PCAWIN Program for Jointed Concrete Pavement Design

Ying-Haur Lee[1] and Samuel H. Carpenter[2]

[1] Department of Civil Engineering
Tamkang University
Tamsui, Taipei, Taiwan 251, R.O.C.
E-mail: yinghaur@mail.tku.edu.tw
[2] Department of Civil and Environmental Engineering,
University of Illinois at Urbana-Champaign,
1206 Newmark CE Lab, 205 N. Mathews Ave.,
Urbana, IL 61801, U.S.A.
E-mail: scarpent@uiuc.edu

Abstract

The primary objective of this study is to unveil the technical know how of the Portland Cement Association (PCA) pavement thickness design procedure. The PCA thickness design criteria are to limit the number of load repetitions based on both fatigue analysis and erosion analysis to prevent the first crack initiation due to critical edge stresses as well as to prevent pavement failures such as pumping, erosion of foundation, and joint faulting due to critical corner deflections. The PCA design equations have been implemented in a window-based computer program (PCAWIN) to facilitate verification against the well-known PCAPAV program. The PCAWIN program was designed to be highly user-friendly and thus came with many well-organized graphical interfaces, selection menus, and command buttons for easy use. Both English version and Chinese version of the program are available at the web site: http://teg.ce.tku.edu.tw. Many tentative modification alternatives including the reconsideration of design period and traffic, axle load distributions, temperature curling and moisture warping, modified equivalent stress calculation, the determination of equivalent stress factors, subbase and subgrade support, and design reliability are discussed.

***Key Words*:** PCA, Concrete Pavements, Thickness Design, Fatigue Analysis, Equivalent Stress, Erosion Analysis, PCAWIN

1. Introduction

Over the years, pavement engineers have been striving to develop rational pavement design procedures, which are generally grouped into two major types, namely purely empirical approach and mechanistic-empirical approach. The AASHTO pavement design procedure [1], originally developed at the AASHO Road Test and formerly known as purely empirical approach, has undergone many serious revisions in 1972, 1986, 1993, and 1998 to become more mechanistic-empirical oriented. The concept of converting different axle loads to standard 18-kip Equivalent Single Axle Loads (ESALs) or the ESAL concept has been adopted worldwide since then, even though many researchers have argued against its continuous use. The current effort to establish the proposed revisions of the AASHTO Guide for Design of Pavements, to be completed by 2002, will be based on mechanistic-empirical procedures and is believed to totally abandon the use of ESAL concept.

On the other hand, the Portland Cement Association (PCA) thickness design procedure, originally developed based on sound mechanistic principles, has been widely accepted for concrete pavement designs for many decades. Since not all the details of the PCA design methodology have been openly documented in the literature, the primary objective of this study is to unveil the technical know of the PCA thickness design approach to provide an alternative approach for not using the ESAL concept. Many technical insights to the current on-going and future development of more refined mechanistic-empirical pavement design procedures are discussed.

2. Know How of the Portland Cement Association Thickness Design Procedure

The Portland Cement Association's thickness design procedure (or PCA method) is the most well-known, widely-adopted, and mechanically-based procedure for the thickness design of jointed concrete pavements [14]. The PCA method uses design tables and charts, implemented in the PCAPAV computer program, to determine the minimum slab thickness based on the results of J-SLAB [15] finite element analysis. The primary design factors of the PCA method are: design period, the flexural strength of concrete (or the concrete modulus of rupture), the modulus of subbase-subgrade reaction, design traffic (including load safety factor, axle load distribution), with or without doweled joints and a tied concrete shoulder [5]. The PCA thickness design criteria are to limit the number of load repetitions based on both fatigue analysis and erosion analysis. Cumulative damage concept is used for the fatigue analysis to prevent the first crack initiation due to critical edge stresses, whereas the principal consideration of erosion analysis is to prevent pavement failures such as pumping, erosion of foundation, and joint faulting due to critical corner deflections during the design period.

2.1 Fatigue Analysis

In the PCA thickness design procedure, the determination of equivalent stress is based on the resulting maximum edge bending stress of J-SLAB F.E. analysis under a single axle (SA) load and a tandem axle (TA) load for different levels of slab thickness and modulus of subgrade reaction. The basic input parameters were assumed as: slab modulus E = 4 Mpsi, Poisson's ratio $\mu = 0.15$, finite slab length L = 180 in., finite slab width W = 144 in. A standard 18-kip single axle load (dual wheels) with each wheel load equal to 4,500 lbs, wheel contact area = 7*10 in.^{2} (or an equivalent load radius a = 4.72 in.), wheel spacing s = 12 in., axle width (distance between the center of dual wheels) D = 72 in. was used for the analysis, whereas a standard 36-kip tandem axle load (dual wheels) with axle spacing t = 50 in. and remaining gear configurations same as the standard single axle was also used. If a tied concrete shoulder (WS) was present, the aggregate interlock factor was assumed as AGG = 25,000 psi. PCA also incorporated the results of computer program MATS to account for the support provided by the subgrade extending beyond the slab edges for a slab with no concrete shoulder (NS). Together with several other adjustment factors, the equivalent stress was defined as follows [6,10]: (Note: 1 in. = 2.54 cm, 1 psi = 0.0689 Mpa, 1 kip = 1000 lbs = 4.45 N)

