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16. Abstract

The sensitivity analysis of the concrete pavement thickness has been conducted to investigate if the current thickness tolerance can be loosened and to propose the acceptable thickness tolerance limits so that NDT for thickness measurements can be used with confidence. The current procedures to measure the concrete pavement thickness and the current thickness tolerance limits have been reviewed. The sensitivity of pavement performance to slab thickness has been investigated based on various models including the AASHTO model, mechanistic distress prediction model, and fatigue failure models. The variability of the thickness in the field has also been investigated. The reasonable thickness tolerance limits have finally been proposed by comparing the results obtained from this study.

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Reconsideration of Thickness Tolerance for Concrete Pavements

Seong-Min Kim
B. Frank McCullough

Research Report No. 4382-1

Research Project 0-4382
Establish an Acceptable Pavement Thickness Tolerance to Allow for Non-Destructive Continuous Concrete Pavement Thickness Measurements

Conducted for the
Texas Department of Transportation
in cooperation with the
U.S. Department of Transportation
Federal Highway Administration
by the
Center for Transportation Research
Bureau of Engineering Research
The University of Texas at Austin

October 2002

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Research performed in cooperation with the Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration.

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1. Introduction

1.1 Background and Objective

The tolerance limit for concrete slab thickness currently used by TxDOT was developed based on engineering judgement and experience. No additional study on the tolerance limit has been conducted since its development in the 1950s. The tolerance limit is currently 5 mm (0.2 in.) for full payment. This tolerance limit is too tight to use existing nondestructive testing (NDT) methods for slab thickness determination because these methods are not as accurate as the direct measurement from coring. If the current tolerance can be shown to have minimal impact on the pavement performance, then the tolerance limit can be loosened to allow NDT methods for thickness determination. This allowance will improve TxDOT's operation significantly because NDT methods are less time-consuming and more cost-effective than coring. Moreover, the slab thickness measured continuously by NDT methods will represent the pavement more reliably than spot-checking by coring.

The objective of this study is to provide TxDOT with the acceptable concrete pavement thickness tolerance so that NDT for thickness measurements may be used with confidence. In this study the sensitivity of pavement performance to slab thickness has been investigated based on various models, including the AASHTO model, mechanistic distress prediction model, and fatigue failure models. The controlling performance indicator from the sensitivity study has been compared with the measured variability of pavement thickness in the field and with the accuracy of the NDT devices. From the comparison the reasonable tolerance limit of the slab thickness has finally been obtained, and the adequacy of existing NDT measurements for slab thickness has been assessed.

1.2 Scope

This report consists of six chapters and four appendices. The background and objective of this study are presented in chapter 1. Chapter 2 presents current procedures to measure pavement thickness and current pavement thickness tolerance limits in Texas and other states. In chapter 3 the concepts to predict the effects of thickness deficiency on pavement performance are presented. Details of the sensitivity studies using various methods, including the AASHTO equation, mechanistic distress prediction model, and fatigue failure equations, are explained. The differences in the analysis results using various methods are also discussed. Chapter 4 describes the measured variability of pavement thickness in the field and the accuracy of the NDT devices. Chapter 5 compares the findings explained in chapters 3 and 4, and presents the reasonable concrete pavement thickness tolerance limits. Finally, chapter 6 includes our summary, conclusions, and recommendations. The guidelines to determine proper pavement thickness tolerance limits are included in Appendix A. Appendices B and C include TxDOT Specification Item 360.13, Deficient Pavement Thickness, and TxDOT Test Method Tex-424-A, Obtaining and Testing Drilled Cores of Concrete. The computer code developed for the sensitivity analysis is listed in Appendix D.

2. Current Thickness Tolerance Limits

The current procedure to measure the concrete pavement thickness in Texas is summarized, and the current thickness tolerance limits and payment adjustment methods in Texas and other states are reviewed in this chapter.

2.1 Current Procedure in Texas

In order to establish an adjusted unit price for concrete pavements, TxDOT Specification Item 360.13 requires that the concrete slab thickness be determined by the cores in accordance with Test Method Tex-424-A or by probing the fresh concrete every 500 ft. (Refs 1, 2). Item 360.13 defines the units to be considered separately for pavement as 300 meters (1,000 ft.) of pavement in each traffic lane and for ramps, widening, acceleration and deceleration lanes that are machine-placed, isolated pavements of traffic lane width less than 300 meters (1,000 ft.) in length, and other areas designated by the engineer as 850 square meters (9,150 square ft.) of pavement. One core is taken at the location selected by the engineer or at random in each unit. When the slab thickness determined by the core from any unit is not deficient by more than 5 mm (0.2 in.) from the plan thickness, full payment will be made. When the thickness is deficient by more than 5 mm (0.2 in.) but not by more than 20 mm (0.75 in.), two additional cores are taken from the unit at intervals of not less than 90 meters (300 ft.). If the average thickness of the three cores (one core with deficiency and two additional cores) is not deficient by more than 5 mm (0.2 in.), full payment will be made. If the average thickness is deficient by more than 5 mm (0.2 in.) but not by more than 20 mm (0.75 in.), an adjusted unit price will be paid for the unit represented by these cores. Table 2.1 lists the thickness deficiency ranges and corresponding adjustment rates by reducing the contract unit price. For any area of pavement found deficient in thickness by more than 20 mm (0.75 in.) but not more than 25 mm (1 in.) or 1/8 of the plan thickness, whichever is greater, the engineer will evaluate and determine whether the area of such deficiency should be removed and replaced. If it should not be removed and replaced, no payment will be made for the area retained. If it should be removed and replaced in the judgment of the engineer, or if the thickness deficiency is more than 25 mm (1 in.) or more than 1/8 of the plan thickness, whichever is greater, the area of deficiency shall be removed and replaced at the contractor's entire expense.

Table 2.1 Thickness deficiency adjustment in Texas

Deficiency in thickness	Percent of contract unit price allowed
0–5 mm (0–0.2 in.)	100
5.0–7.5 mm (0.2–0.3 in.)	80
7.5–10.0 mm (0.3–0.4 in.)	72
10.0–12.5 mm (0.4–0.5 in.)	68
12.5–20.0 mm (0.5–0.75 in.)	57

To measure the length of drilled concrete cores, first a concrete core specimen is taken perpendicular to a horizontal surface of pavement. The specimen is then placed in the measuring apparatus with the smooth end of the core (upper surface of a concrete slab) down against the three hardened-steel supports so the central measuring position of the measuring apparatus is directly over the midpoint of the upper end of the specimen. The apparatus is designed to make nine measurements of the length on each specimen, one at the central position and one each at eight additional positions spaced at equal intervals along the circumference of a circle whose radius is not less than one half nor more than three fourths of the radius of the specimen. To determine the length of the concrete core, each of the nine measurements is read to the nearest 1 mm (0.05 in.), and the average of the nine measurements is obtained, expressed to the nearest 3 mm (0.1 in.), as the reported length of the core. If at one or more measuring points the surface of the specimen is not representative of the general plane of the core end because of a small projection or depression, the specimen can be rotated slightly about its axis, and a complete set of nine measurements can be made with the specimen in the new position. TxDOT Specification 360.13 and Test Method Tex-424-A can be found in Appendices B and C, respectively.

TxDOT Specification Item 360.13 defines the units to be considered separately as 300 meters (1,000 ft.) of pavement and allows a random selection of coring location in each unit. In practice, however, the cores are taken every 300 meters (1,000 ft.). In this procedure it is assumed that the slab thickness measured from the core adequately represents the slab thickness in the unit. The coring area relative to the pavement area in each unit is negligibly small, so there is a question if the slab thickness measured from the core can be representative in the unit. Moreover, when measuring the length of drilled cores, the measurements will be different according to the measuring locations because of the roughness of the measuring surface.

2.2 Tolerance Limits in Other States

The current thickness tolerance limits and payment adjustment methods in other states are summarized in this section. The most widely used payment adjustment method is to pay an adjusted percentage of the contract unit price according to the thickness deficiency amount. Other payment adjustment methods include the predetermined dollar amount reduction and the use of the adjustment points.

Table 2.2 lists the states that employ the thickness deficiency adjustment by a percentage of the contract unit price (Refs 3-12). Texas also uses this method, as explained in the previous section. The thickness deficiency ranges and corresponding percentage of adjustments vary among the states. For instance, if a thickness deficiency is 15 mm, 57% of the contract unit price is paid in the states of Texas, Connecticut, North Carolina, and Virginia. Oregon pays 63%, Alabama and Massachusetts pay 70%, and West Virginia pays 88.4%. On the other hand, Hawaii pays 40%, and New York and Pennsylvania do not pay for that contract. Therefore, the difference in the payment amount is significantly large among the different states even if the thickness deficiency is the same.

Table 2.2 Thickness deficiency adjustment by percentage of contract price

Deficiency in thickness	Percentage of contract unit price allowed	Deficiency in thickness	Percentage of contract unit price allowed
Alabama		**Pennsylvania**	
0–5 (mm)	100	0–6.5 (mm)	100
5.1–10 (mm)	80	6.6–7.7 (mm)	95
10.1–15 (mm)	70	7.8–8.9 (mm)	85
15.1–20 (mm)	60	9.0–10.1 (mm)	75
20.1–25 (mm)	50	10.2–11.3 (mm)	50
Connecticut		11.4–12.5 (mm)	25
0–5.1 (in.)	100	**North Carolina**	
5.2–7.6 (mm)	80	0–0.2 (in.)	100
7.7–10.2 (mm)	72	0.21–0.3 (in.)	80
10.3–12.7 (mm)	68	0.31–0.4 (in.)	72
12.8–19.1 (mm)	57	0.41–0.5 (in.)	68
19.2–25.4 (mm)	50	0.51–0.75 (in.)	57
Massachusetts		0.76–1 (in.)	50
0–5 (mm)	100	**Virginia**	
5–10 (mm)	80	0–0.2 (in.)	100
10–15 (mm)	70	0.21–0.3 (in.)	80
New York		0.31–0.4 (in.)	72
0–13 (mm)	100	0.41–0.5 (in.)	68
Oregon		0.51–0.75 (in.)	57
0–5 (mm)	100	0.76–1 (in.)	50
5.1–7.6 (mm)	83	**West Virginia**	
7.7–10.1 (mm)	76	0.01–0.1 (in.)	98
10.2–12.7 (mm)	73	0.11–0.2 (in.)	96
12.8–19 (mm)	63	0.21–0.3 (in.)	94
19.1–25 (mm)	59	0.31–0.4 (in.)	92.2
Hawaii		0.41–0.5 (in.)	90.3
0–0.2 (in.)	100	0.51–0.6 (in.)	88.4
0.21–0.4 (in.)	75	0.61–0.7 (in.)	86.5
0.41–0.6 (in.)	40		

As listed in Table 2.3, California and Minnesota employ the dollar amount adjustment (Refs 13, 14). California uses the average thickness deficiency instead of the deficiency range. A large difference in the adjustment amount also exists between these two states. For instance, if the thickness deficiency is 10 mm, the adjustment amount in California is $2.50 per square meter and that in Minnesota is $1.00. In this case, the penalty is higher in California. However, if the thickness deficiency is 15 mm, the adjustment amounts in California and Minnesota are $4.70 and $25.00, respectively. In this case, the penalty is much higher in Minnesota.

Table 2.3 Thickness deficiency adjustment by dollars per square meter

Average thickness deficiency (mm)	Adjustment (dollars per square meter)	Deficiency in thickness (mm)	Adjustment (dollars per square meter)
California		**Minnesota**	
2.5	0.40	0–2	0.2
5	0.95	2–4	0.4
7.5	1.65	4–6	0.6
10	2.50	6–8	0.8
12.5	3.55	8–10	1.0
15	4.70	10–25	25

The thickness deficiency adjustment method in Indiana is different (Ref 15). Indiana uses adjustment points as listed in Table 2.4. The adjustment points are used to calculate a quality assurance adjustment quantity for a lot as follows:

$$q = L \times U \times \frac{P}{100}, \tag{2.1}$$

where q is the quality assurance adjustment quantity, L is lot quantity, U is unit price for Portland cement concrete pavement, and P is adjustment points. The total quality assurance adjustments are calculated by adding adjustments for thickness, flexural strength, air content, range for air content, and smoothness. The payment adjustment is dependent on the total quality assurance adjustments.

Table 2.4 Thickness deficiency adjustment in Indiana

Deficiency in thickness (mm)	Adjustment Points
0–3	0
3–13	4
13–25	8

The thickness tolerance limits for full payment and no payment in some states are listed in Table 2.5. Minnesota and West Virginia do not allow any thickness deficiency for full payment, and California has a tight tolerance limit of 2.5 mm for full payment. Most states, including Texas, have the full payment tolerance limits around 5 mm (0.2 in.). New York has a loose tolerance limit of 13 mm for full payment, but if the thickness deficiency is larger than 13 mm, no payment is made. The thickness tolerance limits for removal or no payment are very tight in the states of New York, Ohio (Ref 16), and Pennsylvania. Most states have a no-payment thickness deficiency of 25 mm (1 in.). Illinois uses 10% of the plan thickness for the no payment tolerance limit. Therefore, the thickness tolerance limits for full payment and no payment vary significantly among the states.

Table 2.5 Tolerance limits for full and no payment

Tolerance limit for full payment	**State**	**Tolerance limit for no payment or removal**	**State**
0	West Virginia, Minnesota	13 mm	New York, Ohio, Pennsylvania
2.5 mm	California	15 mm (0.6 in.)	California, Hawaii, Massachusetts
3 mm	Indiana	17.78 mm (0.7 in.)	West Virginia
5 mm (0.2 in.)	Alabama, Ohio, Connecticut, Texas, Hawaii, Oregon, Massachusetts, North Carolina, Virginia,	20 mm	Texas
6.5 mm	Pennsylvania	25 mm (1 in.)	Alabama, Indiana, Minnesota, Oregon, Virginia, Connecticut, North Carolina
13 mm	New York	10% of plan thickness	Illinois

3. Sensitivity Analysis of Pavement Thickness

3.1 Concepts

If the pavement thickness is deficient from the plan thickness, full payment is not made and a payment reduction is made according to the amount of the deficiency. The payment reduction should be made for two reasons. One is that the total construction cost would be less than the proposed cost because the Portland cement concrete amount for construction is less than the design amount. The other reason is that the pavement life can be reduced because the thickness is less than the design thickness. The latter seems to be more important. Therefore, the thickness tolerance limits and corresponding penalties should be related to the loss of pavement life caused by the thickness deficiency.

Three different approaches have been taken in this study to find the relationship between the pavement thickness deficiency and the loss of pavement design life. One is based on the change in present serviceability index (PSI) to predict the pavement life, which includes the AASHTO pavement life prediction equation (Ref 17). Another is based on fatigue failure, which includes a number of fatigue failure equations. The other is based on distresses such as cracks and punchouts, which can be predicted by mechanistic models.

First the concept to determine the pavement thickness sensitivity to the pavement life by using the AASHTO equation is explained. As shown in Figures 3.1 and 3.2, the pavement design life can be obtained from the pavement design thickness by using the AASHTO equation. Then an allowable loss of the pavement life is selected, and the allowable design life is obtained by subtracting the allowable loss of life from the design life. The corresponding allowable pavement thickness can then be obtained by using the AASHTO equation inversely, and finally the thickness tolerance for the allowable loss of life can be obtained by subtracting the allowable thickness from the design thickness.

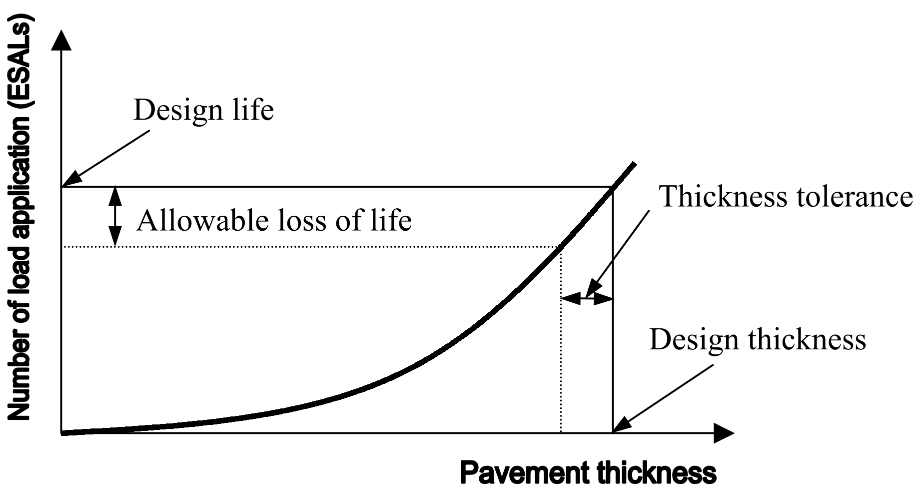


Figure 3.1 Relationship between pavement thickness and life from AASHTO equation

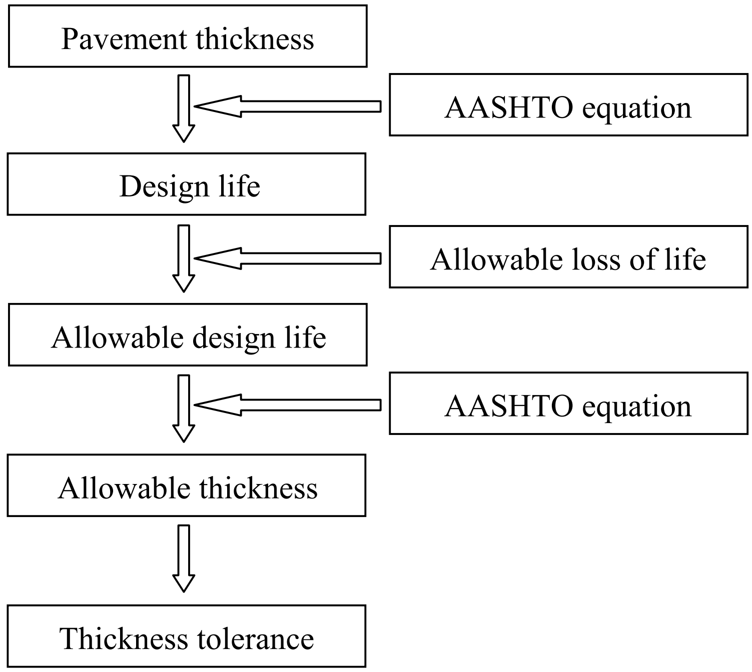


Figure 3.2 Thickness tolerance determination with AASHTO equation

The concept of determining the pavement thickness sensitivity to the pavement life by using the fatigue failure equations is similar. As shown in Figures 3.3 and 3.4, for a design thickness the design pavement stress is calculated using the Westergaard equations (Refs 18-20) or other method. Then the design stress level is obtained by dividing the stress by the strength (modulus of rupture), and the design pavement life is determined by using a fatigue failure equation. An allowable loss of pavement life is then selected, and the allowable design life is obtained by subtracting the allowable loss of life from the design life. The corresponding allowable stress level can be obtained by using the fatigue failure equation inversely, and the allowable stress can be calculated by multiplying the allowable stress level by the strength. The corresponding allowable thickness can then be obtained by using any stress calculation method inversely. Finally, the thickness tolerance for the allowable loss of pavement life can be obtained by subtracting the allowable thickness from the design thickness.

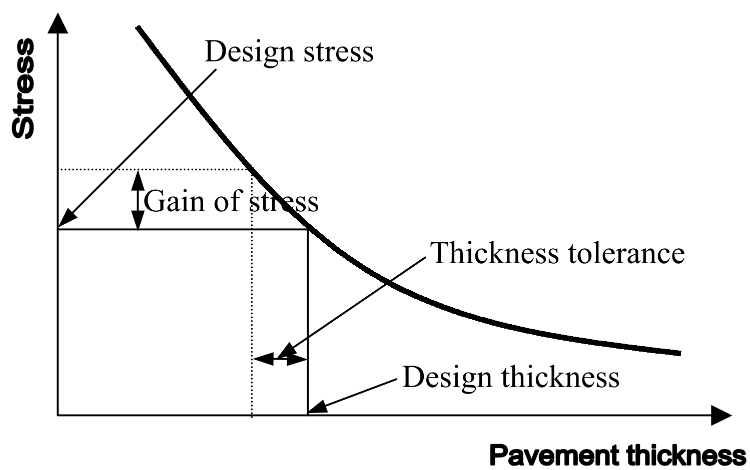
Another concept to find the pavement thickness sensitivity to the pavement life is based on distresses such as cracks and punchouts. If a pavement with a thickness deficiency does not induce more cracks compared with the design pavement, the thickness deficiency can be acceptable with this concept. To predict crack and punchout formations, mechanistic models such as CRCP-8, CRCP-9, and CRCP-10 can be used (Refs 21-25).

The payment adjustment should be related to the thickness deficiency and corresponding loss of pavement life and total cost. For example, if the thickness deficiency is 10 mm beyond the no-penalty limit and the corresponding loss of pavement life is 10%, the payment reduction should be at least 10% of the life cycle cost of the pavement.

