

ANALYSIS OF STRUCTURAL RESPONSE OF CONCRETE PAVEMENTS UNDER CRITICAL THERMAL-LOADING CONDITIONS

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ABSTRACT

This paper presents the results of a parametric analysis of structural response of concrete pavements under simultaneous action of traffic loads and temperature variations in the slab. The parameters studied include (1) temperature differential in the slab, (2) slab length, (3) modulus of subgrade reaction, (4) concrete elastic modulus, (5) slab thickness, (6) edge stiffness, and (7) joint stiffness. The effects of using a bonded interface in a composite pavement slab were also analyzed under the thermal-load condition. The finite element computer program FEACONS, developed at the University of Florida, was used to compute the maximum thermal-load-induced stresses in the concrete slabs. Temperature was assumed to vary linearly along the slab depth. The results were also compared with those obtained by the Westergaard equations and the influence charts developed by Pickett and Ray. The results of the analysis show that the temperature differential in the slab has significant effects on the structural response of concrete pavements. Also, the effects of these pavement parameters under critical thermal-loading conditions are different from those under full subgrade support condition. It was observed that, with the presence of temperature differential in the slab, the effects of modulus of subgrade reaction can not be determined without considering other pavement parameters. For example, with a shorter slab length, the computed maximum thermal-load induced stress increases as the modulus of subgrade increases. The reverse is true for a pavement with longer slab lengths. The use of a bonded interface in a composite pavement slab is most effective in reducing the maximum stresses in the slab when a thinner layer is placed on top of a thicker layer. These observations point to the importance of considering thermal curling effects in concrete pavement analysis and design.

INTRODUCTION

It is a well-known fact that variations of temperature in a concrete pavement slab can cause the slab to curl and lose partial contact with the subgrade (1-6). During the day, when the top of the slab is warmer than the bottom, the slab tends to curl up the slab interior. During the night, when the top is cooler than the bottom, the slab tends to curl up at the edges and joints. When loads are applied to the slab during these curling conditions, the induced stresses in the slab could be substantially higher than those when the slab is in full contact with the subgrade. Thus, the damage to the slab caused by these critical thermal-load-induced stresses could be much higher than those under a full subgrade support condition. Because of the complexity of the analysis involving thermal curling effects, the maximum thermal-load-induced stresses have conventionally determined by summing up the stresses due to the applied loads and those induced by curling (7,8). However, this approach has long been demonstrated to underestimate the maximum thermal-load-induced stresses in the slab (1,9). A better understanding about how concrete pavements behave under combined action of loads and thermal gradients may help in the understanding of some of the existing problems in concrete pavements and also provide better guidelines for design.

A parametric analysis of structural response of concrete pavements under critical thermal-loading conditions was performed in this study. The effects of various parameters on the maximum stresses were analyzed. The parameters studied included (1) the temperature differential in the slab (ΔT), which is equal to the temperature at the top of the slab minus that at the bottom of the slab, (2) the concrete slab length (L), (3) the modulus of subgrade reaction or subgrade stiffness (K_s), (4) the elastic modulus of concrete (E_c), (5) the thickness of the concrete slab (h), and (6) the joint load transfer characteristics,

which are modeled by linear and torsional springs in the finite element model. The response of a pavement with an econocrete base was also analyzed. The effects on stresses of a bonded interface between the concrete and econocrete layers were analyzed and compared with those of an unbonded interface.

MODELING OF CONCRETE PAVEMENT

The program FEACONS (Finite Element Analysis of CONcrete Slabs) Version 4, which was developed at the University of Florida, was used to perform the analysis. A detailed description of the program can be found in References 10 and 11. A brief description of the model is given in this section.

A jointed concrete pavement is modeled as a three-slab system as shown in Figure 1.

Since the analysis of the response of a concrete pavement generally involves computing the stresses and deflections in a slab, which is affected mainly by its two adjacent slabs, it is usually adequate to model a concrete pavement as a three-slab system. A concrete slab is modeled as an assemblage of rectangular plate bending elements with three degrees of freedom at each node. Either a homogeneous slab or a composite slab made up of two layers bonded together can be modeled.

The subgrade is modeled as a dense liquid or a Winkler foundation which is modeled by a series of vertical springs with stiffness of K_s at the nodes. Load transfers across the joints between two adjoining slabs are modeled by shear (or linear) and torsional springs (with stiffness of K_l and K_t , respectively) connecting the slabs at the nodes of the elements along the joints. Edge support from shoulder or adjacent lane (edge stiffness) is modeled by shear springs (with stiffness of K_e) at the nodes along the edges.

When a temperature differential in the slab is considered, the temperature is assumed to vary linearly from the top to the bottom of the slab. The concrete is modeled as linearly elastic and isotropic. The FEACONS program uses an incremental computational procedure. The force vectors due to the weight of the slab, thermal gradients and applied loads are applied in increments. At the end of each load increment, the stiffness matrix of the system is adjusted according to the new subgrade support condition. A subgrade spring stiffness of zero is used when a gap exists between the subgrade and the slab.

The FEACONS program has been used extensively in conducting research work at the University of Florida (4,12,13). The structural responses compared well with those measured on the field and those computed by theoretical equations.

METHOD OF ANALYSIS

A preliminary analysis was performed to determine the combination of load position and temperature differential which would produce the highest thermal-load-induced stresses in the pavement slab. The two temperature differentials considered in the analysis were $+11.1^\circ\text{C}$ ($+20^\circ\text{F}$) and -5.6°C (-10°F), which represent typical severe slab temperature gradients at day time and nighttime conditions in Florida (12). The applied load used in the analysis was a 89-kN (20-kip) single-axle load (two 44.5-kN [10-kip] loads at 1.8 m [6 feet] apart), which represents the approximate maximum allowable axle load in Florida. The four load positions were (1) slab center, (2) slab edge, (3) slab joint and (4) slab corner. Stresses in a typical pavement slab caused by the axle load for the various combinations of temperature differentials and load positions were computed using the FEACONS program. The pavement system had a slab thickness of 23 cm (9 in.), an E_c of 27.6 GPa (4000 ksi), a K_s of 67.9 MPa/m (250 pci), a K_l of 69.0 MPa (10 ksi), a K_t of 2.23 MN-m/m (500 k-in./in.), and an edge stiffness of 34.5 MPa (5 ksi).

The results of the analysis indicate that when temperature in the slab is positive, the critical load position is at the edge of the slab. Figures 2 through 5 show plots of the computed stresses in a typical pavement slab caused by a temperature differential of $+11.1^\circ\text{C}$ ($+20^\circ\text{F}$) and a 89-kN (20-kip) axle load applied at the center, the edge, the joint and the corner of the slab, respectively. The highest stress of 3716 kPa (539 psi) is obtained when the load is applied to the edge of the slab. The edge load position was thus used in the computation of the maximum thermal-load-induced stresses for the condition of positive temperature differential.

When the temperature differential is negative, the critical load position is at the slab corner. Figures 6 through 9 show plots of the computed stresses in the same pavement slab caused by a temperature differential of -5.6°C (-10°F) and a 89-kN (20-kip) axle load applied at the center, the edge, the joint and the corner of the slab, respectively. The highest stress of 1310 kPa (190 psi) is obtained when the load is applied to the corner of the slab. The corner load position was thus used in the computation of the maximum thermal-load-induced stresses for the case of negative temperature differential. However, the maximum stresses produced under the negative thermal gradient condition were substantially lower than those produced under the positive thermal gradient condition. The critical stresses under the positive thermal gradient condition were considered in most of the cases in this study.

In the main study presented in this paper, the FEACONS program was used to compute the maximum thermal-load-induced stresses for various combinations of pavement parameters and temperature differentials in the slab. The reference load used was a 89-kN (20-kip) single-axle load (two 44.5-kN [10-kip] loads at 1.8 m [6 feet] apart). Temperature gradient in the slab was assumed to be linear. However, it has been reported that the temperature distribution within concrete slabs were mostly nonlinear.^(4,13) The maximum computed tensile stresses caused by a linear temperature gradient tend to be higher for the day time condition (with slab top warmer than the bottom).⁽¹³⁾ Nevertheless, this approach could be used to provide information on how the presence of temperature gradient in the concrete slabs would affect the structural response of the pavement system.

The maximum stresses computed by the FEACONS program were also compared with those computed by using Westergaard's 1948 edge stress formula⁽¹⁴⁾ and those by the influence charts developed by Pickett and Ray^(15,16). However, the application of the Westergaard equation and Pickett and Ray's influence charts is limited to the case of zero thermal gradient in the slab. The maximum stresses were expressed as ratios to the estimated flexural strength or modulus of rupture (MR) of the concrete material. The concrete modulus of rupture were estimated from the following two equations^(17,18):

$$E_c = W^{1.5} \cdot 33 \cdot (f_c)^{1/2} \quad (1)$$

$$MR = 9 \cdot (f_c)^{1/2} \quad (2)$$

where E_c = concrete modulus, psi

W = concrete unit weight, pcf

f_c = compressive strength of concrete, psi

MR = concrete modulus of rupture or compressive strength, psi

RESULTS OF ANALYSIS

Effects of Temperature Differential and Slab Length

The combined effects of temperature differential in the slab and slab length on the maximum stresses in a typical concrete pavement were analyzed. A typical pavement system with the following dimensions and parameters was used:

1. Slab thickness of 23 cm (9 inches).
2. Concrete modulus (E_c) of 27.6 GPa (4000 ksi).
3. Subgrade stiffness (K_s) of 81.5 MN/m³ (300 pci).
4. Edge stiffness (K_e) of 34.5 MPa (5 ksi).
5. Linear joint stiffness (K_l) of 345 MPa (50 ksi).
6. Torsional joint stiffness (K_t) of 2.23 MN-m/m

(500 k-in./in.).