$$\sigma_{eq} = \frac{6 * M_e}{h^2} * f_1 * f_2 * f_3 * f_4 \qquad (1)$$

$$M_e \begin{cases} = -1600 + 2525 * \log(\ell) + 24.42 * \ell + 0.204 * \ell^2 & \text{SA/NS} \\ = 3029 - 2966.8 * \log(\ell) + 133.69 * \ell - 0.0632 * \ell^2 & \text{TA/NS} \\ = (-970.4 + 1202.6 * \log(\ell) + 53.587 * \ell) * \\ \quad (0.8742 + 0.01088 * k^{0.447}) & \text{SA/WS} \\ = (2005.4 - 1980.9 * \log(\ell) + 99.008 * \ell) * \\ \quad (0.8742 + 0.01088 * k^{0.447}) & \text{TA/WS} \end{cases}$$

$$f_1 = \begin{cases} (24/\mathrm{SAL})^{0.06} * (SAL/18) & \text{SA} \\ (48/\mathrm{TAL})^{0.06} * (TAL/36) & \text{TA} \end{cases}$$

$$f_2 = \begin{cases} 0.892 + h/85.71 - h^2/3000 & \text{NS} \\ 1 & \text{WS} \end{cases}$$

$$f_3 = 0.894 \quad \text{for 6\% truck at the slab edge}$$

$$f_4 = 1/[1.235 * (1 - CV)]$$

Where, σ_{eq} = equivalent stress, psi; h = thickness of the slab, in.; $\ell=(E*h^3/(12*(1-\mu^2)*k))^{0.25}$, radius of relative stiffness of the slab-subgrade system, in.; k = modulus of subgrade reaction, pci; f_1 = adjustment factor for the effect of axle loads and contact areas; f_2 = adjustment factor for a slab with no concrete shoulder based on the results of MATS computer program; f_3 = adjustment factor to account for the effect of truck placement on the edge stress (PCA recommended a 6% truck encroachment, f_3=0.894); f_4 = adjustment factor to account for the increase in concrete strength with age after the 28*th* day, along with a reduction in concrete strength by one coefficient of variation (CV); (PCA used CV=15%, f_4=0.953); and SAL, TAL = actual single axle or tandem axle load, kips. (Note: 1 in. = 2.54 cm, 1 psi = 0.0689 Mpa, 1 pci = 0.027 kPa/mm, 1 kip = 1000 lbs = 4.45 N)

PCA's fatigue analysis concept was to avoid pavement failures (or first initiation of crack) by fatigue of concrete due to critical stress repetitions. Based on Miner's cumulative fatigue damage assumption, the PCA thickness design procedure first lets the users select a trial slab thickness, calculate the ratio of equivalent stress versus concrete modulus of rupture (stress ratio, σ_{eq}/S_c) for each axle load and axle type, then determine the maximum allowable load repetitions (N_f) based on the following σ_{eq}/S_c - N_f relationship:

$$\begin{cases} \log N_f = 11.737 - 12.077 * (\sigma_{eq} / S_c) & \sigma_{eq} / S_c \geq 0.55 \\ N_f = \left(\dfrac{4.2577}{\sigma_{eq} / S_C - 0.4325} \right)^{3.268} & 0.45 < \sigma_{eq} / S_c < 0.55 \\ N_f = \text{Unlimited} & \sigma_{eq} / S_c \leq 0.45 \end{cases} \tag{2}$$

The PCA thickness design procedure then uses the expected number of load repetitions dividing by N_f to calculate the percentage of fatigue damage for each axle load and axle type. The total cumulative fatigue damage has to be within the specified 100% limiting design criterion, or a different trial slab thickness has to be used and repeat previous calculations again.