3.2 Sensitivity study based on AASHTO equation

The analysis to find the sensitivity of the pavement thickness to the pavement life, based on the AASHTO design equation, has been performed. In the current AASHTO Guide for Design of Pavement Structures (Ref 17), the design equation for rigid pavements is as follows:

(a)



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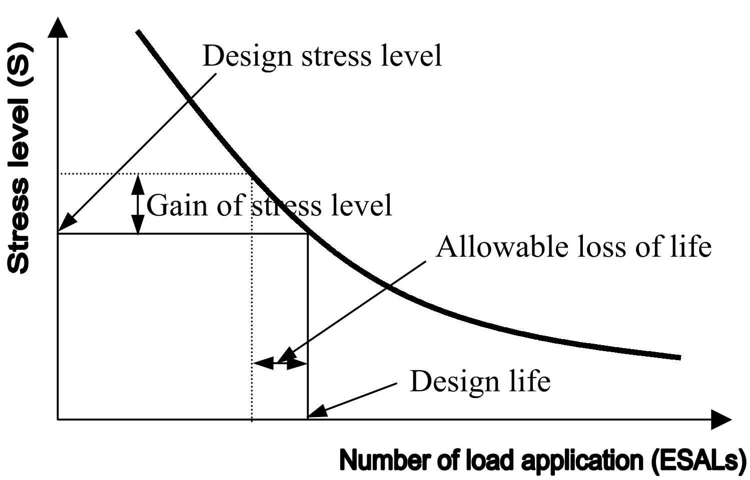


Figure 3.3 Relationships between pavement thickness and stress and between stress level and number of load application

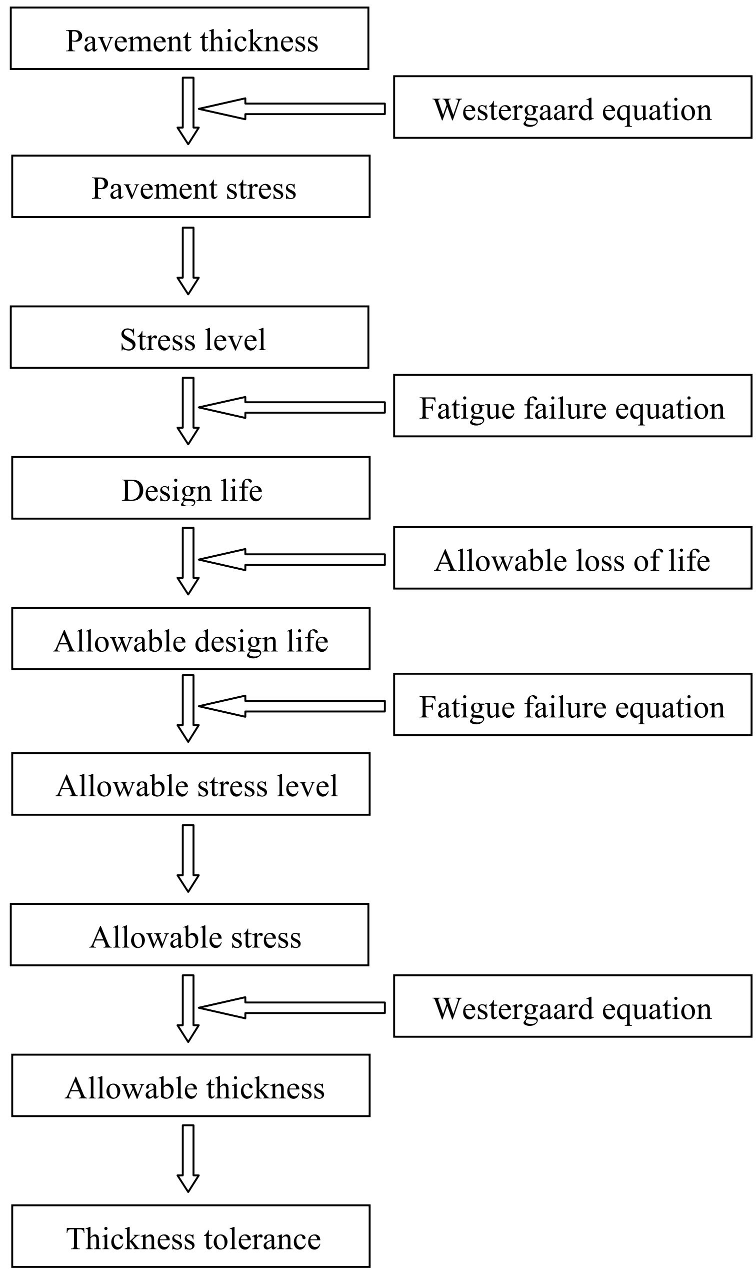


Figure 3.4 Thickness tolerance determination with fatigue failure equations

$$\log_{10}(W_{18}) = Z_R \times S_0 + 7.35 \times \log_{10}(D+1) - 0.06 + \frac{\log_{10}\left[\frac{\Delta PSI}{4.5-1.5}\right]}{1+\frac{1.624\times 10^7}{(D+1)^{8.46}}} + (4.22 - 0.32 \times p_t)$$

$$\times \log_{10}\left[\frac{S'_c \times C_d \times (D^{0.75} - 1.132)}{215.63 \times J\left[D^{0.75} - \frac{18.42}{(E_c / k)^{0.25}}\right]}\right] \tag{3.1}$$

where

W_{18} = predicted number of 18-kip equivalent single axle load applications,

Z_R = standard normal deviate,

S_0 = combined standard error of the traffic prediction and performance prediction,

D = thickness (inches) of pavement slab,

ΔPSI = difference between the initial design serviceability index, p_0, and the design terminal serviceability index, p_t,

S'_c = modulus of rupture (psi) for Portland cement concrete used on a specific project,

J = load transfer coefficient used to adjust for load transfer characteristics of a specific design,

C_d = drainage coefficient,

E_c = modulus of elasticity (psi) for Portland cement concrete, and

k = modulus of subgrade reaction (pci).

This equation is a mechanistic-empirical equation that was obtained by extrapolating the AASHO road test (Ref 26) equations (empirical) to other conditions using the Spangler equation (mechanistic). Variability was also added to the equation using results from the AASHO road test supplemented by other data. As can be seen from the equation, a number of variables affect the design life (number of load applications). Of all the variables, the slab thickness has the strongest relationship to the predicted number of load applications.

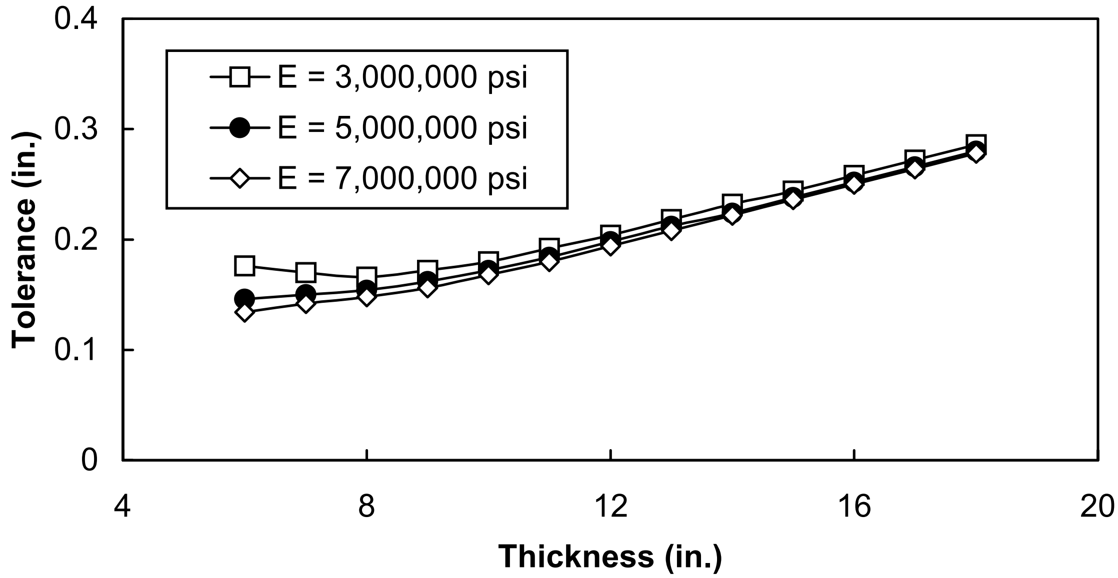
The sensitivity analysis of the pavement thickness using the AASHTO equation has been performed with the values listed in Table 3.1. A computer program has been developed based on the concepts described in the previous section and is listed in Appendix D.

Table 3.1 Values used in sensitivity analysis with AASHTO equation

E_c	5,000,000 psi	ΔPSI	2
k	500 pci	C_d	1.0
Z_R	-1.645	J	3.2
S_0	0.29	P_t	2.5

The allowable thickness deficiency (tolerance) corresponding to a 10% loss of design life is shown in Figure 3.5. As shown in Figure 3.5(a), the thickness tolerance tends to increase as the pavement thickness increases. The increase in concrete elastic modulus makes the tolerance smaller, but as the thickness increases, the effect of the elastic modulus on the tolerance becomes smaller. Instead of comparing the absolute values of the tolerances among different thicknesses, it is more convenient to compare the relative (or percentage) tolerances with respect to corresponding thicknesses. Figure 3.5(b) shows the relationship between the relative tolerance and the pavement thickness. The relative tolerance slightly decreases initially as the thickness increases, but the relative tolerance remains almost constant for thicknesses greater than a certain thickness (about 10 in. in this case). The same analysis has been performed when the loss of design life is 20%, and the results are shown in Figure 3.6. The overall results are very similar to the previous results, but both the absolute and relative tolerance values are about two times greater than the previous ones that have been obtained with the 10% loss of design life.

(a)



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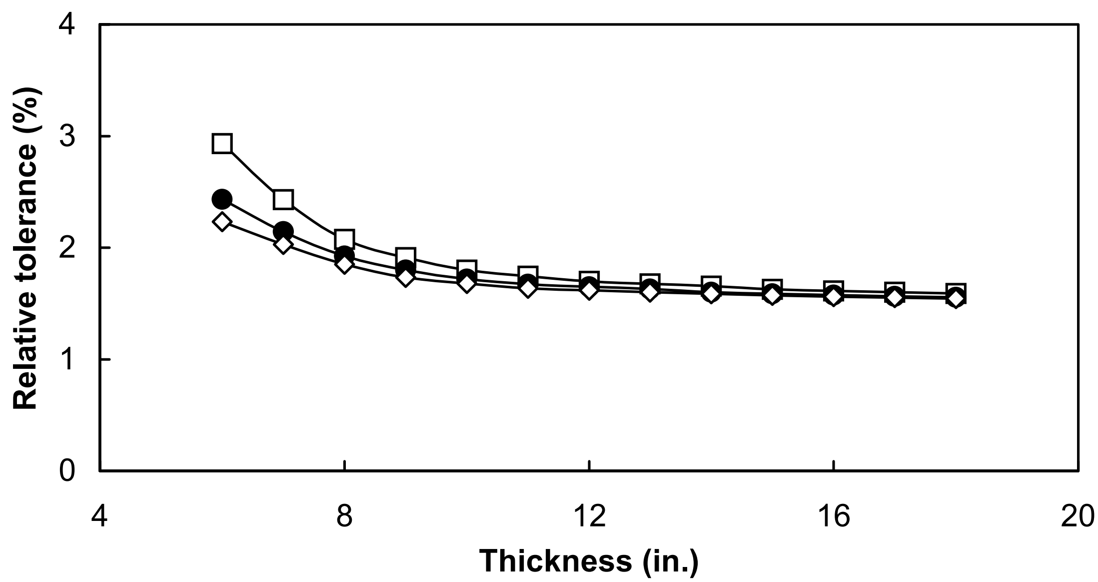
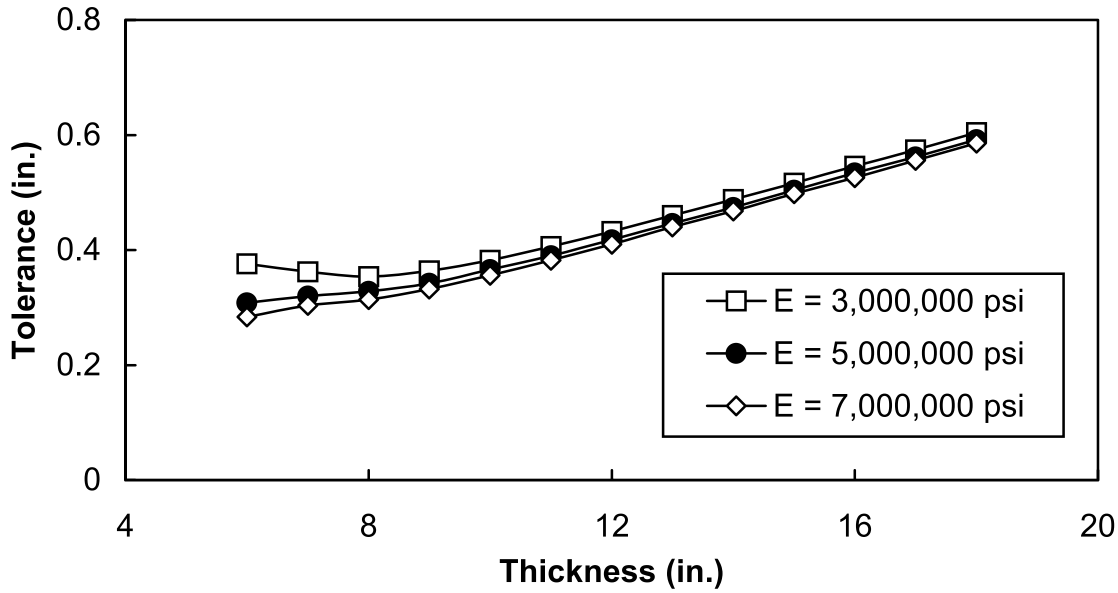


Figure 3.5 Effect of elastic modulus on thickness tolerance with AASHTO equation

(a)



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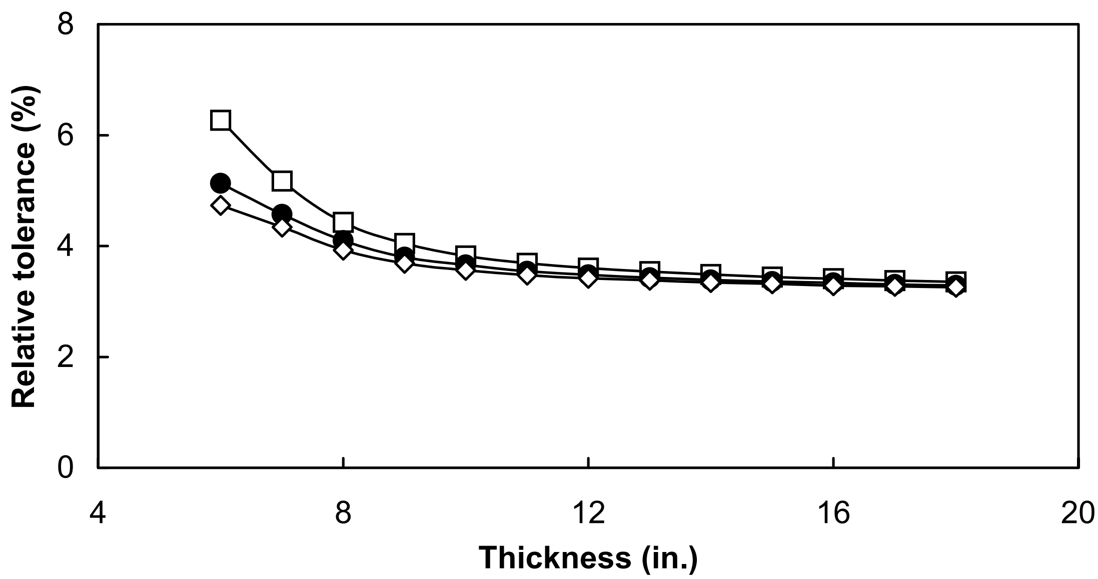


Figure 3.6 Effect of elastic modulus on thickness tolerance with AASHTO equation when loss of life is 20%

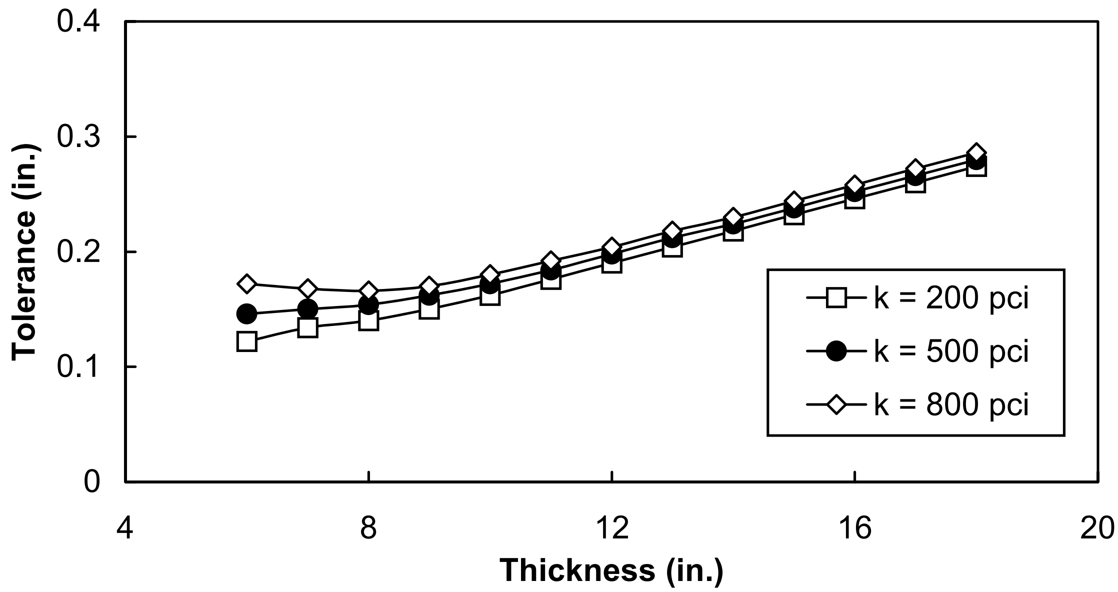
The effect of the vertical stiffness of underlying layers (modulus of subgrade reaction) on the tolerance is shown in Figure 3.7. As the stiffness value increases, the tolerance increases. The stiffness effect is more pronounced for smaller thicknesses, and the effect becomes negligible as the thickness increases.

The relationship between the tolerance and the loss of pavement life for various pavement thicknesses is shown in Figure 3.8. The tolerance becomes larger as the allowable loss of pavement life increases, as shown in Figure 3.8(a). The relationship seems to be almost linear. Similar results can be observed for the relationship between the relative tolerance and the allowable loss of pavement life as shown in Figure 3.8(b). As already investigated with the previous figures (Figures 3.5[b], 3.6[b], and 3.7[b]), the relationship is almost the same for the thicknesses of 12 and 18 inches.

The results from the thickness sensitivity analysis based on the AASHTO equation are summarized as follows:

- The tolerance increases as the thickness increases for a given percentage of allowable loss of design life.
- The relative (percentage) tolerance decreases initially and remains almost constant as the thickness increases for a given percentage allowable loss of design life. The thickness over which the relative tolerance becomes constant is about 10 inches.
- As the elastic modulus of concrete decreases and the vertical stiffness of underlying layers increases, both the absolute and relative tolerances increase. These effects become negligible as the pavement thickness increases.
- The absolute and relative tolerances increase as the percentage of allowable loss of pavement life increases. The relationship is almost linear.

(a)



(b)

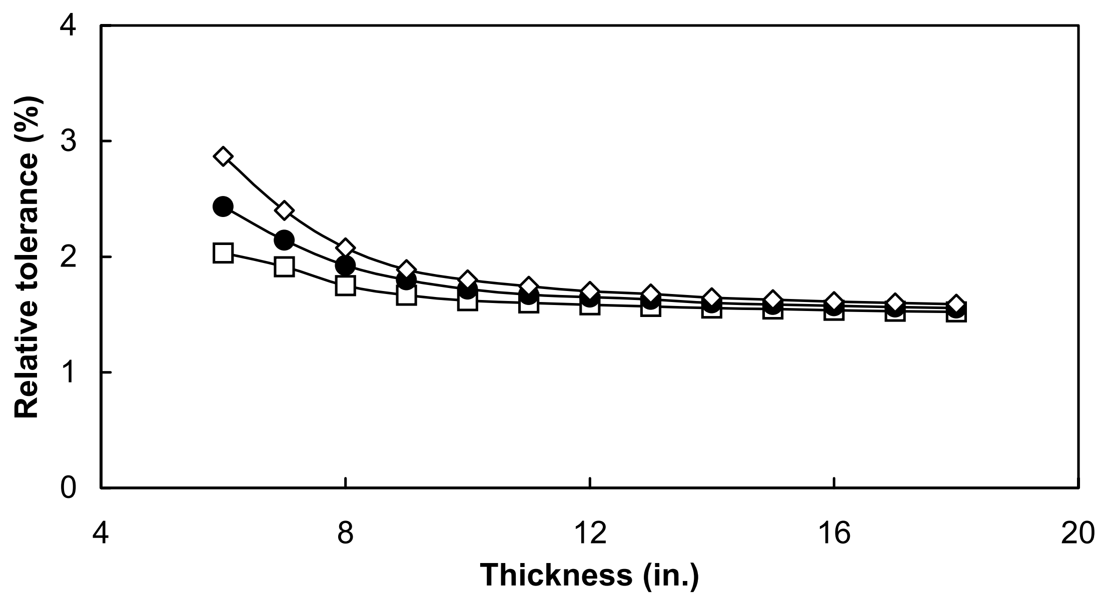
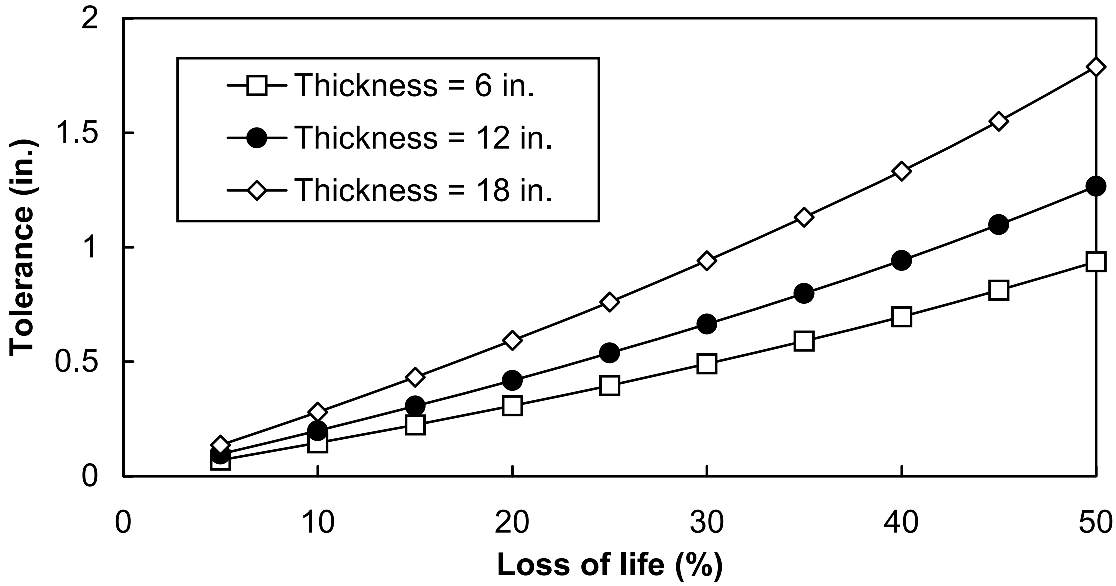


Figure 3.7   Effect of vertical stiffness on thickness tolerance with AASHTO equation

(a)



(b)

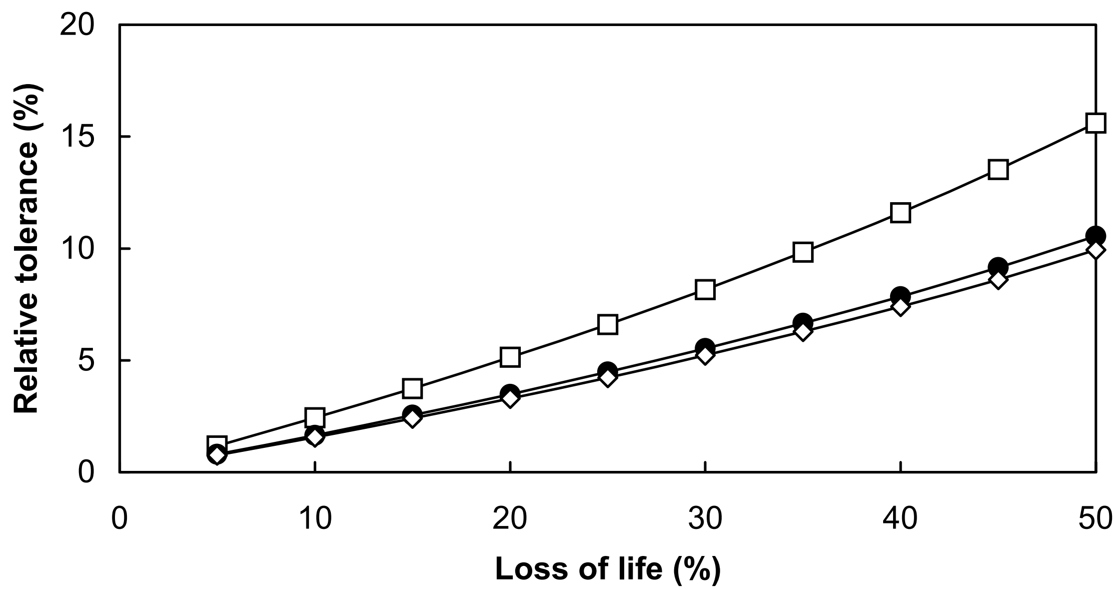


Figure 3.8 Relationship between loss of life and thickness tolerance obtained with AASHTO equation

3.3 Sensitivity Study Based on Stress and Fatigue Failure

The sensitivity analysis of the pavement thickness has been performed to find the relationship between the thickness deficiency and the loss of pavement life based on concrete stresses and fatigue failure models. There are a number of fatigue failure equations, and some of them will be explained in the next section. To calculate the concrete stresses caused by the loads imposed by trucks, various methods can be used. The Westergaard equations have been used in this study (Refs 18-20).