The maximum longitudinal stresses (S_x) caused by a 89-kN (20-kip) single-axle load at the edge for various combinations of temperature differential (ΔT) and slab length (L) were computed using the FEACONS program. For the case of zero temperature differential, the Westergaard equation and Pickett and Ray influence charts were also used to compute the maximum stresses.

Figure 10 shows the plot of the maximum computed stress to the modulus of rupture ratios (S_x/MR) as functions of slab length for various thermal conditions. Slab length is expressed as a dimensionless term L/l , where

l = radius of relative stiffness of the pavement system

$$= \{(E_c \cdot h^3) / [12 \cdot (1 - \mu^2) \cdot K_s]\}^{1/4}$$

μ = Poisson's ratio = 0.15

When the temperature differential is zero, the maximum stresses are not affected by the change of the slab length. This implies that, for the edge load case in a typical pavement system, the assumption of a infinite size slab used by Westergaard^(14,19,20,21) is valid when there is no temperature differential in the slab. Also, the stresses computed by the FEACONS program are very close to those computed by the two classical methods.

As observed from the plot, the computed stresses increase with an increase in temperature differential in the slab. For a slab length of 4.9*1 (3.7 m or 12 feet), the maximum stress in the slab with a temperature differential of 16.7°C (30 °F) is twice as that in the slab with no temperature differential. Also, as the temperature differential increases the effects of the slab length on the maximum stress become more significant. For the pavement system studied, when the temperature differential in the slab is less than 8.3 °C (15 °F), the maximum stress increases with an increase of slab length up to 6*1 ($L \approx 4.6$ m or 15 feet). Beyond that, the slab length has essentially no effects on the maximum stress. When the temperature differential in the slab is greater than 8.3 °C (15 °F), the maximum stress increases as the slab length increases even if the slab length is greater than 6*1. However, the rate of the stress increase decreases as the slab length increases.

The analysis results point to the importance of consideration of temperature differential in the slab and slab length in concrete pavement analysis and design.

Effects of Subgrade Stiffness and Slab Length

The combined effects of subgrade stiffness and slab length were analyzed. A typical pavement system with the following dimensions and material properties was used in the analysis:

1. Slab thickness of 23 cm (9 inches).
2. Concrete modulus (E_c) of 27.6 GPa (4000 ksi).
3. Edge stiffness (K_e) of 34.5 MPa (5 ksi).
4. Linear joint stiffness (K_l) of 345 MPa (50 ksi).
5. Torsional joint stiffness (K_t) of 2.23 MN-m/m (500 k-in./in.).

The maximum stresses in the slab caused by a 89-kN (20-kip) single-axle load at the edge center were computed for the condition of temperature differential of +11.1 °C (+20 °F) and for the condition of zero thermal gradient. The slab length was varied from 3.7 m (12 feet) to 7.3 m (24 feet) while the subgrade stiffness was varied from 27 MN/m³ to 216 MN/m³ (100 pci to 800 pci).

Figure 11 shows the effects of subgrade stiffness and slab length on the maximum longitudinal stresses which are presented as ratios to the concrete modulus of rupture. It can be noted that, with a temperature differential of +11.1 °C (+20 °F) in the slab, the maximum stress increase as the subgrade stiffness increases for a pavement with a slab length of 3.7 m (12 feet). For a pavement with a slab length of 4.6 m (15 feet), the maximum stress remains approximately constant regardless of the change in subgrade stiffness. For a pavement with a 6.1- or 7.3-m (20- or 24-foot) slab, the maximum stress decreases with the increase of subgrade stiffness.

For any given subgrade stiffness, the maximum stress increases as the slab length increases from 3.7 m to 6.1 m (12 feet to 20 feet), and remains unchanged as the slab length increases from 6.1 m to 7.3 m (20 feet to 24 feet).

When the temperature differential is not considered, the maximum stresses decrease slowly as the subgrade stiffness increases for all cases. The maximum stresses calculated by the three methods are very close to one another. The change of slab length has very little effect on the maximum computed stress for this case.

The results of the analysis indicate that the effects of the subgrade stiffness on a pavement can not be analyzed without considering other pavement parameters at the same time. With the presence of temperature differential in the slab, the use of a stiff base may not be beneficial to the concrete pavement.

Effects of Elastic Modulus of Concrete

The effects of elastic modulus of concrete were analyzed. A typical pavement system with the following parameters was used in the analysis:

1. Slab thickness of 23 cm (9 inches).
2. Slab length (L) of 6.1 m (20 feet).
3. Subgrade stiffness (K_s) of 81.5 MN/m³ (300 pci).

4. Edge stiffness (K_e) of 34.5 MPa (5 ksi).
5. Linear joint stiffness (K_l) of 345 MPa (50 ksi).
6. Torsional joint stiffness (K_t) of 2.23 MN-m/m (500 k-in./in.).

The maximum longitudinal stresses in the slab caused by a 89-kN (20-kip) single-axle load at the edge center were computed for the condition of temperature differential of +11.1 °C (+20 °F) and for the condition of zero thermal gradient.

The maximum stresses, expressed in terms of the concrete modulus of rupture, are plot as functions of concrete elastic modulus in Figure 12. The concrete modulus of rupture was estimated from its elastic modulus using Equations 1 and 2 presented earlier. It can be noted that, with or without the consideration of temperature differential in the slab, the maximum stress to strength ratios decrease as the concrete modulus increases. However, the rate of decrease in the maximum stress to strength ratio is slower when the temperature differential in the slab is considered. In other words, with the presence of a temperature differential in the slab, the maximum stress increases in a faster rate than that under no temperature differential condition. For the case of zero thermal gradient, the maximum stresses computed by the three methods show the same trends and are very close to one another.

Effects of Concrete Slab Thickness

The effects of concrete slab thickness were evaluated in a similar manner. A pavement system with the following parameters and dimensions was used:

1. Slab length (L) of 6.1 m (20 feet).
2. Concrete modulus (E_c) of 27.6 GPa (4000 ksi).
3. Subgrade stiffness (K_s) of 81.5 MN/m³ (300 pci).
4. Edge stiffness (K_e) of 34.5 MPa (5 ksi).
5. Linear joint stiffness (K_l) of 345 MPa (50 ksi).
6. Torsional joint stiffness (K_t) of 2.23 MN-m/m (500 k-in./in.).

The maximum stresses in the slab caused by a 89-kN (20-kip) single-axle load at the edge center were computed for the condition of temperature differential of +11.1 °C (+20 °F) and for the condition of zero thermal gradient. The slab thickness was varied from 15 cm (6 inches) to 51 cm (20 inches).

The effects of concrete slab thickness on the maximum stress to strength ratio are shown in Figure 13. It can be observed that the maximum stresses decrease with the increase of the slab thickness. The rate of stress decrease gradually decreases with the increase of slab thickness. However, as noted from the figure, the maximum stress to strength ratios

decrease in a faster rate when the temperature differential in the slab is considered.

Effects of Edge Stiffness

The effects of edge condition on the response of pavement under the critical thermal-load condition were evaluated. The typical pavement analyzed had the following parameters and dimensions:

1. Slab length (L) of 6.1 m (20 feet).
2. Slab thickness of 23 cm (9 inches).
3. Concrete modulus (E_c) of 27.6 GPa (4000 ksi).
4. Subgrade stiffness (K_s) of 81.5 MN/m³ (300 pci).
5. Linear joint stiffness (K_l) of 345 MPa (50 ksi).
6. Torsional joint stiffness (K_t) of 2.23 MN-m/m (500 k-in./in.).

The maximum stresses in the slab caused by a 89-kN (20-kip) single-axle load at the edge center were computed for the condition of temperature differential of +11.1 °C (+20 °F) and for the condition of zero thermal gradient. For the case of zero temperature differential, the Westergaard equation and the Pickett and Ray influence charts were also used to compute the maximum load-induced stresses.

Figure 14 displays the maximum stress to strength ratios as functions of the edge stiffness. It should be pointed out that since the Westergaard equation and influence charts did not take into account the effects of edge condition in the computation of stresses, only one value of maximum stress was obtained by each of the two methods. As can be observed from Figure 14, in general, the maximum stress to strength ratios decrease as the edge stiffness increases. However, when the temperature differential in the slab is considered, the maximum stress to strength ratio decreases only when the edge stiffness increases from 0 to 69 MPa (10 ksi). Beyond this point, it remains about constant and is not affected by the change in the edge stiffness.

Effects of Joint Stiffness

The effects of joint condition on the response of pavement under the critical thermal-loading conditions were evaluated by studying the effects of varying the linear joint stiffness (K_l) and torsional joint stiffness (K_t). The typical pavement analyzed had the following parameters and dimensions:

1. Slab length (L) of 6.1 m (20 feet).
2. Slab thickness of 23 cm (9 inches).
3. Concrete modulus (E_c) of 27.6 GPa (4000 ksi).
4. Subgrade stiffness (K_s) of 81.5 MN/m³ (300 pci).
5. Edge stiffness (K_e) of 34.5 MPa (5 ksi).

Two loading conditions were considered. The first condition was the combination of a temperature differential of -

5.6 °C (-10 °F) in the slab and a 89-kN (20-kip) single-axle load at the slab corner. The second was a 89-kN (20-kip) single-axle load at the slab corner only. The effects of K_l and K_t on the maximum stresses are shown in Figure 15. It should be pointed out that, under load only, the maximum stresses occurred at points along the transverse joint and are located at about the mid-point between two wheel loads. The maximum stresses were found to occur at points 1.2 to 1.5 m (4 to 5 feet) away from the corner along the edge for the case of a combined action of load and temperature differential. For both loading conditions, the torsional joint stiffness has essentially no effect on the computed maximum stresses.