2.2 Erosion Analysis

The principal mode of failure in the AASHO Road test was pumping or erosion of the granular subbase. Thus, PCA's erosion analysis concept is to avoid pavement failures due to pumping, erosion of foundation, and joint faulting, which are closely related to pavement deflection. The most critical pavement deflection occurs at the slab corner when an axle load is placed at the joint near to the corner. Likewise, based on unpublished manuscripts, equivalent corner deflection (δ_{eq}) equations were developed as the following for slabs with no concrete shoulder (NS) or a tied concrete shoulder (WS) and with aggregate interlock joints (ND) or doweled joints (WD) under a single axle (SA) load or a tandem axle (TA) load:

$$\delta_{eq} = \frac{p_c}{k} * f_5 * f_6 * f_7 \tag{3}$$

$$p_c = \begin{cases} 1.571 + \dfrac{46.127}{\ell} + \dfrac{4372.7}{\ell^2} - \dfrac{22886}{\ell^3} & \text{SA/NS/ND} \\ 1.847 + \dfrac{213.68}{\ell} - \dfrac{1260.8}{\ell^2} + \dfrac{22989}{\ell^3} & \text{TA/NS/ND} \\ 0.5874 + \dfrac{65.108}{\ell} + \dfrac{1130.9}{\ell^2} - \dfrac{5245.8}{\ell^3} & \text{SA/WS/ND} \\ 1.47 + \dfrac{102.2}{\ell} - \dfrac{1072}{\ell^2} + \dfrac{14451}{\ell^3} & \text{TA/WS/ND} \end{cases}$$

$$p_c = \begin{cases} -0.3019 + \dfrac{128.85}{\ell} + \dfrac{1105.8}{\ell^2} + \dfrac{3269.1}{\ell^3} & \text{SA/NS/WD} \\ 1.258 + \dfrac{97.491}{\ell} + \dfrac{1484.1}{\ell^2} - \dfrac{180}{\ell^3} & \text{TA/NS/WD} \\ 0.018 + \dfrac{72.99}{\ell} + \dfrac{323.1}{\ell^2} + \dfrac{1620}{\ell^3} & \text{SA/WS/WD} \\ 0.0345 + \dfrac{146.25}{\ell} - \dfrac{2385.6}{\ell^2} + \dfrac{23848}{\ell^3} & \text{TA/WS/WD} \end{cases}$$

$$f_5 = \begin{cases} SAL/18 & \text{SA} \\ TAL/36 & \text{TA} \end{cases}$$

$$f_6 = \begin{cases} 0.95 & \text{ND/NS} \\ 1.001 - \left(0.26363 - \dfrac{k}{3034.5} \right)^2 & \text{ND/WS} \\ 1 & \text{WD} \end{cases}$$

$$f_7 = \begin{cases} 0.896 & \text{NS} \\ 1 & \text{WS} \end{cases}$$

In which, δ_{eq} = equivalent corner deflection, in.; p_c = pressure at slab-foundation interface, psi; f_5 = adjustment factor for the effect of axle loads. f_6 = adjustment factor for a slab with no doweled joints and no tied concrete shoulder based on the results of MATS computer program; f_7 = adjustment factor to account for the effect of truck placement on the corner deflection; and SAL, ℓ, k, = same definitions as previously described. (Note: 1 in. = 2.54 cm, 1 psi = 0.0689 Mpa)

Since satisfactory correlations between corner deflections and the performance of the AASHO Road Test pavement sections could not be obtained, a better correlation was obtained by relating the performance to the rate of work or power (P) which is defined as the product of corner deflection (δ_{eq}) and pressure at the slab-foundation interface (p_c) divided by a measure of the length of deflection basin or the radius of relative stiffness (ℓ). The concept is that for a unit area a thinner pavement with its shorter deflection basin received a faster punch than a thicker slab did. As shown elsewhere in the literature [5,7,13], the rate of work or power (P) was derived as:

$$P = 268.7 \left(\frac{p_c^{\,2}}{h * k^{0.73}} \right) = 268.7 \left(\frac{k^{1.27} * \delta_{eq}^{\,2}}{h} \right) \tag{4}$$

Where p_c is the pressure on the foundation under the slab corner, which is equal to the product of corner deflection (δ_{eq}) and modulus of subgrade reaction (k) by definition.