By using the Westergaard equations, concrete stresses can be obtained for four different loading conditions, which include interior, corner, circular edge, and semicircular edge loads. The maximum tensile stress in the interior of a slab under a circular loaded area of radius a is

$$\sigma = \frac{3(1+\nu)P}{2\pi h^2}(\ln\frac{l}{b} + 0.6159) \tag{3.2}$$

where h is the thickness of the slab (inches), ν is Poisson's ratio, and P is the magnitude of the load (lbs.). The radius of relative stiffness l is defined by

$$l = \left[\frac{Eh^3}{12(1-\nu^2)k}\right]^{0.25} \tag{3.3}$$

where E is the modulus of elasticity and k is the stiffness of underlying layers (modulus of subgrade reaction). In eq. 3.2, b is defined by

$$b = a \qquad \text{when } a \geq 1.724h \tag{3.4}$$

$$b = \sqrt{1.6a^2 + h^2} - 0.675h \qquad \text{when } a < 1.724h \tag{3.5}$$

The maximum stress due to corner loading can be obtained by

$$\sigma = \frac{3P}{h^2}[1 - (\frac{a\sqrt{2}}{l})^{0.6}] \tag{3.6}$$

The maximum stress due to edge loading with a circular loaded area is

$$\sigma = \frac{3(1+\nu)P}{\pi(3+\nu)h^2}[\ln(\frac{Eh^3}{100ka^4}) + 1.84 - \frac{4\nu}{3} + \frac{1-\nu}{2} + \frac{1.18(1+2\nu)a}{l}] \tag{3.7}$$

The maximum stress due to edge loading with a semicircular loaded area is

$$\sigma = \frac{3(1+\nu)P}{\pi(3+\nu)h^2}[\ln(\frac{Eh^3}{100ka^4}) + 3.84 - \frac{4\nu}{3} + \frac{(1+2\nu)a}{2l}] \tag{3.8}$$

3.3.1 Fatigue Failure Models

When a material is subjected to repeated loads smaller than the ultimate static strength, a fatigue failure may occur, especially for large loads and a large number of load applications. Concrete pavements are subjected to many repetitions of traffic loads during their service lives; therefore, fatigue in concrete pavement is an important design consideration.

Concrete pavements are subjected to fatigue loading, and concrete has been shown to exhibit fatigue behavior. Fatigue loading is qualified as "repeated applications of a load at a level below the ultimate strength capacity of the concrete." Under these conditions, concrete will eventually fail. Pavements are subjected to numerous load cycles, which are below the ultimate capacity of the pavements (Ref 27).

Flexural strength of plain concrete is an important parameter in the design of concrete pavement because PCCP failure by cracking is caused by the repeated applications of flexural stresses. A number of studies have been performed to investigate the fatigue behavior of plain concrete. The flexural fatigue strength of concrete is defined as a fraction of the static strength, which can support repeatedly for a given number of cycles. In other words, the number of loading cycles to failure depends on the level of stress applied to concrete. As the stress level (S, stress/strength) increases, the cycles to failure decrease. The fatigue life is influenced by several factors, such as range of loading, rate of loading, eccentricity of loading, load history, material properties, and environmental conditions.

Three general forms of fatigue equations have often been used. Those are linear (or Wholer), modified linear (or modified Wholer), and Power formulas.

Linear Equation

Most researchers adopted a relationship so called Wholer equation or S-N curve expressed as follows:

$$\log(N) = aS + b = a\frac{\sigma_{\max}}{MR} + b \tag{3.9}$$

where N = number of load repetition

S = stress level

a = experimental coefficients (slope of the semilogarithmic relationship)

b = experimental coefficients (intercept of the semilogarithmic relationship)

σ_{max} = maximum flexural stress

MR = modulus of rupture

Fatigue models of this form have been developed by Kesler (Ref 28), PCA (Ref 29), and Crumley and Kennedy (Ref 30) to predict the fatigue life of concrete pavements by performing laboratory tests.

The fatigue equation developed by Kesler is

$$\log(N) = -20.224S + 19.292 \tag{3.10}$$

for 70 cycles per minute loading and 3,600 psi concrete and

$$\log(N) = -22.07S + 17.81 \tag{3.11}$$

for 70 cycles per minute loading and 4,600 psi concrete.

The PCA fatigue equation is

$$N = 10^{(0.97187 - S)/0.0828} \qquad \text{for S > 0.55} \tag{3.12}$$

$$N = \left(\frac{4.2577}{S - 0.43248}\right)^{3.628} \qquad \text{for 0.45 < S < 0.55} \tag{3.13}$$

$$N = unlimited \qquad \text{for S < 0.45} \tag{3.14}$$

The fatigue equation developed by Crumley and Kennedy using indirect tensile testing with limestone aggregate is

$$\log(N) = -\frac{S}{0.0924} + 9.98 \tag{3.15}$$

Modified Linear Equation

The second type of the fatigue equation is a modification to the Wholer equation. The second form incorporates the stress ratio *R* into the Wholer equation as follows:

$$S = \frac{\sigma_{max}}{MR} = 1 - b(1-R)\log(N)$$
$$[R = \frac{\sigma_{min}}{\sigma_{max}}, 0 \le R \le 1] \tag{3.16}$$

where S = stress level

σ_{max} = maximum flexural stress

σ_{min} = minimum flexural stress

MR = modulus of rupture

b = experimental coefficients which varies with loading conditions

R = stress ratio = $\frac{\sigma_{min}}{\sigma_{max}}$

N = number of load repetition

Aas-Jakobsen (Ref 31) demonstrated this relationship in compression and suggested the following equation.

$$S = 1 - 0.064(1-R)\log(N) \tag{3.17}$$

Tepfers and Kutti (Ref 32) verified this equation by laboratory compression fatigue testing and developed a slightly different equation as follows:

$$S = 1 - 0.0685(1-R)\log(N) \tag{3.18}$$

Power Formula

The third form of the fatigue equation is a power formula that has been used by many pavement researchers (Refs 33-36). The equations were developed after the concrete pavement slab sections developed cracking in the AASHO road test. The third form of the fatigue equation is generally written as

$$N = A\left(\frac{MR}{\sigma_{max}}\right)^{B} \tag{3.19}$$

where N = number of load repetition

A, B = regression coefficients

MR = modulus of rupture

σ_{max} = maximum flexural stress

Vesic (Ref 33) developed a power formula considering the terminal PSI value of 2.5 from the AASHO road test and suggested the following equation.

$$N = 225{,}000\left(\frac{1}{S}\right)^{4} \tag{3.20}$$

Yimprasert and McCullough (Ref 34) modified the Vesic equation for MR = 79 psi with the load application at 2 ft. from the edge. Their equation is

$$N = 8{,}750\left(\frac{1}{S}\right)^{4.34} \tag{3.21}$$

Treybig et al. (Ref 35) suggested the following equation. This fatigue curve is known as ARE curve.

$$N = 23{,}440\left(\frac{1}{S}\right)^{3.21} \tag{3.22}$$

Taute et al. (Ref 36) developed a similar formula with slightly different coefficient values as

$$N = 43{,}000\left(\frac{1}{S}\right)^{3.2} \tag{3.23}$$

Some of the fatigue failure curves explained in this section are shown in Figure 3.9.

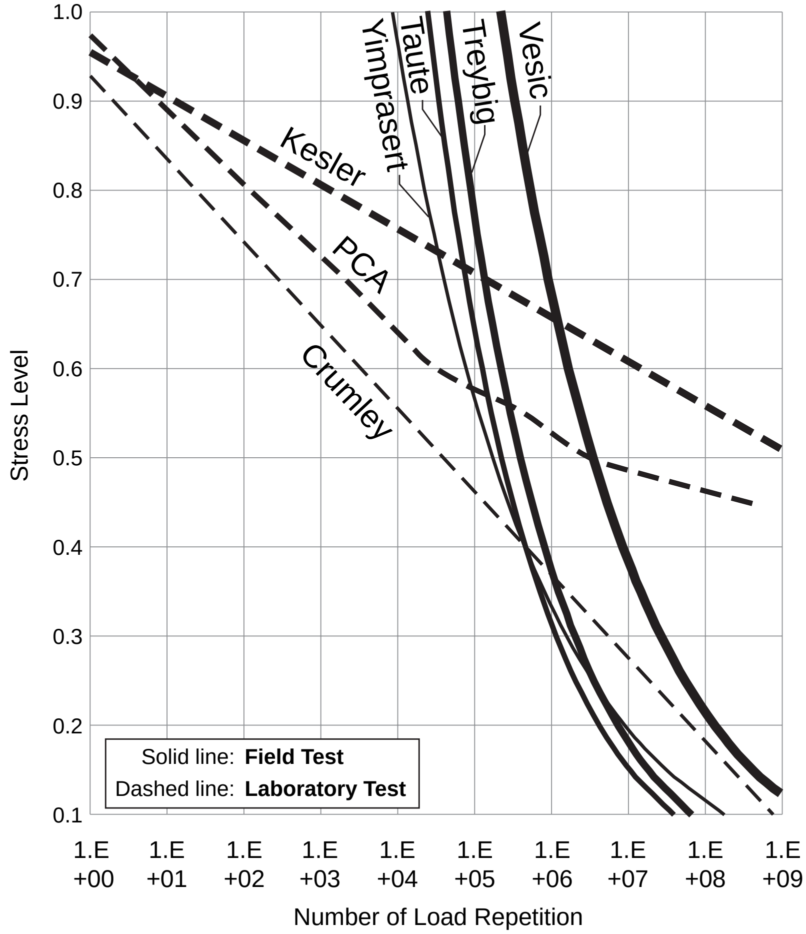


Figure 3.9 Relationship between stress level and fatigue life

3.3.2 Sensitivity Study with Power Formulas

The sensitivity analysis of the pavement thickness using the power fatigue equations has been performed. Figure 3.10 shows the relationship between the tolerance and the thickness for four different loading conditions obtained with the Vesic power formula when the allowable loss of pavement life is 10%. The magnitude of the single wheel load used to calculate concrete stresses using the Westergaard equations was 9,000 pounds. The thickness tolerance increases with increasing the pavement thickness, as shown in Figure 3.10(a), and slight differences in the results can be observed among the different loading conditions. As shown in Figure 3.10(b), the relative tolerance initially decreases and then remains almost constant as the thickness increases. The initial decrease is clear for the corner loading, but the initial decrease can be negligible for the circular and semicircular edge loadings. The tolerance obtained with interior loading tends to yield the smallest value.

The differences in the tolerances obtained with interior loading when using different power formulas are shown in Figure 3.11. The tolerance obtained with the Yimprasert power formula yields the smallest, and that obtained with Treybig and Taute power formulas gives the largest. As the coefficient B in eq. 3.19 increases, the tolerance decreases, and the coefficient A does not seem to affect the tolerance.

Figures 3.12 and 3.13 show the effects of the elastic modulus of concrete and the vertical stiffness of underlying layers, respectively, on the thickness tolerance obtained with the Vesic power formula. The differences in the tolerance can be negligible. Therefore, the tolerance is not affected by the elastic modulus and vertical stiffness when using the power fatigue formula.

The relationship between the tolerance and the allowable loss of pavement life when the Vesic power fatigue formula is considered is shown in Figure 3.14. The relationship is almost linear. Slight differences in the relative tolerance can be observed among different pavement thicknesses. The difference between 12- and 18-inch pavements is smaller than that between 6- and 12-inch ones.

(a)

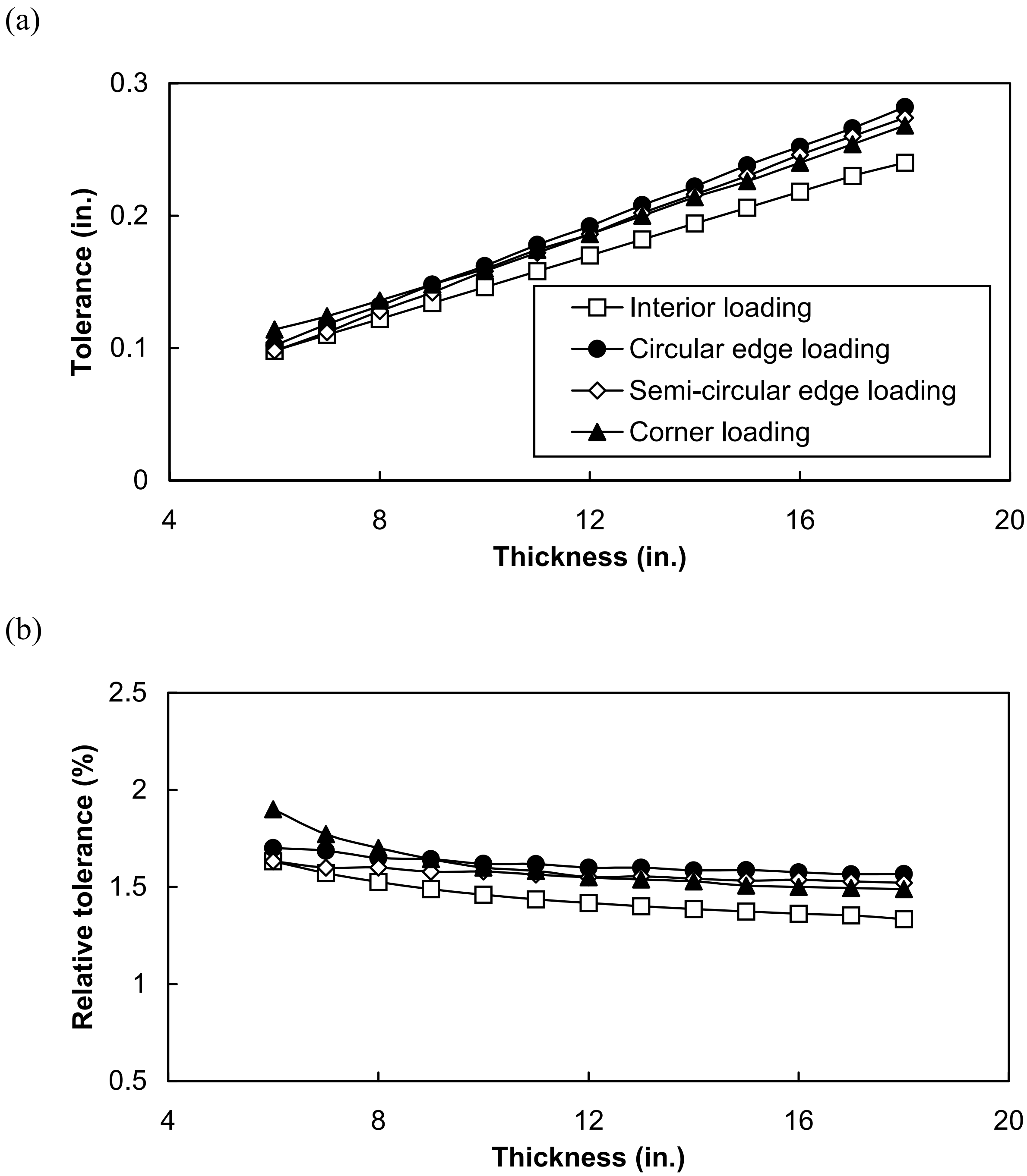
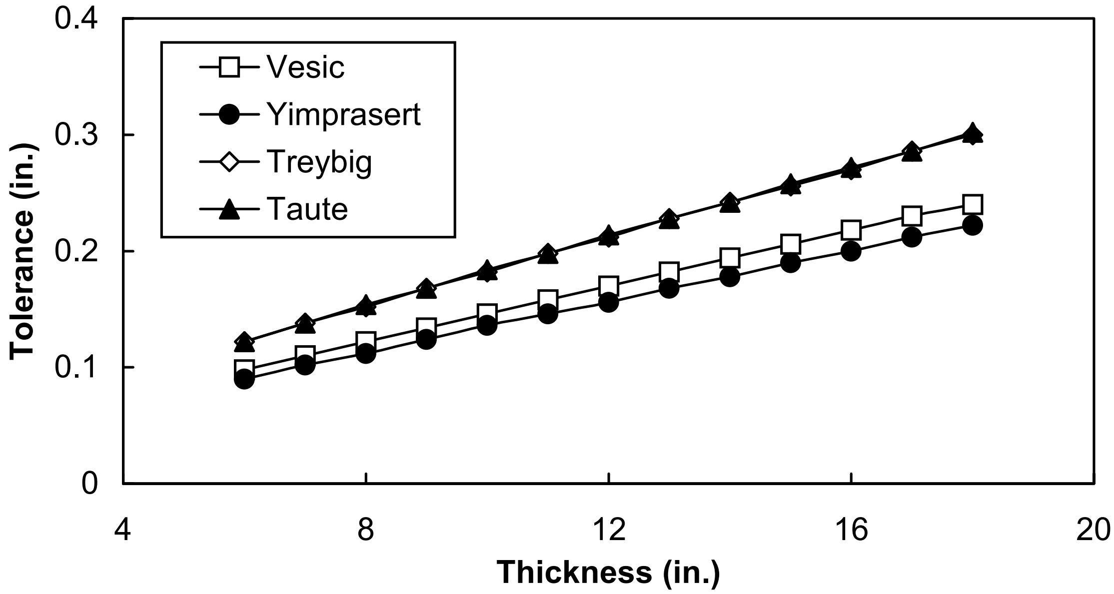


Figure 3.10 Effect of loading conditions on thickness tolerance with power formula

(a)



(b)

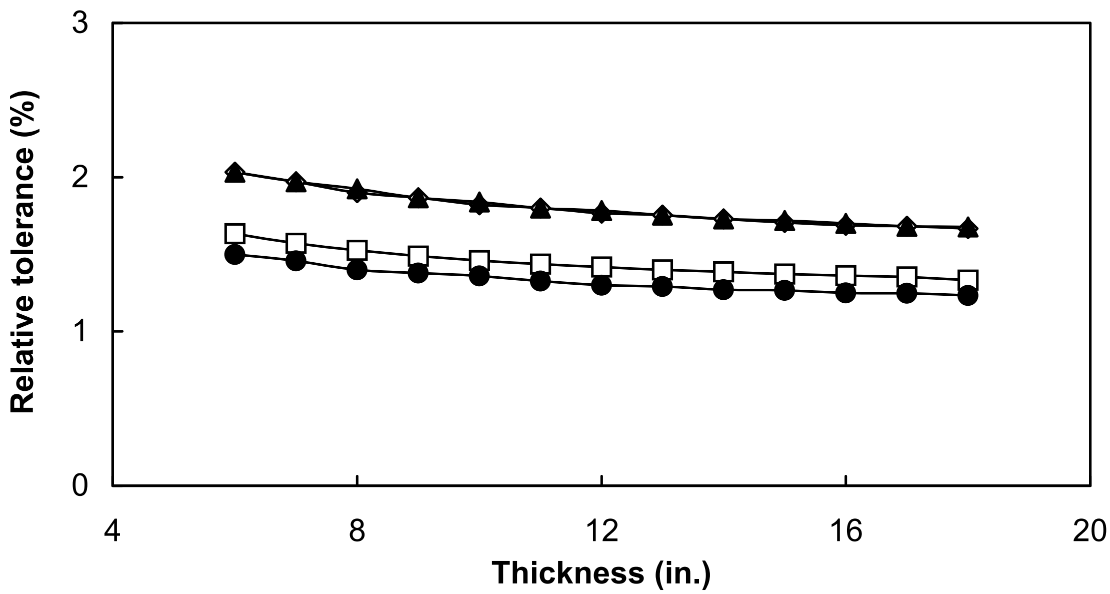
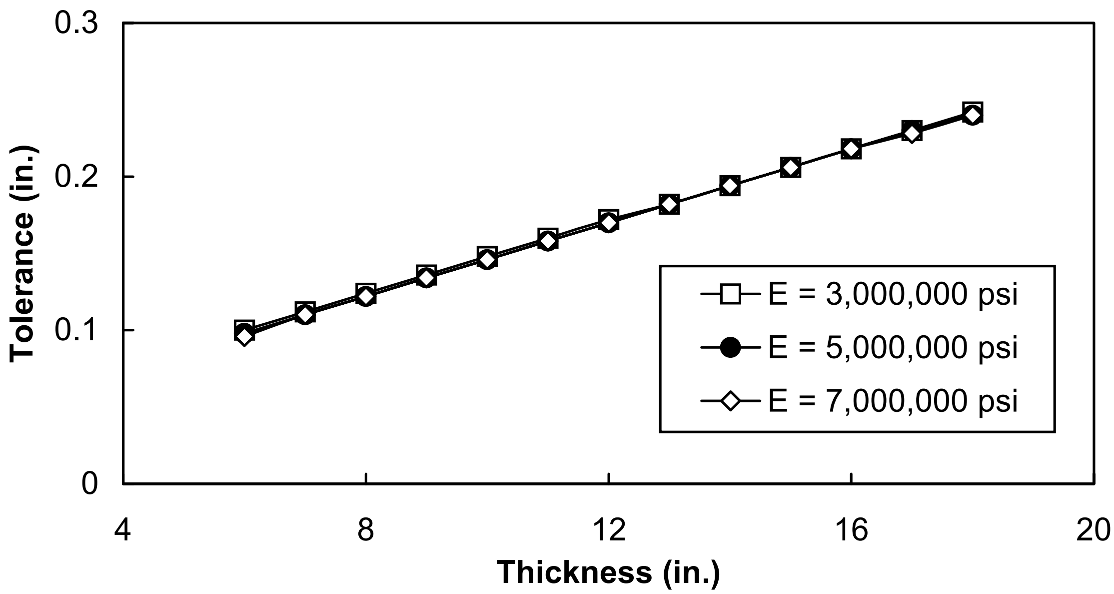