When there is a temperature differential in the slab, the maximum stresses decrease sharply as the linear joint stiffness increases from 0 to 138 MPa (20 ksi). Beyond this point, the maximum stress decreases in a slower rate until it reaches a constant at K_t of 690 MPa (100 ksi).

Without considering the temperature differential, the maximum stresses decrease as the linear joint stiffness increases. However, the maximum stress decreases in a slower rate. Also, the maximum stresses in the slab caused by the load only are greater than those caused by the combined action of the load and the temperature differential in the slab when the linear joint stiffness is less than about 1724 MPa (250 ksi).

Effects of Bonded Interface in a Composite Pavement

The effects of using a bonded interface between the concrete and the subbase (or base) layers were evaluated under the critical loading concept. Two groups of analyses were performed. In the first group, the structural response of a typical pavement section on I-75 highway in Sarasota and Manatee Counties in Florida, which had a 23-cm (9-inch) concrete layer laid unbonded over a 15-cm (6-inch) econocrete base was compared with that of a hypothetical pavement in which the concrete slab was bonded to the econocrete base. The FEACONS program was used to compute the maximum tensile stresses in the slabs caused by the loading condition of a 89-kN (20-kip) single-axle load at the slab edge and a temperature differential of +11.1 °C (+20 °F) in the slab. The following pavement dimensions and parameters were used for both pavement systems:

1. Slab length (L) of 7.0 m (23 feet).
2. Concrete modulus (E_c) of 27.6 GPa (4000 ksi).
3. Econocrete modulus (E_e) of 12.4 GPa (1800 ksi).
4. Edge stiffness (K_e) of 34.5 MPa (5 ksi).
5. Linear joint stiffness (K_l) of 345 MPa (50 ksi).
6. Torsional joint stiffness (K_t) of 2.23 MN-m/m (500 k-in./in.).

For the pavement system with a bonded interface, the concrete and econocrete slabs were modeled as a composite layer while the subgrade was modeled as a Winkler foundation with a modulus of reaction of 81.5 MN/m^3 (300 pci). For the pavement with an unbonded interface, the base and the subgrade were modeled as a Winkler foundation with a combined stiffness of 217 MN/m^3 (800 pci). It is realized that it might not be entirely feasible to model a stiff econocrete layer as a Winkler foundation. However, the analysis of a two-layer and a subgrade system becomes extremely complicated when temperature differential in the slab is considered and the FEACONS program does not have this capability at this time. Nevertheless, this approach should give a measure on how the bonding of the interface would affect the pavement's response. The modulus of rupture (or flexural strength) of concrete was estimated to be 4.48 MPa (650 psi) using Equations 1 and 2. The modulus of rupture of econocrete was assumed to be 2.41 MPa (350 psi) which is the typical value for this material used in Florida. Figure 16 shows the two pavement sections, the maximum stresses and the ratios of the maximum stresses to the modulus of rupture for these two pavements. When a bonded interface is assumed the critical tensile stress occurs at the bottom of the econocrete slab. The maximum stress is computed to be 1613 kPa (234 psi) or 67% of the econocrete flexural strength. For the pavement with an unbonded interface, the maximum stress occurs at the bottom of the concrete slab and is 3475 kPa (504 psi) or 78% of the concrete strength.

In the second group, the structural response of two typical pavement sections on the Econocrete Test Road in Florida were analyzed. The first section had a 8-cm (3-inch) concrete layer laid unbonded over a 23-cm (9-inch) econocrete base, while the second one had a bonded interface between the two layers. The same loading condition as in the first group was used in computing the maximum stresses. The following pavement parameters were used for both sections:

1. Slab length of 6.1 m (20 feet).
2. Concrete modulus (E_c) of 27.6 GPa (4000 ksi).
3. Econocrete modulus (E_e) of 12.4 GPa (1800 ksi).
4. Edge stiffness (K_e) of 34.5 MPa (5 ksi).
5. Linear joint stiffness (K_l) of 345 MPa (50 ksi).
6. Torsional joint stiffness (K_t) of 2.23 MN-m/m (500 k-in./in.).
7. Concrete flexural strength of 4.48 MPa (650 psi).
8. Econocrete flexural strength of 2.41 MPa (350 psi).

In the first case (with an unbonded interface), the econocrete layer and the subgrade were modeled as a Winkler foundation with a combined subgrade stiffness of 217 MN/m^3

(800 pci). In the second case (with a bonded interface) the concrete and the econocrete slabs were modeled as a composite layer, while the subgrade was modeled as a Winkler foundation with a stiffness of 81.5 MN/m^3 (300 pci). Figure 17 shows the two pavement sections and the maximum computed stresses in them. The ratio of the maximum tensile stress to the flexural strength is 186% for the unbonded pavement system. It is thus no surprise that all the pavement sections with unbonded interfaces in the Econocrete Test Road failed within six months after they were open to traffic.

When the concrete layer is bonded to the econocrete layer, the maximum stress to flexural strength ratio drops from 186% to 79%. The results of these critical stress analyses show clearly that using a bonded interface is greatly beneficial to the structural performance of this type of pavement.

By comparing the results displayed in Figures 16 and 17, it can also be noted that the decrease in the maximum stress to strength ratio due to the use of a bonded interface is 11% for a pavement with a 23 cm (9-inch) concrete layer and a 15 cm (6-inch) econocrete layer. For a pavement with a 8 cm (3-inch) concrete layer and a 23 cm (9-inch) econocrete layer, the decrease in the ratio due to bonding is 107%. It appears that the use of a thinner concrete layer and thicker econocrete layer with a bonded interface is more effective in reducing the thermal-load-induced stress in a pavement system.

CONCLUSIONS

The effects of various pavement parameters on the structural response of concrete pavements under critical thermal loading conditions were analyzed using the finite element program FEACONS. The main findings are summarized as follows:

1. When the pavement slab is fully supported by the subgrade, the maximum load-induced stresses computed by the finite element program FEACONS are very close to those computed by Westergaard equation and influence charts developed by Pickett and Ray.
2. The maximum thermal-load-induced stresses in the pavement slab increase with an increase in temperature differential. For a typical pavement section, the maximum stresses can exceed the flexural strength of the concrete when the temperature differential gets very high.
3. In general, the maximum stresses increase as the slab length increases, especially when subjected to higher thermal gradient.
4. For pavements with short slabs, the maximum thermal-load-induced stresses increase slightly as the subgrade stiffness increases. The stresses decrease with an increase of

subgrade stiffness for pavements with longer slabs. However, for both cases, the effects of the subgrade stiffness are relatively small.

5. The maximum stress increases as the elastic modulus increases. However, the stress increases in faster rate when the temperature differential in the slab is considered.

6. When a bonded interface is provided between the concrete and econcrete layers in a composite pavement, the maximum stress in the slab can be reduced substantially. A thinner concrete layer laid bonded over a thicker econcrete layer appears to be more effective in reducing the maximum stress in the slab.

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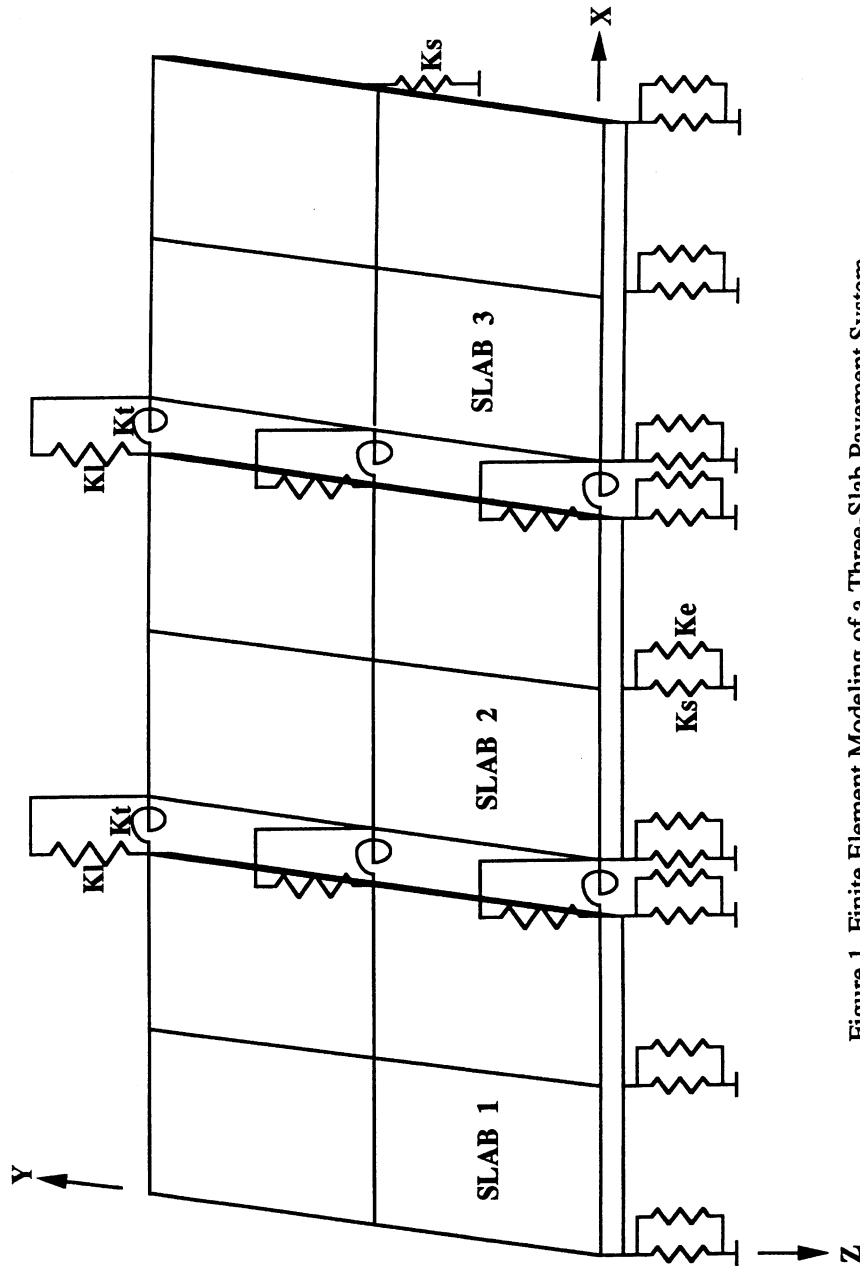