The development of the erosion criteria was generally related to joint faulting studies of the pavements in Wisconsin, Minnesota, North Dakota, Georgia, and California to include a wider range of pavement design features such as mixed and higher truck traffic loadings, undoweled pavements, and stabilized subbases, which could not be found at the AASHO Road Test. From unpublished manuscripts, the determination of the well-known erosion factor (EF) in the PCA thickness design procedure was defined by:

$$EF = \log \left[\frac{11111 * (0.896 * P)^2 * C_1}{h * k^{0.73}} \right] \tag{5}$$

$$C_1 = 1 - \left(\frac{k}{2000} * \frac{4}{h} \right)^2$$

In which, C_1 is an adjustment factor which has a value close to 1.0 for untreated subbases and decreases to approximately 0.90 for stabilized subbases. In addition, the following equations were developed to compute the allowable number of repetitions (N_e) based on PCA's erosion criteria [5,7]:

$$\begin{cases} \log N_e = 14.524 - 6.777 * (C_1 * P - 9)^{0.103} - \log C_2 & C_1 * P > 9 \\ N_e = \text{Unlimited} & C_1 * P \le 9 \end{cases} \quad (6)$$

$$C_2 = \begin{cases} 0.06 & \text{for NS} \\ 0.94 & \text{for WS} \end{cases}$$

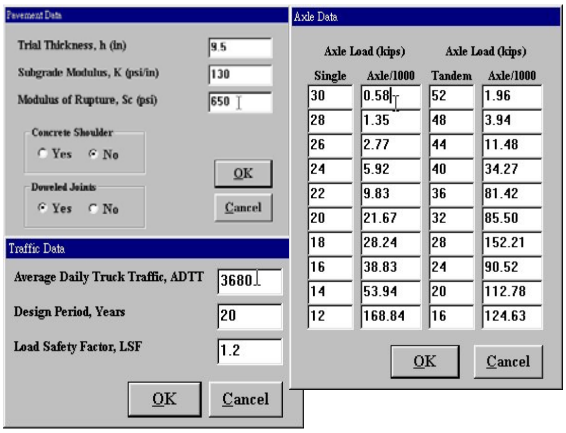
Where the constant C_2=0.06 is an adjustment factor for pavements without concrete shoulders. With a concrete shoulder, the corner deflection is not significantly affected by truck load placement, so a large value of C_2=0.94 should be used. Note that the $-\log C_2$ term of equation (6) is needed to account for the adjustment made to the allowable load repetitions in the PCA design methodology.

The thickness design procedure then uses the expected number of load repetitions dividing by N_e to calculate the percentage of erosion damage for each axle load and axle type. The total cumulative erosion damage has to be within the specified 100% limiting design criterion as well, or a different trial slab thickness has to be used and repeat previous calculations again.

3. Development and Verification of the PCAWIN Program

The aforementioned design equations have been implemented in a window-based computer program (PCAWIN) using Microsoft Visual Basic software package [11] to facilitate verification against the PCAPAV program. Suppose there exists a four-lane divided highway with the following design factors: design period = 20 years, load safety factor LSF = 1.2, modulus of subgrade reaction k = 130 pci, concrete modulus of rupture S_C = 650 psi, and coefficient of variation = 15%. The expected cumulative axle load repetitions during the analysis period are the same as those given elsewhere in the literature [5,10,14]. A trial slab thickness h = 9.5 in. with no concrete shoulder was assumed. (Note: 1 in. = 2.54 cm, 1 psi = 0.0689 Mpa, 1 pci = 0.027 kPa/mm, 1 kip = 100 lbs = 4.45 N)

Several input screens of the PCAWIN program are shown in Figure 1. The resulting output screens including the design inputs, fatigue analysis, and erosion analysis solutions are given in Figure 2 to Figure 4. In addition, the five PCAPAV program sample input files for different axle load categories, joint types, shoulder types, and other design factors were reanalyzed using both PCAWIN program and PCAPAV program. By comparing each element of the outputs from both programs, almost identical results were obtained. The only minor difference is believed due to truncation error of the computation alone.



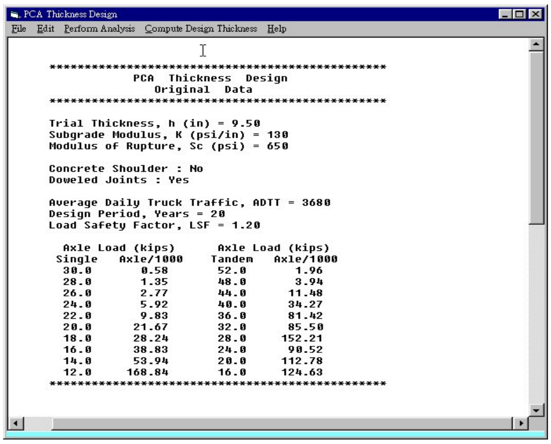
Trial Thickness, h (in) 9.5
Subgrade Modulus, K (psi/in) 130
Modulus of Rupture, Sc (psi) 650

Concrete Shoulder ○ Yes ● No
Doweled Joints ● Yes ○ No

Average Daily Truck Traffic, ADTT 3680
Design Period, Years 20
Load Safety Factor, LSF 1.2

