E 剛性鋪面之厚度設計法之建立

E.1 PCA厚度設計法之發展過程

資料來源：

Portland Cement Association, “Thickness Design for Concrete Highway and Street Pavements,” Skokie, Illinois, 1984.

E.2 FAA厚度設計法之簡介

資料來源：

周義華，運殊工程，鼎漢國際工程顧問股份有限公司，第二版，中華民國八十二年八月。

Federal Aviation Administration, “Airport Pavement Design and Evaluation,” FAA Advisory Circular AC 150/5320-6C, 1978.

E.3 FAA厚度設計法之發展過程

資料來源：

Federal Aviation Administration, “Airport Pavement Design and Evaluation,” FAA Advisory Circular AC 150/5320-6C, 1978.

E.4 Modified PCA Stress Analysis and Thickness Design Procedures

資料來源：

Lee, Y. H., J.. H. Bair, C. T. Lee, S. T. Yen, Y. M. Lee, “Modified PCA Stress Analysis and Thickness Design Procedures,” Presented at the 76th Annual Meeting of the Transportation Research Board and Accepted for Publication in the Future Transportation Research Record, 1997.

E.1 PCA厚度設計法之發展過程

APPENDIX A

Development of Design Procedure

The thickness design procedure presented here was prepared to recognize current practices in concrete pavement construction and performance experience with concrete pavements that previous design procedures have not addressed. These include:

- Pavements with different types of load transfer at transverse joints or cracks
- Lean concrete subbases under concrete pavements
- Concrete shoulders
- Modes of distress, primarily due to erosion of pavement foundations, that are unrelated to the traditional criteria used in previous design procedures

A new aspect of the procedure is the erosion criterion that is applied in addition to the stress-fatigue criterion. The erosion criterion recognizes that pavements can fail from excessive pumping, erosion of foundation, and joint faulting. The stress criterion recognizes that pavements can crack in fatigue from excessive load repetitions.

This appendix explains the basis for these criteria and the development of the design procedure. Reference 30 gives a more detailed account of the topic.

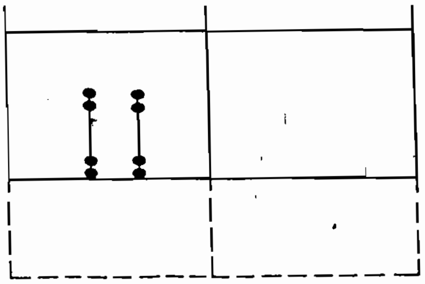
Analysis of Concrete Pavements

The design procedure is based on a comprehensive analysis of concrete stresses and deflections at pavement joints, corners, and edges by a finite-element computer program.[8] It allows considerations of slabs with finite dimensions, variable axle-load placement, and the modeling of load transfer at transverse joints or cracks and load transfer at the joint between pavement and concrete shoulder. For doweled joints, dowel properties such as diameter and modulus of elasticity are used directly. For aggregate interlock, keyway joints, and cracks in continuously reinforced pavements, a spring stiffness value is used to represent the load-deflection characteristics of such joints based on field and laboratory tests.

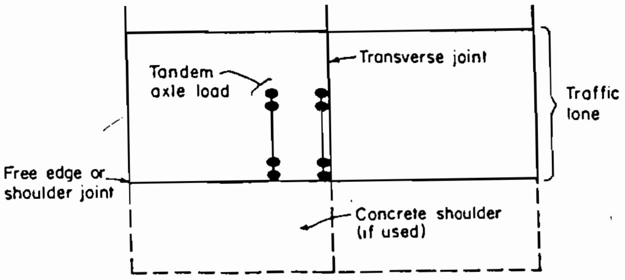
Jointed Pavements

After analysis of different axle-load positions on the slab, the critical placements shown in Fig. A1 were established with the following conclusions:

1. The most critical pavement stresses occur when the truck wheels are placed at or near the pavement edge and midway between the joints, Fig. A1(*a*). Since the joints are at some distance from this location, transverse joint spacing and type of load transfer have very little effect on the magnitude of stress. In the design procedure, therefore, the analysis based on flexural stresses and fatigue yield the same values for different joint spacings and different types of load transfer mechanisms (dowels or aggregate interlock) at transverse joints. When a concrete shoulder is tied



(a) Axle-load position for critical flexural stresses



(b) Axle-load position for critical deflections

Fig. A1. Critical axle-load positions.

on to the mainline pavement, the magnitude of the critical stresses is considerably reduced.