Figure 1 Finite Element Modeling of a Three-Slab Pavement System

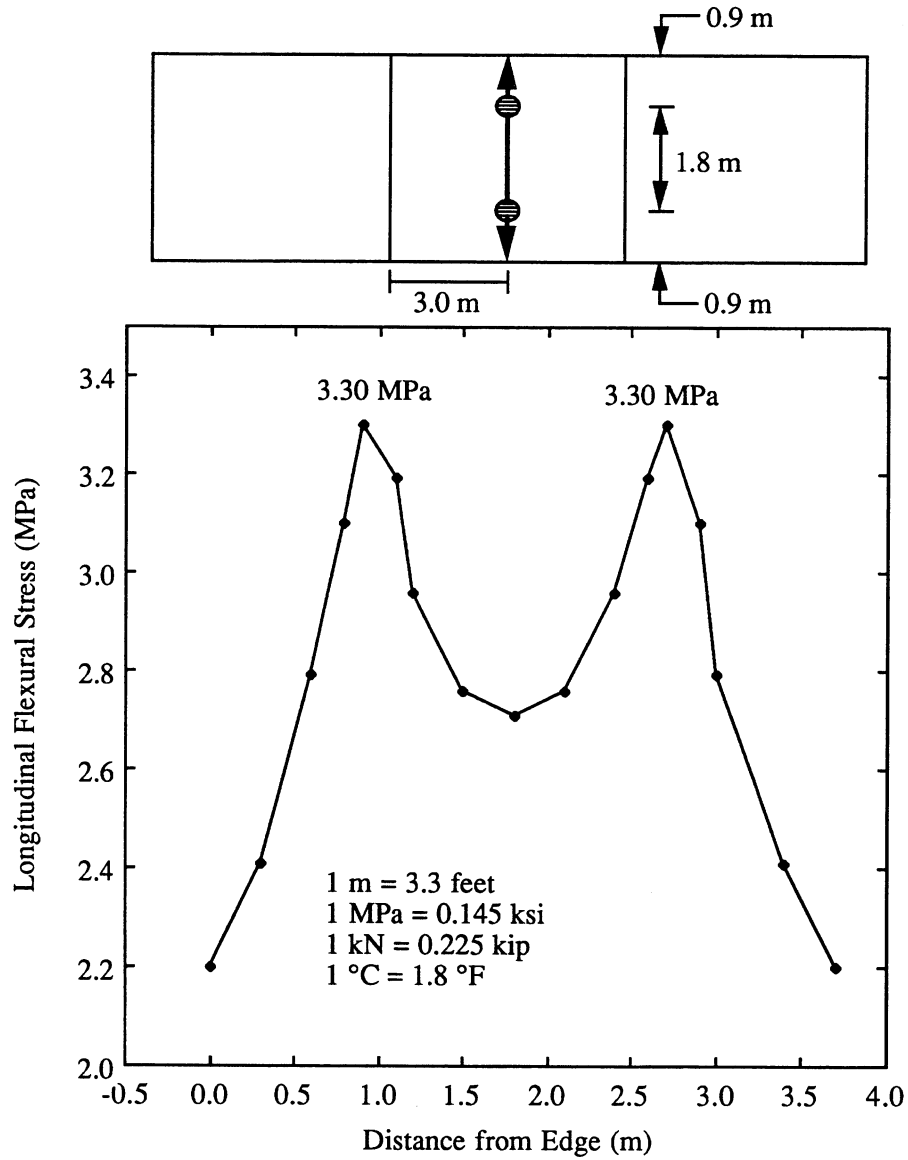


Figure 2 Longitudinal Flexural Stress Along the Transverse Centerline Caused by a 89-kN Single-Axle Load at the Slab Center and a Temperature Differential of +11.1 °C

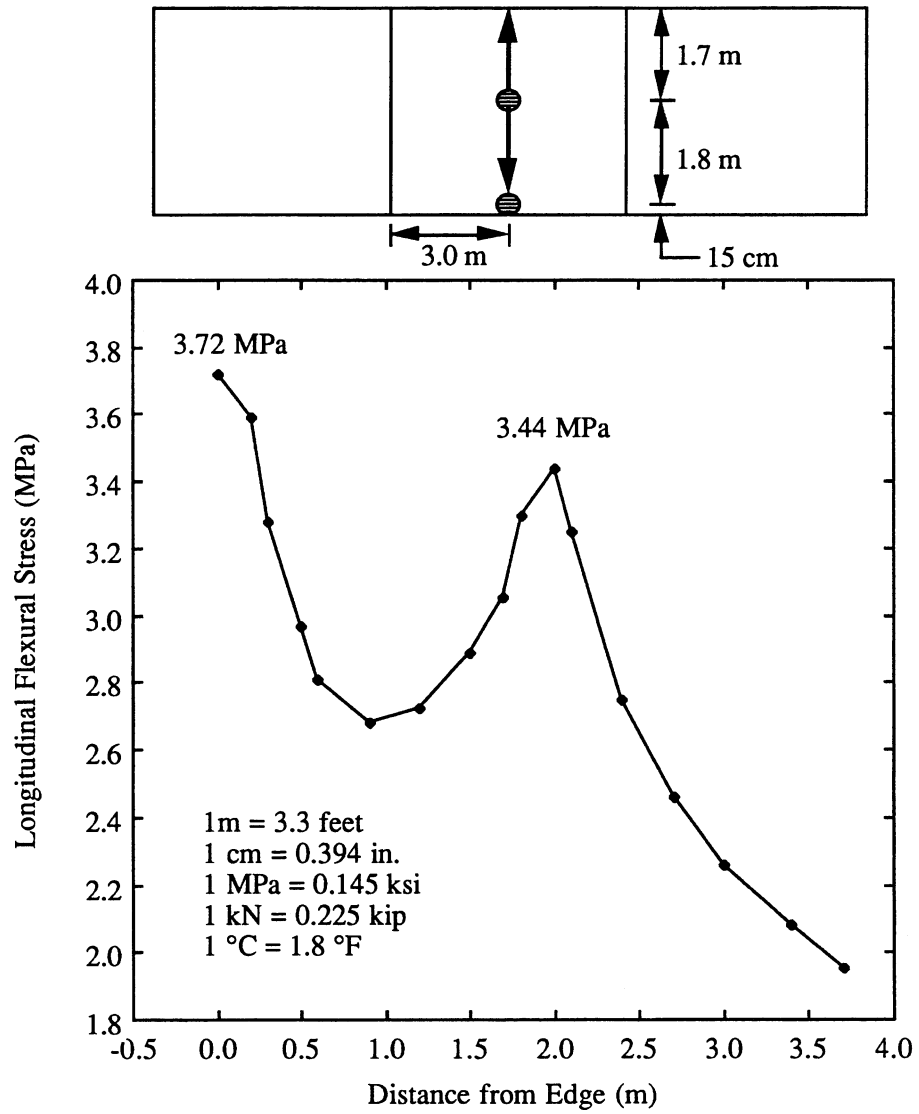


Figure 3 Longitudinal Flexural Stress Along the Transverse Centerline Caused by a 89-kN Single-Axle Load at the Slab Edge and a Temperature Differential of +11.1 °C

