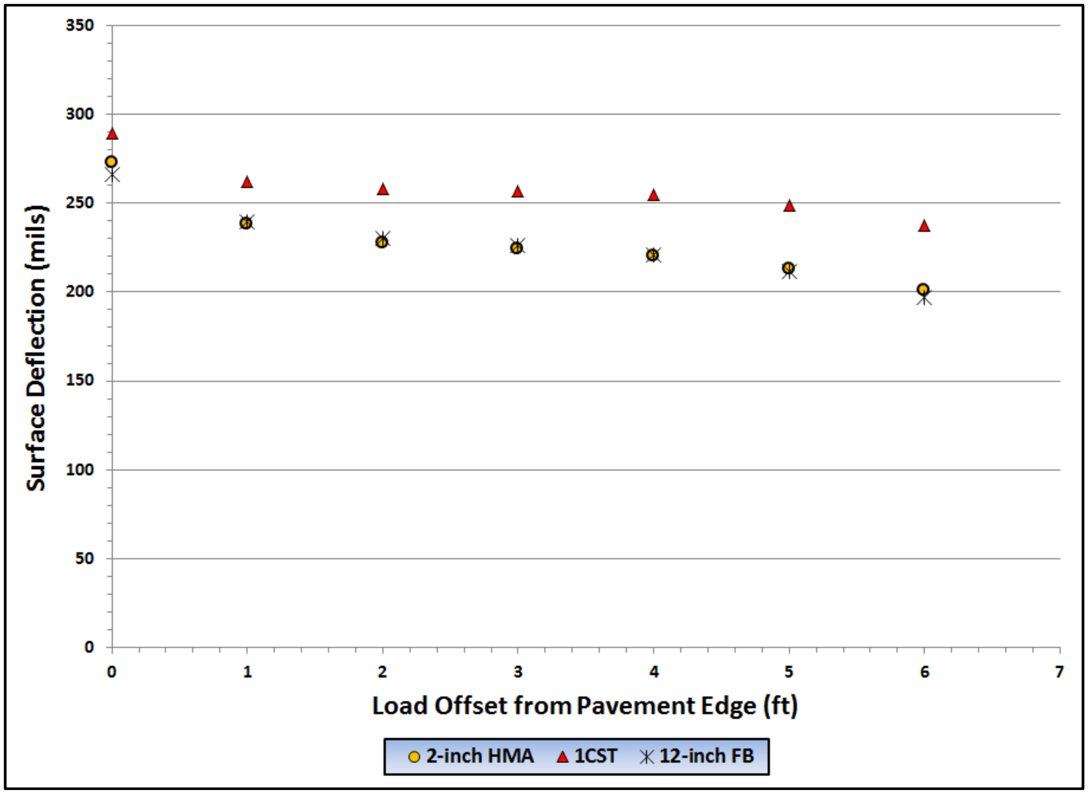

Figure 17. Effect of Surface Material and Thickness on Predicted Deflections.