Figure 3.11 Comparison of various power formulas with interior loading

(a)



(b)

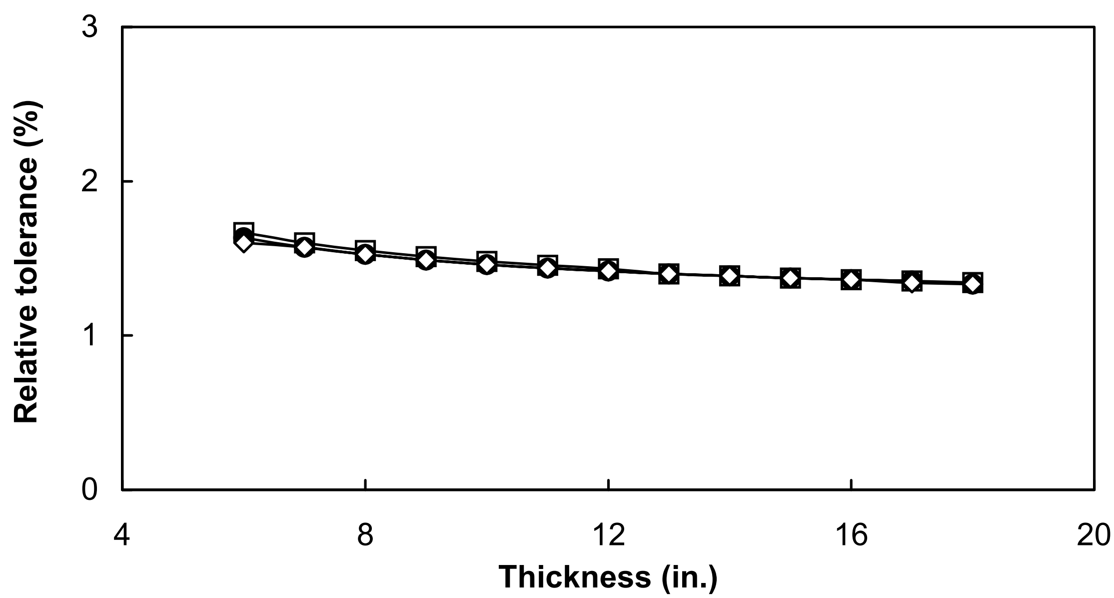
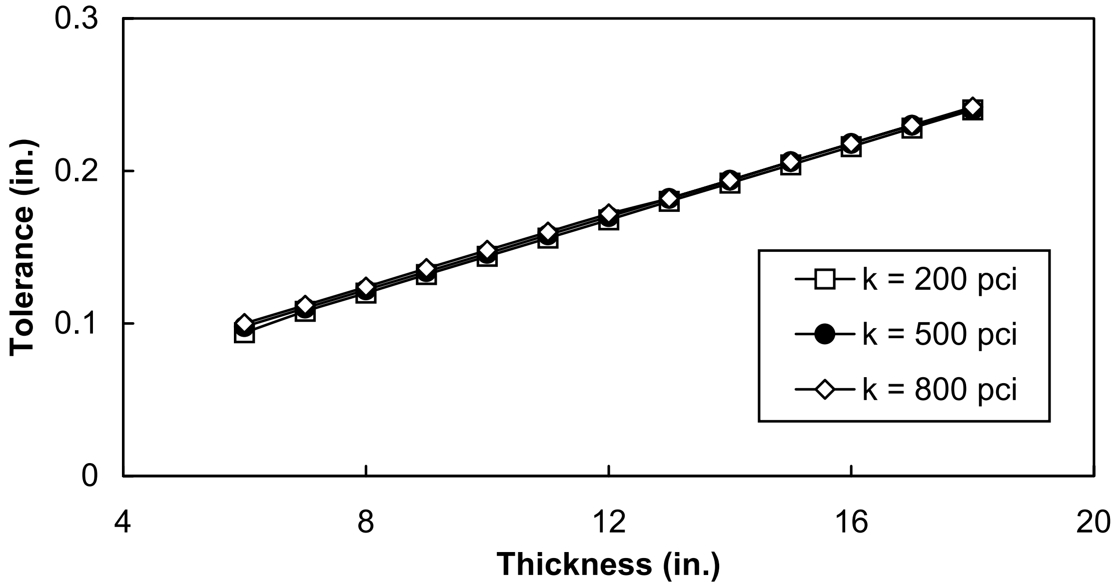


Figure 3.12 Effect of elastic modulus on thickness tolerance with power formula

(a)



(b)

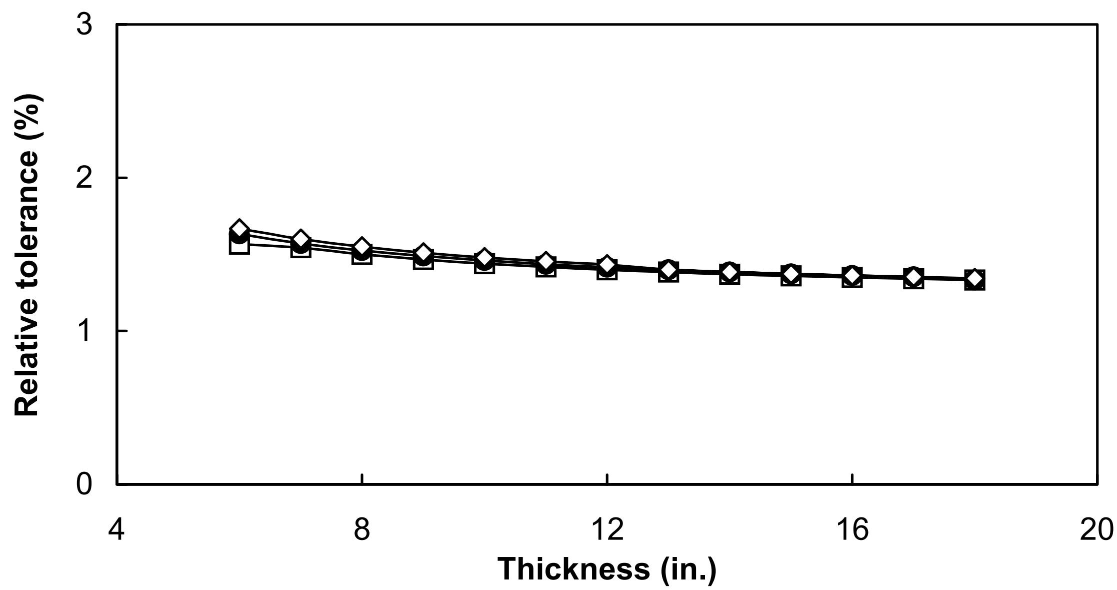
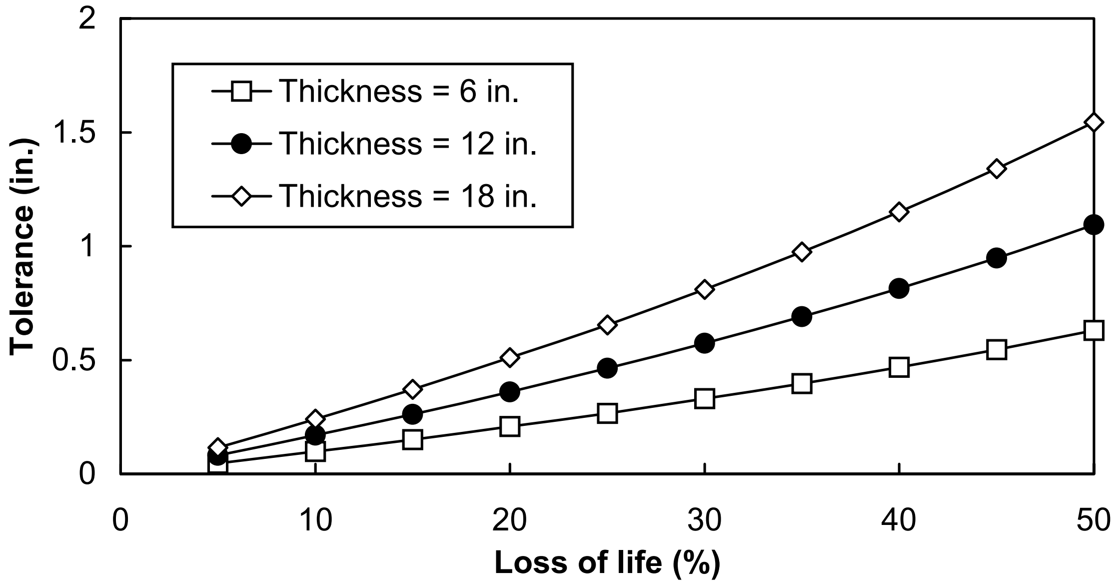


Figure 3.13 Effect of vertical stiffness on thickness tolerance with power formula

(a)



(b)

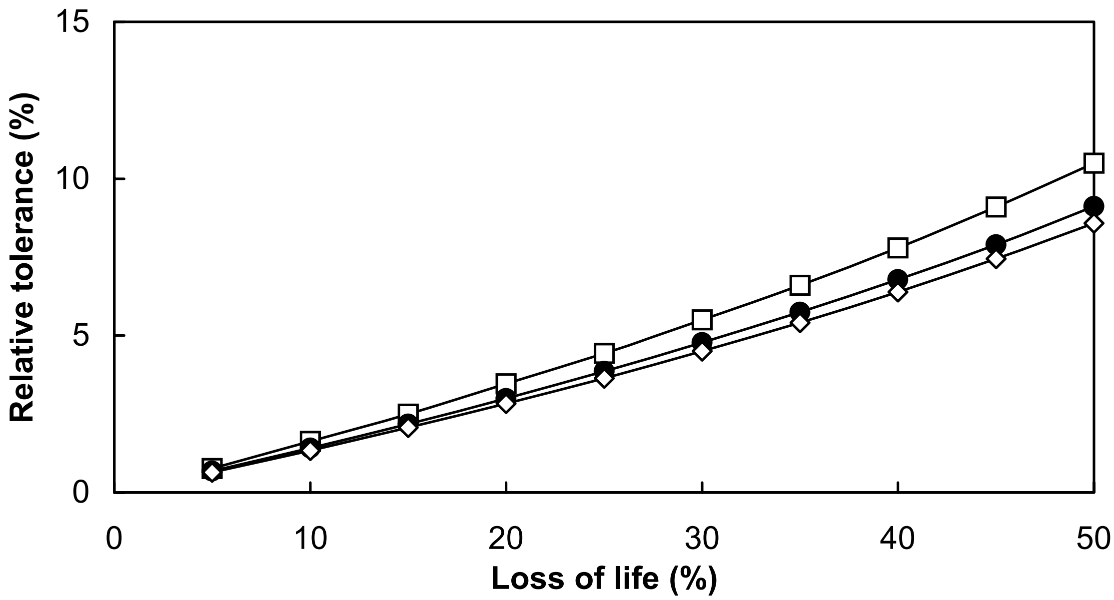


Figure 3.14 Relationship between loss of life and thickness tolerance obtained with power formula

3.3.3 Sensitivity Study with Linear Formulas

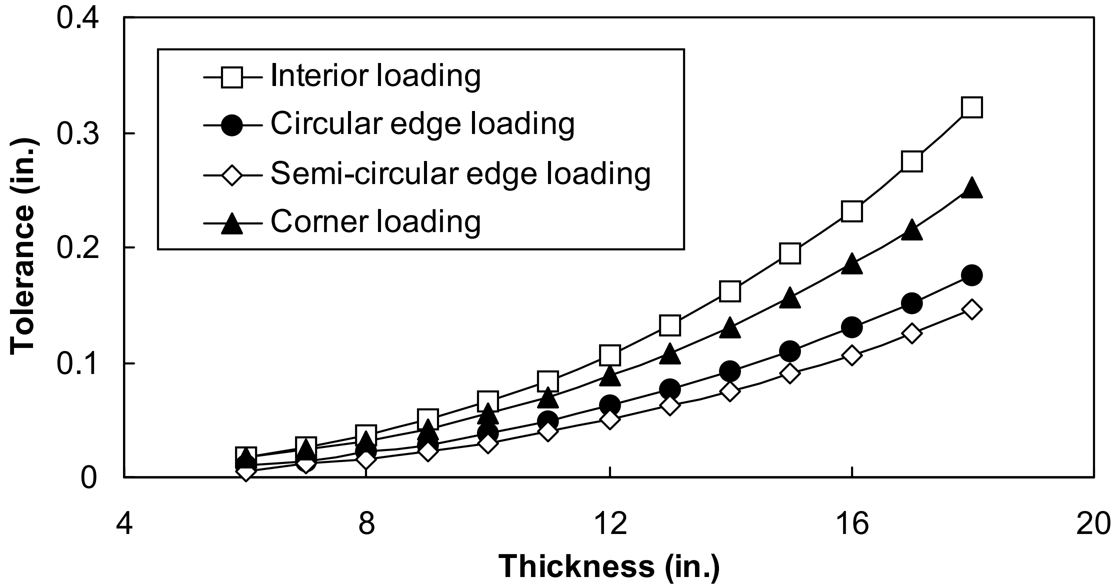
The thickness sensitivity analysis using the linear fatigue failure equations has been performed. Figure 3.15 shows the relationship between the thickness tolerance and the pavement thickness for four different loading conditions obtained with the Kesler linear fatigue failure equation shown in Eq. (3.11) when the allowable loss of pavement life is 10%. The thickness tolerance increases with increasing the pavement thickness, as shown in Figure 3.15(a), and differences in the results can be observed among the different loading conditions. The tolerance obtained with interior loading is the largest, and that obtained with the corner loading is the second largest. The tolerances obtained with the edge loadings are the smallest, and the semicircular edge loading makes the tolerance smaller. As shown in Figure 3.15(b), the relative tolerance also increases as the thickness increases.

The differences in the tolerances obtained with the interior loading when using different linear fatigue failure formulas are shown in Figure 3.16. The tolerance obtained with the Crumley linear fatigue formula yields the largest. The tolerance obtained with the modified linear fatigue formula is dependent on the stress ratio R in eq. 3.16. As the stress ratio R decreases (or the difference between the maximum and minimum stresses increases), the tolerance becomes larger.

Figures 3.17 and 3.18 show the effects of the elastic modulus of concrete and the vertical stiffness of underlying layers, respectively, on the thickness tolerance obtained with the Kesler linear fatigue failure formula. As the elastic modulus or the vertical stiffness increases, the thickness tolerance becomes larger. However, the elastic modulus affects the tolerance more significantly than the vertical stiffness.

The relationship between the tolerance and the allowable loss of pavement life when the Kesler linear fatigue failure formula is used is shown in Figure 3.19. The tolerance increases as the loss of life increases, and the relationship seems to be almost linear. As the pavement thickness increases, both the absolute and relative tolerances become larger. The differences in the tolerances among different thicknesses are significantly large.

(a)



(b)

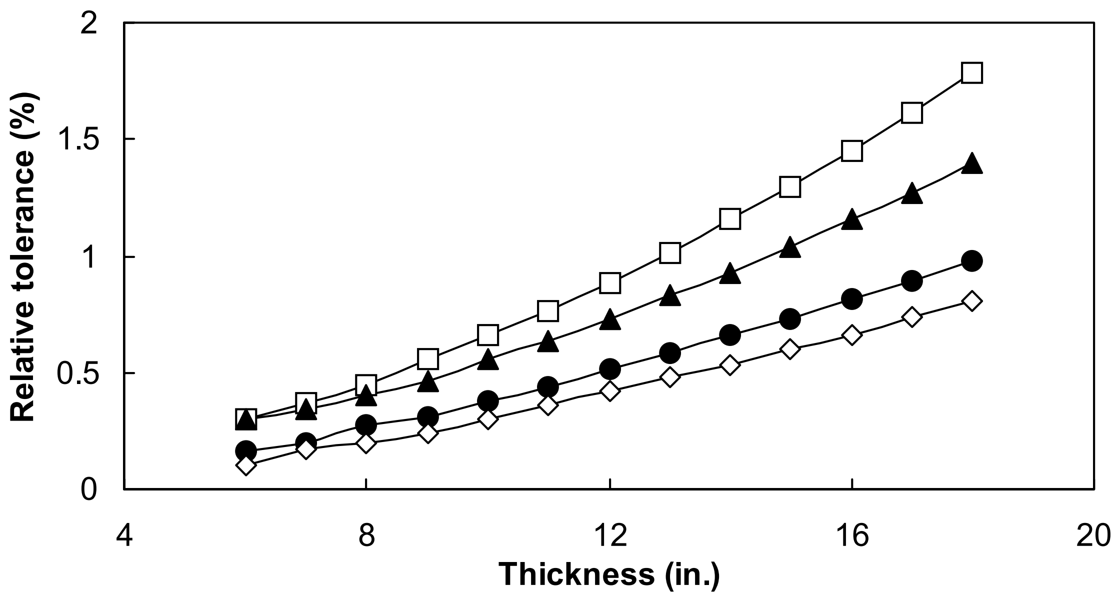
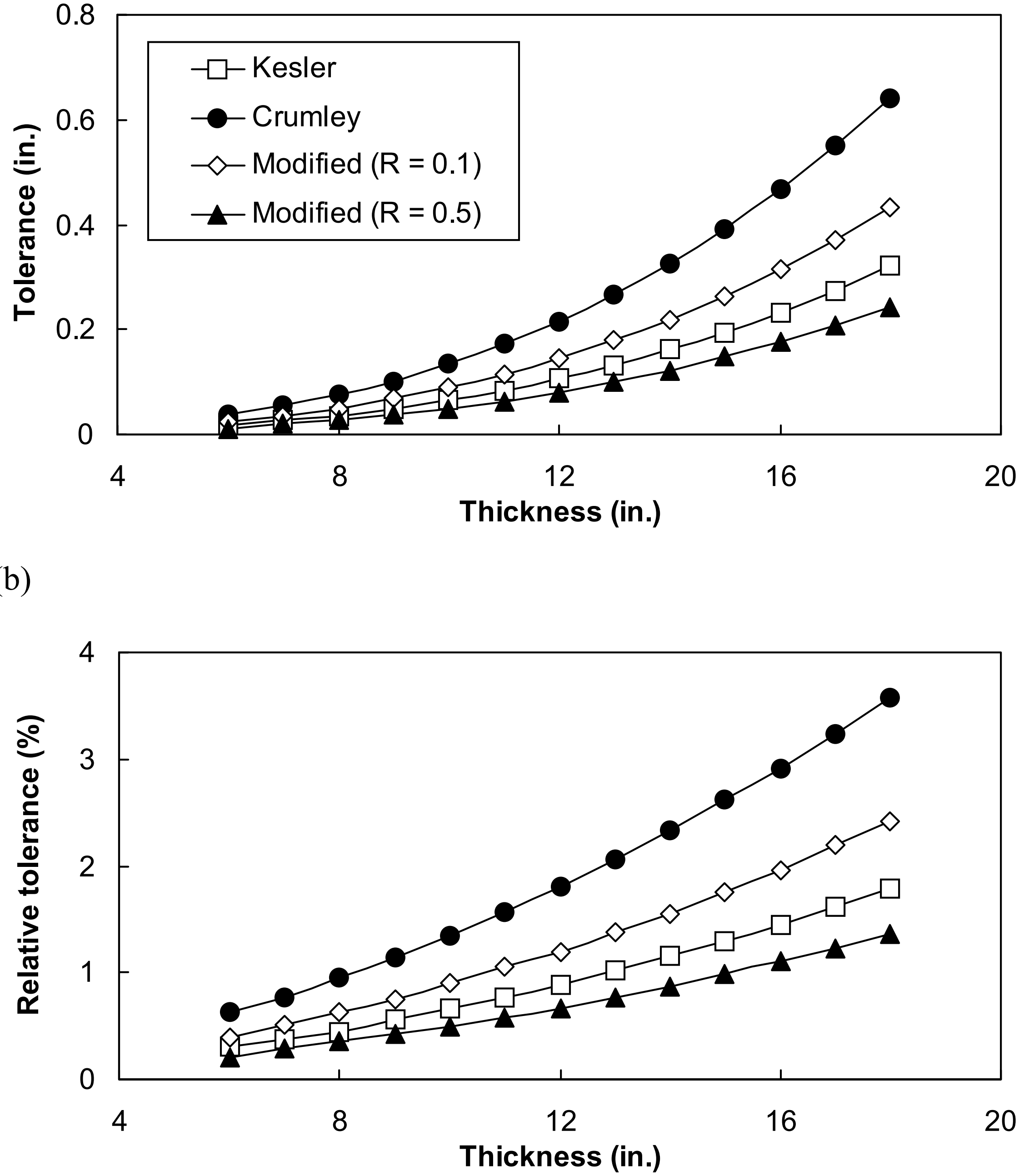


Figure 3.15 Effect of loading conditions on thickness tolerance with linear formula

(a)



(b)

Figure 3.16 Comparison of various linear formulas with interior loading

(a)