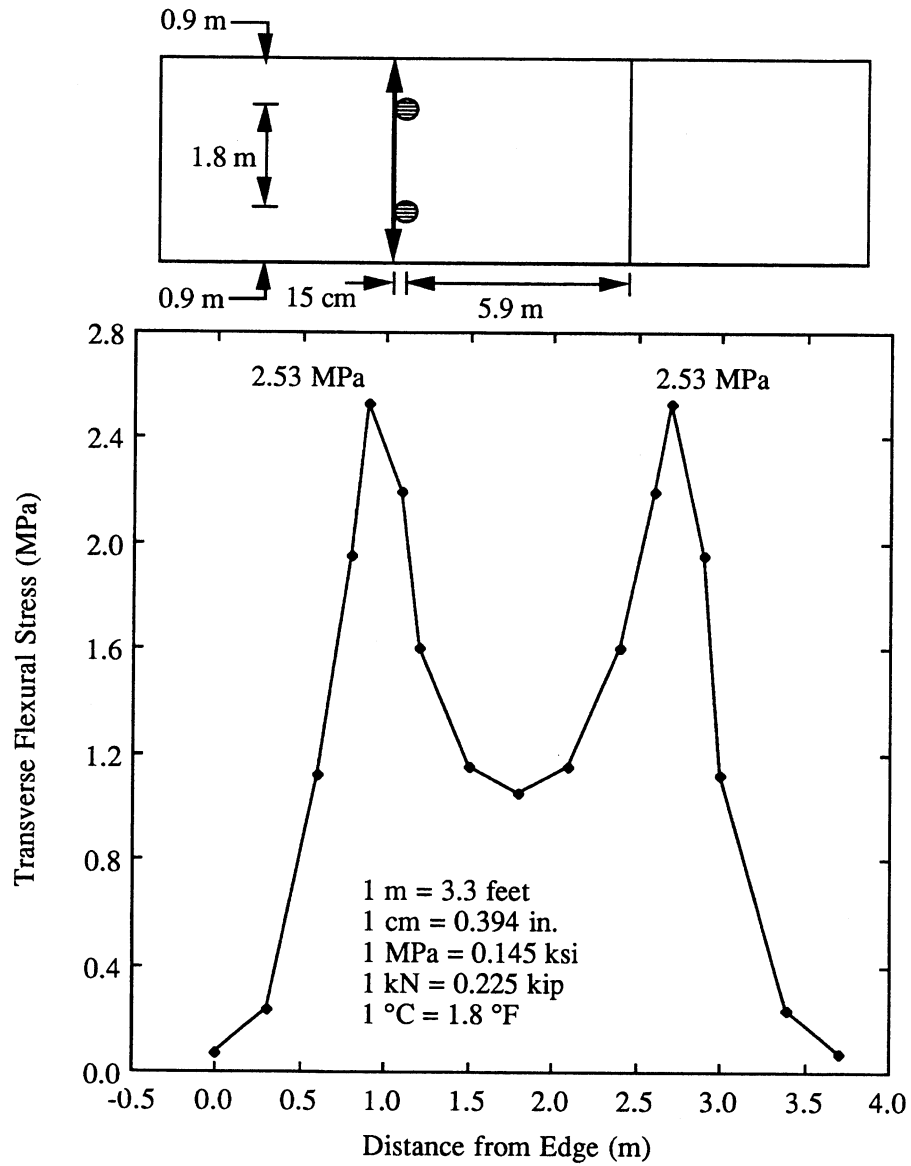


Figure 4 Transverse Flexural Stress Along the Joint
Caused by a 89-kN Single-Axle Load at the
Joint and a Temperature Differential of +11.1 °C

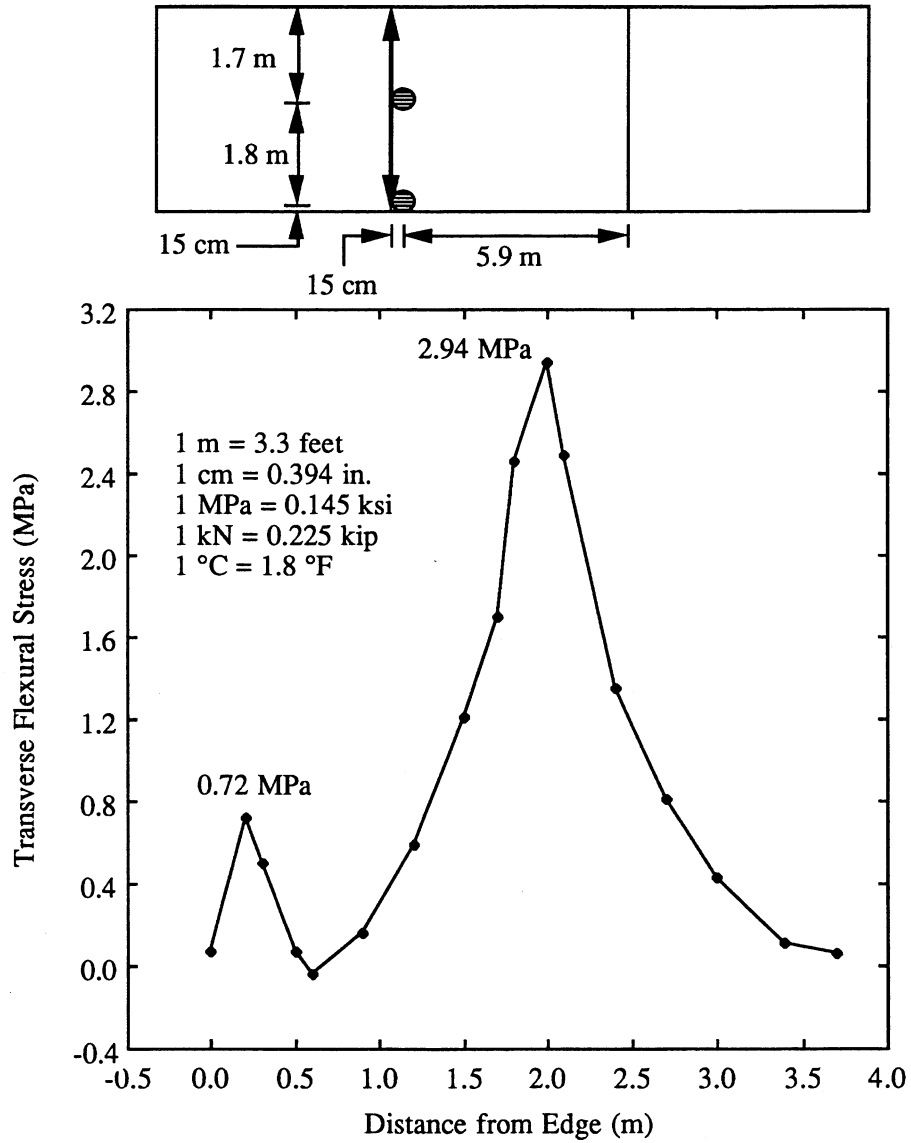


Figure 5 Transverse Flexural Stress Along the Joint
Caused by a 89-kN Single-Axle Load at the Slab
Corner and a Temperature Differential of +11.1 °C

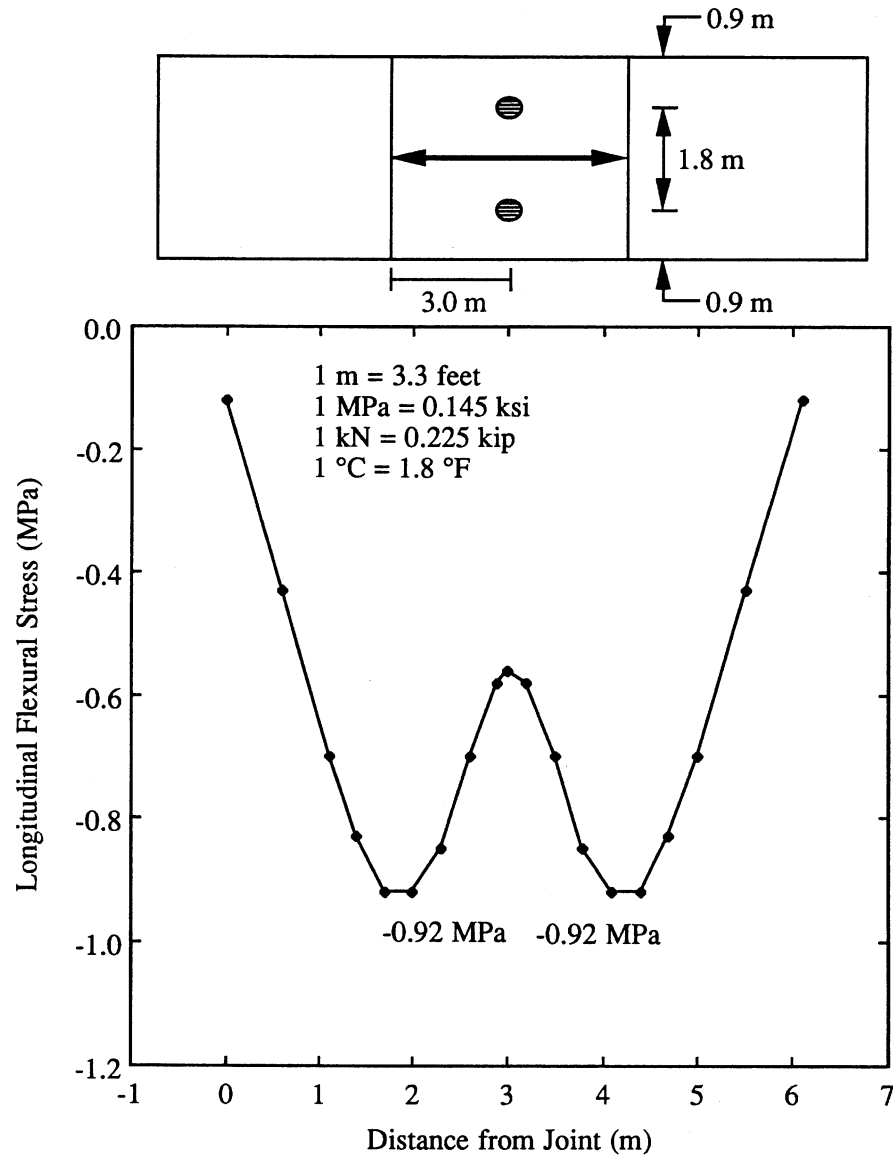


Figure 6 Longitudinal Flexural Stress Along the Longitudinal Centerline Caused by a 89-kN Single-Axle Load at the Slab Center and a Temperature Differential of -5.6 °C

