Q. 剛性路面之厚度設計，是否應考慮溫差應力？

1. Yoder & Witczak (1975) P.125

"Principles of Pavement Design", 2nd Edition

CONSIDERATION OF WARPING STRESSES IN DESIGN

Previous paragraphs have suggested that warping stresses can be very high. In fact, when added to load stresses, the combined stress is enough to cause the pavement to crack under just one application of load (see Figure 3.28). *It is important to note that warping stresses are not considered when determining thickness of pavement. The philosophy that governs the design, simply stated, is, "Joints and steel are used to relieve and/or take care of warping stresses, and the design, then, is based upon load alone when considering thickness." This principle is so important that it must be clearly understood by the designer. Recall that a joint is nothing more than a "designed crack." Refer to Figure 3.8.*

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2. Y. H. Huang (1993)

"Pavement Analysis and Design"

4.1.4 Combined Stresses

(p.173 - 174)

Even though curling stresses may be quite large and cause concrete to crack when combined with loading stresses, they are usually not considered in the thickness design for the following reasons:

1. Joints and steel are used to relieve and take care of curling stresses. Curling stresses are relieved when the concrete cracks. Minute cracks will not affect the load-carrying capacity of pavements as long as the load transfer across cracks can be maintained.
2. When the fatigue principle is used for design, it is not practical to combine loading and curling stresses. A pavement may be subjected to millions of load repetitions during the design period, but the number of stress reversals due to curling is quite limited.
3. Curling stresses may be added to or subtracted from loading stresses to obtain the combined stresses. If the design is governed by the edge stress,

curling stresses should be added to loading stresses during the day but subtracted from the loading stresses at night. Due to this compensative effect and the fact that a large number of heavy trucks are driven at night, it may not be critical if curling stresses are ignored.

Whether the curling stress should be considered in pavement design is quite controversial. The Portland Cement Association does not consider curling stress in fatigue analysis, but many others indicate that it should be considered. Past experience has demonstrated that more cracks appear in longer slabs because longer slabs have much greater curling stress than shorter slabs. The nontraffic loop in the AASHO site did not have any cracks during the road test. However, when the site was surveyed after 16 years most of the 40-ft (12.2-m) long slabs had cracks, but not the 15-ft (4.6-m) slabs (Darter and Barenberg, 1977).

In designing zero-maintenance jointed plain concrete pavements, Darter and Barenberg (1977) suggested the inclusion of curling stress with loading stress for fatigue analysis. This is necessary because curling stresses are so large that when combined with the loading stresses they may cause the concrete to crack even under a few repetitions. The cracking of the slab will require proper maintenance, thus defeating the zero-maintenance concept. If curling stresses are really so important, it is more reasonable to consider the fatigue damage due to loading and curling separately and then combined, similar to the analysis of thermal cracking in flexible pavements described in Section 11.1.4.

The moisture gradient in concrete slabs also induces warping stresses. Determining the moisture gradient is difficult because it depends on a variety of factors, such as the ambient relative humidity at the surface, the free water in the concrete, and the moisture content of the subbase or subgrade. Since the moisture content at the top of a slab is generally lower than that at the bottom, the bottom of a slab is in compression, which compensates for the tensile stresses caused by edge loading. Furthermore, the moisture effect is seasonal and remains constant for a long time, thus resulting in very few stress reversals and very low fatigue damage. For this reason, warping stresses due to moisture gradient are not considered in the design of concrete pavements.

Curling Stress

Report 1-26 suggested the use of combined loading and curling stresses for determining the stress ratio and thus the allowable number of load repetitions. In addition to the number of periods and load groups, a new loop indicating curling conditions must be added to Eq. 3.19:

$$D_r = \sum_{i=1}^{p}\sum_{k=1}^{3}\sum_{j=1}^{m}\frac{n_{i,k,j}}{N_{i,k,j}} \qquad (12.1)$$

in which D_r is the accumulated damage ratio over the design period at the critical location, i is the counter for periods or subgrade support values, p is the total number of periods, k is the counter for three curing conditions (day, night, and zero temperature gradient), j is the counter for load groups, m is the total number of load groups, $n_{i,k,j}$ is the predicted number of load repetitions for the jth load group, kth curling condition, and ith period, and $N_{i,k,j}$ is the allowable number of load repetitions for the jth load groups, kth curling condition, and ith period. The inclusion of curling stress complicates the computation because the traffic has to be divided into three time periods, each with a different temperature gradient. It does not appear reasonable to combine loading and temperature stresses because they do not occur at the same frequency. A pavement may be subject to thousands of load repetitions per day due to traffic but the number of repetitions due to temperature curling is mostly only once a day. If curling stresses cannot be ignored and longer panel lengths have significant effects on fatigue cracking because of higher curling stresses, it is more reasonable to consider the damage ratios due to loading and curling separately and then combined, as illustrated by the Shahin–McCullough model for flexible pavements presented in Section 11.1.4.