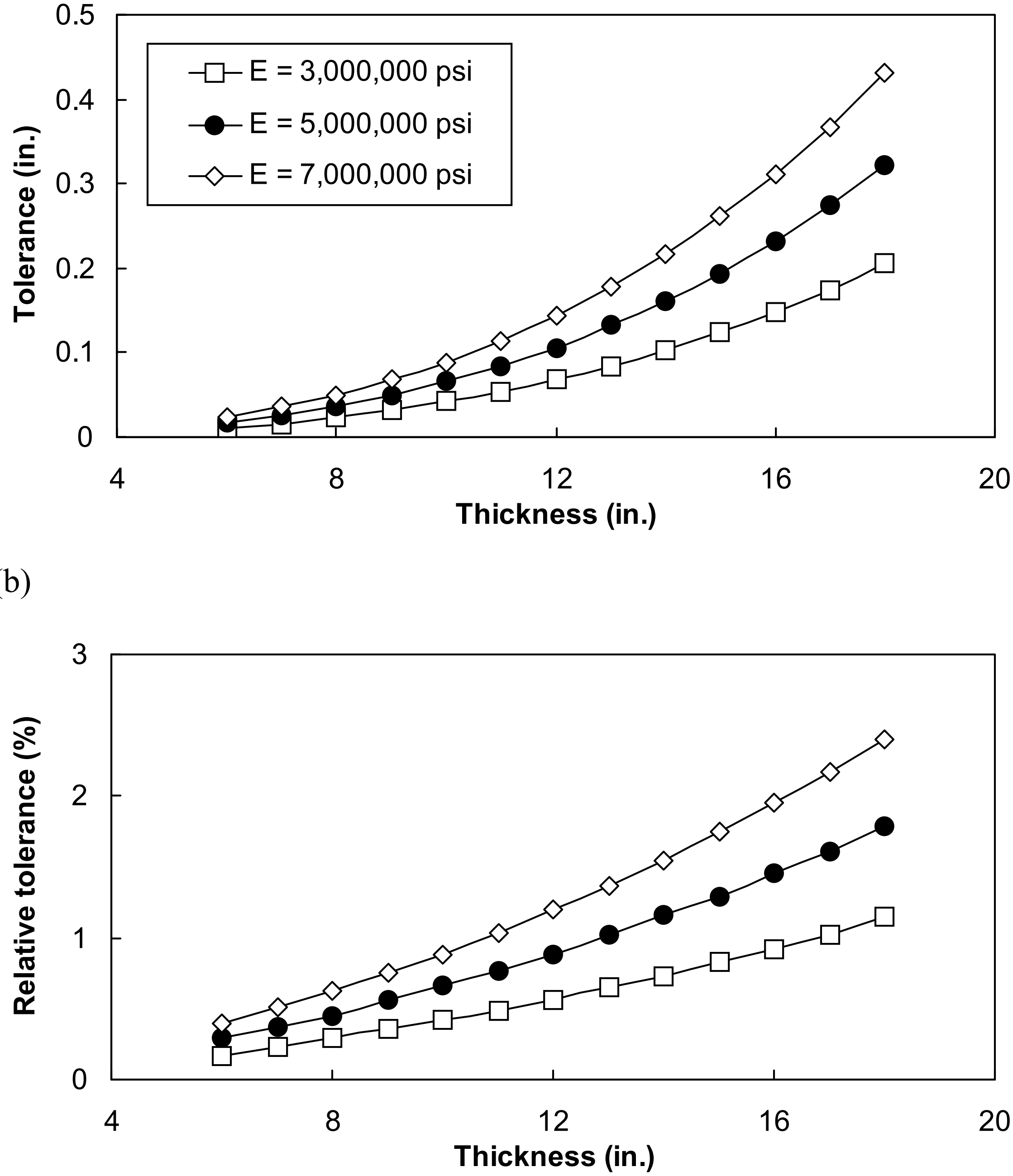
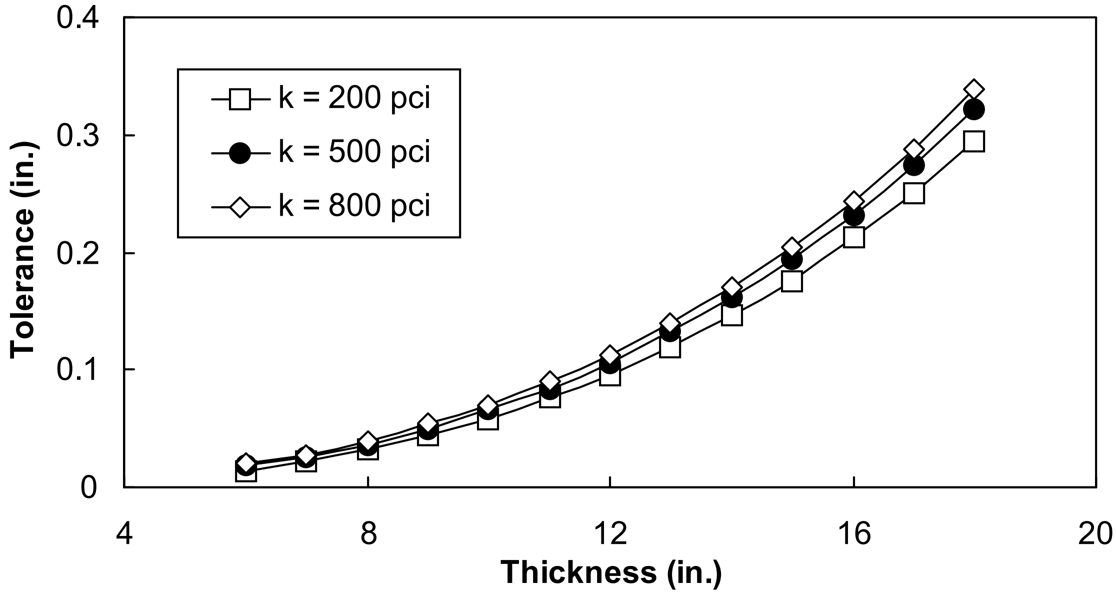


Figure 3.17 Effect of elastic modulus on thickness tolerance with linear formula

(a)



(b)

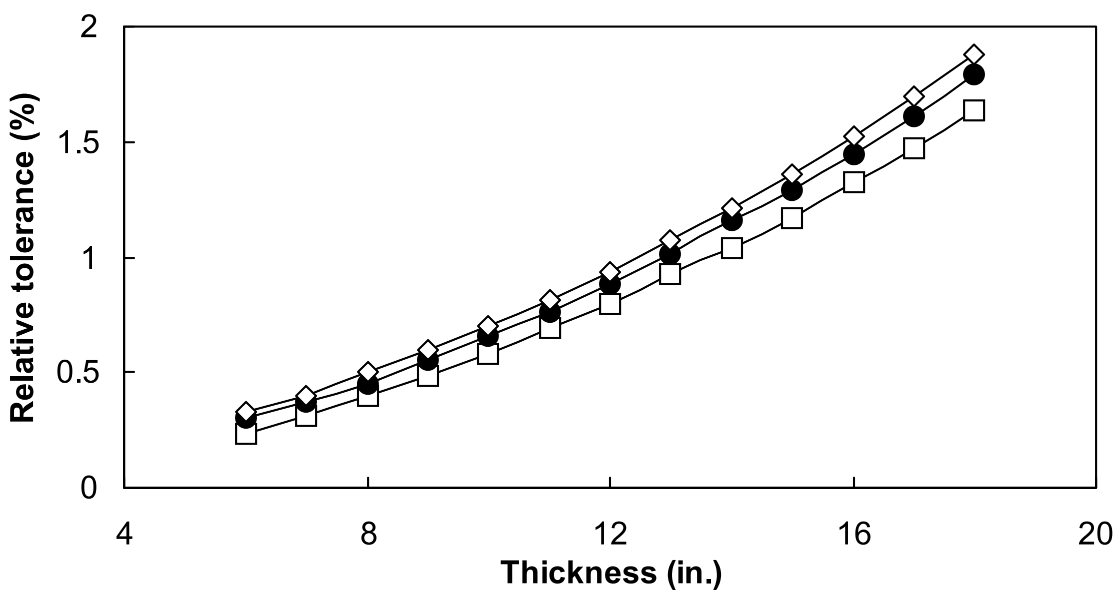
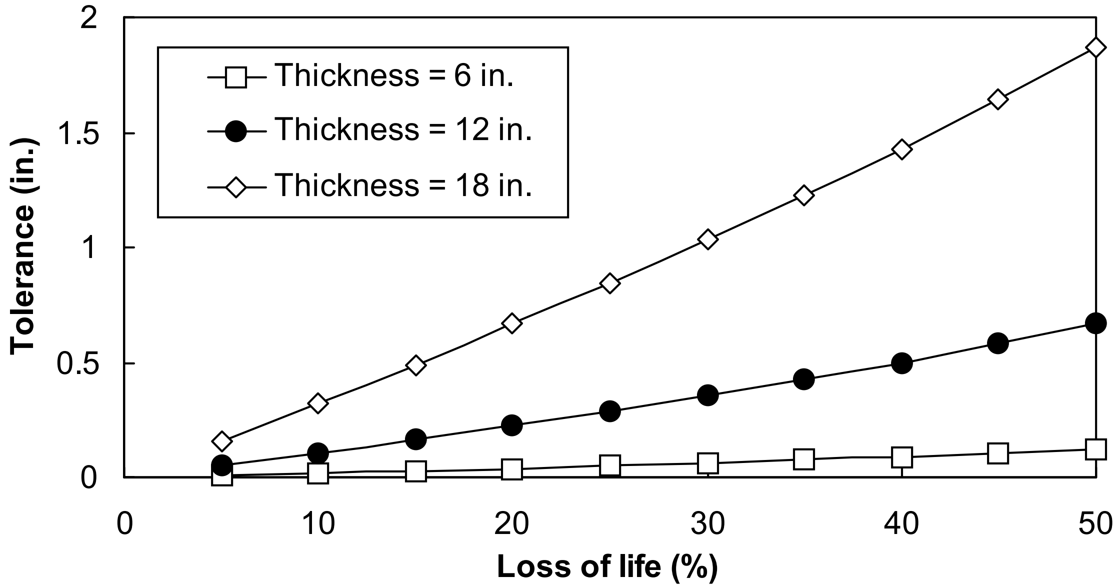


Figure 3.18 Effect of vertical stiffness on thickness tolerance with linear formula

(a)



(b)

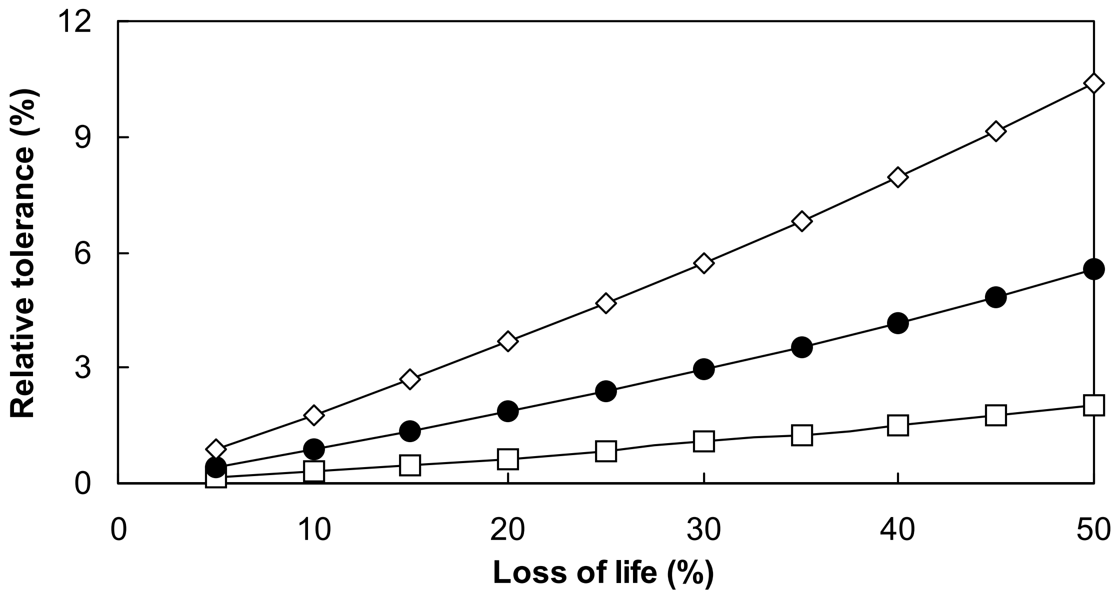


Figure 3.19 Relationship between loss of life and thickness tolerance obtained with linear formula

3.3.4 Summary

The sensitivity analysis of the thickness based on various fatigue failure equations has been performed. The results obtained with the power fatigue formulas are as follows:

- The thickness tolerance increases with increasing the pavement thickness when an allowable loss of life is given.
- The relative tolerance initially decreases for smaller thicknesses and then remains almost constant as the thickness increases.
- The tolerance is not affected by the elastic modulus of concrete and the vertical stiffness of underlying layers.
- The relationship between the thickness tolerance and the allowable loss of life is almost linear.

The results obtained with the linear fatigue formulas are as follows:

- Both the absolute and relative thickness tolerances increase with increasing the pavement thickness for a given allowable loss of life.
- When using the modified linear fatigue formulas, the tolerance becomes larger as the stress ratio *R* decreases (or the difference between the maximum and minimum stresses increases).
- As the elastic modulus of concrete or the vertical stiffness of underlying layers increases, the thickness tolerance increases.
- Both the absolute and relative thickness tolerances increase as the allowable loss of life increases, and the relationship is almost linear.

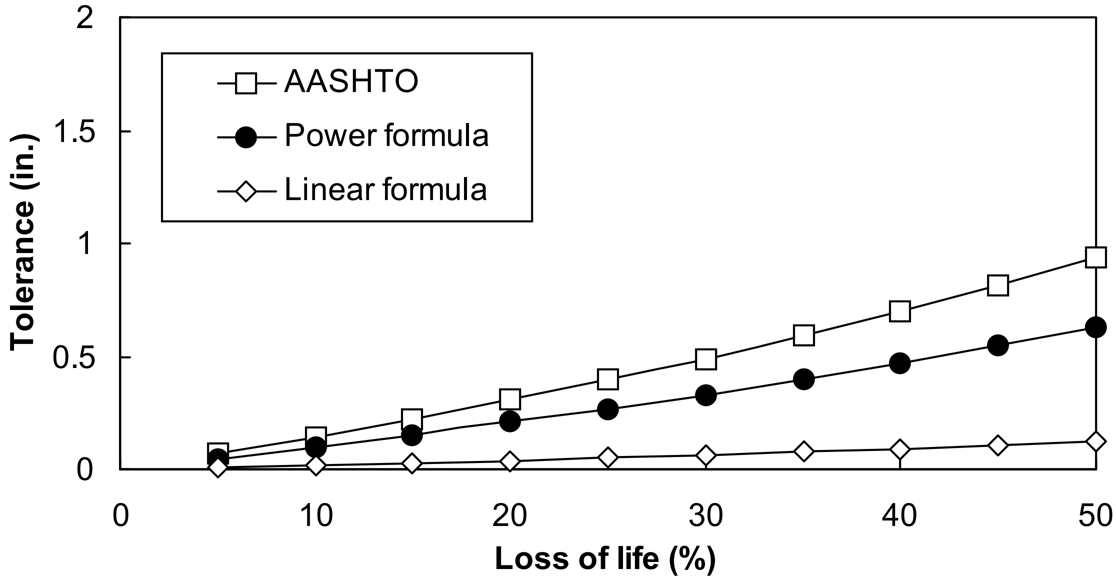
The relationships between the tolerance and the allowable loss of pavement life obtained with the AASHTO, power fatigue, and linear fatigue equations are compared and shown in Figures 3.20, 3.21, and 3.22 for the pavement thicknesses of 6, 12, and 18 inches, respectively. For the thicknesses of 6 and 12 inches, the tolerance obtained with the AASHTO equation is the largest, and that obtained with the linear fatigue failure equation is the smallest, as shown in Figures 3.20 and 3.21. For a pavement thickness of 18 inches, the tolerance obtained with the linear fatigue formula is the largest, and that obtained with the power fatigue formula is the smallest, as shown in Figure 3.22. The differences in the thickness tolerances obtained with different formulas become smaller as the pavement thickness increases.

3.4 Sensitivity Study Based on Distress

The thickness sensitivity study has been performed based on distresses. If the pavement life is primarily determined by distresses such as cracks and punchouts, the effect of the thickness deficiency can be investigated by comparing distresses between the plan pavement and the pavement with thickness deficiency. For instance, if a thickness deficient pavement does not induce more distresses compared with the plan pavement, that thickness deficiency can be acceptable. In CRCP the most serious structural failure is punchouts. The punchouts are directly related to the crack spacing because the probability of punchout formation becomes larger as the crack spacing decreases (as more cracks occur). Therefore, in this study the crack spacing is considered in order to investigate the thickness deficiency. To predict the crack spacing, a mechanistic model, CRCP-10, has been used.

The CRC pavements with the thicknesses of 6, 9, 12, 15, and 18 inches have been modeled using the typical values of the variables listed in Table 3.2. The deficient pavements have also been modeled by reducing the thickness and keeping the other variables, including steel design, the same. If the CRC pavement has a deficiency in the thickness, the steel ratio will be higher than the design steel ratio because the cross sectional area of the concrete slab decreases but the design steel amount remains the same. The mean crack spacings have been obtained by using CRCP-10 for the plan pavements with the five different thicknesses mentioned above, and comparisons have been made for the mean crack spacings obtained with the deficient pavements. The decrement in the thickness for the deficient pavements for the analysis was 0.2 inches.

(a)



(b)

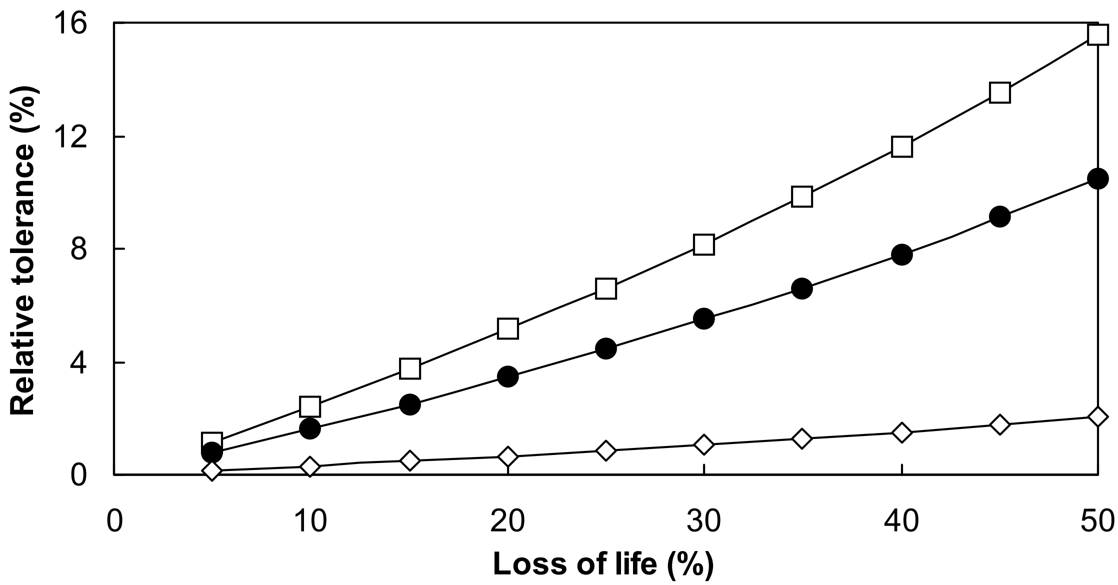
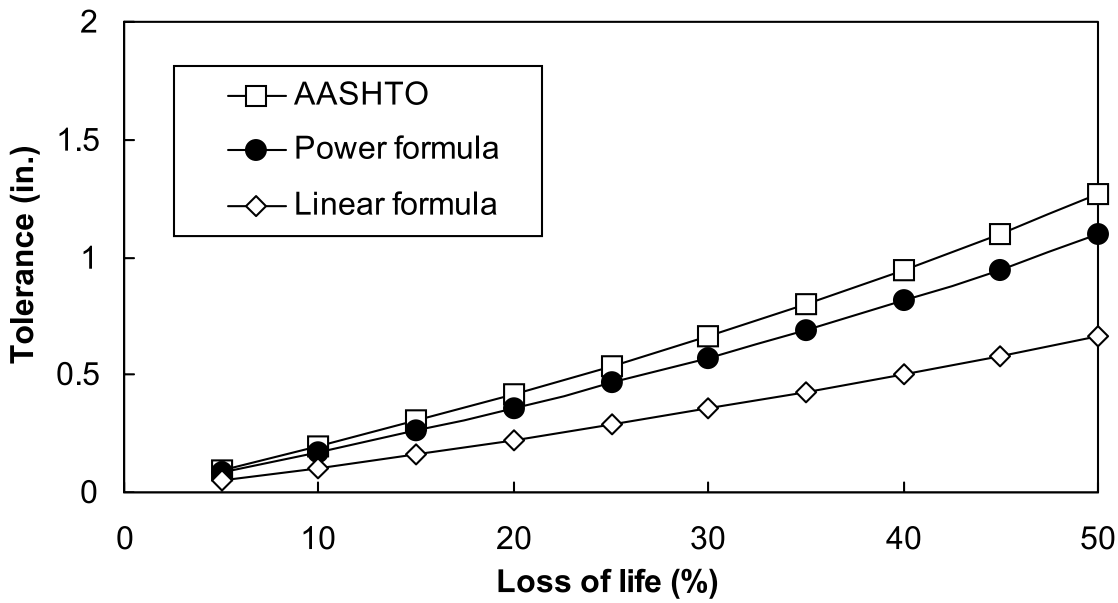


Figure 3.20 Comparison of relationships between loss of life and thickness tolerance obtained with various models for pavement thickness of 6 in.

(a)



(b)

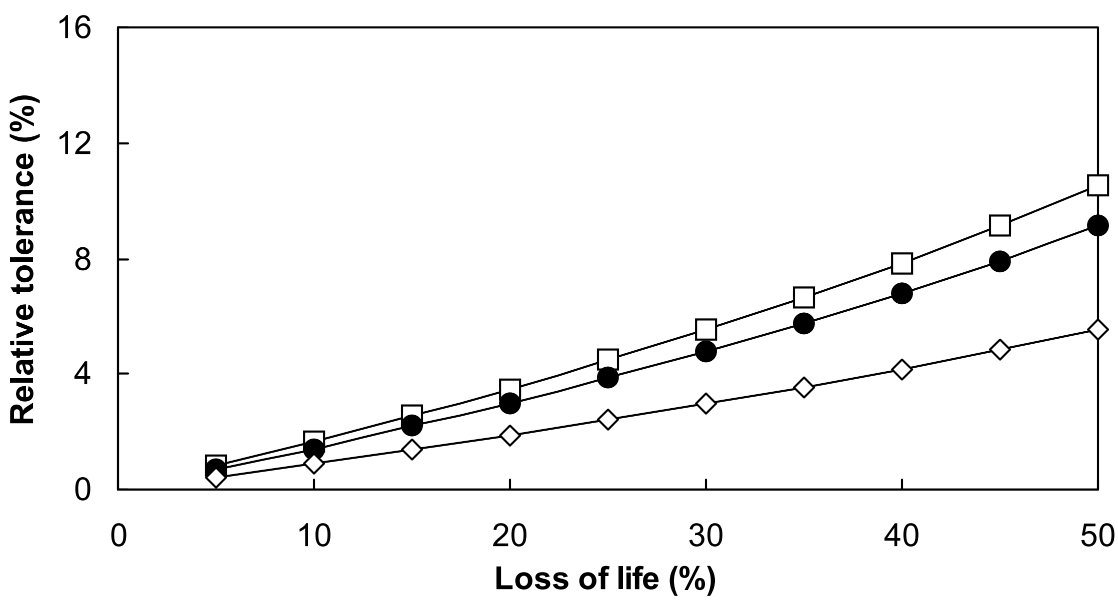
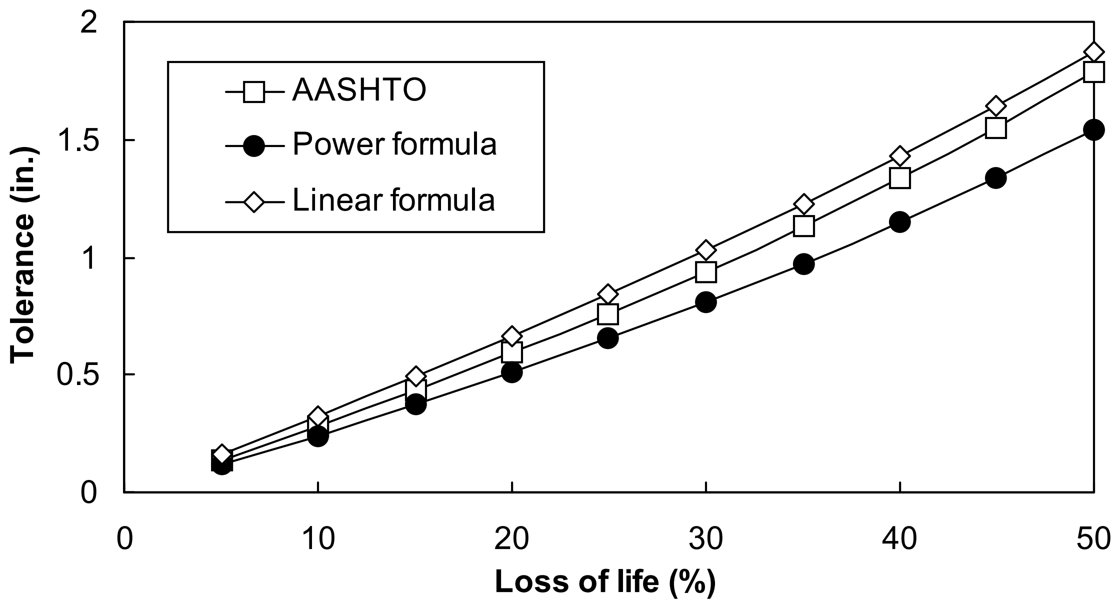


Figure 3.21 Comparison of relationships between loss of life and thickness tolerance obtained with various models for pavement thickness of 12 in.

