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7. Author(s)
H. F. Southgate and R. C. Deen

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University of Kentucky
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16. Abstract
Past experience indicates that thickness designs using portland cement concrete best agree with criterion used in the Portland Cement Association's design method for 18-kip EAL of 2 to 3 million or less. For EALs greater than 2 to 3 million, past experience best agrees with criterion developed from the AASHO Road Test. Research herein indicates the two criterion become asymptotic to each other at approximately 2.5 million EAL. For a variation in thickness and elastic moduli in portland cement concrete, dense-graded aggregate, and subgrade elastic modulus, research indicates that a general conic equation (included herein) very closely duplicates the work at the bottom of the portland cement concrete caused by an 18-kip single axleload. The transition from a tensile strain to a work criterion is presented. Decreasing the thickness of dense-graded aggregate base caused a maximum increase of 0.15 inches in the thickness of portland cement concrete. Thus, the thicknesses of the portland cement concrete were averaged. The resulting thickness design curves are presented for a concrete elastic modulus of 4.2 million psi (Kentucky concrete strength).

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Portland cement, concrete, pavements, thickness, design, dense-graded aggregate, subgrade, CBR, modulus, tensile strain, vertical compressive strain, work EAL, DCA Method, AASHTO Method.	

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Research Report
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THICKNESS DESIGN CURVES FOR PORTLAND CEMENT CONCRETE PAVEMENTS

by

Herbert F. Southgate
Chief Research Engineer

and

Robert C. Deen
Director

Kentucky Transportation Research Program
College of Engineering
University of Kentucky
Lexington, Kentucky

in cooperation with the
Transportation Cabinet
Commonwealth of Kentucky

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INTRODUCTION

An extensive discussion of "strain energy" and "strain energy density" was given in an earlier report (1). In summary, "work" done by a force when its point of application is displaced is the product of that force (parallel to the direction of movement) and the displacement. When work is done on some systems, the internal geometry is altered in such a way that there is a potential to "give back" work when the force is removed, and the system returns to its original configuration. This stored energy is defined as strain energy. Strain energy per unit volume at a given point in the body is the strain energy density at that point, which is dependent upon Young's modulus of elasticity and Poisson's ratio of the material at that point in the body and the square of the individual strain components, or their sum squared. The Chevron N-layered computer program calculates all nine components of strain, and the program was extended to calculate the "strain energy density".

Recent research efforts for flexible pavements showed that strain energy density at the top of the subgrade provided the most sensitivity for fatigue analyses and the next most sensitive location was at the bottom of the asphaltic concrete layer. Therefore, the top of the subgrade was investigated first for portland cement concrete pavements. Figure 1 shows the relationship between work (equal and opposite to strain energy density) and thickness of the portland cement concrete slab. As expected, the amount of work was significantly decreased for an increase of 1 inch of portland cement concrete. However, a ten-fold increase in subgrade modulus (CBR) produced virtually no change in the amount of work for the same thickness of portland cement concrete. Thus, it was concluded that the top of the subgrade was not the most sensitive location for thickness design purposes.

Figure 2 illustrates the relationship between work at the bottom of the portland cement concrete slab and the thickness of the slab. A 1-inch increase in the thickness of the pavement significantly decreased the amount of work caused by the 18-kip single axleload. However, an increase in the subgrade modulus (CBR) also resulted in a significant reduction in the amount of work. Therefore, for thickness design purposes, the most sensitive location is at the bottom of the portland cement concrete slab. The orderly family of curves in Figure 2 are for a wide range of realistic moduli of the materials involved and for a wide range of thicknesses of portland cement concrete, but for a fixed value of 6 inches of crushed-stone base. Chevron analyses were made for the same range of moduli and thicknesses of portland cement concrete and for crushed-stone bases 3, 4, and 5, inches thick.