Curling may not affect the fatigue life significantly because the curling stress may be subtracted from or added to the loading stress, thus neutralizing the effect.

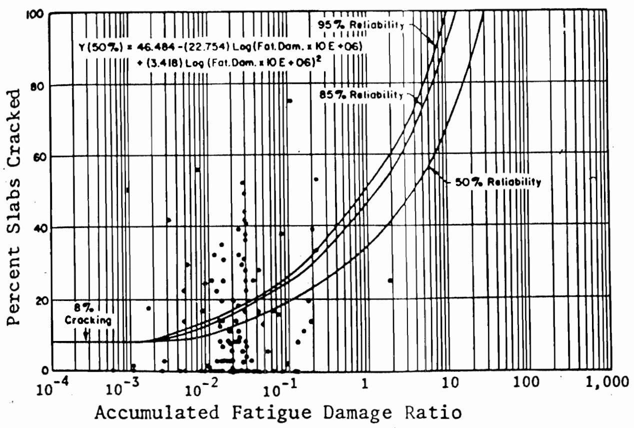

Figure 12.3 Calibrated performance curves based on Illinois COPES data. (After NCHRP (1990).)

The edge stress is further reduced by moisture warping because the moisture contents at the bottom of slab are more frequently higher than those at the top. The curling stress should be much reduced when new pavements are to be constructed with reasonably short panel lengths. The calibration of the model can further minimize the effect of curling stress. For example, Figure 12.3 shows a plot of calibrated performance curves for jointed concrete pavements relating the percent slabs cracked to the accumulated damage ratio. The stress ratio used in calculating the fatigue relationships shown in the figure included both loading and curling stresses. If curling stresses were eliminated from this calculation, different performance curves would be obtained. However, the percent slabs cracked should not be significantly affected if the same procedure, either including or excluding the curling stress, is used in both design and calibration processes.

The performance curves shown in Figure 12.3 were based on field calibration. For 50% reliability, the theoretical percent slabs cracked at a damage ratio of 1 should be 50%, but the percentage shown in the figure is only 27%. One possible cause for the discrepancy is the difficulty of determining the concrete modulus of rupture during the entire evaluation period from the initial loading to the time of evaluation. Additional research needs to be done on the best method for estimating concrete strength in existing pavements and how the observed cracking can be correlated with the damage ratio and the probability of cracking.

4.1.3 Temperature Differentials

Curling stresses in concrete pavements vary with the temperature differentials between the top and bottom of a slab. Unless actual field measurements are made, it is reasonable to assume a maximum temperature gradient of 2.5 to 3.5°F per inch of slab (0.055 to 0.077°C/mm) during the day and about half the above values at night.

In the Arlington Road Test, the maximum temperature differentials between the top and bottom surfaces of slabs were measured during the months of April and May when there was probably as much curling as at any time during the year (Teller and Sutherland, 1935–1943). If the largest five measurements were averaged, the maximum temperature differential of a 6-in. (152-mm) slab was 22°F (12.2°C) and that of a 9-in. (229-mm) slab was 31°F (17.2°C); these values correspond to temperature gradients of 3.7°F/in. (0.080°C/mm) and 3.4°F/in. (0.074°C/mm), respectively.

In the AASHO Road Test (HRB, 1962), temperatures were measured in a 6.5-in. (165-mm) slab. The temperature at a point 0.25 in. (6.4 mm) below the top surface of the 6.5-in. (165-mm) slab minus the temperature at a point 0.5 in. (12.7 mm) above the bottom surface was referred to as the standard temperature differential. The maximum standard temperature differential for the months of June and July averaged about 18.5°F (10.2°C) when the slab curled down and −8.8°F (−4.9°C) when it curled up; these values correspond to temperature gradients of 3.2°F/in. (0.07°C/mm) and 1.5°F/in. (0.03°C/mm), respectively. Temperature measurements in slabs of other thicknesses at the AASHO test site also showed that the temperature differential was not proportional to the thickness of slab and that the increase in temperature differential was not as rapid as the increase in thickness. Therefore, greater temperature gradients should be used for thinner slabs.