Axle Load (kips)		Axle Load (kips)	
Single	Axle/1000	Tandem	Axle/1000
30	0.58	52	1.96
28	1.35	48	3.94
26	2.77	44	11.48
24	5.92	40	34.27
22	9.83	36	81.42
20	21.67	32	85.50
18	28.24	28	152.21
16	38.83	24	90.52
14	53.94	20	112.78
12	168.84	16	124.63

Figure 1. Sample input screens of PCAWIN program



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**********************************************
           PCA  Thickness  Design
              Original  Data
**********************************************

Trial Thickness, h (in) = 9.50
Subgrade Modulus, K (psi/in) = 130
Modulus of Rupture, Sc (psi) = 650

Concrete Shoulder : No
Doweled Joints : Yes

Average Daily Truck Traffic, ADTT = 3680
Design Period, Years = 20
Load Safety Factor, LSF = 1.20

  Axle Load (kips)      Axle Load (kips)
 Single   Axle/1000    Tandem   Axle/1000
  30.0        0.58      52.0        1.96
  28.0        1.35      48.0        3.94
  26.0        2.77      44.0       11.48
  24.0        5.92      40.0       34.27
  22.0        9.83      36.0       81.42
  20.0       21.67      32.0       85.50
  18.0       28.24      28.0      152.21
  16.0       38.83      24.0       90.52
  14.0       53.94      20.0      112.78
  12.0      168.84      16.0      124.63
**********************************************
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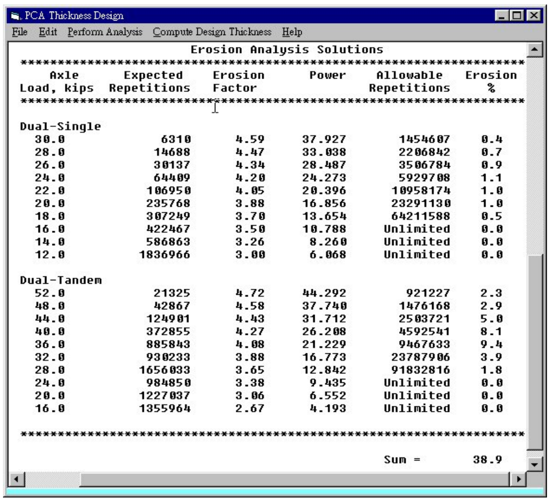
Figure 2. Sample output screen of the design inputs



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                   Erosion Analysis Solutions
*******************************************************************
    Axle       Expected     Erosion       Power     Allowable    Erosion
Load, kips   Repetitions    Factor                  Repetitions     %
*******************************************************************

Dual-Single
  30.0              6310      4.59     37.927       1454607     0.4
  28.0             14688      4.47     33.038       2206842     0.7
  26.0             30137      4.34     28.487       3506784     0.9
  24.0             64409      4.20     24.273       5929708     1.1
  22.0            106950      4.05     20.396      10958174     1.0
  20.0            235768      3.88     16.856      23291130     1.0
  18.0            307249      3.70     13.654      64211588     0.5
  16.0            422467      3.50     10.788     Unlimited     0.0
  14.0            586863      3.26      8.260     Unlimited     0.0
  12.0           1836966      3.00      6.068     Unlimited     0.0

Dual-Tandem
  52.0             21325      4.72     44.292        921227     2.3
  48.0             42867      4.58     37.740       1476168     2.9
  44.0            124901      4.43     31.712       2503721     5.0
  40.0            372855      4.27     26.208       4592541     8.1
  36.0            885843      4.08     21.229       9467633     9.4
  32.0            930233      3.88     16.773      23787906     3.9
  28.0           1656033      3.65     12.842      91832816     1.8
  24.0            984850      3.38      9.435     Unlimited     0.0
  20.0           1227037      3.06      6.552     Unlimited     0.0
  16.0           1355964      2.67      4.193     Unlimited     0.0