GENERAL EQUATION

The shape of the family of curves displayed in Figure 2 suggested that they can be expressed by the general conic equation. Earlier research of the behavior of asphaltic concrete pavements indicated a similar conclusion and resulted in an excellent agreement between solutions from the Chevron N-layered computer program and the fitted general conic equation. Thus, the same approach was attempted for portland cement concrete pavements. A general conic equation can be expanded to include as many variables as desired or needed. If the relationship is a straight line, then all squared terms are eliminated because their coefficients will have a numerical value of zero. Likewise, if the relationship is a circle, then all variables to their first power will be eliminated because their coefficients will be zero. Matrix analyses were used to determine the numerical values for the coefficients and constant in the general conic equation

$$Y = a(X1)^2 + b(X1)(X2) + c(X2)^2 + d(X1)(X3) + e(X3)^2 + f(X2)(X3) + g(X4)^2 + h(X1)(X4) + i(X2)(X4) + j(X3)(X4) + k(X1) + l(X2) + m(X3) + n(X4) + p, \qquad 1$$

where Y = log(work),
X1 = thickness of portland cement concrete, inches,
X2 = thickness of crushed-stone base (DGA), inches,
X3 = modulus of elasticity of portland cement concrete, million psi (for a modulus of 3 million psi, enter as 3.0),
X4 = modulus of elasticity of subgrade, ksi,
a-n= coefficients determined by matrix analyses (see Table 1), and,
p = constant (see Table 1).

The adequacy of the fitted equation can be seen in Figure 3.

Values of the coefficients (Table 1) produced quite accurate results for a range of CBR values from 3 to 30. Sensitivity analyses revealed that the family of curves, Figure 2, was best expressed by a parabolic form. For a CBR of 100, the required thickness of portland cement concrete is greater than for a CBR 30. Thus, extrapolation beyond CBR 30 is not recommended.

While Equation 1 appears to be cumbersome, each term is the product of a coefficient, a variable, a variable squared, or two variables. Equation 1 should be used when different values for one or more variables are to be investigated. The equation can be solved using programmable desk-top calculators. Once the input data has been entered, solutions can be obtained in a few seconds and depends upon the specific calculator. When specific values are chosen, the equation reduces to one unknown and can be solved as a polynomial. Table 2 gives the reduced coefficients for specific combinations of crushed-stone thicknesses and moduli of portland cement concrete and the subgrade.

FATIGUE ANALYSES

Figure 4 illustrates the relationship between tensile strain in the "xx" direction and 18-kip EAL's and the merger of the limiting strain criteria used in the Portland Cement Association's and AASHTO design methods. For Kentucky conditions, portland cement concrete was assumed to have a Young's modulus of elasticity of 4,200,000 psi. The relationship between tensile strain and "work" is given by

$$\text{Work} = 0.5(E)[10^{(0.1534709969 + 1.010508693 \log(exx))}]^2, \qquad 2$$

where Work = opposite of strain energy density at the bottom of the portland cement concrete slab,

E = Young's modulus of elasticity of the concrete, psi,

exx = tensile strain in the "xx" direction at the bottom of the portland cement concrete slab, and,

log = logarithm to the base 10.

Converting tensile strain criteria in Figure 4 using Equation 2 to a criteria based upon "work" resulted in the relationship shown in Figure 5 and is identical to the term "work" used in Equation 1.

THICKNESS DESIGN CURVES

Equation 1 and numerical values in Table 1 were used to determine the thickness design curves shown in Figure 6. When the CBR, thickness of the crushed-stone base (DGA), and modulus of the portland cement concrete were fixed, the thickness of the portland cement concrete was determined. Analyses of resulting thicknesses for a given CBR and EAL indicated a maximum difference of 0.15 inches when the thickness of the crushed-stone base was varied from 3 to 6 inches. The usual difference was between 0.05 and 0.10 inches. Thus, the average of the pavement thicknesses for a specific CBR and EAL was calculated and plotted to produce Figure 6. The variation in the required thicknesses is well within construction tolerances and thus deemed to be not worth the trouble to have a separate set of thickness design curves for each thickness of crushed- stone base.

SUMMARY

Varying the thickness of crushed- stone base from 3 to 6 inches has been analyzed with respect to required thicknesses of portland cement concrete pavements. Analyses indicated only a minor change in the resulting thicknesses of portland cement concrete; therefore, it was decided that only one set of thickness design curves was required for pavements placed on 3 to 6 inches of crushed-stone base. Equation 1 is valid for a range of CBR from 3 to 30. Additional analyses are required for higher CBR values.