2. The most critical pavement deflections occur at the slab corner when an axle load is placed at the joint with the wheels at or near the corner, Fig. A1(*b*).* In this situation, transverse joint spacing has no effect on the magnitude of corner deflections but the type of load transfer mechanism has a substantial effect. This means that design results based on the erosion criteria (deflections) may be substantially affected by the type of load transfer selected, especially when large numbers of trucks are being designed for. A concrete shoulder reduces corner deflections considerably.

Continuously Reinforced Pavements

A continuously reinforced concrete pavement (CRCP) is one with no transverse joints and, due to the heavy, continuous steel reinforcement in the longitudinal direction, the pavement develops cracks at close intervals. These crack spacings on a given project are variable, running generally from 3 to 10 ft with averages of 4 to 5 ft.

In the finite-element computer analysis, a high degree of load transfer was assigned at the cracks of CRCP and the crack spacing was varied. The critical load positions established were the same as those for jointed pavements.

For the longer crack spacings, edge stresses for loads placed midway between cracks are of about the same magnitude as those for jointed pavements. For the average and shorter crack spacings, the edge stresses are less than those for jointed pavements, because there is not enough length of uncracked pavement to develop as much bending moment.

For the longer crack spacings, corner deflections are somewhat less than those for jointed pavements with doweled transverse joints. For average to long crack spacings, corner deflections are about the same as those for jointed, doweled pavements. For short crack spacings of 3 or 4 ft, corner deflections are somewhat greater than those for jointed, doweled pavements, especially for tandem-axle loads.

Considering natural variations in crack spacing that occur in one stretch of pavement, the following comparison of continuously reinforced pavements with jointed, doweled pavements is made. Edge stresses will sometimes be the same and sometimes less, while corner deflections will sometimes be less, the same, and greater at different areas of the pavement depending on crack spacing.

The average of these pavement responses is neither substantially better nor worse than those for jointed, doweled pavements. As a result, in this design procedure, the same pavement responses and criteria are applied to continuously reinforced pavements as those used with jointed, doweled pavements. This recommendation is consistent with pavement performance experience. Most design agencies suggest that the thickness of continuously reinforced pavements should be about the same as the thickness of doweled-jointed pavements.

Truck Load Placement

Truck wheel loads placed at the outside pavement edge create more severe conditions than any other load position. As the truck placement moves inward a few inches from the edge, the effects decrease substantially.(39)

Only a small fraction of all the trucks run with their outside wheels placed at the edge. Most of the trucks traveling the pavement are driven with their outside wheel placed about 2 ft from the edge. Taragin's(40) studies reported in 1958, showed very little truck encroachment at pavement edge for 12-ft lanes for pavements with unpaved shoulders. More recent studies by Emery(41) showed more trucks at edge. Other recent studies(42) showed fewer trucks at edge than Emery. For this design procedure, the most severe condition, 6% of trucks at edge,* is assumed so as to be on the safe side and to take account of recent changes in United States law permitting wider trucks.

At increasing distances inward from the pavement edge, the frequency of load applications increases while the magnitudes of stress and deflection decrease. Data on truck placement distribution and distribution of stress and deflection due to loads placed at and near the pavement edge are difficult to use directly in a design procedure. As a result, the distributions were analyzed and more easily applied techniques were prepared for design purposes.

For stress-fatigue analysis, fatigue was computed incrementally at fractions of inches inward from the slab edge for different truck-placement distributions; this gave the equivalent edge-stress factors shown in Fig. A2. (This factor, when multiplied by edge-load stress, gives the same degree of fatigue consumption that would result from a given truck placement distribution.) The most severe condition, 6% truck encroachment, has been incorporated in the design tables.

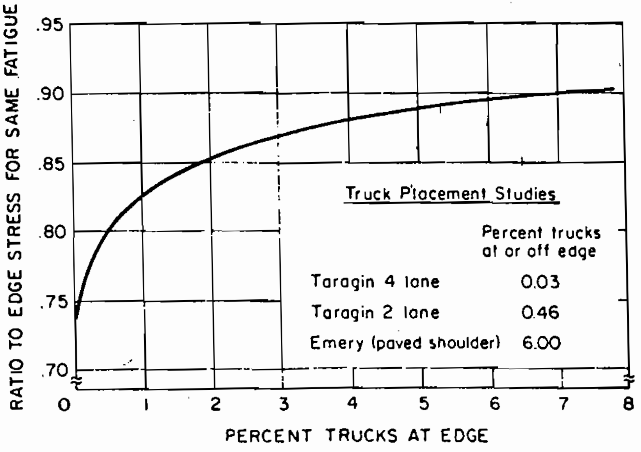


Fig. A2. Equivalent edge stress factor depends on percent of trucks at edge.