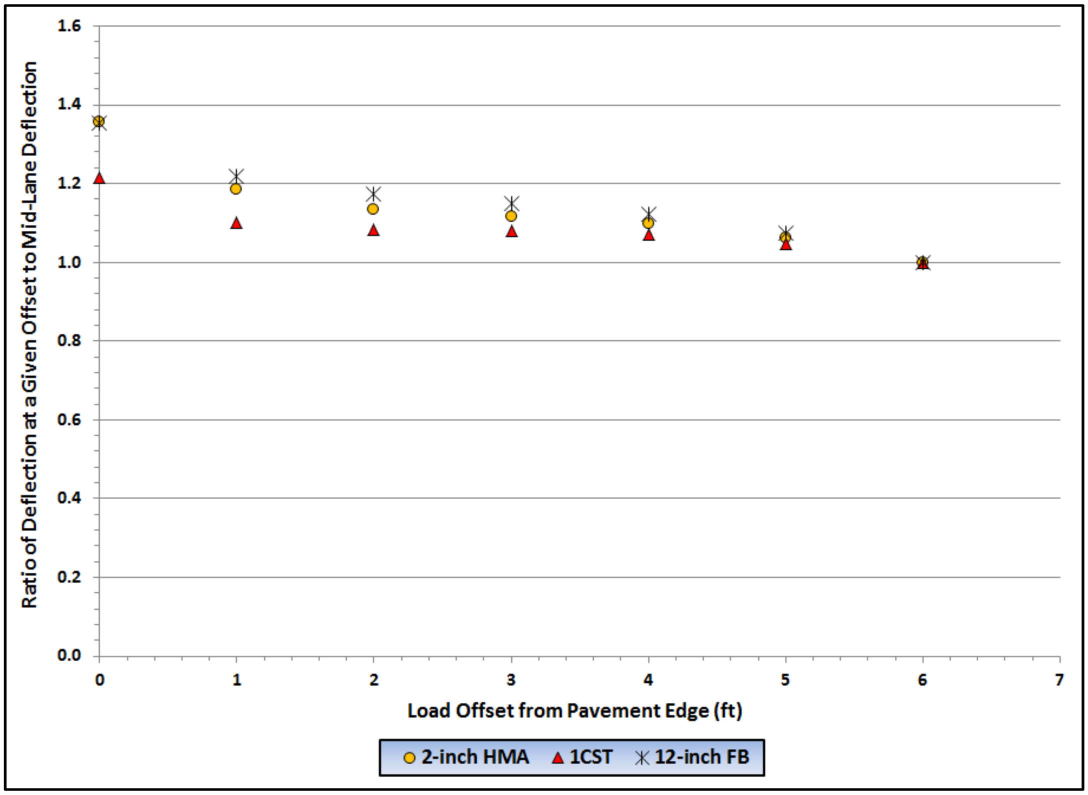

Figure 18. Deflection Ratios for Three Pavement Designs of Varying Surface Material and Flexible Base Thickness.

Figure 19 compares the predicted subgrade compressive strains between the three pavement designs identified in Figure 17. With respect to reducing the subgrade compressive strain and the potential for pavement rutting when the subgrade material is weak or soft (i.e., modulus of 5-ksi), this figure suggests that changing the flexible base thickness from 6 to 12 inches would be more effective than changing the surface material from a 1-CST to a 2-inch HMA. In addition, Figure 19 shows that the predicted subgrade compressive strain for the 2-inch HMA pavement approximates the value at the mid-lane position at an offset of 1 ft from the pavement edge. Similar to the earlier results, there is minimal variation in the predicted subgrade compressive strains from the corresponding mid-lane value beyond this 1-ft offset.