While sandstones have been tested and determined to have a CBR much higher than 30, three of six projects tested in eastern Kentucky using the Road Rater indicated a design CBR of 11 to 15. A study of geologic descriptions of the materials revealed that plastic underclays were present in those three projects. The construction process of blasting and using bulldozers and earth moving equipment apparently had mixed those plastic underclays with the good sandstones to such an extent that the potential load-carrying capacity of the sandstone had been significantly negated. The underclays apparently were too thin to warrant special construction procedures and, even if such procedures were utilized, the resulting pavement thickness would be less that 0.5 inches thinner than for a CBR 30 design. Economic analyses would probably show that such extreme construction controls would cost far more than the savings of the comparatively small amount of concrete involved.

ACKNOWLEDGEMENTS

The authors wish to express their appreciation for the help and guidance given by Professor Ted Suffridge, Math Department, University of Kentucky, in the selection of the equations used in this study.

REFERENCES

1. Southgate, H. F.; Havens, J. H.; Deen, R. C.; and Newberry, D. C., Jr.; "Development of a Thickness Design System for Portland Cement Concrete Pavements," Research Report UKTRP-83-5, Kentucky Transportation Research Program, University of Kentucky, February 1983.

TABLE 1. REGRESSION COEFFICIENTS FOR GENERAL CONIC EQUATION

COEFFICIENT	NUMERICAL VALUE
a	0.600052E-02
b	-0.267029E-03
c	0.505066E-02
d	0.110149E-02
e	0.100708E-01
f	0.241089E-02
g	0.349686E-03
h	-0.196695E-03
i	0.356436E-04
j	0.152409E-03
k	-0.248306E-00
l	-0.563965E-01
m	-0.165527E-00
n	-0.281134E-01
p	0.156250E-01

TABLE 2. EVALUATION OF EQUATION 1 YIELDS VALUES FOR COEFFICIENTS FOR PARABOLIC EQUATION FOR SPECIFIC COMBINATIONS OF VARIABLES

CBR	EAL (MILLION)	3" DGA "C"	3" DGA "B"	6" DGA "C"	6" DGA "B"
3	0.1	1.0643460	-0.24536596	1.0623827	-0.24616704
	1.0	1.4095616		1.4075983	
	8.0	1.8545215		1.8525582	
	10.0	1.9073693		1.905406	
	40.0	2.2356896		2.2337264	
5	0.1	0.99483561	-0.24595604	0.99319312	-0.24675713
	1.0	1.3400512		1.3384087	
	8.0	1.7850111		1.7833686	
	10.0	1.8378589		1.8362164	
	40.0	2.1661793		2.1645368	
7	0.1	0.9316196	-0.24654613	0.9302979	-0.24734721
	1.0	1.2768352		1.2755135	
	8.0	1.7217951		1.7204734	
	10.0	1.7746429		1.7733212	
	40.0	2.1029633		2.1016416	
10	0.1	0.84859748	-0.24743125	0.84775698	-0.24823234
	1.0	1.1938131		1.1929726	
	8.0	1.6387730		1.6379325	
	10.0	1.6916208		1.6907803	
	40.0	2.0199412		2.0191007	
15	0.1	0.74169904	-0.24890647	0.74166051	-0.24970755
	1.0	1.0869146		1.0868761	
	8.0	1.5318746		1.5318360	
	10.0	1.5847223		1.5846838	
	40.0	1.9130427		1.9130042	
20	0.1	0.67414026	-0.25038168	0.67490372	-0.25118277
	1.0	1.0193559		1.0201193	
	8.0	1.4643158		1.4650792	
	10.0	1.5171636		1.5179270	
	40.0	1.8454839		1.8462474	
30	0.1	0.65704174	-0.2533321	0.65940916	-0.25413319
	1.0	1.0022573		1.0046248	
	8.0	1.4472173		1.4495847	
	10.0	1.5000650		1.5024325	
	40.0	1.8283854		1.8307528	

NOTE: FOR A GIVEN SET OF PARAMETERS, EQUATION 1 REDUCES TO THE FORM $AX^2 + BX + C = 0$ WHERE X = THICKNESS OF PORTLAND CEMENT CONCRETE. THE VALUE OF THE COEFFICIENT "A" IS 0.00600052 AND IS VALID FOR ALL THICKNESSES OF DGA AND ANY MODULUS OF THE CONCRETE. THE VALUE FOR "B" IS THE SAME FOR ALL EAL VALUES FOR THAT CBR.

