"blowups" will be held to a minimum and that with such a pavement neither expansion joints nor contraction joints will be necessary.

CONCLUSIONS

It will be evident from the foregoing data and discussion that many factors must be considered by the highway engineer in deciding upon the need and justification for expansion and contraction joints and for the determination of the correct spacing of joints when they are used. The scope of the 11-year study of an experimental section of pavement covered by this report was limited to only a few of the factors to be considered and provides factual data for a particular pavement, notably the "growth" of the concrete for which measured data are not generally available in the literature

The results of this study are presented at this time to supplement in a small way the large mass of factual material on joint spacing and the expansion and contraction of concrete pavements which is being assembled by the six States which are reporting on their extensive cooperative research on this subject.

SPACING OF DOWELS

By L. W. Teller, *Principal Engineer of Tests, Public Roads Administration*

SYNOPSIS

A study of the effect of varying the spacing of dowels on the structural efficiency of doweled joints in concrete pavements. By means of the Westergaard analyses, graphs are developed which show that if slab edges are to be adequately protected through stress control the individual dowels must be closely spaced

At the Eighth Annual Meeting of the Highway Research Board, Dr. H. M. Westergaard presented a paper containing an analysis of the mechanics involved in the relief of load stress through the action of dowels at joints in concrete pavements.[1] The analysis covers the case of a load applied on one side of the joint and midway between uniformly spaced dowels It is assumed that at each dowel the two abutting slab ends will deflect equally, that is, the dowel itself will be infinitely stiff For these conditions a method is developed that makes it possible to compute the relief of load stress that will be obtained in the edge of the loaded slab for various dowel spacings

It is of course apparent that the analysis is based upon an assumed ideal condition of dowel stiffness that will not be found in the devices commonly used for load transfer in concrete pavements For this reason values of stress reduction computed by the method are likely to be considerably greater than will be obtained in an actual installation. However, for studies of the effect of varying dowel spacing under different conditions of slab thickness, subgrade stiffness, concrete stiffness and wheel load, the analysis is very useful

By means of the Westergaard analysis the theoretical stress relief obtained with rigid dowels at spacings of 12 to 36 in. with slab thicknesses of 6 to 10 in has been calculated for given conditions of load, slab stiffness and subgrade stiffness. The effect of dowel spacing on relief of edge stress for the several slab thicknesses (h) are shown in Figure 1.

Keeping in mind that the absolute values of stress relief shown could be obtained only with dowels that were infinitely stiff, the graph is of value in demonstrating how rapidly stress relief decreases with increase in dowel spacing particularly with thinner slabs at high bending stresses. It will be noted that for computing the relations shown in Figure 1, a constant load (P) of 10,000 lb. was assumed Obviously the application of a 10,000-lb load

[1] "Spacing of Dowels" by H M Westergaard. *Proceedings*, Highway Research Board, Vol 8, p. 154 (1928).

on a 6-in. slab will produce a very much higher bending stress than it will on a 10-in. slab. Thus, the relations shown in Figure 1 represent a different stress condition in each thickness of pavement It is of interest, therefore, to examine the effect of variation in dowel spacing on the relief of edge stress under conditions such that the loads are in proportion to the strengths of the slabs or, in other words, for a condition of constant stress For the other conditions assumed in Figure 1 the loads required to produce a stress of 300 lb per

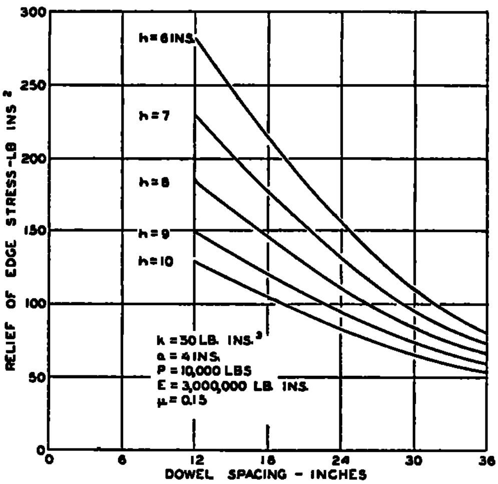

Figure 1. Effect of Dowel spacing on relief of edge stress—for the condition of constant oad.