(a)



(b)

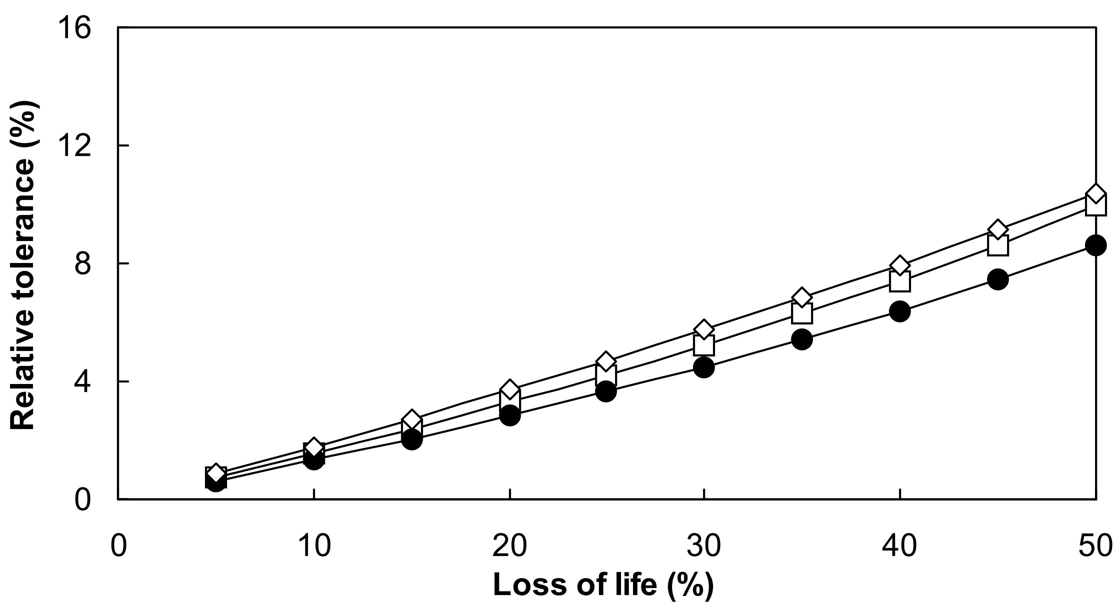


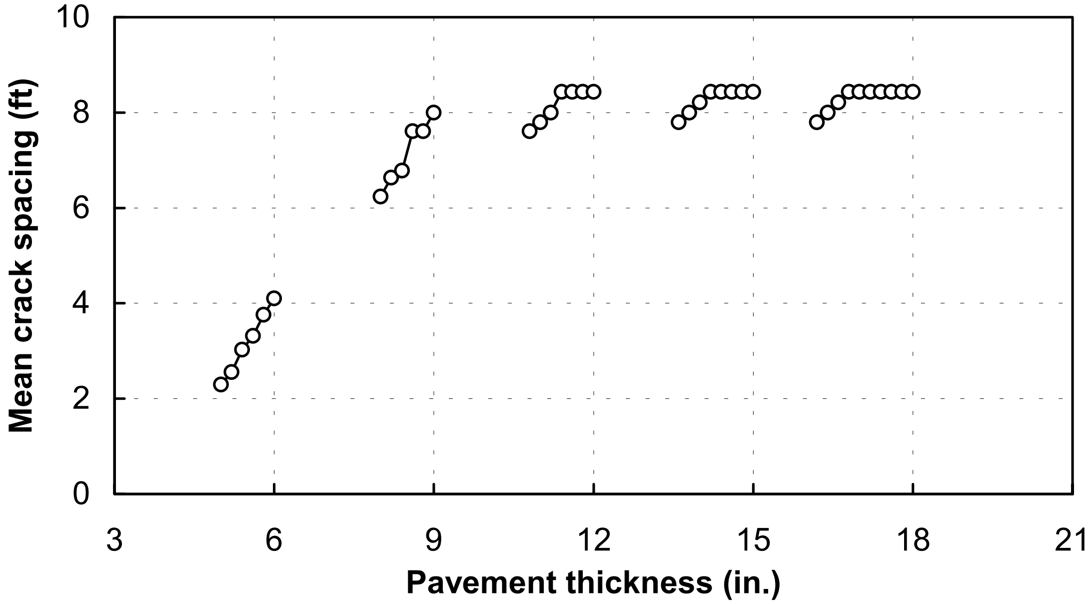
Figure 3.22 Comparison of relationships between loss of life and thickness tolerance obtained with various models for pavement thickness of 18 in.

Table 3.2 Values used in sensitivity analysis with CRCP-10

Design Variable	Value
Coefficient of Variation for Concrete Tensile Strength (%)	15
Thermal Coefficient (microstrain/°C)	9.00
Elastic Modulus at 28 Days (MPa)	29,090
Tensile Strength at 28 Days (MPa)	3.65
Drying Shrinkage at 256 Days	0.000394
Steel Bar Diameter (mm)	19.1
Thermal Coefficient of Steel (microstrain/°C)	9
Percent Reinforcement (Steel Ratio) (%)	0.6
Vertical Stiffness of Underlying Layers (MPa/mm)	0.14
Subbase Type	Flexible
Frictional Bond (MPa/mm)	0.04
Single Wheel Load (kN)	40
Curing Temperature (°C)	32.22
Minimum Temperature at First Day after Placement (°C)	15.56

Figure 3.23 shows the thickness deficiency effect on the mean crack spacing. As the pavement thickness increases, the thickness deficiency that makes the crack spacing smaller becomes larger. For instance, the 6- and 9-inch pavements have smaller crack spacings than the crack spacings from their design thicknesses when there is a thickness deficiency of 0.2 inch or more. However, the 12-inch pavement has the same crack spacing until the thickness deficiency is 0.6 inch, and the 15- and 18-inch pavements do not experience more cracks until the thickness deficiencies are 0.8 and 1.2 inches, respectively. The relative crack spacing variation with respect to the crack spacing obtained with the plan thickness is also shown in Figure 3.23. The decrement ratio of the crack spacing increases as the pavement thickness decreases. Therefore, the thickness tolerance should be larger for thicker pavements.

(a)



(b)

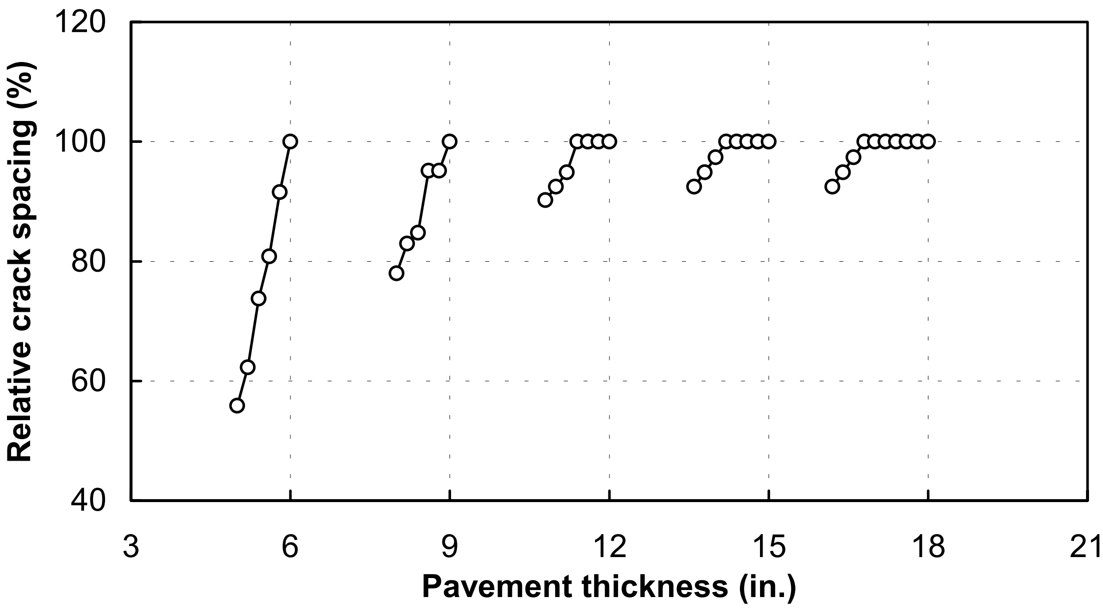


Figure 3.23 Change in crack spacing caused by loss of thickness in CRCP

4. Thickness Variability and NDT Device Accuracy

4.1 Field Variability of Pavement Thickness

It is well known that there is significant concrete slab thickness variation in the field. The actual variability of the thickness has been investigated to quantify this variability. The thickness data have been collected on U.S. Highway 59. The design thicknesses of the main lane and frontage road were 375 mm (15 in.) and 250 mm (10 in.), respectively. The pavement thickness has been measured using a dipstick at the left, center, and right of the lane at each measurement station, and the average of the three measurements was selected for the thickness at the station.

Figure 4.1 shows the thickness measurement data. For the frontage road, shown in Figure 4.1(a), the average thicknesses of the southbound and northbound frontage roads are 265 and 266.6 mm, respectively, which are about 15 and 17 mm or 6% and 7% larger than the design thickness of 250 mm. The standard deviations are 11 and 8.5 mm for the southbound and northbound frontage roads, respectively. For the main lane, shown in Figure 4.1(b), the average thicknesses of the southbound and northbound main lanes are 386 and 387.7 mm, respectively, which are about 11 and 13 mm, or 3% larger than the design thickness of 375 mm. The standard deviations are 11.8 and 15.7 mm for the southbound and northbound main lanes, respectively.

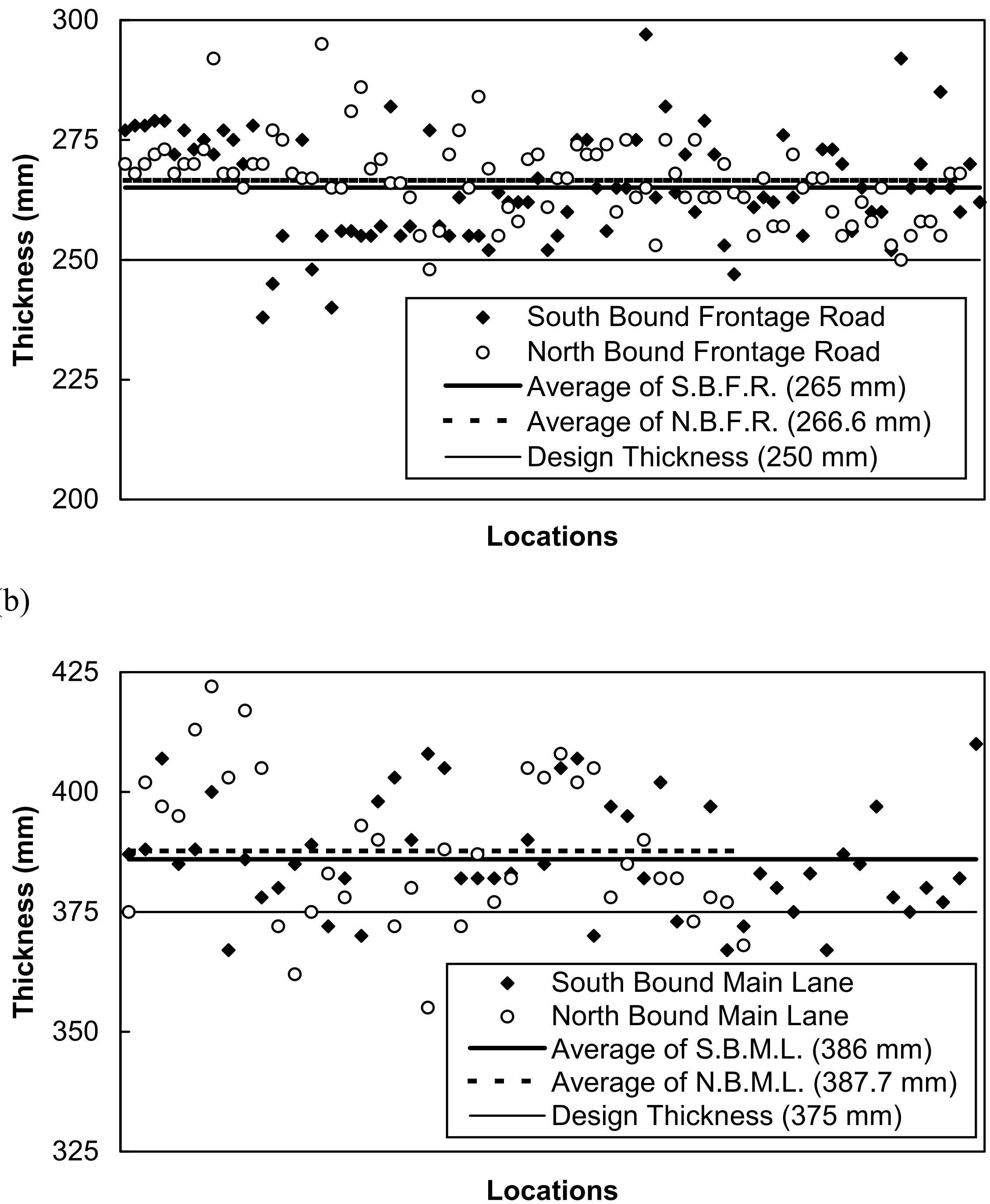
There are some locations where the thickness deficiency can be observed in the figure. More deficient locations can be seen on the main lane in this case. The largest thickness deficiencies are 12 and 2 mm (4.8% and 0.8%) for the southbound and northbound frontage roads, respectively, and 8 and 20 mm (2.1% and 5.3%) for the southbound and northbound main lanes, respectively. The largest additional thicknesses are 47 and 45 mm (18.8% and 18.0%) for the southbound and northbound frontage roads, respectively, and 35 and 47 mm (9.3% and 12.5%) for the southbound and northbound main lanes, respectively. To further investigate the thickness variability, the average absolute difference from the average thickness has been calculated. The average thickness differences from the average thicknesses for the southbound and northbound frontage roads and the south- and north-bound main lanes are 8.8, 6.3, 9.4, and 13.0 mm (3.3%, 2.4%, 2.4%, and 3.4%), respectively.

From this study, it has been found that the average thickness is generally 3% to 7% larger than the design thickness, and the average thickness difference from the average thickness is about 3%. The largest thickness deficiency is about 5%, and the largest additional thickness is about 10% to 20%.

4.2 Accuracy of NDT Device

To measure the thickness of the concrete slab nondestructively, a ground penetrating radar (GPR) system has recently been developed under the TxDOT studies 0-4172 and 0-4414 (Refs 37, 38). A prototype of GPR for the measurement of concrete slab thickness was developed under 0-4172, and the hardware and software of GPR has been improved under 0-4414 to measure the thickness of the reinforced concrete pavement. The GPR system is mainly composed of eight parts including transmitter, transmitting antenna, receiving antenna, sampling unit, filtering and amplifying unit, data acquisition unit, control unit, and laptop computer. When the control unit receives a command from the computer, it triggers the transmitter to emit a short pulse wave into the space via the transmitting antenna. At the same time, the control unit also sends a command to the sampling unit to get the unit ready for the incoming reflected signals. The transmitted wave from the transmitting antenna will propagate in all directions in the space, and part of it will penetrate into the pavement. When the penetrated wave encounters the subsurface interface, it will be reflected back and will be picked up by the receiving antenna. There is also a part of the transmitted wave propagating directly from the transmitting antenna to the receiving antenna, or from the transmitting antenna to the pavement surface, and then bouncing back to the receiving antenna, which is called the direct wave. Hence, the received signal mainly consists of two parts, the direct wave and the subsurface reflected wave. By processing the received signals, the thickness of the pavement can be obtained.

(a)



(b)

Figure 4.1 Field variation in pavement thickness

Under study 0-4172 the accuracy of the GPR was investigated with the laboratory test (Ref 37). The results showed that the errors were -0.15, +0.02, and +0.3 inch for the concrete slab thicknesses of 9.5, 11, and 16.5 inches, respectively, where the negative sign of the error means that the measured thickness is smaller than the actual thickness. The measured thicknesses by GPR were slightly larger than the actual thicknesses when the slab thicknesses were 11 and 16.5 inches, but the reverse occurred when the slab thickness was 9.5 inches.

Field tests using GPR have also been performed (Refs 37-38). A recent field test performed in the early 2002 on U.S. Highway 59 at Williams Trace Boulevard in Sugar Land shows that the measured thickness by GPR is generally slightly larger than the actual thickness measured by a ruler. The average thicknesses by GPR and ruler were 10.822 and 10.607 inches, respectively. The average difference was 0.215 inch, and the relative average error was 2% (Ref 38).

5. Determination of Thickness Tolerance Limit

5.1 Summary of Thickness Sensitivity

The findings of this study for determination of the thickness tolerance limits of the concrete pavements are described as follows:

- The current thickness tolerance limits are independent of the design pavement thickness. Given the same thickness deficiency for different design thicknesses, the contractor for the pavement with a greater thickness should pay a higher penalty because the penalty is determined as a percentage of the contract price corresponding to the deficiency, and the contract price for the thicker pavement is generally more expensive than that for the thinner pavement.
- The sensitivity analysis of the pavement thickness based on the AASHTO design equation to predict the pavement life shows that the tolerance increases as the thickness increases for a given percentage of allowable loss of design life. The relative (percentage) tolerance remains almost constant when the pavement thickness is over 10 inches. The tolerance increases as the elastic modulus of concrete decreases or the modulus of subgrade reaction increases. The relationship between the tolerance (both absolute and relative) and the percentage of allowable loss of pavement life is almost linearly proportional.
- The thickness sensitivity analysis based on various power fatigue failure equations shows that the absolute tolerance increases and the relative tolerance remains almost constant as the pavement thickness increases for a given percentage of allowable loss of design life. The tolerance is little affected by the concrete elastic modulus and the modulus of subgrade reaction. Both the absolute and relative tolerances increase as the percentage of allowable loss of pavement life increases, and the relationship is almost linear.
- The thickness sensitivity study based on various linear fatigue failure equations shows that both the absolute and relative thickness tolerances increase with an increase in the pavement thickness for a given percentage of allowable loss of pavement life. The tolerance increases as the elastic modulus of concrete or the modulus of subgrade reaction increases. As the percentage of allowable loss of pavement life increases, both the absolute and relative tolerances become larger, and the relationship is almost linear.
- The sensitivity analysis of the pavement thickness based on distresses shows that as the pavement thickness increases, the thickness deficiency that induces more cracks becomes larger. The thickness deficiency of 0.2 inch does not affect the CRC pavement performance when the pavement thickness is over about 10 inches. The thickness deficiencies that do not affect the CRC pavement performance are 0.6, 0.8, and 1.2 inch (5%, 5.3%, and 6.7%) for 12-, 15-, and 18-inch thick pavements, respectively.

- The field variability of the thickness shows that the average thickness is generally 3% to 7% larger than the design thickness and the average thickness difference from the average thickness is about 3%.
- The current GPR system, a nondestructive testing device, tends to slightly overestimate the pavement thickness. The relative average error of the measurement is about 2% of the pavement thickness.

5.2 Proposed Thickness Tolerance Limit Determination

As described in the previous section, it is recommended that the thickness tolerance limits be dependent on the design thickness and the payment adjustments be linearly proportional to the thickness deficiency beyond the no penalty limit. The life cycle costs of the design pavement and the pavement with no penalty thickness deficiency need to be calculated, and then the allowable loss of the cost is calculated by subtracting the life cycle cost of the pavement with no penalty thickness deficiency from the life cycle cost of the design pavement. This allowable loss of the life cycle cost can be used to calculate the penalty beyond the no penalty thickness limit as follows:

$$PENALTY_i = (LC_{DESIGN} - LC_{NP})\frac{TD_i - TD_{NP}}{TD_{NP}} \tag{5.1}$$

where $PENALTY_i$ = price reduction at unit i

LC_{DESIGN} = life cycle cost of design pavement

LC_{NP} = life cycle cost of pavement with maximum thickness deficiency without penalty

TD_i = thickness deficiency at unit i

TD_{NP} = maximum thickness deficiency without penalty

For a given percentage (relative) of allowable loss of pavement life (or life cycle cost), the thickness tolerance corresponding to the loss of pavement life increases as the thickness increases, and the percentage (relative) of tolerance also increases or remains almost constant with increasing the pavement thickness. Therefore, the relative thickness tolerance should be at least constant. In other words, the thickness tolerance should be linearly proportional to the pavement thickness. If a tolerance for a pavement thickness can be determined, the thickness tolerances of other pavement thicknesses can be determined by the following equation.

$$TD_{NP}(i) = TD_{NP\,KNOWN}\frac{H(i)}{H_{KNOWN}} \tag{5.2}$$

where $H(i)$ = pavement thickness

H_{KNOWN} = pavement thickness with known thickness tolerance

$TD_{NP}(i)$ = thickness tolerance or maximum thickness deficiency without penalty corresponding to $H(i)$

$TD_{NP\ KNOWN}$ = known thickness tolerance for thickness H_{KNOWN}

By combining eqs. 5.1 and 5.2, the thickness tolerance limits and corresponding price adjustments can be obtained.