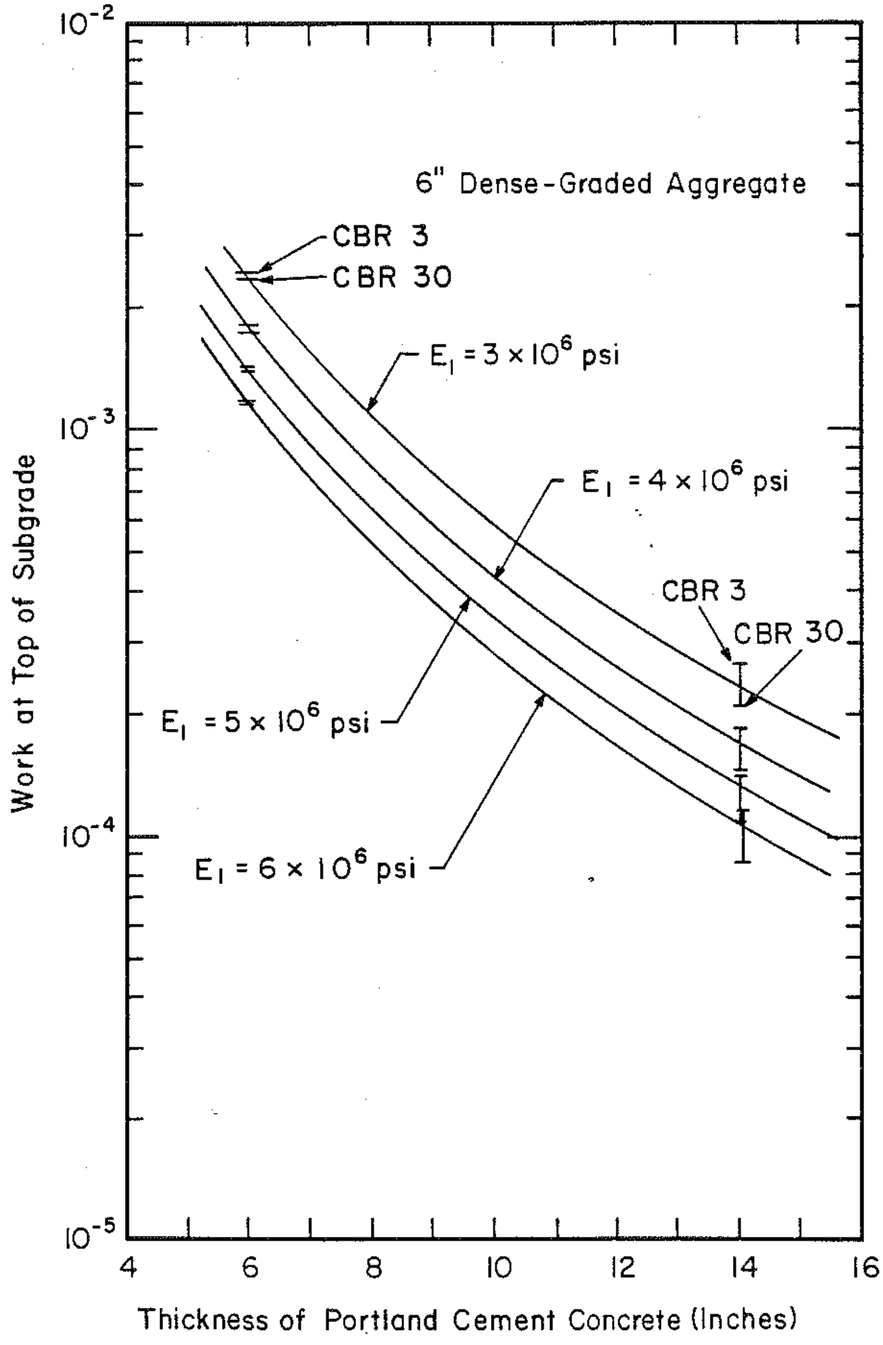

FIGURE 1. WORK AT THE TOP OF THE SUBGRADE AS A FUNCTION OF MODULUS AND THICKNESS OF PORTLAND CEMENT CONCRETE PAVEMENT AND MODULUS OF SUBGRADE.