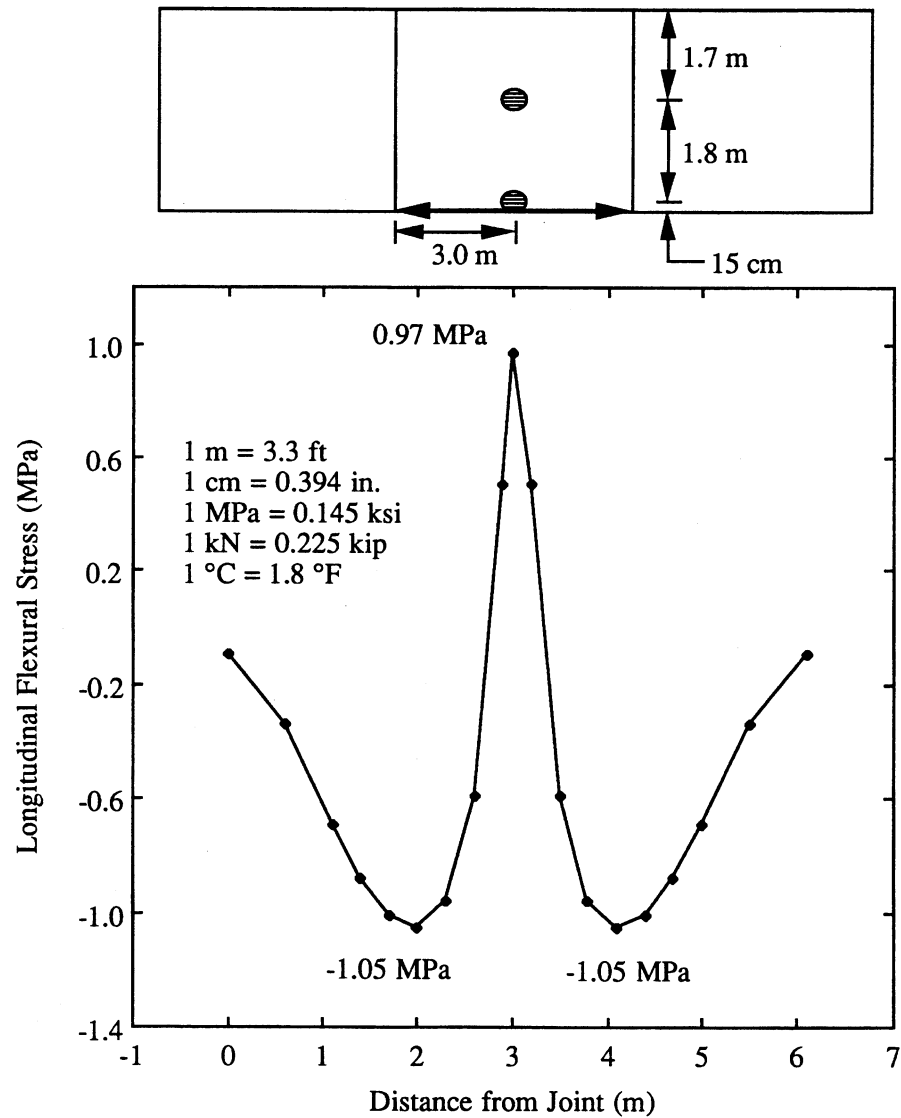


Figure 7 Longitudinal Flexural Stress Along the Slab Edge Caused by a 89-kN Single-Axle Load at the Slab Edge and a Temperature Differential of -5.6 °C

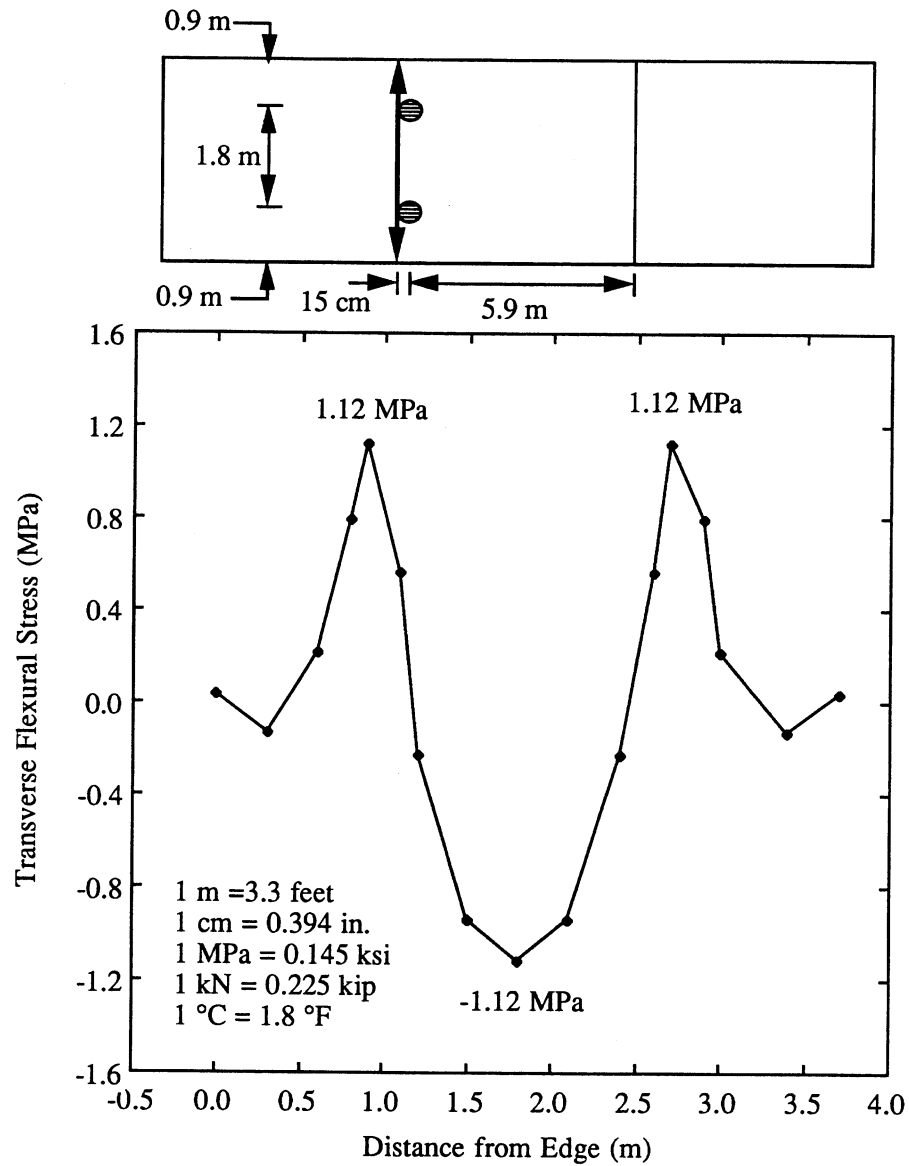


Figure 8 Transverse Flexural Stress Along the Joint Caused by a 89-kN Single-Axle Load at the Joint and a Temperature Differential of -5.6 °C

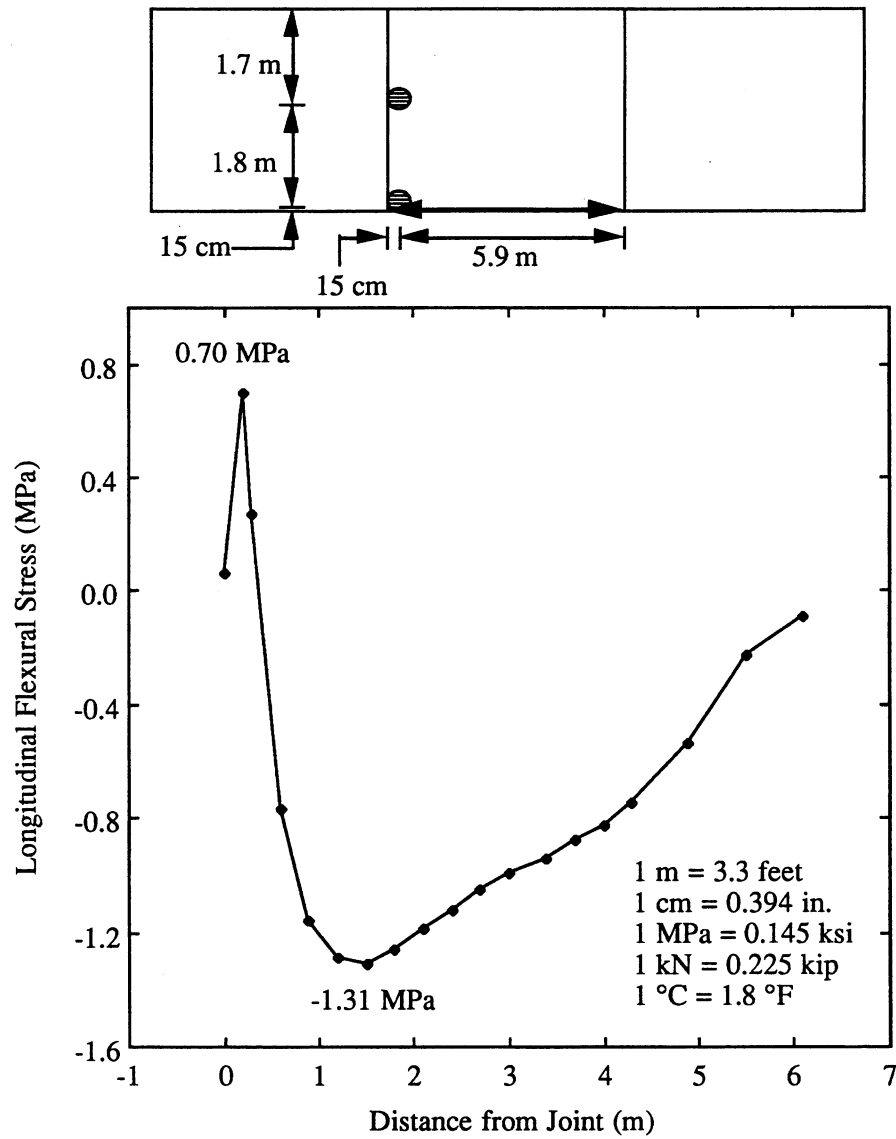


Figure 9 Longitudinal Flexural Stress Along the Slab Edge Caused by a 89-kN Single-Axle Load at the Slab Corner and a Temperature Differential of -5.6 °C