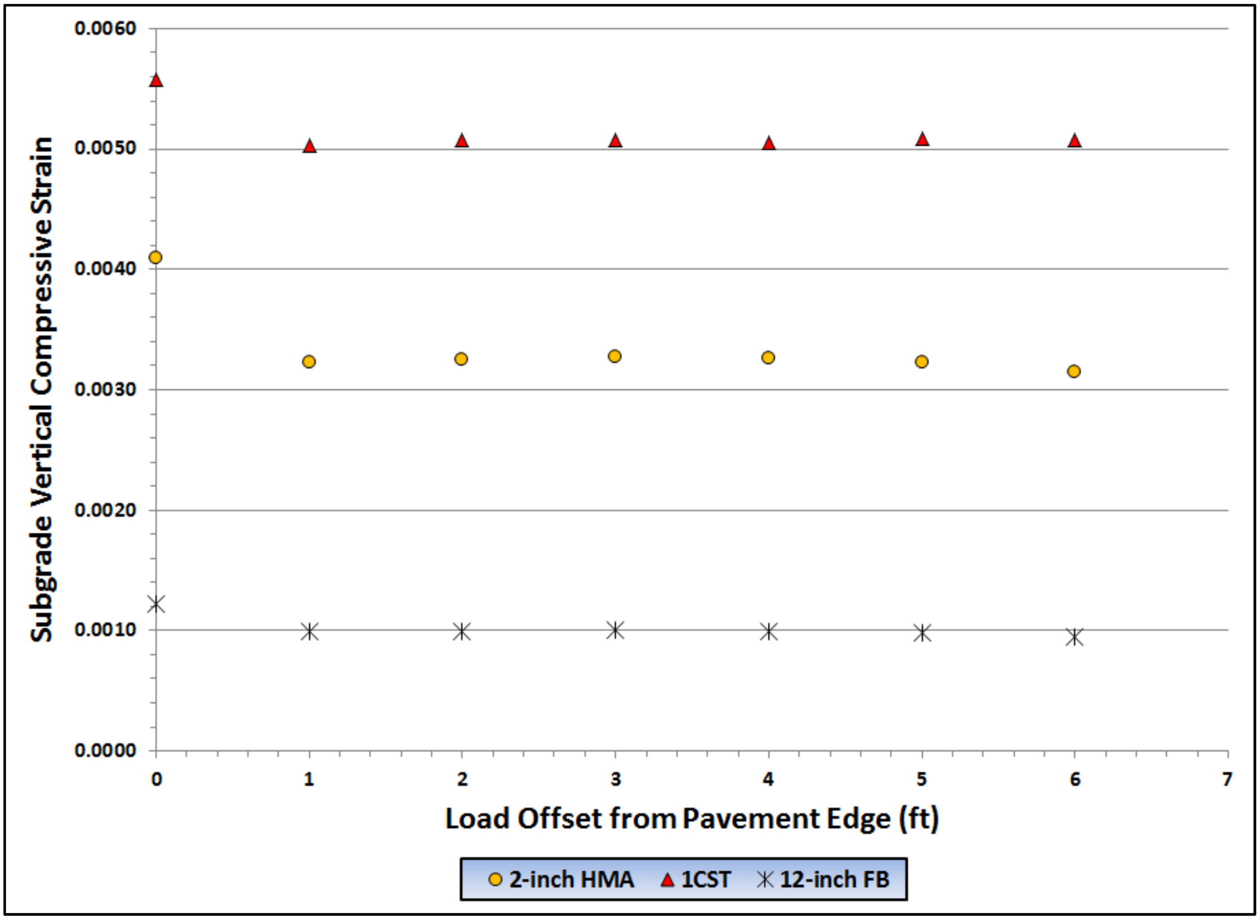

Figure 19. Predicted Subgrade Compressive Strains for Three Pavement Designs of Varying Surface Material and Flexible Base Thickness.

The study also investigated the effect of changing from a 2-inch thick HMA surface layer to a 6-inch hot-mix surface. Figure 20 compares the predicted surface deflections between this pavement design and the other 3 designs identified in Figure 17. It is observed that the 6-inch HMA pavement exhibits the lowest surface deflections among the 4 pavement designs identified in Figure 20. Note that the predicted edge deflection for this pavement approximates the mid-lane deflection for the 1-CST pavement. Also, the predicted mid-lane deflection for the 6-inch HMA pavement is 149 mils compared to 197, 201, and 238 mils for the 12-inch flexible base, 2-inch HMA, and 1-CST pavements, respectively.