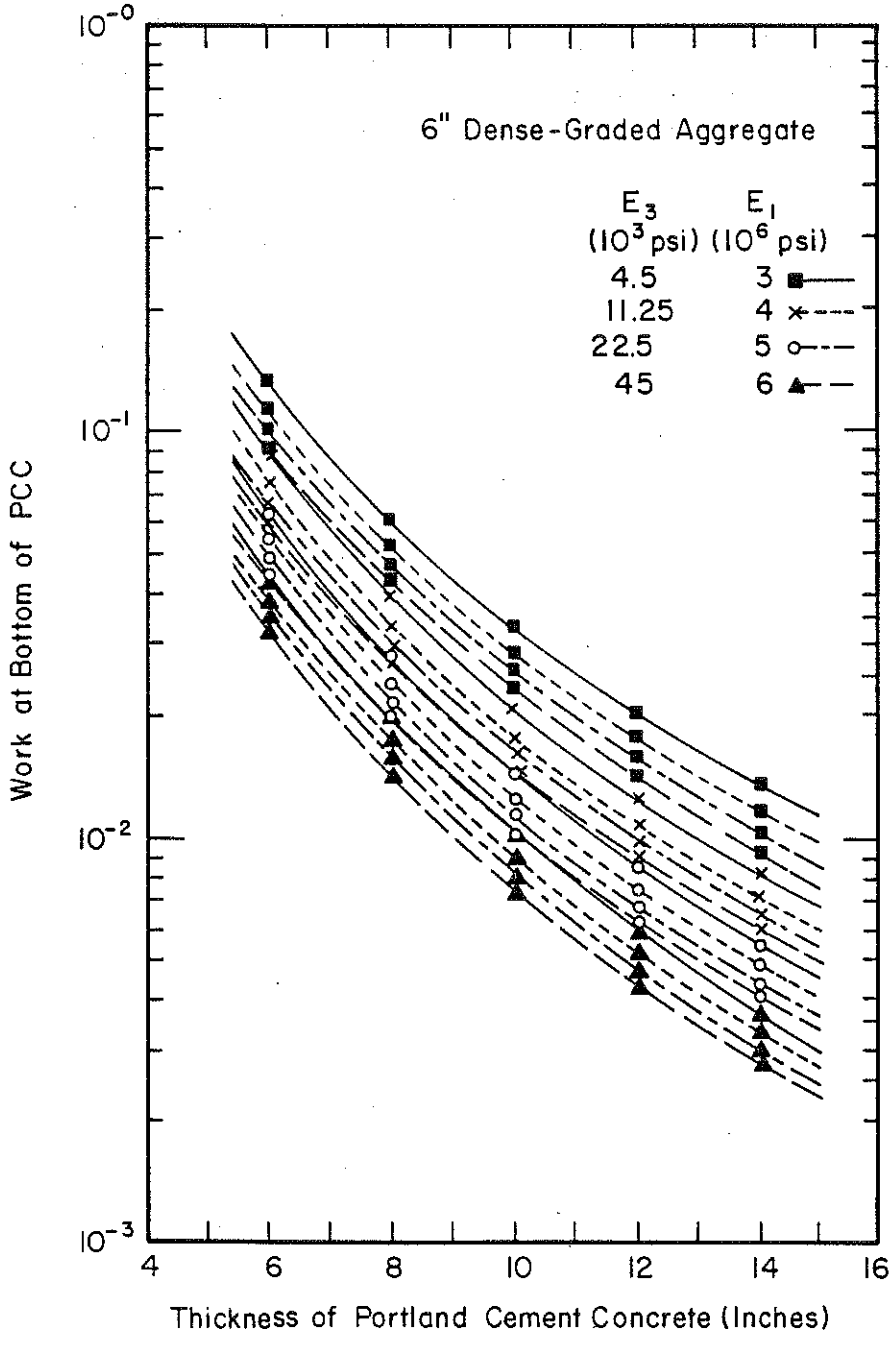

FIGURE 2. WORK AT THE BOTTOM OF THE PORTLAND CEMENT CONCRETE PAVEMENT AS A FUNCTION OF THE MODULUS AND THICKNESS OF THE PORTLAND CEMENT CONCRETE AND MODULUS OF THE SUBGRADE.