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                                                 Sum =        38.9
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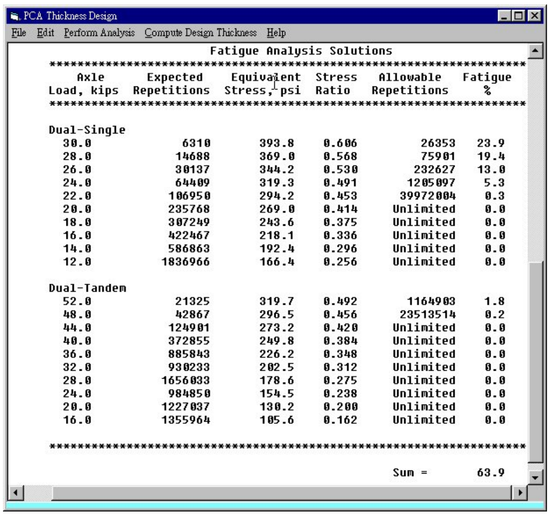
Figure 3. Sample fatigue analysis output screen



```
                     Fatigue Analysis Solutions
******************************************************************
   Axle      Expected    Equivalent  Stress   Allowable   Fatigue
Load, kips  Repetitions  Stress, psi  Ratio   Repetitions     %
******************************************************************

Dual-Single
  30.0          6310        393.8    0.606       26353    23.9
  28.0         14688        369.0    0.568       75901    19.4
  26.0         30137        344.2    0.530      232627    13.0
  24.0         64409        319.3    0.491     1205097     5.3
  22.0        106950        294.2    0.453    39972004     0.3
  20.0        235768        269.0    0.414   Unlimited     0.0
  18.0        307249        243.6    0.375   Unlimited     0.0
  16.0        422467        218.1    0.336   Unlimited     0.0
  14.0        586863        192.4    0.296   Unlimited     0.0
  12.0       1836966        166.4    0.256   Unlimited     0.0

Dual-Tandem
  52.0         21325        319.7    0.492     1164903     1.8
  48.0         42867        296.5    0.456    23513514     0.2
  44.0        124901        273.2    0.420   Unlimited     0.0
  40.0        372855        249.8    0.384   Unlimited     0.0
  36.0        885843        226.2    0.348   Unlimited     0.0
  32.0        930233        202.5    0.312   Unlimited     0.0
  28.0       1656033        178.6    0.275   Unlimited     0.0
  24.0        984850        154.5    0.238   Unlimited     0.0
  20.0       1227037        130.2    0.200   Unlimited     0.0
  16.0       1355964        105.6    0.162   Unlimited     0.0

******************************************************************

                                            Sum =        63.9
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Figure 4. Sample erosion analysis output screen

The PCAWIN program was designed to be highly user-friendly and thus came with many well-organized graphical interfaces, selection menus, and command buttons for easy use. Both English version and Chinese version of the program are available at the following web site: http://teg.ce.tku.edu.tw. To comply with US government requirements on the use of international standard measurement systems, both metric (SI) and US customary units can be used in the program.

4. Tentative Modification Alternatives of the PCA Design Methodology

4.1 Design Period and Traffic

In the current PCA thickness design method, the design period and design traffic were fixed to some specific values, i.e., design period = 20 years, directional distribution = 50%. No annual traffic growth during the design period was assumed. Thus, the pertinent inputs should be modified accordingly to allow more flexible design traffic estimation such as including annual traffic growth rather than having to *a priori* adjust the traffic input manually for various design purposes.

In addition, proper consideration of traffic loading in pavement design requires good knowledge of the full axle load distribution by main axle types. Kim, et al. [8] developed practical procedures and models for predicting axle load distribution with reasonable accuracy using the weigh-in-motion data from the North Central Region of the Long-Term Pavement Performance database. Statistical analysis results showed that the distribution patterns of both single and tandem axles were significantly different. Improved representation of axle load distribution may be obtained for different regions and local conditions, if necessary.

4.2 Effects of Thermal Curling and Moisture Warping

Whether curling and warping stresses should be considered in concrete pavement thickness design is quite controversial for many decades. For a daytime positive curling condition, the temperature differential through the slab thickness induces additional tensile stresses at the bottom of the slab. Whereas higher moisture content generally exists at the bottom of the slab during daytime non-raining periods, additional compressive stresses will occur at the bottom of the slab due to this negative moisture gradient. Even though the effects of thermal curling and moisture warping may result in very different critical tensile stresses and thus cumulative fatigue damage, temperature gradient was not considered in the fatigue analysis due to the possible compensative effect of most heavy trucks driving at night, only quite limited number of heavy load repetitions combined with daytime curling, and the difficulty in selecting a representative temperature differential for design. Furthermore, similar to temperature gradient, moisture gradient highly depends on a variety of factors such as air temperature, the ambient relative humidity at the slab surface, free water in the slab, and the moisture content of the subbase or subgrade, which are very difficult to measure accurately, thus it was also ignored in the PCA's fatigue analysis criteria.