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*The greatest deflections for tridems occur when two axles are placed at one side of the joint and one axle at the other side.

*As used here, the term "percent trucks at edge" is defined as the percent of total trucks that are traveling with the outside of the contact area of the outside tire at or beyond the pavement edge.

For erosion analysis, which involves deflection at the slab corner, the most severe case (6% of trucks at edge) is again assumed. Where there is no concrete shoulder, corner loadings (6% of trucks) are critical; and where there is a concrete shoulder, the greater number of loadings inward from the pavement corner (94% of trucks) are critical. These factors are incorporated into the design charts as follows:

$$\text{Percent erosion damage} = 100\ \Sigma n_i\ (C/Ni)$$

where: n_i = expected number of axle-load repetitions for axle-group i

Ni = allowable number of repetitions for axle-group i

C = 0.06 for pavements without shoulder, and 0.94 for pavements with shoulder

To save a design calculation step, the effects of (C/Ni) are incorporated in Figs. 6*a* and 6*b* of Chapter 3 and Tables 11 through 14 of Chapter 4.

Variation in Concrete Strength

Recognition of the variations in concrete strength is considered a realistic addition to the design procedure. Expected ranges of variations in the concrete's modulus of rupture have far greater effect than the usual variations in the properties of other materials, such as subgrade and subbase strength, and layer thicknesses. Variation in concrete strength is introduced by reducing the modulus of rupture by one coefficient of variation.

For design purposes, a coefficient of variation of 15% is assumed and is incorporated into the design charts and tables. The user does not directly apply this effect. The value of 15% represents fair-to-good quality control, and, combined with other effects discussed elsewhere in this appendix, was selected as being realistic and giving reasonable design results.

Concrete Strength Gain With Age

The 28-day flexural strength (modulus of rupture) is used as the design strength. This design procedure, however, incorporates the effect of concrete strength gain after 28 days. This modification is based on an analysis that incremented strength gain and load repetitions month by month for 20-year and 40-year design periods. The effect is included in the design charts and tables so the user simply inputs the 28-day value as the design strength.

Warping and Curling of Concrete

In addition to traffic loading, concrete slabs are also subjected to warping and curling. Warping is the upward concave deformation of the slab due to variations in moisture content with slab depth. The effect of warping is twofold: It results in loss of support along the slab edges and also in compressive restraint stresses in the slab bottom. Since warping is a long-term phenomenon, its resultant effect is influenced greatly by creep.

Curling refers to slab behavior due to variations of temperature. During the day, when the top surface is warmer than the bottom, tensile-restraint stresses develop at the slab bottom. During the night, the temperature distribution is reversed and tensile restraint stresses develop at the slab surface. Temperature distribution is usually nonlinear and constantly changing. Also, maximum daytime and nighttime temperature differentials exist for short durations.

Usually the combined effect of curling and warping stresses are subtractive from load stresses because the moisture content and temperature at the bottom of the slab exceed that at the top more than the reverse.

The complex situation of differential conditions at a slab's top and bottom plus the uncertainty of the zero-stress position make it difficult to compute or measure the restraint stresses with any degree of confidence or verification. At present, the information available on actual magnitudes of restraint stresses does not warrant incorporation of the items in this design procedure.

As for the loss of support, this is considered indirectly in the erodibility criterion, which is derived from actual field performance and therefore incorporates normal loss of support conditions.

Calculated stress increase due to loss of support varies from about 5% to 15%. This theoretical stress increase is counteracted in the real case because a portion of the load is dissipated in bringing the slab edges back in contact with the support. Thus, the incremental load stress due to a warping-type loss of support is not incorporated in this design procedure.