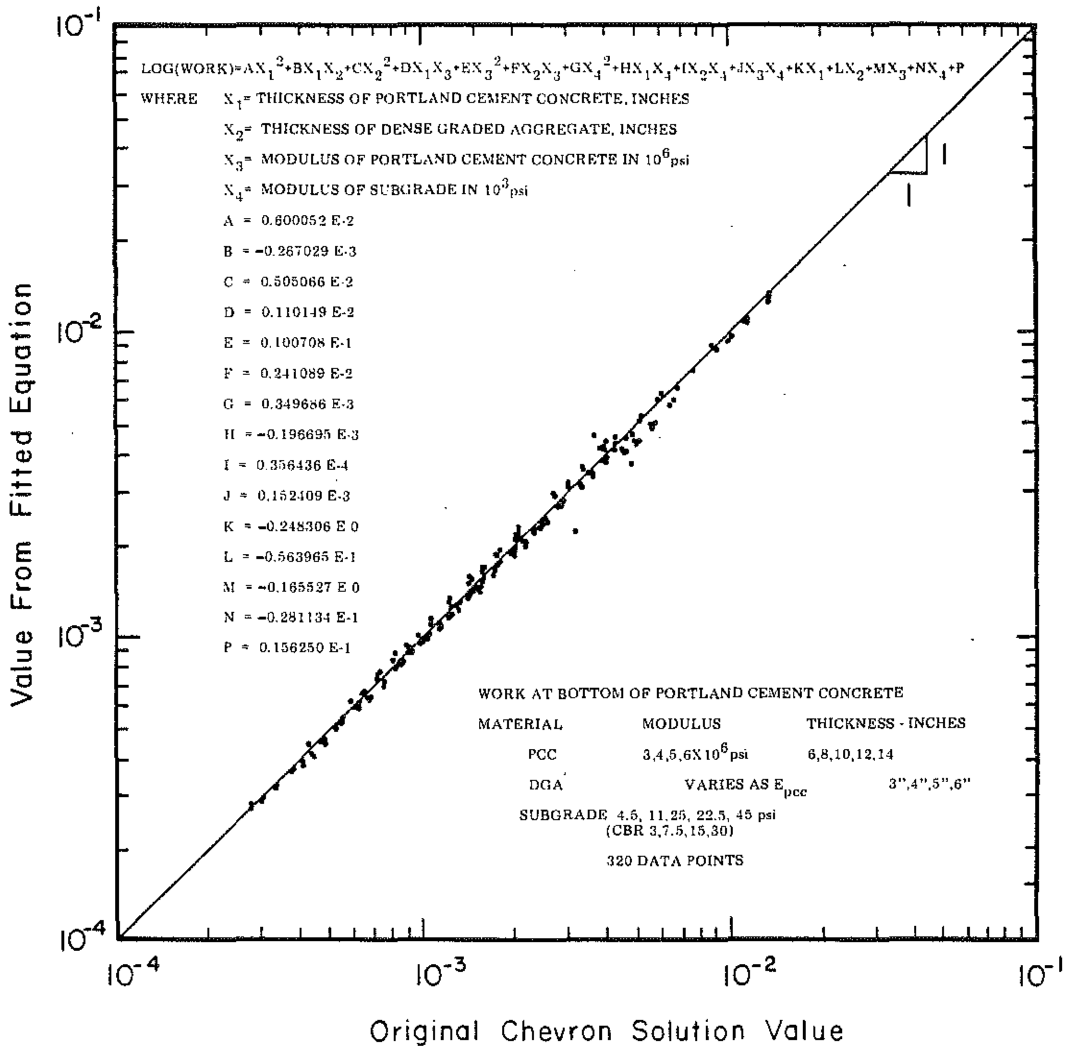

FIGURE 3. COMPARISON OF THEORETICAL CALCULATIONS FROM CHEVRON N-LAYER COMPUTER PROGRAM WITH RESULTS FROM DERIVED GENERAL CONIC EQUATION.