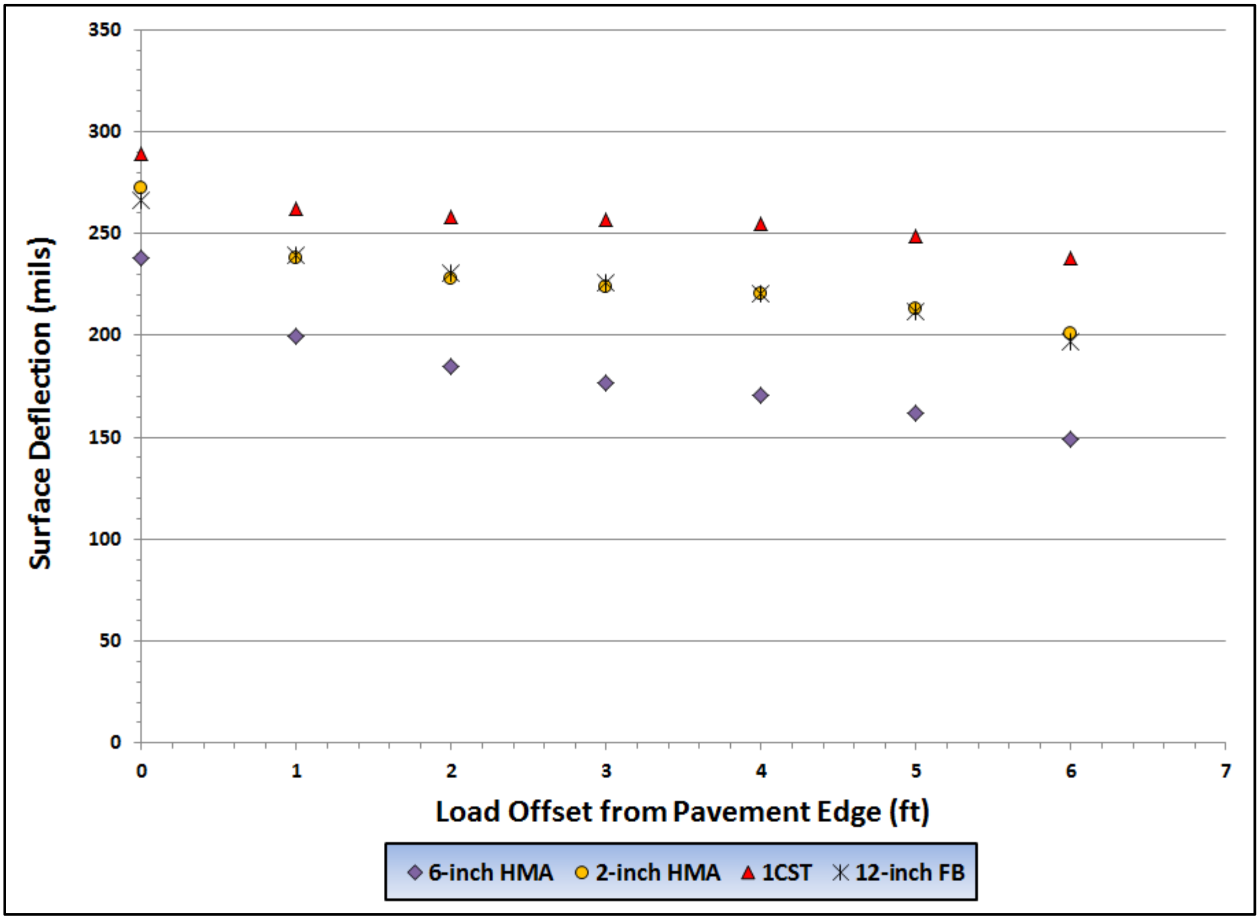

Figure 20. Effect of Thicker HMA Surface Layer on Predicted Deflections.

The study also examined the ratios of the deflections at different offsets to the corresponding deflections at the mid-lane position. For the 6-inch HMA pavement, the relative differences between deflections decreased to within 10 percent of the corresponding mid-lane value at a 5-ft load offset from the pavement edge. Thus, for this pavement design, the analysis indicates the need for a 5-ft wide paved shoulder similar to earlier results.