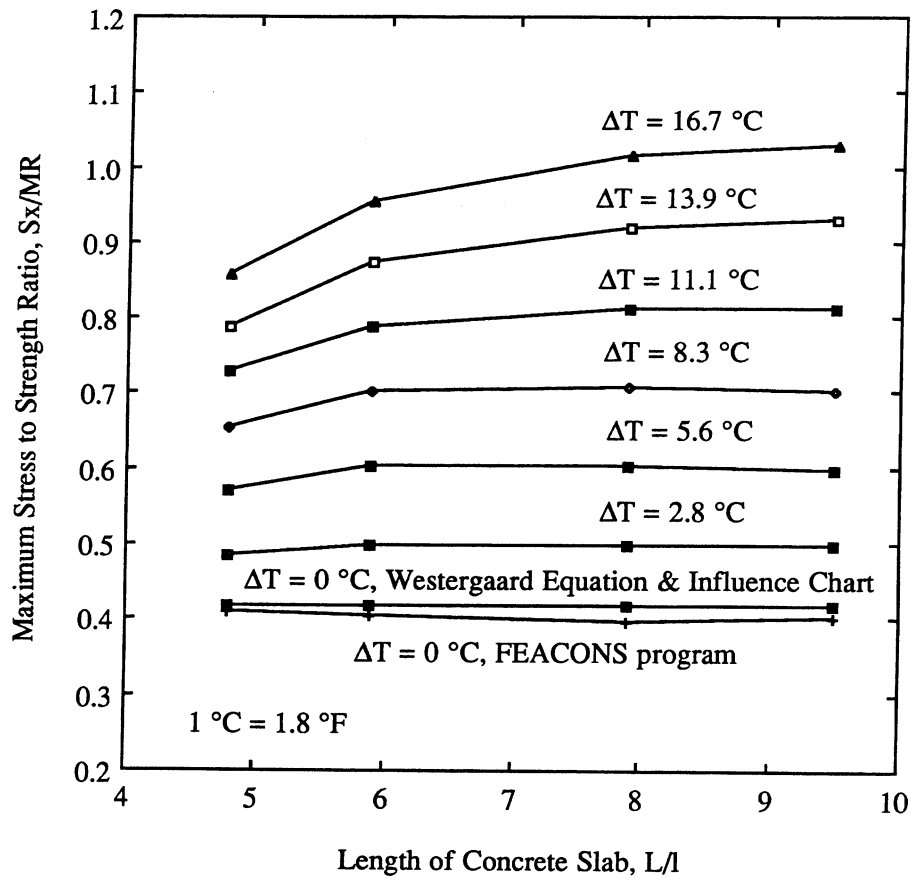


Figure 10 Effects of Slab Length and ΔT on Maximum Stress to Strength Ratio

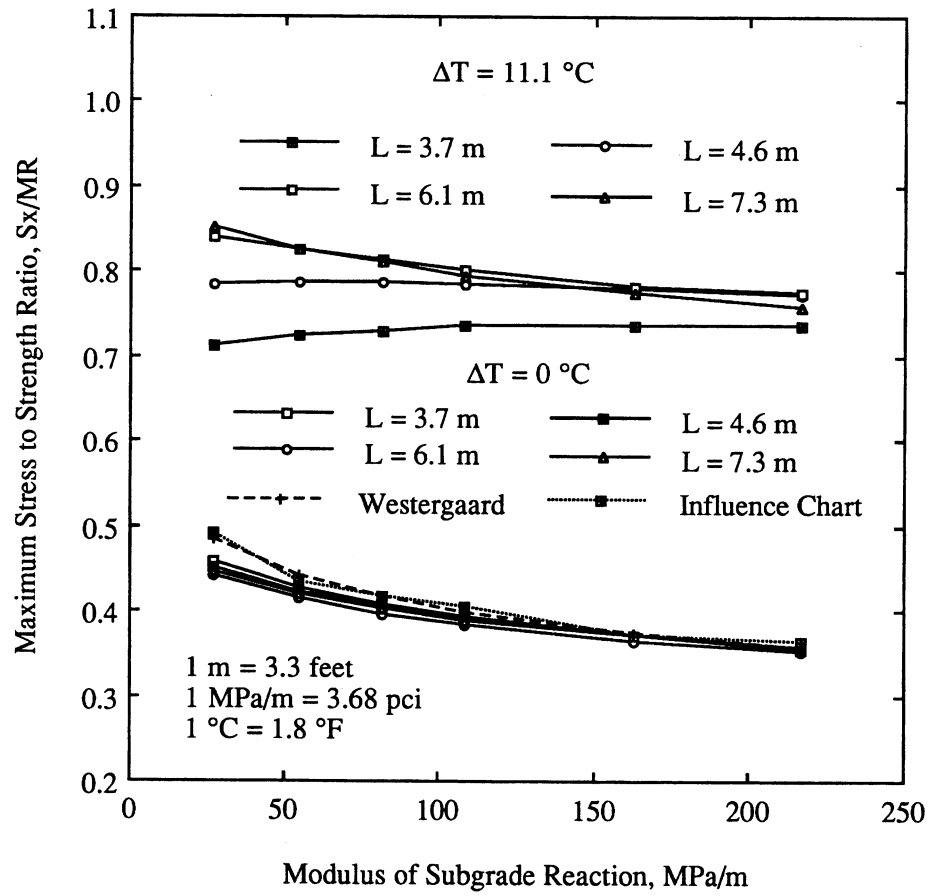


Figure 11 Effects of Modulus of Subgrade Reaction and Slab Length on Maximum Stress to Strength Ratio

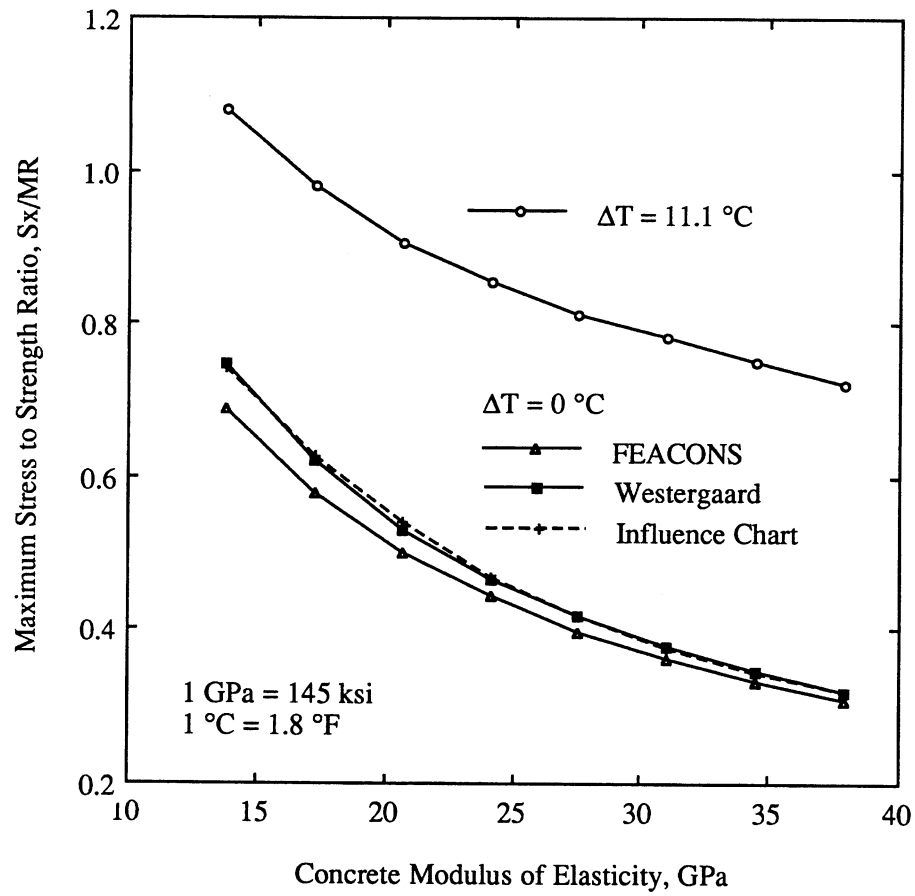


Figure 12 Effects of Concrete Elastic Modulus on Maximum Stress to Strength Ratio