On the other hand, many researchers [2,12] have repetitively indicated that curling stress should be considered in pavement thickness design, because curling stress may be quite large and cause the slab to crack when combined with only very few number of load repetitions. In a recent study conducted by Lee, *et al.* [10], an alternative approach for the determination of "modified equivalent stresses" has been proposed and implemented in a window-based TKUPAV program [9]. The possible detrimental effect of loading plus daytime curling was illustrated in a case study, which indicated the effect of thermal curling should be considered. The effect of moisture gradient may be accounted for by converting it to equivalent thermal gradient.

4.3 Modified Equivalent Stress Calculation

PCA's equivalent stress was determined based on the assumptions of a fixed slab modulus, a fixed slab length and width, a constant contact area, wheel spacing, axle spacing, and aggregate interlock factor, which may influence the stress occurrence, in order to simplify the calculations. Thus, the required minimum slab thickness will be the same based on the PCA thickness design procedure disregard the fact that a shorter or longer joint spacing, a better or worse load transfer mechanism, different wheel spacing and axle spacing, and environmental effects are considered.

To expand the applicability of the PCA's equivalent stress for different material properties, finite slab sizes, gear configurations, and environmental effects (e.g., temperature differentials), Lee, *et al.* [10] proposed the following equation:

$$\sigma_{eq} = \left(\sigma_w * R_1 * R_2 * R_3 * R_4 * R_5 + R_T * \sigma_c\right) * f_3 * f_4 \qquad (7)$$

Where, σ_{eq} = modified equivalent stress, [FL^{-2}]; σ_w = Westergaard's edge stress solution, [FL^{-2}]. σ_c = Westergaard/Bradbury's curling stress, [FL^{-2}]; R_1 = adjustment factor for different gear configurations including dual-wheel, tandem axle, and tridem axle; R_2 = adjustment factor for finite slab length and width; R_3 = adjustment factor for a tied concrete shoulder; R_4 = adjustment factor for a widened outer lane; R_5 = adjustment factor for a bonded or unbonded second layer using the concept of transformed section; and R_T = adjustment factor for the combined effect of loading plus daytime curling.

4.4 Determination of Equivalent Stress Factor (f_3)

The placement of outside wheels at the edge of the slab produces a critical stress higher than that at other locations. Theoretically, the distribution of the lateral load placement across the traffic lane must be known in order to calculate the fatigue damage. To simplify the calculation for design purposes, the equivalent stress factor (f_3) as recommended by PCA is often referred as a constant adjustment factor (f_3=0.894) for the effect of 6% truck encroachment at the pavement edge.

The f_3 factor is defined in this study as the stress adjustment factor (or reduction factor) based on the equivalency of the cumulative fatigue damages to account for the lateral wandering effect. The effect of stress reduction due to the lateral wheel load placement can be treated as the effect of a widened outer lane in the literature. The following R_4 prediction model was proposed by Lee, et al. (*1*) to account for the stress reduction due to the width of a widened outer lane (D_0):

$$R_4 = 0.61711 + 0.15373\Phi_1 + 0.02504\Phi_2$$

$$\Phi_1 = \begin{cases} 0.693 + 1.279(A1) + 0.369(A1)^2 + 0.037(A1)^3 & A1 \le -2.5 \\ 2.839 + 8.234(A1) + 8.158(A1)^2 + 3.608(A1)^3 + 0.576(A1)^4 & A1 > -2.5 \end{cases}$$

$$\Phi_2 = \begin{cases} -2.285 + 5.921(A2) - 6.001(A2)^2 + 7.743(A2)^3 & A2 \le 0.5 \\ -3.008 + 4.693(A2) + 4.334(A2)^2 - 2.167(A2)^3 & A2 > 0.5 \end{cases}$$

$$A1 = -0.98868\left(\frac{D_0}{\ell}\right) - 0.12214\left(\frac{a}{\ell}\right) - 0.08717\left(\frac{D_0}{a}\right)$$

$$A2 = 0.19802\left(\frac{D_0}{\ell}\right) + 0.98019\left(\frac{a}{\ell}\right) + 0.00305\left(\frac{D_0}{a}\right)$$

$$Limits: 0.1 \le \frac{a}{\ell} \le 0.4\ ,\ 0 \le \frac{D_0}{\ell} \le 2 \qquad (8)$$

Since the equivalent stress factor (f_3) may vary for different load configurations, lateral distributions, and other pertinent design parameters, it may be determined by the following procedures:

1. Select a load configuration, a standard deviation of the lateral distribution and pertinent design parameters including slab modulus, subgrade modulus, flexural strength, and slab thickness.
2. Subdivide the normally distributed load placement data (n_i) into smaller intervals.
3. Calculate the critical edge stress for each interval.
4. Calculate the corresponding allowable number of load repetitions (N_i) for each interval using the aforementioned fatigue relationship.
5. Calculate the cumulative fatigue damage $\Sigma(n_i/N_i)$ for the given load distribution.
6. Determine the maximum edge stress (σ_{max}) or the critical edge stress of the first interval.