The study also examined the predicted horizontal strain at the bottom of the HMA layer. For thick HMA surfaces, the FPS program computes the horizontal tensile strain at the bottom of this layer to check the potential for bottom-up fatigue cracking due to repeated load applications. Figure 21 compares the predicted horizontal strains at the bottom of the HMA material for the two levels of HMA thickness considered in the analysis. Positive strains in this figure indicate tension in the horizontal direction while negative strains indicate compression. The following observations are noted from the figure:

1. Horizontal tensile strains are predicted at the bottom of the 6-inch HMA material at all load offsets, with the strain magnitudes increasing as the load moves farther from the pavement edge. This variation in the predicted tensile strains is similar to the variation in the predicted tensile stresses at the bottom of the CMB material shown in Figure 16. The increased tensile strain results from greater bending action within the HMA layer as the load moves away from the shoulder where there is less restraint. Thus, Figure 21

indicates that paved shoulder width requirements will not be governed by the predicted tensile strain at the bottom of thick HMA surface layers.

2. In contrast to the 6-inch HMA material, Figure 21 indicates that the thin 2-inch HMA surface is primarily in compression under load, except at the pavement edge where the horizontal strain is tensile at the bottom of the material. In addition, the maximum shear stress at the bottom of the HMA is predicted when the load is at the pavement edge. These predictions of pavement response are consistent with the observed edge breaks on narrow thin-surfaced roads where the wheel loads track at the pavement edge, and could help explain why these failures develop.