There are several methods for determining the thickness deficiency adjustments. Three examples are explained in this report.

Example 1

A thickness deficiency corresponding to an allowable loss of pavement life is calculated, and that thickness deficiency is used as a no penalty tolerance. For example, if 10% loss of design life can be allowable, the corresponding thickness deficiency is about 2% if the AASHTO equation is used (see Figures 3.20 through 3.22). Then the thickness deficiency adjustment can be determined as shown in Table 5.1.

Table 5.1 Thickness deficiency adjustment (Example 1)

Deficiency in thickness (%)	Contract unit price allowed
0–2%	100%
More than 2%	100% - eq. 5.1

Example problem: The life cycle costs of pavements for design thicknesses of 10 and 15 inches are $100,000 and $200,000, respectively. The loss of the cost caused by the thickness deficiency is 5% of the life cycle cost per 1% thickness deficiency. What are the thickness tolerances without penalty for 10- and 15-inch pavements? What are the penalties for a thickness deficiency of 0.4 inch?

Answer: The thickness tolerances without penalty are 0.2 and 0.3 in. for 10- and 15-inch pavements, respectively, because the no penalty tolerance is 2% of the design thickness. The penalties can be obtained as follows:

For 10-inch pavement:

$LC_{NP} = [100 - (5 \times 2)]\% \times 100{,}000 = 90{,}000$ (Dollars)

$$PENALTY = (100{,}000 - 90{,}000)\frac{0.4 - 0.2}{0.2} = 10{,}000 \text{ (Dollars)}$$

For 15-inch pavement:

$$LC_{NP} = [100 - (5 \times 2)]\% \times 200{,}000 = 180{,}000 \text{ (Dollars)}$$

$$PENALTY = (200{,}000 - 180{,}000)\frac{0.4 - 0.3}{0.3} = 6{,}667 \text{ (Dollars)}$$

Example 2

The current thickness tolerance without penalty is 0.2 inch, and that tolerance was determined when the pavement thickness was normally less than 10 inches. Therefore, the current payment adjustment table is used for 10-inch and thinner pavements, and eq. 5.2 is used for pavement thicknesses greater than 10 inches. In this case, the adjustment price can either be determined using the method described in the previous example or be determined as it is in the current specifications. Then the thickness deficiency adjustment table can be obtained as shown in Table 5.2.

Table 5.2 Thickness deficiency adjustment (Example 2)

Deficiency in thickness (%)	Percent of contract unit price allowed
0–2	100
2–3	80
3–4	72
4–5	68
5–8	57

Example problem: What are the thickness tolerances without penalty for 10- and 15-inch pavements? What are the penalties for a thickness deficiency of 0.4 inch?

Answer: The thickness tolerances without penalty are 0.2 and 0.3 inch for 10- and 15-inch pavements, respectively, because the no penalty tolerance is 2% of the design thickness. The penalties for a thickness deficiency of 0.4 inch can be obtained as follows:

For 10-inch pavement:

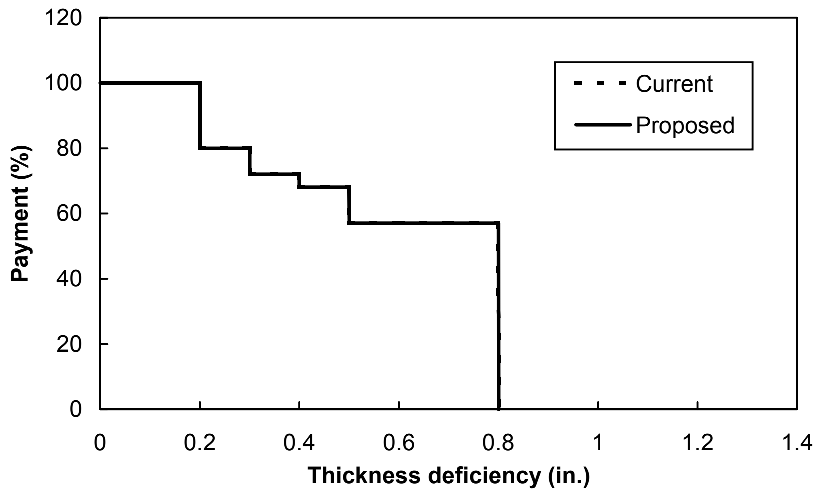
The 0.4-inch deficiency is 4% of the 10-inch pavement. The percent of the contract price allowed is 72% (see Table 5.2). Therefore, the penalty is 28% of the contract price.

For 15-inch pavement:

The 0.4-inch deficiency is 2.67% of the 15-inch pavement. The contract price allowed is 80% (see Table 5.2). Therefore, the penalty is 20% of the contract price.

Figure 5.1 shows the thickness tolerance limits for 10- and 15-inch pavements obtained from the current specifications and the proposed method described in this example. As shown in the figure, the current and proposed thickness tolerance limits are identical for 10- and 15-inch pavements, but the tolerance limits are loosened for a 15-inch pavement with the proposed method.

(a)



(b)

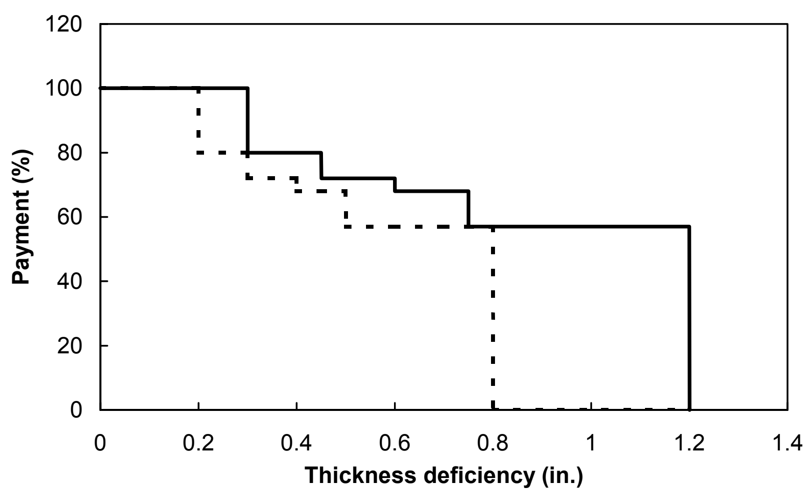


Figure 5.1 Comparison of current and proposed thickness tolerance limits: (a) for 10-in pavement, (b) for 15-in pavement

Example 3

Since the average pavement thickness in the field is at least 3% larger than the design thickness, and the average thickness deviation from the average thickness is about 3%, the tolerance limit without penalty can be selected as 3% of the design thickness. This 3% tolerance is also within the distress failure limit of about 5%. Then the thickness deficiency adjustment can be determined as shown in Table 5.3.

Table 5.3 Thickness deficiency adjustment (Example 3)

Deficiency in thickness (%)	Contract unit price allowed
0–3%	100%
More than 3%	100% - eq. 5.1

Example problem: The life cycle costs of pavements for design thicknesses of 10 and 15 in. are \$100,000 and \$200,000, respectively. The loss of the cost caused by the thickness deficiency is 5% of the life cycle cost per 1% thickness deficiency. What are the thickness tolerances without penalty for 10- and 15-inch pavements? What are the penalties for a thickness deficiency of 0.4 inch?

Answer: The thickness tolerances without penalty are 0.3 and 0.45 inch for 10- and 15-inch pavements, respectively, because the no penalty tolerance is 3% of the design thickness. The penalties can be obtained as follows:

For 10-inch pavement:

$$LC_{NP} = [100 - (5 \times 3)]\% \times 100{,}000 = 85{,}000 \text{ (Dollars)}$$

$$PENALTY = (100{,}000 - 85{,}000)\frac{0.4 - 0.3}{0.3} = 5{,}000 \text{ (Dollars)}$$

For 15-inch pavement:

There will be no penalty because the 0.4-inch thickness deficiency is smaller than the no penalty thickness deficiency of 0.45 inch.

As investigated in the examples, the current thickness tolerance limit can be loosened. This is much clearer for thicker pavements.

6. Summary, Conclusions, and Recommendations

6.1 Summary

This sensitivity analysis of concrete pavement thickness has been conducted to determine whether the current thickness tolerance can be loosened and to propose the acceptable thickness tolerance limits so that NDT for thickness measurements can be used with confidence. Current procedures to measure the concrete pavement thickness and the current thickness tolerance limits have been reviewed. The sensitivity of pavement performance to slab thickness has been investigated based on various models, including the AASHTO model, mechanistic distress prediction model, and fatigue failure models. The variability of the thickness in the field and the accuracy of the GPR system have also been investigated. Finally, the reasonable thickness tolerance limits have been proposed by comparing the results obtained from this study.

6.2 Conclusions

The investigation of the sensitivity of the pavement thickness points to the following conclusions.

1. The sensitivity analysis of the pavement thickness based on the AASHTO design equation to predict the pavement life shows that the tolerance increases as the thickness increases for a given percentage of allowable loss of design life. The relative (percentage of) tolerance remains almost constant when the pavement thickness is over about 10 inches. The tolerance increases as the elastic modulus of concrete decreases or the modulus of subgrade reaction increases. The relationship between the tolerance (both absolute and relative) and the percentage of allowable loss of pavement life is almost linearly proportional.
2. The thickness sensitivity analysis based on various power fatigue failure equations shows that the absolute tolerance increases and the relative tolerance remains almost constant as the pavement thickness increases for a given percentage of allowable loss of design life. The tolerance is little affected by the concrete elastic modulus and the modulus of subgrade reaction. Both the absolute and relative tolerances increase as the percentage of allowable loss of life increases, and the relationship is almost linear.
3. The thickness sensitivity study based on various linear fatigue failure equations shows that both the absolute and relative thickness tolerances increase with increasing the pavement thickness for a given percentage of allowable loss of pavement life. The tolerance increases as the elastic modulus of concrete or the modulus of subgrade reaction increases. As the percentage of allowable loss of pavement life increases, both the absolute and relative tolerances become larger, and the relationship is almost linear.
4. The sensitivity analysis of the pavement thickness based on distresses shows that as the pavement thickness increases, the thickness deficiency that induces more cracks increases. The thickness deficiency of 0.2 inch does not affect the CRC pavement performance when the pavement thickness is over about 10 inches. The thickness deficiencies that do not affect the CRC pavement performance are 0.6, 0.8, and 1.2 inch (5%, 5.3%, and 6.7%) for 12-, 15-, and 18-inch thick pavements, respectively.

5. The field variability of the thickness shows that the average thickness is generally 3% to 7% larger than the design thickness, and the average thickness difference from the average thickness is about 3%.
6. The current GPR system, a nondestructive testing device, tends to slightly overestimate the pavement thickness. The relative average error of the measurement is about 2% of the pavement thickness.
7. The thickness tolerance limits should be dependent on the design thickness, and the linearly proportional relationship between the thickness and the tolerance may be used.
8. The payment adjustments should be dependent on the thickness deficiency, and the linearly proportional relationship between the payment adjustment and the thickness deficiency may be used beyond the no-penalty tolerance limit.
9. The proposed tolerance limits show that the current thickness tolerance limits can be loosened. This is much clearer for thicker pavements.

6.3 Recommendations

The findings from this study clearly indicate that the current thickness tolerance limits can be loosened. It is recommended that the thickness tolerance limits be dependent on the design thickness and that the linearly proportional relationship between the tolerance and the design thickness be used. As investigated in this study, the tolerance limits vary depending on the pavement performance models selected. For instance, tolerance limits obtained using various fatigue failure models are different even if the trends are similar. A more reliable pavement performance prediction model for obtaining the thickness tolerance needs to be developed. Further studies are required in this area.

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Appendix A.
Guidelines: Recommendation on Proper Thickness Tolerance Limit

RECOMMENDATION ON PROPER THICKNESS TOLERANCE LIMIT

The findings from the thickness sensitivity study clearly indicate that the current thickness tolerance limits can be loosened. It is recommended that the thickness tolerance limits be dependent on the design thickness and that the linearly proportional relationship between the tolerance and the design thickness be used. As investigated in the sensitivity study, the tolerance limits vary depending on the pavement performance models selected. The results from the thickness sensitivity study are summarized as follows:

- The sensitivity analysis of the pavement thickness based on the AASHTO design equation to predict pavement life shows that the tolerance increases as the thickness increases for a given percentage of allowable loss of design life. The relative (percentage) tolerance remains almost constant when the pavement thickness is over 10 inches. The tolerance increases as the elastic modulus of concrete decreases or the modulus of subgrade reaction increases. The relationship between the tolerance (both absolute and relative) and the percentage of allowable loss of pavement life is almost linearly proportional.

- The thickness sensitivity analysis based on various power fatigue failure equations shows that the absolute tolerance increases and the relative tolerance remains almost constant as the pavement thickness increases for a given percentage of allowable loss of design life. The tolerance is little affected by the concrete elastic modulus and the modulus of subgrade reaction. Both the absolute and relative tolerances increase as the percentage of allowable loss of pavement life increases, and the relationship is almost linear.

- The thickness sensitivity study based on various linear fatigue failure equations shows that both the absolute and relative thickness tolerances increase with increasing the pavement thickness for a given percentage of allowable loss of life. The tolerance increases as the elastic modulus of concrete or the modulus of subgrade reaction increases. As the percentage of allowable loss of pavement life increases, both the absolute and relative tolerances become larger, and the relationship is almost linear.

- The sensitivity analysis of the pavement thickness based on distresses shows that as the pavement thickness increases, the thickness deficiency that induces more cracks increases. The thickness deficiency of 0.2 inch does not affect the CRC pavement performance when the pavement thickness is over about 10 inches. The thickness deficiencies that do not affect the CRC pavement performance are 0.6, 0.8, and 1.2 inch (5%, 5.3%, and 6.7%) for 12-, 15-, and 18-inch thick pavements, respectively.

- The field variability of the thickness shows that the average thickness is generally 3% to 7% larger than the design thickness, and the average thickness deviation from the average thickness is about 3%.

- The current GPR system, a nondestructive testing device, tends to slightly overestimate the pavement thickness. The relative average error of the measurement is about 2% of the pavement thickness.

Based on this study, any determination of acceptable thickness tolerance limits and corresponding payment adjustments should consider the following.

- The thickness tolerance limits should be dependent on the design thickness, and the linearly proportional relationship between the thickness and the tolerance may be used.

- The payment adjustments should be dependent on the thickness deficiency, and the linearly proportional relationship between the payment adjustment and the thickness deficiency may exceed the no-penalty tolerance limit.

There are several methods for selecting the thickness tolerance limits. In this report, three examples are given to explain how to determine the reasonable tolerance limits and corresponding payment adjustments.

Example 1

Method: A thickness deficiency corresponding to an allowable loss of pavement life is calculated, and that thickness deficiency is used as a no penalty tolerance. For example, if 10% loss of design life is allowed, the corresponding thickness deficiency is about 2% if the AASHTO equation is used (see Figures 3.20 through 3.22). Then the thickness deficiency adjustment can be determined (as shown in Table A.1) using the equation below.

$$PENALTY_i = (LC_{DESIGN} - LC_{NP})\frac{TD_i - TD_{NP}}{TD_{NP}} \tag{A.1}$$

where $PENALTY_i$ = price reduction at unit i

LC_{DESIGN} = life cycle cost of design pavement

LC_{NP} = life cycle cost of pavement with maximum thickness deficiency without penalty

TD_i = thickness deficiency at unit i

TD_{NP} = maximum thickness deficiency without penalty

Table A.1. Thickness deficiency adjustment table from Example 1

Deficiency in thickness (%)	Contract unit price allowed
0–2%	100%
More than 2%	100% - eq. A.1

Example problem: The life cycle costs of pavements for design thicknesses of 10 and 15 inches are \$100,000 and \$200,000, respectively. The decreased cost caused by the thickness deficiency is 5% of the life cycle cost per 1% of thickness deficiency. What are the thickness tolerances without penalty for 10- and 15-inch pavements? What are the penalties for a thickness deficiency of 0.4 inch?

Answer: The thickness tolerances without penalty are 0.2 and 0.3 inch for 10- and 15-inch pavements, respectively, because the no penalty tolerance is 2% of the design thickness. The penalties can be obtained as follows:

- For 10-inch pavement:

$$LC_{NP} = [100 - (5 \times 2)]\% \times 100{,}000 = 90{,}000 \text{ (Dollars)}$$

$$PENALTY = (100{,}000 - 90{,}000)\frac{0.4 - 0.2}{0.2} = 10{,}000 \text{ (Dollars)}$$

- For 15-inch pavement:

$$LC_{NP} = [100 - (5 \times 2)]\% \times 200{,}000 = 180{,}000 \text{ (Dollars)}$$

$$PENALTY = (200{,}000 - 180{,}000)\frac{0.4 - 0.3}{0.3} = 6{,}667 \text{ (Dollars)}$$

Example 2

Method: The current thickness tolerance without penalty is 0.2 inch, and that tolerance was determined when the pavement thickness was normally less than 10 inches. Therefore, the current thickness deficiency adjustment table is used for 10-inch and thinner pavements, and the relative tolerance limits are used for pavement thicknesses greater than 10 inches as shown in eq. A.2. In this case, the adjustment price can either be determined using the method explained in *Example 1* or can be determined as it is in the current specifications. Then the thickness deficiency adjustments can be calculated as shown in Table A.2.

$$TD_{NP}(i) = TD_{NP\,KNOWN}\frac{H(i)}{H_{KNOWN}} \tag{A.2}$$

where $H(i)$ = pavement thickness

H_{KNOWN} = pavement thickness with known thickness tolerance

$TD_{NP}(i)$ = thickness tolerance or maximum thickness deficiency without penalty corresponding to $H(i)$

$TD_{NP\,KNOWN}$ = known thickness tolerance for thickness H_{KNOWN}

Table A.2. Thickness deficiency adjustment table from Example 2

Deficiency in thickness (%)	Percent of contract unit price allowed
0–2	100
2–3	80
3–4	72
4–5	68
5–8	57

Example problem: What are the thickness tolerances without penalty for 10- and 15-inch pavements? What are the penalties for a thickness deficiency of 0.4 in.?

Answer: The thickness tolerances without penalty are 0.2 and 0.3 inch for 10- and 15-inch pavements, respectively, because the no-penalty tolerance is 2% of the design thickness. The penalties for a thickness deficiency of 0.4 inch can be obtained as follows:

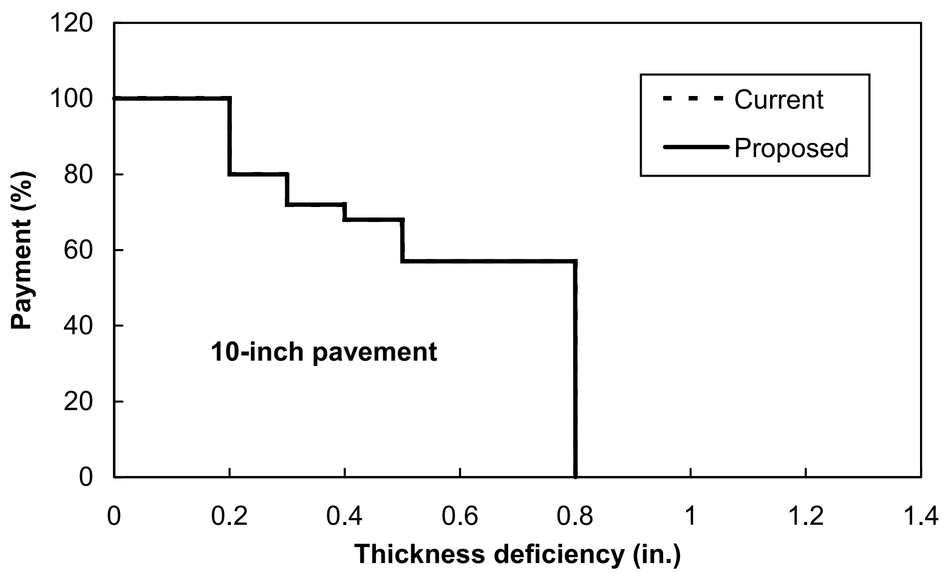
- For 10-inch pavement:

The 0.4-inch deficiency is 4% of the 10-inch pavement. The percentage of the contract price allowed is 72% (see Table A.2). Therefore, the penalty is 28% of the contract price.

- For 15-inch pavement:

  The 0.4-inch deficiency is 2.67% of the 15-inch pavement. The percentage of the contract price allowed is 80% (see Table A.2). Therefore, the penalty is 20% of the contract price.

Figure A.1 shows the thickness tolerance limits for 10- and 15-inch pavements obtained from the current specifications and the proposed method described in this example. As shown in the figure, the current and proposed thickness tolerance limits are identical for 10- and 15-inch pavements, but the tolerance limits are loosened for a 15-inch pavement with the proposed method.



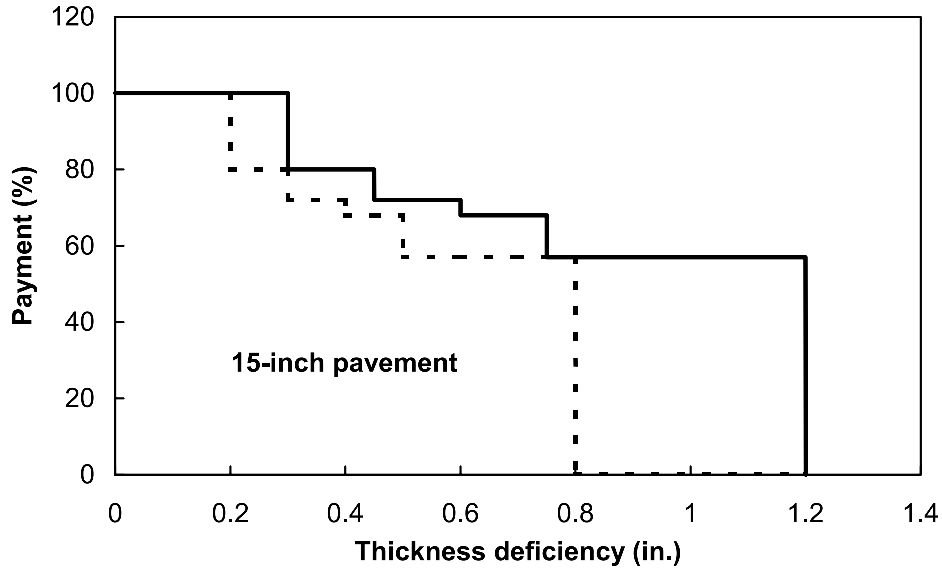


Figure A.1. Current and proposed thickness tolerance limits for 10- and 15-inch pavements

Example 3

Method: Since the average pavement thickness in the field is at least 3% larger than the design thickness and the average thickness deviation from the average thickness is about 3%, the tolerance limit without penalty can be selected as 3% of the design thickness. This 3% tolerance is also within the distress failure limit of about 5%. Then the thickness deficiency adjustment can be calculated as shown in Table A.3.