sq in in the free edge of slabs of the several thicknesses would be as follows:

Slab thickness (*h*)	Required load
in	*lb*
6	4,620
7	6,075
8	7,730
9	9,615
10	11,720

With these load values the stress relief-dowel spacing relation for each of the several slabs is as shown in Figure 2 It will be observed that for the condition of a constant stress, the effect of dowel spacing on stress relief as shown by the shape of the curve is similar for all of the different thicknesses of slab The amount, however, increases with slab thickness. This graph indicates that to bring about a given amount of stress reduction the dowel spacing should be increased as the slab thickness is increased. For example, assume that to balance the design it is desired to reduce the edge stress by 140 lb per sq in. Figure 2 indicates that to accomplish this reduction a dowel spacing of 10⅜ in. would be required in the case of the 6-in. slab while for the 10-in. slab thickness the required dowel spacing would be 14¼ in.

The legend of Figure 1 shows that it was based upon an assumed load of 10,000 lb, a concrete stiffness, measured by a modulus of elasticity of 3,000,000 lb per sq in. and a subgrade stiffness measured by a coefficient, k, of 50 lb. per sq in per inch of deflection.

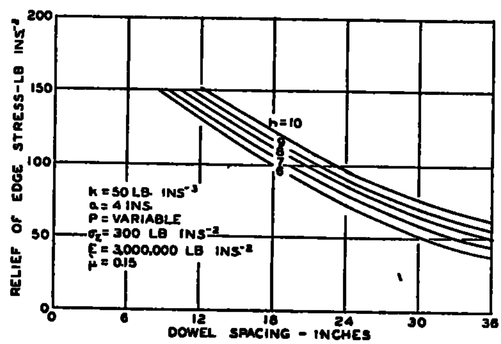

Figure 2. Effect of Dowel spacing on the relief of edge stress—for the condition of constant stress.

Some knowledge of the importance of variations in each of these terms may be desirable An examination of the Westergaard stress equations shows that stress reduction, like stress, varies directly with load, other conditions remaining the same This is shown graphically in Figure 3, where stress reduction curves are given for wheel loads of 5,000, 10,000 and 15,000 lb It will be noted that at any given dowel spacing the stress reduction values are proportional to these loads

The effect of a variation in the stiffness of the concrete on the relief of edge stress to be obtained with various dowel spacings is shown for the case of an 8-in. slab thickness in Figure 4 It is evident from this figure that a relatively large change in concrete stiffness produces a small effect on the amount of stress relief obtained with a given dowel spacing