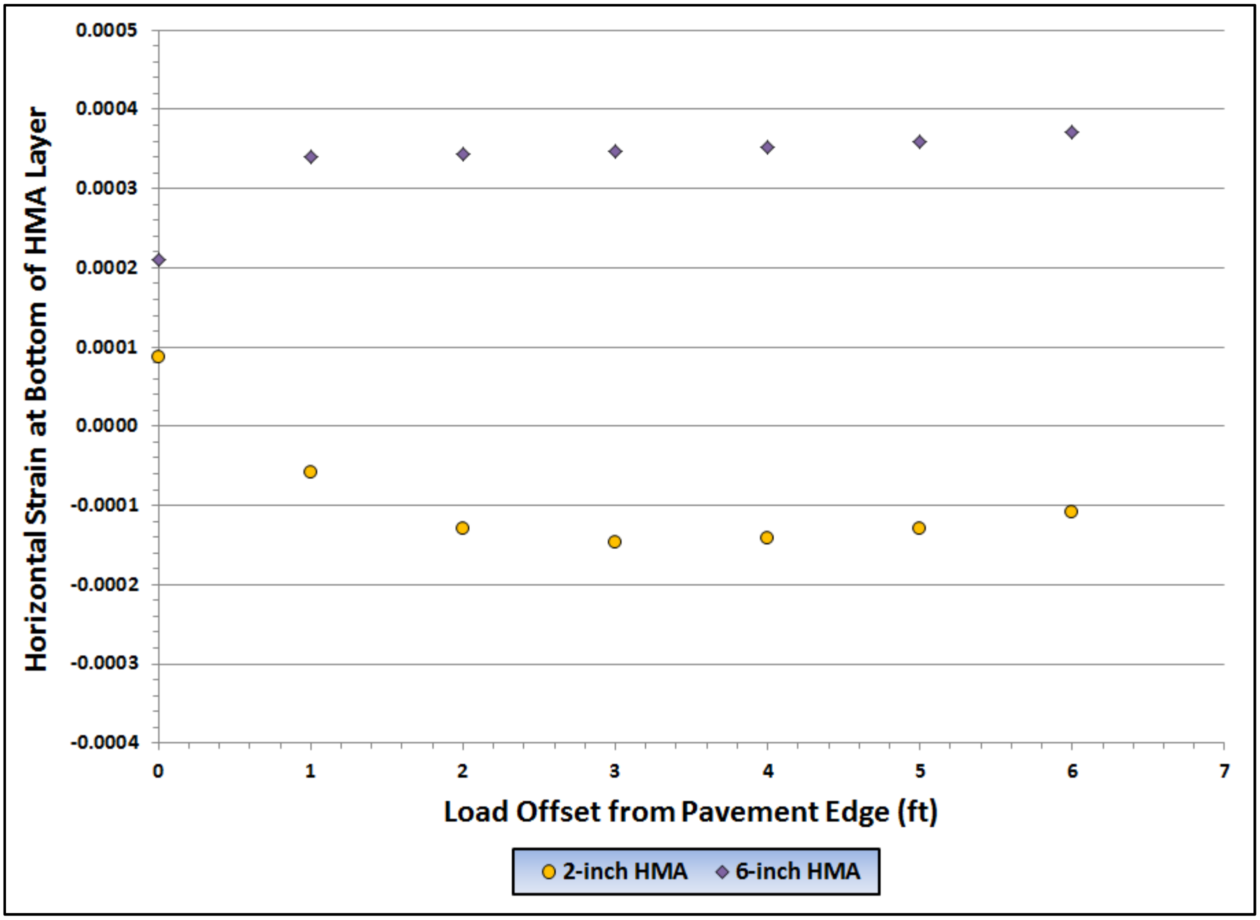

Figure 21. Predicted Horizontal Strains at the Bottom of HMA Surface Layer.

Figure 22 compares the predicted subgrade vertical compressive strains for the 6-inch thick HMA pavement with the other three pavements considered in this analysis. The results suggest that changing the flexible base thickness from 6 to 12 inches provides a better measure of protection against the potential for pavement rutting compared to changing the surface material from a 1-course surface treatment to a 2- or 6-inch HMA surface. The 12-inch flexible base design yields the lowest predicted subgrade vertical compressive strains under load among the four pavement designs identified in Figure 22. With respect to shoulder width requirements, the subgrade vertical compressive strain for the 6-inch HMA pavement reduces to within 10 percent of the corresponding mid-lane value at an offset of 1 foot from the pavement edge. At load offsets of 1 foot and higher, all four pavements exhibit minimal variation in the predicted subgrade vertical compressive strains.