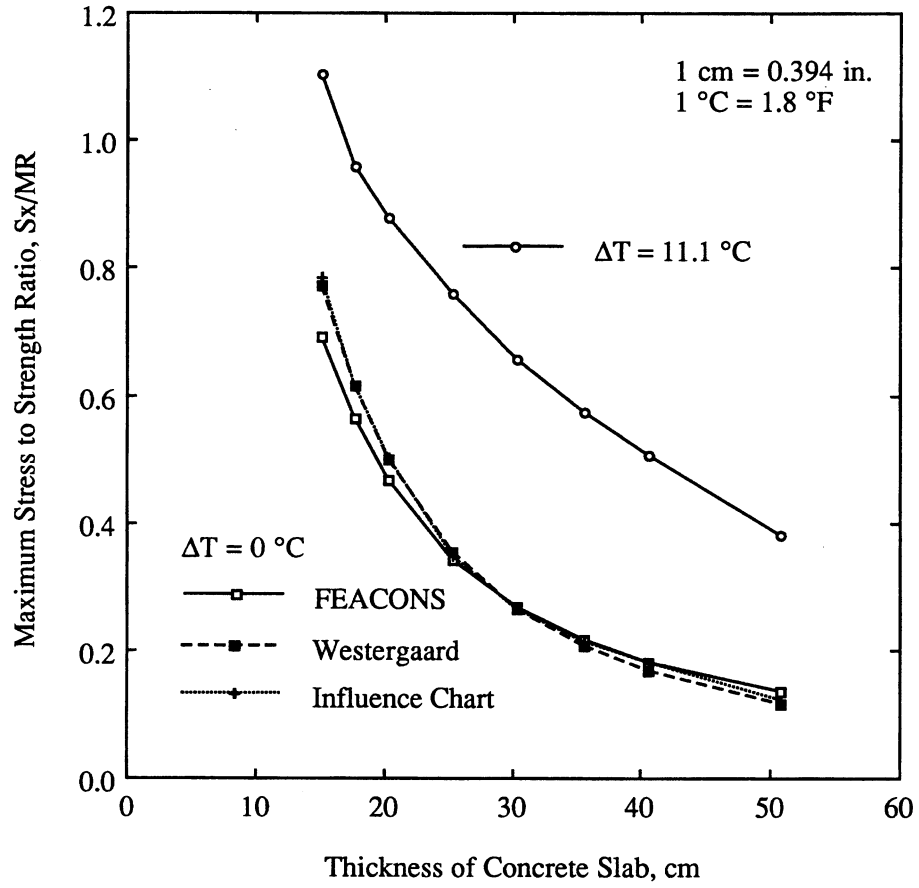


Figure 13 Effects of Concrete Slab Thickness on Maximum Stress to Strength Ratio

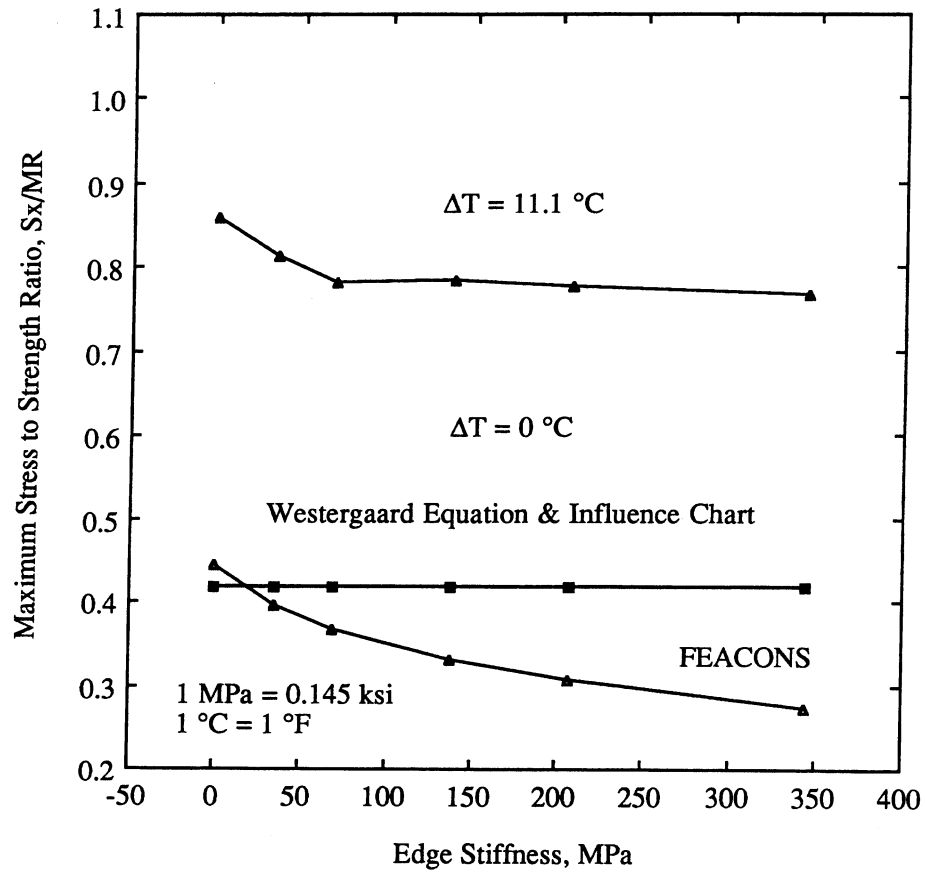


Figure 14 Effects of Edge Stiffness on Maximum Stress to Strength Ratio

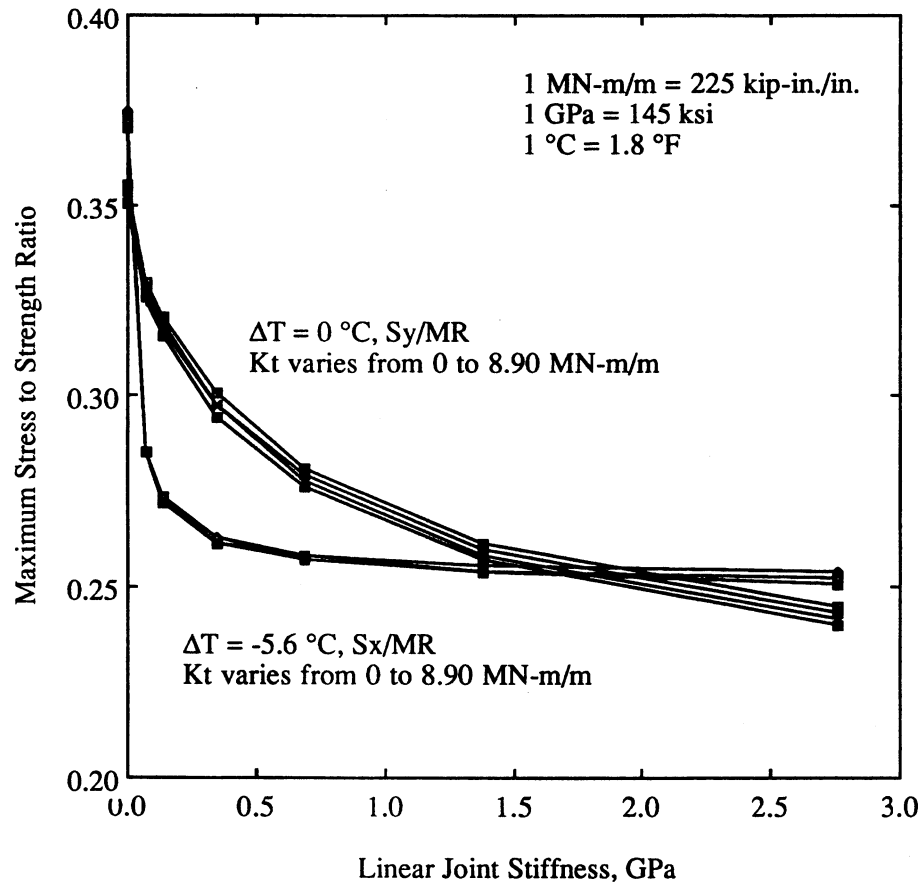
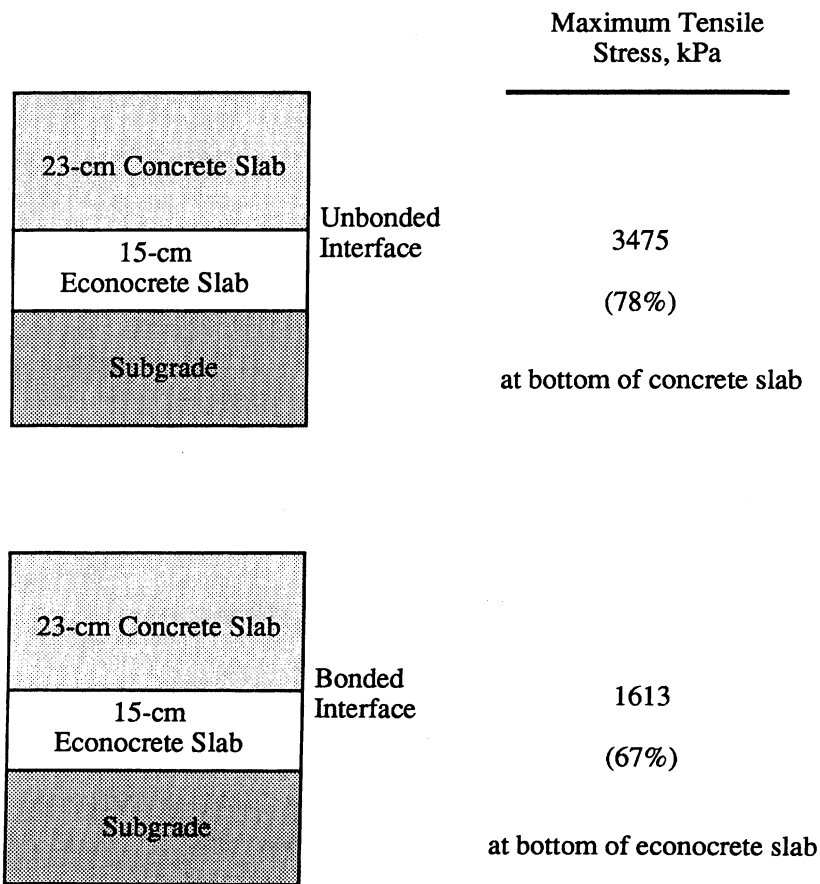


Figure 15 Effects of Joint Stiffness on Maximum Stress to Strength Ratio



1 kPa = 0.145 psi 1 cm = 0.394 in.
1 kN = 0.225 kip 1 °C = 1.8 °F

Figure 16 Comparison of Maximum Stresses Caused by a 89-kN Axle Load and a ΔT of +11.1 °C on a Composite Pavement With a 15-cm Econocrete Base With and Without a Bonded Interface

		Maximum Tensile Stress, kPa
8-cm Concrete Slab 23-cm Econocrete Slab Subgrade	Unbonded Interface	
		8350
		(186%)
		at bottom of concrete slab
8-cm Concrete Slab 23-cm Econocrete Slab Subgrade	Bonded Interface	
		1903
		(79%)
		at bottom of econocrete slab

1 kPa = 0.145 psi 1 cm = 0.394 in.
 1 kN = 0.225 kip 1 °C = 1.8 °F

Figure 17 Comparison of Maximum Stresses Caused by a 89-kN Axle Load and a ΔT of +11.1 °C on a Composite Pavement With a 23-cm Econocrete Base With and Without a Bonded Interface