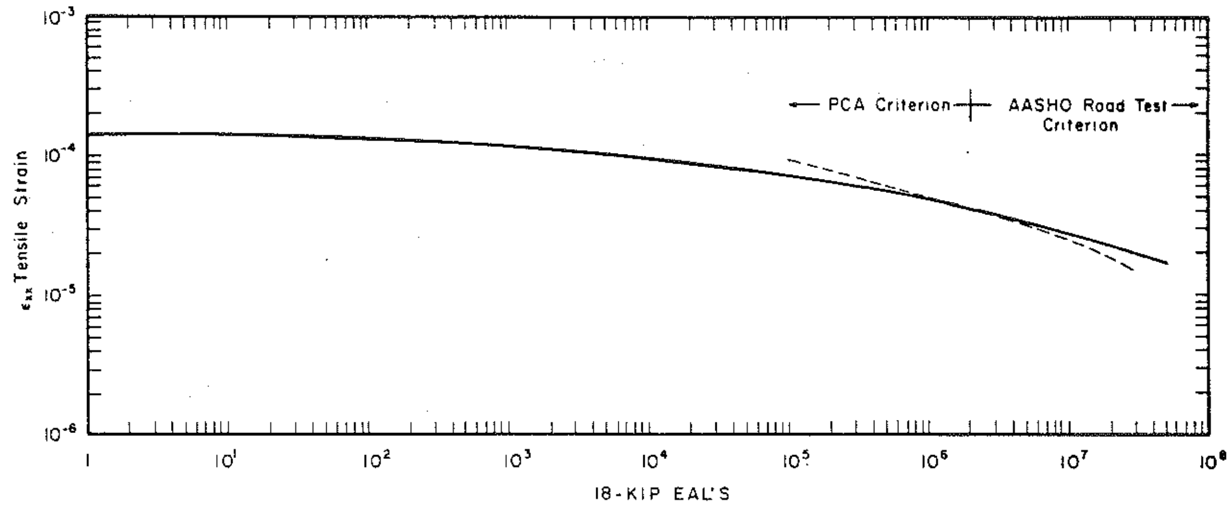

FIGURE 4. RELATIONSHIP BETWEEN TENSILE STRAIN IN THE "XX" DIRECTION AND 18-KIP EQUIVALENT AXLELOADS.

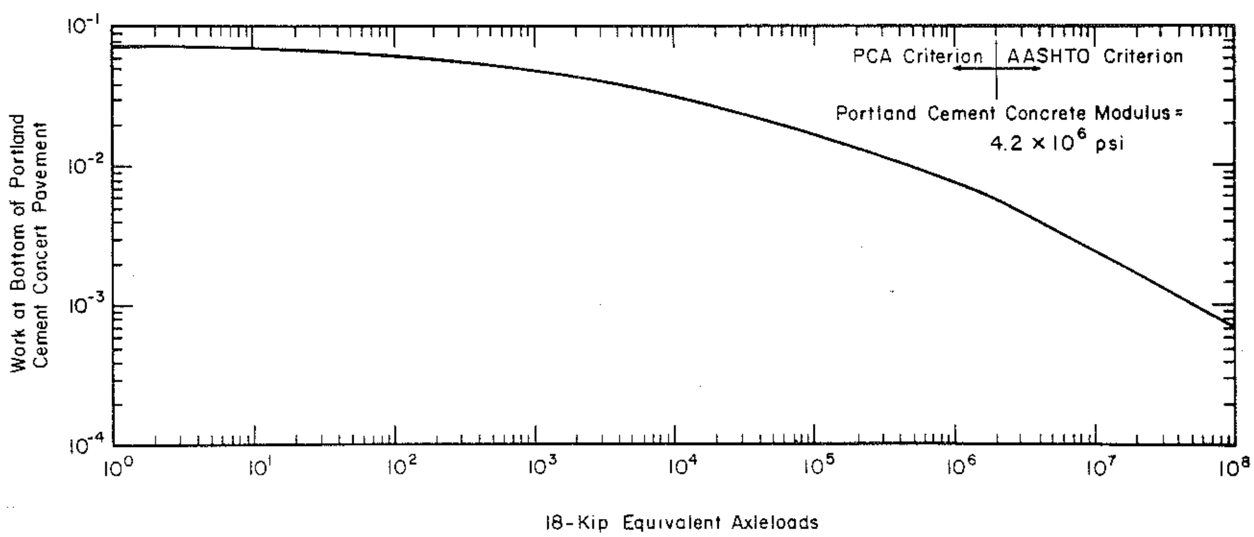

FIGURE 5. WORK AT THE BOTTOM OF THE PORTLAND CEMENT CONCRETE PAVEMENT AS A FUNCTION OF 18-KIP EQUIVALENT AXLELOADS.