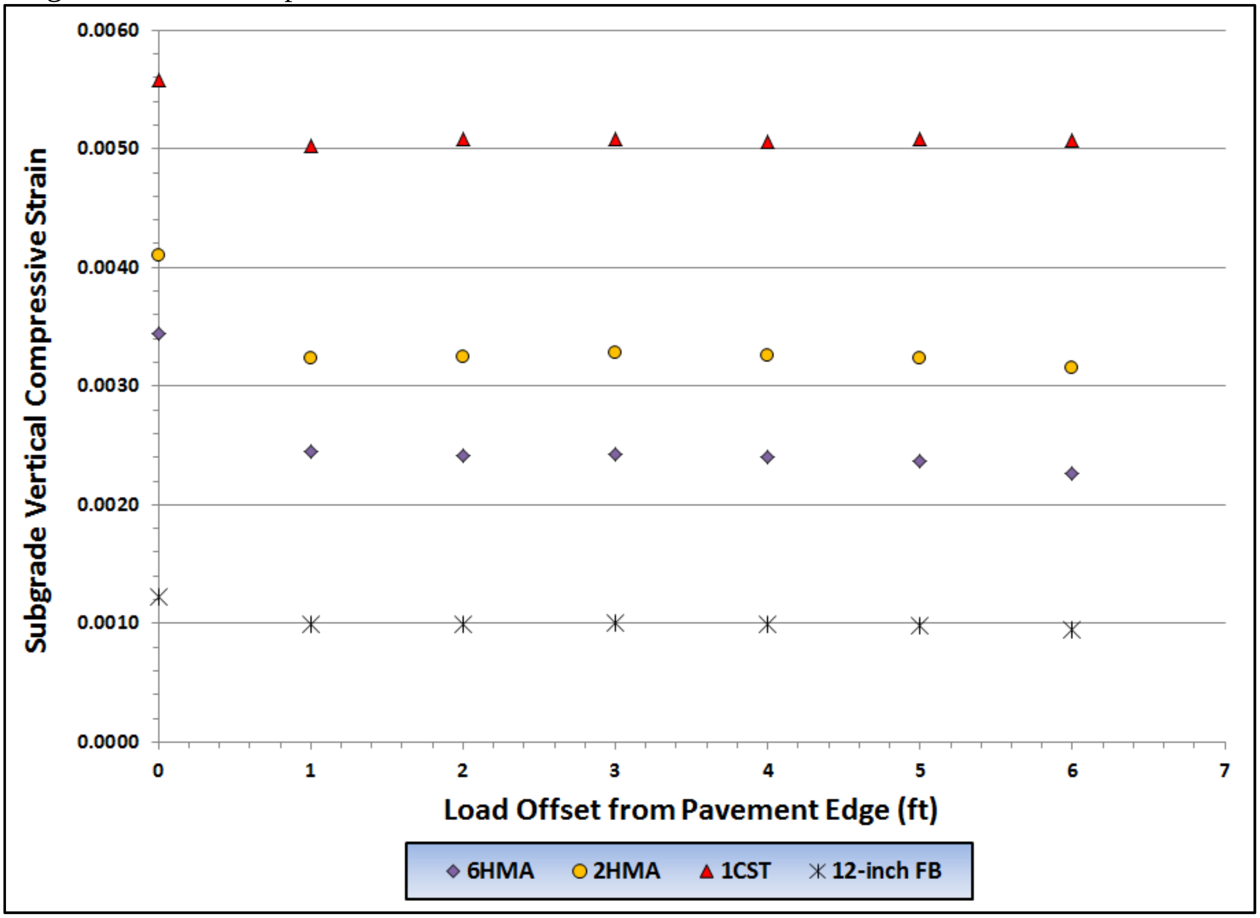

Figure 22. Predicted Subgrade Vertical Compressive Strains for Different Pavements.

SUMMARY AND CONCLUSIONS

The analysis of paved shoulder width requirements considered the current methodology used by TxDOT to design flexible pavements. This methodology, as implemented in TxDOT's FPS program, is based on modeling the pavement as a linear-elastic layered system, with each layer characterized by a modulus and a Poisson's ratio. This model assumes pavement layers that extend infinitely in the horizontal direction with applied loads acting within the layered system, i.e., no edge loading. In reality, roadways are of finite width. Thus, this study examined the variation of the predicted pavement response at different load offsets from the pavement edge to determine paved shoulder width requirements that minimize the effect of the edge boundary and maintain consistency with the interior loading assumption used in FPS. For flexible pavements designed using this program, it is important that this assumption be realized during the service life of the given pavement.

To analyze shoulder width requirements, this study used a 2-dimensional finite element program to predict the variation in pavement response as the load is positioned at different offsets from the pavement edge. This analysis covered a representative range of flexible pavements that included different material types and thicknesses. Based on the results obtained, the following findings are noted:

1. The predicted variation in surface deflections exhibits the most sensitivity over the range of load offsets from the edge compared to other performance-related pavement response parameters considered in the analysis. Based on predicted surface deflections, the minimum suggested paved shoulder width varies from 3 to 6 feet over the range of material types and layer thickness included in the evaluation. For the case where the subgrade is stiff, the predicted deflection drops to within 5 percent of the corresponding mid-lane value at an offset between 3 to 4 ft from the pavement edge. In contrast, the required offset is between 5 to 6 ft for a weak or soft subgrade. The analysis found the effect of edge loading to be not as severe on a stiff subgrade, where the predicted deflections more rapidly approach the corresponding deflections at the mid-lane position compared to the condition where the subgrade is weak.
2. Variations in pavement design, such as changing from a 1-course surface treatment (1-CST) to a hot-mix asphalt (HMA) surface, increasing the HMA or flexible base thickness, and using a stiffer base material on a weak or soft subgrade reduce the predicted deflections and subgrade vertical compressive strains in varying degrees. The results suggest that using higher quality materials or placing thicker layers will require minimum paved shoulder widths in the 2- to 5-ft range. Wider paved shoulders are indicated for higher class roadways designed for heavy truck traffic where the predicted pavement response under load must be kept at the levels necessary to achieve the design service life. Thus, realizing the interior loading condition assumed in pavement design becomes even more critical under high-volume, heavy truck traffic service conditions.
3. For the range of pavements considered in the analysis, the predicted subgrade vertical compressive strain reduces to within 5 percent of the corresponding mid-lane value at a 1-ft load offset from the pavement edge. Beyond this offset, there is minimal variation in the predicted subgrade compressive strains from the mid-lane value.
4. The predicted horizontal tensile stress at the bottom of a cement modified base and horizontal tensile strain at the bottom of a thick (6-inch) HMA surface increases as the