Fatigue

The flexural fatigue criterion used in the procedure presented here is shown in Fig. A3. It is similar to that used in the previous PCA method[44] based conservatively on

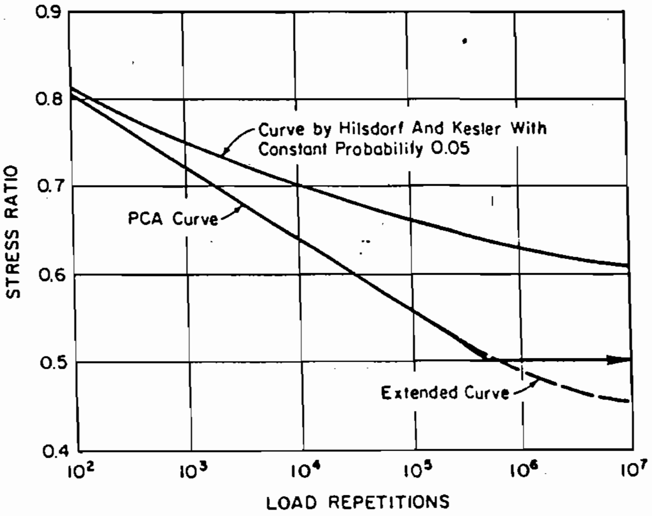

Fig. A3. Fatigue relationships.

studies of fatigue research(45-49) except that it is applied to edge-load stresses that are of higher magnitude. A modification in the high-load-repetition range has been made to eliminate the discontinuity in the previous curve that sometimes causes unrealistic effects.

The allowable number of load repetitions for a given axle load is determined based on the stress ratio (flexural stress divided by the 28-day modulus of rupture). The fatigue curve is incorporated into the design charts for use by the designer.

Use of the fatigue criterion is made on the Miner hypothesis(48) that fatigue resistance not consumed by repetitions of one load is available for repetitions of other loads. In a design problem, the total fatigue consumed should not exceed 100%.

Combined with the effect of reducing the design modulus of rupture by one coefficient of variation, the fatigue criterion is considered to be conservative for thickness design purposes.

Erosion

Previous mechanistic design procedures for concrete pavements are based on the principle of limiting the flexural stresses in a slab to safe values. This is done to avoid flexural fatigue cracks due to load repetitions.

It has been apparent that there is an important mode of distress in addition to fatigue cracking that needs to be addressed in the design process. This is the erosion of material beneath and beside the slab.

Many repetitions of heavy axle loads at slab corners and edges cause pumping; erosion of subgrade, subbase, and shoulder materials; voids under and adjacent to the slab; and faulting of pavement joints, especially in pavements with undoweled joints.

These particular pavement distresses are considered to be more closely related to pavement deflections than to flexural stresses.

Correlations of deflections computed from the finite-element analysis(8) with AASHO Road Test(24) performance data were not completely satisfactory for design purposes. (The principal mode of failure of concrete pavements at the AASHO Road Test was pumping or erosion of the granular subbase from under the slabs.) It was found that to be able to predict the AASHO Road Test performance, different values of deflection criteria would have to be applied to different slab thicknesses, and to a small extent, different foundation moduli (k values).

More useful correlation was obtained by multiplying the computed corner deflection values (w) by computed pressure values (p) at the slab-foundation interface. Power, or rate of work, with which an axle load deflects the slab is the parameter used for the erosion criterion—for a unit area, the product of pressure and deflection divided by a measure of the length of the deflection basin (ℓ — radius of relative stiffness, in inches). The concept is that a thin pavement with its shorter deflection basin receives a faster load punch than a thicker slab. That is, at equal pw's and equal truck speed, the thinner slab is subjected to a faster rate of work or power (inch-pound per second). A successful correlation with road test performance was obtained with this parameter.

The development of the erosion criterion was also generally related to studies on joint faulting.(28 29) These studies included pavements in Wisconsin, Minnesota, North Dakota, Georgia, and California, and included a range of variables not found at the AASHO Road Test, such as a greater number of trucks, undoweled pavements, a wide range of years of pavement service, and stabilized subbases.

Brokaw's studies(28) of undoweled pavements suggest that climate or drainage is a significant factor in pavement performance. So far, this aspect of design has not been included in the design procedure, but it deserves further study. Investigations of the effects of climate on design and performance of concrete pavements have also been reported by Darter.(43)

The erosion criterion is suggested for use as a guideline. It can be modified according to local experience since climate, drainage, local factors, and design innovations may have an influence. Accordingly, the 100% erosion-damage criterion, an index number correlated with general performance experience, can be increased or decreased based on specific performance data gathered in the future for more favorable or more adverse conditions.