7. Determine the equivalent allowable number of load repetitions (N_{eq}) by calculating the ratio of $\Sigma(n_i)$ and $\Sigma(n_i/N_i)$ assuming all load applications applied on the maximum edge stress location.
8. Backcalculate the equivalent edge stress (σ_{eq}).
9. The equivalent stress factor (f_3) is determined by the ratio of σ_{eq} and σ_{max}.

Thus, a control pavement is assumed with the following design features: a single axle load SAL = 36 kip, slab thickness = 8 in., subgrade k value = 130 pci, modulus of rupture S_c = 650 psi, and a normal distributed lateral load centered at 24 in. away from the slab edge with a standard deviation (sd) of 15.5 in. By subdividing the lateral load placement by an increment (wt) of 10 in consecutively, a value of f_3=0.893 (very close to 0.894 used by the PCA method) was obtained. The f_3 factor versus the standard deviation (sd) or the corresponding percentage of total number of load repetitions at the slab edge is given in Table 1 (Note: 1 in. = 2.54 cm, 1 psi = 0.0689 Mpa, 1 pci = 0.027 kPa/mm, 1 kip = 4.45 N)

Table 1 Determination of the f_3 Factor

sd, in.	10	12	14	16	18	20	22	24
% Edge Truck	0.82	2.3	4.3	6.7	9.1	11.5	13.8	15.9
f_3	0.778	0.860	0.854	0.890	0.918	0.905	0.925	0.917

Note: 1 in. = 2.54 cm

4.5 Subbase and Subgrade Support

The subgrade k value was originally developed for characterizing the support of natural soils with fairly low shear strength. Substantially higher k values were obtained based on plate tests on top granular and stabilized base layers. The current PCA design procedure as well as the 1986 AASHTO Guide both adopt the concept of a composite “top-of-the-base” k-value for the design of concrete pavements, though many researchers have indicated the inadequacy of this concept in earlier literature. In the NCHRP Project 1-26 [12], however, the effect of a second bonded or unbonded subbase layer is accounted for in the critical edge stress calculation and subsequently in the fatigue damage calculation based on the transformed section concept. Calibrated mechanistic structural analysis procedures for pavement are incorporated in the ILLI-CON program. “It is recommended that k values be selected for natural soil materials, and that base layers be considered in concrete pavement design in terms of their effect on the slab response, rather than their supposed effect on k value” [3,4]. Improved guidelines for k-value selection from a variety of methods are provided in the 1998 Supplement Guide [1] for the design of concrete pavement structures accordingly.

4.6 Design Reliability

Due to that the variations in concrete flexural strength have far greater effects on thickness design than the usual variations in other material properties, the design reliability of the PCA approach is achieved by reducing the modulus of rupture by one coefficient of variation (CV) and by using a load safety factor (LSF), ranging from 1.0 to 1.3. The deficiency of not considering the variability of many other factors such as slab thickness, foundation support, slab modulus, etc. and the associated inherent biases in determining fatigue damage and erosion damage in the present PCA design approach should be cautioned and further investigated.

To account for input variability, Timm, et al. [16] incorporated reliability analysis into the mechanistic-empirical flexible pavement design procedure (ROADENT program) for Minnesota using Monte Carlo simulation. Monte Carlo simulation is essentially a process of randomly combining each of the input parameters according to their respective distributions and obtaining an output distribution. The proposed design framework may be incorporated into the future version of PCAWIN program to eliminate such deficiency.

5. Conclusions and Recommendations

The technical know how of the Portland Cement Association (PCA) thickness design procedure was first unveiled. The PCA thickness design criteria are to limit the number of load repetitions based on both fatigue analysis and erosion analysis. Cumulative damage concept is used for the fatigue analysis to prevent the first crack initiation due to critical edge stresses, whereas the principal consideration of erosion analysis is to prevent pavement failures such as pumping, erosion of foundation, and joint faulting due to critical corner deflections during the design period. The PCA design equations have been implemented in a window-based computer program (PCAWIN) to facilitate verification against the well-known PCAPAV program. The PCAWIN program was designed to be highly user-friendly and thus came with many well-organized graphical interfaces, selection menus, and command buttons for easy use. Both English version and Chinese version of the program are available at the following web site: http://teg.ce.tku.edu.tw.

Many tentative modification alternatives including the reconsideration of design period and traffic, axle load distributions, the effect of temperature curling and moisture warping, modified equivalent stress calculation, the determination of equivalent stress factors, subbase and subgrade support, and design reliability are discussed as well.

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