Table A.3. Thickness deficiency adjustment table from Example 3

Deficiency in thickness (%)	Contract unit price allowed
0–3%	100%
More than 3%	100% - eq. A.1

Example problem: The life cycle costs of pavements for design thicknesses of 10 and 15 inches are \$100,000 and \$200,000, respectively. The loss of the cost caused by the thickness deficiency is 5% of the life cycle cost per 1% thickness deficiency. What are the thickness tolerances without penalty for 10- and 15-inch pavements? What are the penalties for a thickness deficiency of 0.4 inch?

Answer: The thickness tolerances without penalty are 0.3 and 0.45 inch for 10- and 15-inch pavements, respectively, because the no penalty tolerance is 3% of the design thickness. The penalties can be calculated as follows:

- For 10-inch pavement:

$$LC_{NP} = [100 - (5 \times 3)]\% \times 100{,}000 = 85{,}000 \text{ (Dollars)}$$

$$PENALTY = (100{,}000 - 85{,}000)\frac{0.4 - 0.3}{0.3} = 5{,}000 \text{ (Dollars)}$$

- For 15-inch pavement:

There will be no penalty because the 0.4-inch thickness deficiency is smaller than the no penalty thickness deficiency of 0.45 inches.

Appendix B.
Texas Standard Specifications:
Item 360.13. Deficient Pavement Thickness

360.13. Deficient Pavement Thickness

The adjustment in unit prices provided for in this subarticle will apply only when measurement for payment is by the square meter. The adjustment may be waived by a note on the plans where concrete pavement work is narrow widening or small placements.

(a) Coring

The pavement will be cored by the Department after all required profile corrective work and prior to final acceptance. Locations of core tests will be selected by the Engineer; however, the spacing interval for core tests, as specified herein, is to be maintained. The thickness of the pavement will be determined by measurement of the cores in accordance with Test Method Tex-424-A.

For the purpose of establishing an adjusted unit price for pavement, units to be considered separately are defined as 300 meters of pavement in each traffic lane starting at the end of the pavement bearing the smaller kilometer station number. The last unit in each lane shall be 300 meters plus the fractional part of 300 meters remaining. Traffic lane width will be as shown on typical sections and pavement design standards.

One (1) core will be taken by the Department at the location selected by the Engineer or at random in each unit. When the measurement of the core from any unit is not deficient by more than five (5) millimeters from the plan thickness, full payment will be made. When the measurement of the core from any unit is deficient by more than five (5) millimeters but not by more than 20 millimeters from the plan thickness two (2) additional cores will be taken from the unit and the average of the three (3) cores determined. The two (2) additional cores from any 300-meter unit will be taken at intervals of not less than 90 meters. The two (2) additional cores from any 850-square meter unit will be taken at locations such that the pavement in the unit will be well represented. If the average measurement of these three (3) cores is not deficient more than five (5) millimeters from the plan thickness, full payment will be made. If the average thickness of the three (3) cores is deficient more than five (5) millimeters but not more than 20 millimeters from the plan thickness, an adjusted unit price as provided in Subarticle 360.13.(2)(b), will be paid for the unit represented by these cores.

In calculating the average thickness of the pavement, measurements which are in excess of the specified thickness by more than five (5) millimeters will be considered as the specified thickness plus five (5) millimeters, and measurements which are less than the specified thickness by more than 20 millimeters will be considered as the specified thickness less 20 millimeters.

When the measurement of any core is less than the specified thickness by more than 20 millimeters, the actual thickness of the pavement in this area will be determined by taking additional cores at 3-meter intervals parallel to the centerline in each direction from the deficient core until, in each direction, a core is taken which is not deficient by more than 20 millimeters. Exploratory cores for deficient thickness will not be used in averages for adjusted unit price.

Exploratory cores are to be used only to determine the length of pavement in a unit that is to be left in place without pay and/or removed and replaced as provided in this subarticle.

Any area of pavement found deficient in thickness by more than 20 millimeters but not more than 25 millimeters or 1/8 of the plan thickness, whichever is greater, shall be evaluated by the Engineer. If, in the judgment of the Engineer, the area of such deficiency should not be removed and replaced, there will be no payment for the area retained. If, in the judgment of the Engineer, the area of such deficiency warrants removal, the area shall be removed and replaced, at the Contractor's entire expense, with concrete of the thickness shown on the plans.

Any area of pavement found deficient in thickness by more than 25 millimeters or more than 1/8 of the plan thickness, whichever is greater, shall be removed and replaced, at the Contractor's entire expense, with concrete of the thickness shown on the plans.

(b) Price Adjustments

Where the average thickness of pavement is deficient in thickness by more than five (5) millimeters, but not more than 20 millimeters, payment will be made at an adjusted price as specified in the following table.

Deficient Thickness Price Adjustment	
Deficiency in Thickness Determined by Cores Millimeters (mm)	**Proportional Part of Contract Price Allowed Price Adjustment Factor**
Over 0.0 through 5.0	1.00
Over 5.0 through 7.5	.80
Over 7.5 through 10.0	.72
Over 10.0 through 12.5	.68
Over 12.5 through 20.0	.57

(c) Additional Thickness

No adjustment to the contract unit price will be made for any pavement of a thickness exceeding that required by the plans.

Appendix C.
TEX-424-A: Obtaining and Testing Drilled Cores of Concrete

Tex-424-A: Obtaining and Testing Drilled Cores of Concrete

Overview

Effective Date: June 2000

This method covers the procedures for obtaining, preparing and testing cores drilled from concrete for length or compressive or splitting tensile strength determinations, and to determine the length of a core drilled from a concrete structure, particularly pavement. Except for editorial differences the procedures in 'Part I, Obtaining Drilled Concrete Cores' and 'Part III, Compressive Strength of Drilled Concrete Cores' are identical with ASTM C 42. The procedures in 'Part II, Measuring Length of Drilled Concrete Cores' are identical to ASTM C 174.

Part I, Obtaining Drilled Concrete Cores

This part describes the method for obtaining drilled concrete cores.

Apparatus

The following apparatus is required:

- Core drill for obtaining cylindrical core specimens.
  - For specimens to be removed by drilling downward perpendicular to a horizontal surface, a shot drill may be satisfactory.
  - For specimens taken by drilling in other directions or when the test specimen diameter is to be determined for more precise calculation of compressive strength, a diamond drill should be used.

Sampling

Below are the sampling requirements for concrete cores used in compressive strength tests:

- General
  - Samples of hardened concrete for use in the preparation of strength test specimens shall not be taken until the concrete has become hard enough to permit sample removal without disturbing the bond between the mortar and the coarse aggregate.
  - In general, the concrete shall be 14 days old before the specimens are removed.
  - When preparing strength test specimens from samples of hardened concrete, samples that show abnormal defects or samples that have been damaged in the process of removal shall not be used.
  - Specimens containing embedded reinforcement shall not be used for determining splitting tensile strength.

NOTE: Cores to determine compressive strength that contain embedded reinforcement can yield either higher or lower values than cores without embedded steel and should be avoided if possible or trimmed to eliminate the reinforcement provided an L/D of 1.00 or greater can be attained.

- Core Drilling
  - A core specimen taken perpendicular to a horizontal surface shall be located, when possible, so that its axis is perpendicular to the bed of the concrete as originally placed and not near formed joints or obvious edges of a unit of deposit.
  - A specimen taken perpendicular to a vertical surface, or perpendicular to a surface with a batter, shall be taken from near the middle of a unit of deposit when possible and not near formed joints or obvious edges of a unit of deposit.

Part II, Measuring Length of Drilled Concrete Cores

This part details the steps for measuring the length of drilled concrete cores.

Apparatus

The following apparatus is required:

- Calipering device, to measure the length of axial elements of the core, that conforms to the requirements specified herein, so designed that it will be possible to make a length measurement at the center of the upper end of the specimen, and at eight additional points spaced at equal intervals along the circumference of a circle whose center point coincides with that of the end area of the specimen and whose radius is not less than one half nor more than three fourths of the radius of the specimen. The calipering device:
- shall provide for the accommodation of specimens of different nominal lengths over a range of at least 100 to 250 mm (4 to 10 in.).
- shall be stable and sufficiently rigid to maintain its shape and alignment without a distortion or deflection of more than 0.25 mm (0.01 in.) during all normal measuring operations.
- Supports, three short posts or studs of hardened steel, designed so the specimen will be held with its axis in a vertical position. The ends that bear against the surface of the specimen should be rounded to a radius of not less than 6.4 mm (0.25 in.) and not more than 12.7 mm (0.5 in.).
- Measuring rod, or other device that makes contact with the end surface of the specimen for measurement, rounded to a radius of 3.2 mm (0.125 in.).
- Scale, on which the length readings are made, marked with clear, definite, accurately spaced graduations. The spacing of the graduations should be 2.5 mm (0.1 in.) or a decimal part thereof.

Test Specimens

Below are the requirements for test specimens used in length measurement:

- Cores used as specimens for length measurement shall be in every way representative of the concrete in the structure from which they are removed.
- The specimen shall be drilled with the axis normal to the surface of the structure, and the ends shall be free from all conditions not typical of the surfaces of the structure.
- Cores that show abnormal defects or that have been damaged appreciably in the drilling operation shall not be used.

Procedure

The following table describes steps used in measuring the length of drilled concrete cores.

Measuring Length of Drilled Concrete Cores	
Step	Action
1	Before any measurements of the core length are made, calibrate the apparatus with suitable gauges so that errors caused by mechanical imperfections in the apparatus are known. When these errors exceed 0.25 mm (0.01 in.), suitable corrections shall be applied to the core length measurements.
2	♦ Place specimen in the measuring apparatus with the smooth end of the core, that is, the end that represents the upper surface of a pavement, the upper surface of a pavement slab or formed surface in the case of other structures, down against the three hardened-steel supports. ♦ Place the specimen on the supports so the central measuring position of the measuring apparatus is directly over the mid-point of the upper end of the specimen.
3	♦ Make nine measurements of the length on each specimen, one at the central position and one each at eight additional positions spaced at equal intervals along the circumference of the circle of measurement described in Calipering Device under 'Apparatus.' ♦ Read each of these nine measurements directly to the nearest millimeter (tenths of an inch and either directly or by estimation to five-hundredths of an inch).

NOTE 1: If, in the course of the measuring operation, it is discovered that at one or more of the measuring points the surface of the specimen is not representative of the general plane of the core end because of a small projection or depression, rotate the specimen slightly about its axis and make a complete set of nine measurements with the specimen in the new position.

NOTE 2: When it can be determined that the length of the concrete core is not deficient more than 5 mm (0.2 in.) from plan thickness, alternate methods may be used to measure the length of the concrete core.

NOTE 3: A drawing of the core measuring apparatus is available upon request from CST/M &P.

Report

Record individual observations to the nearest 1 mm (0.05 in.). Report the average of the nine measurements, expressed to the nearest 3 mm (0.1 in.), as the length of the concrete core.

Appendix D.
List of Computer Code for Sensitivity Analysis

```
      PROGRAM THICKTOL
C
C     Version 1.0
C     Program to find the thickness tolerance of concrete pavements
C
      IMPLICIT REAL*8 (A-H,O-Z)
      CHARACTER*80 TITLE
      CHARACTER*80 OUTPUT
      DIMENSION STR(8001),ANUM(8001),IDEF(13)
C
C     open input and output files
C
      WRITE(*,*)' ENTER NAME OF INPUT FILE '
      READ(*,180)TITLE
      WRITE(*,*)' ENTER NAME OF OUTPUT FILE '
      READ(*,180)OUTPUT
  180 FORMAT(A)
      OPEN(UNIT=5,FILE=TITLE,STATUS='OLD')
      OPEN(UNIT=6,FILE=OUTPUT,STATUS='UNKNOWN')
C
C     read input data
C
      READ(5,*) E,H,AK,POI,RADIUS,P
      READ(5,*) CA,CB,WEI
      READ(5,*) CAL,CBL
      READ(5,*) CBLM,CRM
      READ(5,*) ZR,S0,DPSI,PT,AJ,CD
      READ(5,*) PERCEN
C
C     WHERE,
C       E = Elastic modulus of concrete (psi)
C       H = Thickness (in.)
C       AK = Stiffness of underlying layers (pci)
C       POI = Poisson's ratio
C       RADIUS = Wheel base radius (in.)
C       P = Single wheel load (lbs)
C       ----------------------------------------------------
C       CA = Coefficient A for fatigue model (Power)
C       CB = Coefficient B for fatigue model (Power)
C       WEI = Specific weight for concrete (pci)
C       ----------------------------------------------------
C       CAL = Coefficient A for fatigue model (Linear)
C       CBL = Coefficient B for fatigue model (Linear)
C       ----------------------------------------------------
C       CBLM = Coefficient b for fatigue model (Modified Linear)
C       CRM = Stress ratio = min. stress / max. stress
C       ----------------------------------------------------
C       ZR = Standard normal deviate
C       S0 = Combined standard error of the traffic prediction
C            and performance prediction
C       DPSI = Difference between the initial design serviceability
C              index, p0, and the design terminal serviceability
C              index, pt
C       PT = Design terminal serviceability index
C       AJ = Load transfer coefficient used to adjust for load
C            transfer characteristics of a specific design
C       CD = Drainage coefficient
C       ----------------------------------------------------
C       PERCEN = % loss of life (% loss of number of load application)
C
C     Define modulus of rupture
      FR=7.5*E/(33.*WEI**1.5)
C
C     Analysis with Westergaard equations and Power fatigue models
```

```
      WRITE(6,*) '**Westergaard equations and Power fatigue models**'
C
      DO 1000 I=1,4
C
        IF(I.EQ.1) INDST=1
        IF(I.EQ.2) INDST=2
        IF(I.EQ.3) INDST=3
        IF(I.EQ.4) INDST=4
C
C          INDST=1: Interior loading
C          INDST=2: Circular edge loading
C          INDST=3: Semicircular edge loading
C          INDST=4: Corner loading
C
      WRITE(6,400) INDST
  400 FORMAT('INDST=',I2,' THICKNESS (in.) ',' DEFICIENCY (in.) ',
     1       ' % DEFICIENCY')
C
      DO J=1,8001
         H=2.+FLOAT(J-1)*0.002
         CALL WESTER(E,H,AK,POI,RADIUS,P,INDST,STRESS)
         CALL FATPOW(CA,CB,FR,STRESS,ANUMBER)
         IF(STRESS.GT.FR) ANUMBER=0.
         STR(J)=STRESS
         ANUM(J)=ANUMBER
      ENDDO
C
      CALL SOL(ANUM,IDEF,PERCEN)
C
 1000 CONTINUE
C
C     Analysis with AASHTO equation
C
      DO J=1,8001
         H=2.+FLOAT(J-1)*0.002
         CALL AASHTO(E,H,AK,FR,ZR,S0,DPSI,PT,AJ,CD,W18)
         ANUM(J)=W18
      ENDDO
C
      WRITE(6,1400)
 1400 FORMAT('AASHTO  ',' THICKNESS (in.) ',' DEFICIENCY (in.) ',
     1       ' % DEFICIENCY')
C
      CALL SOL(ANUM,IDEF,PERCEN)
C
C     Analysis with Westergaard eq. and Linear fatigue model
      WRITE(6,*) '**Westergaard eq. and Linear fatigue model**'
C
      DO 2000 I=1,4
C
        IF(I.EQ.1) INDST=1
        IF(I.EQ.2) INDST=2
        IF(I.EQ.3) INDST=3
        IF(I.EQ.4) INDST=4
C
      WRITE(6,2400) INDST
 2400 FORMAT('INDST=',I2,' THICKNESS (in.) ',' DEFICIENCY (in.) ',
     1       ' % DEFICIENCY')
C
      DO J=1,8001
         H=2.+FLOAT(J-1)*0.002
         CALL WESTER(E,H,AK,POI,RADIUS,P,INDST,STRESS)
         CALL FATLIN(CAL,CBL,FR,STRESS,ANUMBER)
         IF(STRESS.GT.FR) ANUMBER=0.
```

```
         STR(J)=STRESS
         ANUM(J)=ANUMBER
      ENDDO
C
      CALL SOL(ANUM,IDEF,PERCEN)
C
 2000 CONTINUE
C
C     Analysis with Westergaard eq. and Modified Linear fatigue model
      WRITE(6,*) '**Westergaard eq. and Modif. Linear fatigue model**'
C
      DO 4000 I=1,4
C
        IF(I.EQ.1) INDST=1
        IF(I.EQ.2) INDST=2
        IF(I.EQ.3) INDST=3
        IF(I.EQ.4) INDST=4
C
      WRITE(6,4400) INDST
 4400 FORMAT('INDST=',I2,' THICKNESS (in.) ',' DEFICIENCY (in.) ',
     1       ' % DEFICIENCY')
C
      DO J=1,8001
         H=2.+FLOAT(J-1)*0.002
         CALL WESTER(E,H,AK,POI,RADIUS,P,INDST,STRESS)
         CALL FATLINM(CBLM,CRM,FR,STRESS,ANUMBER)
         IF(STRESS.GT.FR) ANUMBER=0.
         STR(J)=STRESS
         ANUM(J)=ANUMBER
      ENDDO
C
      CALL SOL(ANUM,IDEF,PERCEN)
C
 4000 CONTINUE
C
      STOP
      END
C***************************************************************
      SUBROUTINE SOL(ANUM,IDEF,PERCEN)
C
C     to calculate thickness tolerance
C
      IMPLICIT REAL*8 (A-H, O-Z)
      DIMENSION ANUM(8001),IDEF(13)
C
      DO K=1,13
         L=500*K+1501
         IF(ANUM(L).EQ.0.) THEN
            IDEF(K)=0
            GO TO 111
         ENDIF
         ANUMDEF=ANUM(L)*(1.-PERCEN/100.)
         DO 110 KK=L,1,-1
            IF(ANUM(KK).EQ.0.) THEN
               IDEF(K)=0
               GO TO 111
            ENDIF
            DIF=ANUMDEF-ANUM(KK)
            IF(DIF.GT.0.) THEN
               DIF1=ANUMDEF-ANUM(KK+1)
               IF(ABS(DIF1).GT.DIF) THEN
                  IDEF(K)=KK
               ELSE
                  IDEF(K)=KK+1
```

```
              ENDIF
              GO TO 111
           ENDIF
           IF(KK.EQ.1) IDEF(K)=0
  110 CONTINUE
  111 CONTINUE
C
      H1=6.+FLOAT(K-1)
      IF(IDEF(K).EQ.0) THEN
         THDEF=H1
      ELSE
         THDEF=H1-(FLOAT(IDEF(K))*0.002+2.)
      ENDIF
      THDEFPER=THDEF/H1*100.
      WRITE(6,500) H1,THDEF,THDEFPER
  500 FORMAT(9X,F7.3,11X,F7.3,13X,F7.3)
C
      ENDDO
C
      RETURN
      END
C****************************************************************
      SUBROUTINE WESTER(E,H,AK,POI,RADIUS,P,INDST,STRESS)
C
C     to calculate stresses using Westergaard equations
C
      IMPLICIT REAL*8 (A-H, O-Z)
C
      AL=(E*H*H*H/(12.*(1.-POI*POI)*AK))**0.25
      IF(RADIUS.GE.1.724*H) THEN
        B=RADIUS
      ELSE
        B=DSQRT(1.6*RADIUS*RADIUS+H*H)-0.675*H
      ENDIF
C
C     Stress due to interior loading
C
      IF(INDST.EQ.1) THEN
      STRESS=3.*(1.+POI)*P/(2.*3.141592*H*H)*(LOG(AL/B)+0.6159)
      ENDIF
C
C     Stress due to circular edge loading
C
      IF(INDST.EQ.2) THEN
      STRESS=3.*(1.+POI)*P/(3.141592*(3.+POI)*H*H)*
     +     (LOG(E*H*H*H/(100.*AK*RADIUS**4))+1.84-4.*POI/3.+
     +      (1.-POI)/2.+1.18*(1.+2.*POI)*RADIUS/AL)
      ENDIF
C
C     Stress due to semicircular edge loading
C
      IF(INDST.EQ.3) THEN
      STRESS=3.*(1.+POI)*P/(3.141592*(3.+POI)*H*H)*
     +     (LOG(E*H*H*H/(100.*AK*RADIUS**4))+3.84-4.*POI/3.+
     +      (1.+2.*POI)*RADIUS/(2.*AL))
      ENDIF
C
C     Stress due to corner loading
C
      IF(INDST.EQ.4) THEN
      STRESS=3.*P/(H*H)*(1.-(RADIUS*SQRT(2.)/AL)**0.6)
      ENDIF
C
      RETURN
```

```
      END
C*************************************************************
      SUBROUTINE FATPOW(CA,CB,FR,STRESS,ANUMBER)
C
C     to calculate the number of load applications to failure
C     using Power fatigue models
C
      IMPLICIT REAL*8 (A-H, O-Z)
C
      ANUMBER=CA*(FR/STRESS)**CB
C     IF(STRESS.GT.FR) ANUMBER=1.
C
      RETURN
      END
C*************************************************************
      SUBROUTINE FATLIN(CAL,CBL,FR,STRESS,ANUMBER)
C
C     to calculate the number of load applications to failure
C     using Linear fatigue model
C
      IMPLICIT REAL*8 (A-H, O-Z)
C
      ANUMBER=10.**(CBL+(STRESS/FR)*CAL)
C     IF(STRESS.GT.FR) ANUMBER=1.
C
      RETURN
      END
C*************************************************************
      SUBROUTINE FATLINM(CBLM,CRM,FR,STRESS,ANUMBER)
C
C     to calculate the number of load applications to failure
C     using Modified Linear fatigue model
C
      IMPLICIT REAL*8 (A-H, O-Z)
C
      CC1=CBLM*(1.-CRM)
      ANUMBER=10.**((1.-(STRESS/FR))/CC1)
C     IF(STRESS.GT.FR) ANUMBER=1.
C
      RETURN
      END
C*************************************************************
      SUBROUTINE AASHTO(E,H,AK,FR,ZR,S0,DPSI,PT,AJ,CD,W18)
C
C     to calculate W18 using AASHTO equations
C
      IMPLICIT REAL*8 (A-H, O-Z)
C
      C1=ZR*S0
      C2=7.35*LOG10(H+1.)-0.06
      C3=LOG10(DPSI/(4.5-1.5))/(1.+1.624*10000000./(H+1.)**8.46)
      C4=FR*CD*(H**0.75-1.132)/(215.63*AJ*
     +   (H**0.75-18.42/(E/AK)**0.25))
      IF(C4.GT.0.) THEN
         C5=(4.22-0.32*PT)*LOG10(C4)
         W18=10.**(C1+C2+C3+C5)
      ELSE
         W18=0.
      ENDIF
C
      RETURN
      END
      C*************************************************************
```