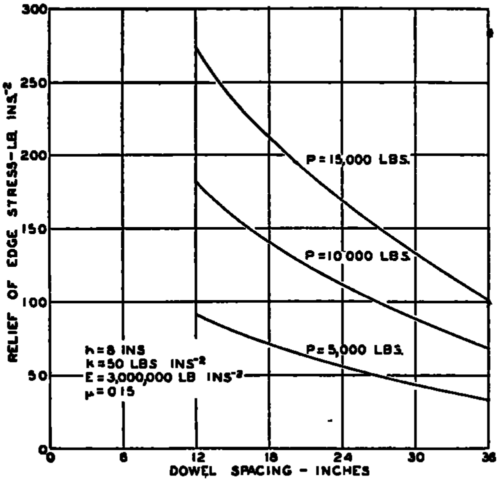

Figure 3. Effect of variations of wheel load

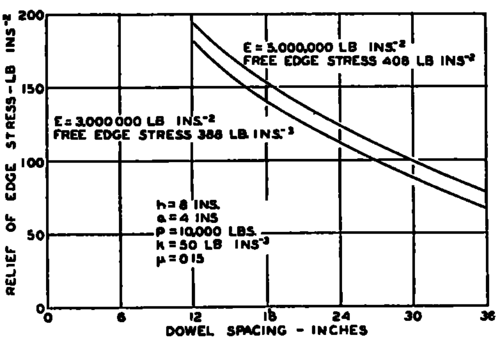

Figure 4. Effect of variation on concrete stiffness

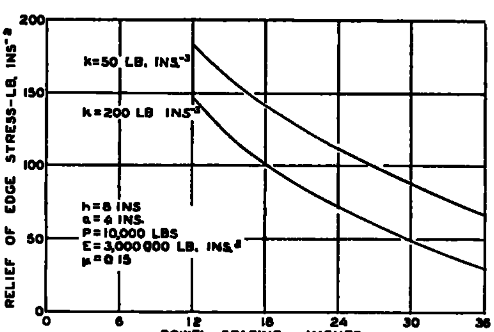

Figure 5. Effect of variation on subgrade stiffness

The effect of variation in the stiffness of the subgrade support is shown in Figure 5 for the case of an 8-in. slab under the action of a 10,000-lb load, the value of the modulus of subgrade reaction being 50 and 200 lb. per cu. in. respectively. This figure indicates that for a given wheel load and slab thickness, to obtain a given amount of stress relief in the slab edge it would be necessary to use a closer dowel spacing on a hard subgrade than on a soft subgrade Since, for given conditions a given load, applied at the edge of a slab of given thickness, will cause smaller stresses on a hard subgrade than on a soft subgrade, it is of interest to express the stress relief values shown in Figure 5 in terms of the edge stress. In Table 1 the stress relief is shown as a percentage of free edge load stress for the conditions that apply to the curves in Figure 5.

This would indicate that, except for very wide dowel spacings, subgrade stiffness does not have an important influence on dowel spacing requirements.

TABLE 1

Subgrade Modulus (k)	Stress Relief (per cent of edge stress)		
	Dowel spacing		
lb per cu. in	*12 in*	*24 in*	*36 in*
50	47	29	17
200	44	22	9

When the study of the structural action of pavement joints, made several years ago at Arlington, Virginia, by the Public Roads Administration, was reported,[2] a method was suggested for measuring the structural efficiency of various joint designs on the basis of the ability of the joint to reduce the critical stress in the loaded slab edge to a value comparable to that which would be produced by the same load applied in the interior region of the slab.

This measure of structural efficiency was expressed in the following manner:

$$e = \frac{\sigma_f - \sigma_j}{\sigma_f - \sigma_i}$$

[2] "The Structural Design of Concrete Pavements, Part 4.—A Study of the Structural Action of Several Types of Transverse and Longitudinal Joint Designs" reported by L. W Teller and Earl C. Sutherland *Public Roads*, Vol 17, No 7, September 1936

in which e = structural efficiency (per cent).

σ_f = critical stress for the load applied at a free edge.

σ_j = critical stress for the load applied at the joint edge

σ_i = critical stress for the load applied at an interior point.

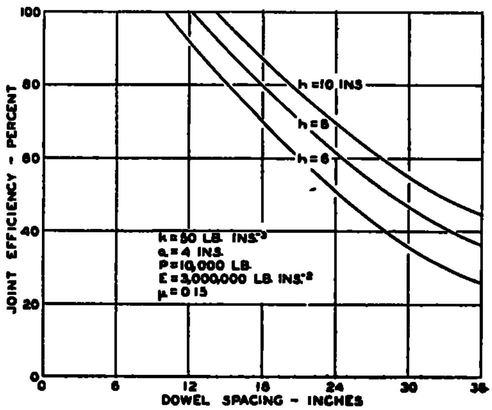

Figure 6. Theoretical effect of Dowel spacing on the structural efficiency of joint-rigid dowels.

Since the Westergaard analyses provide means for computing free edge stress, joint edge stress and stress for the case of interior loading, it is possible to apply these computed theoretical values to the expression for structural efficiency and thus obtain values for the theoretical efficiency of joints containing rigid dowels at various spacings. A graph of the relation between dowel spacing and structural efficiency developed in this manner is shown in Figure 6 for slab thicknesses of 6, 8 and 10 in. and the other conditions indicated. This graph is of interest as an indication of the rapidity with which structural efficiency falls off as dowel spacing is increased, even with perfect dowel action.

From tests of doweled joints at Arlington it is known that when stresses obtained by strain measurements are related in the foregoing efficiency formula the efficiency values that result are generally much lower than those indicated in Figure 6. That this is so is not surprising since dowels in pavements are not infinitely stiff nor are they perfectly seated in their bearings.

From this analysis it seems clear that, where dowels or other load transfer devices are to be installed for the purpose of protecting slab edges through stress reduction, the individual units must be closely spaced if they are to be effective in performing their intended function.