load moves away from the unpaved shoulder. Thus, the edge is not the critical location for these performance-related pavement response parameters.

5. The analysis also predicts that a thin (2-inch) HMA surface is primarily in compression under load, except at the pavement edge where the horizontal strain is tensile at the bottom of the material. In addition, the maximum shear stress at the bottom of this thin HMA surface is predicted when the load is at the pavement edge. These predictions of pavement response are consistent with the observed edge breaks on narrow thin-surfaced roads where the wheel loads track at the pavement edge, and could help explain why these failures develop.
6. The analysis also considered the effect of shoulder slope on the predicted pavement response under the applied wheel loads on the travel lane. This analysis assumed the shoulder as consisting of non-stabilized, loose material, placed on top of the subgrade adjacent to the travel lane. Everything else being the same, the analysis revealed minimal differences in predicted pavement response between a 1:3 and a 1:6 shoulder slope.
7. The analysis also resulted in a number of findings useful for developing pavement design guidelines applicable to roadways that serve energy development and production activities. The relevant findings are summarized below:
    a. The effect of the flexible base stiffness on the predicted surface deflections is not as significant as the effect of subgrade stiffness. The predicted deflections drop significantly with increase in subgrade stiffness. The predicted deflections also diminish with increase in base stiffness but the change is not as significant, and depends on the level of subgrade stiffness.
    b. The analysis suggests that a higher quality flexible base would be more effective at minimizing the development of pavement rutting due to repeated load repetitions when placed on a soft or weak subgrade than when founded on a stiff subgrade, where the predicted deflections are governed by the stiff subgrade.
    c. The analysis found that flexible base thickness has a greater effect on the predicted surface deflections under load compared to flexible base stiffness. For a pavement on a soft or weak subgrade, increasing the base thickness from 6 to 12 inches leads to larger reductions in the predicted surface deflections compared to the reductions achieved when a stiffer (100 vs. 40 ksi modulus) base material is used.
    d. Changing the surface material from a 1-course surface treatment to a 2-inch HMA significantly reduces the predicted deflections under load for the pavements considered in the analysis. However, in lieu of changing the surface material, another option to consider is to increase the flexible base thickness. The predicted surface deflections for the thicker flexible base (12 vs. 6 inches) were found to be comparable to the calculated deflections for the 2-inch HMA pavement.
    e. With respect to reducing the subgrade vertical compressive strain and the potential for pavement rutting, the results suggest that changing the flexible base thickness from 6 to 12 inches would be more effective than changing the surface material from a 1-CST to hot-mix asphalt.

In summary, TxDOT Districts currently place 2-ft shoulders as a minimum. Assuming 12-ft travel lanes, this practice translates to paved two-lane roadway widths of 28 ft. This study found that the predicted surface deflections govern the minimum paved shoulder width requirements. The results suggest that these requirements range from 4 ft for a pavement founded on a stiff subgrade, to 6 ft for a pavement founded on a weak or soft subgrade but built with higher quality or thicker surface or base layers. Assuming 12-ft travel lanes, these findings translate to minimum paved two-lane roadway widths ranging from 32 to 36 ft. These minimum requirements are based on structural pavement design considerations. Paved shoulders exceeding these requirements could further enhance roadway safety and protection against moisture infiltration.