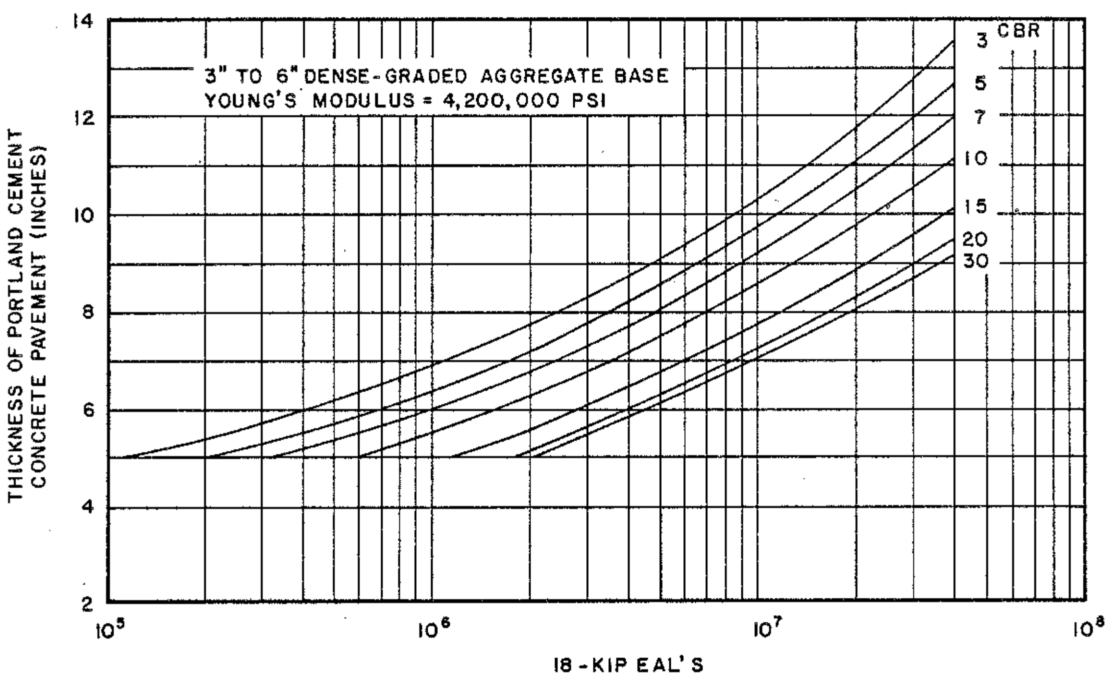

FIGURE 6. THICKNESS DESIGN CURVES FOR PORTLAND CEMENT CONCRETE PAVEMENT AS A FUNCTION OF CBR AND 18-KIP EQUIVALENT AXLELOADS.

LIMITATIONS

The design procedures and curves presented in this report are based upon a fatigue criterion applicable to the loading of a rigid slab at its center. Since the Chevron N-layer computer program was used to calculate stresses, strains, and deflections upon which the design curves were based, the design schema assumes the various layers of the pavement system remain in intimate contact. It is further assumed that the stress levels induced in the pavement system are sufficiently low that the various materials perform in an elastic manner. These same assumptions are the basis for the design system for flexible pavements used in Kentucky, as well as the AASHTO systems for both rigid and flexible pavements and the Portland Cement Association design method for rigid pavements.

Because of the nature of a rigid or portland cement concrete pavement, there may be stress concentrations induced within the pavement system that are not properly considered by the above assumptions. Modes of failure other than by fatigue loading also may become significant with regard to the overall performance of portland cement concrete pavements. Increased stresses due to edge loadings, corner loadings, or voids under the slab that have developed for whatever reason are not addressed or included within the design schema. Curling and warping forces are included indirectly only through the long-term fatigue stresses induced by temperature gradients. Failure of the slab by D-cracking is not normally included in thickness design procedures. The design of joints, joint spacings, and load transfer between slabs has not been examined in this study and thus are not accounted for in the design schema presented herein.

Thickness design curves presented in the report were prepared on the basis of calculations using the Chevron N-layer program with the moduli of elasticity of the various materials as input parameters. In Kentucky, the load-carrying capacity of the subgrade has been expressed in terms of the CBR. The modulus scale on the plot of design curves was converted to a CBR scale using a correlation factor between modulus and CBR. It has been noted in the literature on a number of occasions that this correlation factor is valid for CBR's only in the range of approximately 3 to 20.