PRESTRESSED PAVEMENTS, THEORY INTO PRACTICE

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INTRODUCTION

Prestressed Structures and Pavements

Prestressed concrete pavement exploration began in the 1930:s, only a short time after the prestressing of building structures cameinto practice. While prestressing of concrete bridges and buildings has attained a prominent place in construction, its application in pavements is still somewhat of a novelty. This is strange, considering that in structures the steel, conventional or prestressed, serves to take the tension stresses; whereas, in pavements the structural action is entirely dependent on the limited tension strength of the plain concrete. A primary reason for this situation appears to be that the economy of concrete pavements is peculiarly dependent on standardization of design and construction procedures. Competitive pricing, related to well known construction routines and construction speed have dominated the the pavement field, with few possibilities for for variations in types and innovations.

The lesson for prestressed construction is that prestressed pavements must equally lend themselves to a well developed construction routine and construction speed, if they are to become an accepted type of design rather than a curiosity. Prestressed pavements may offer advantages in performance and maintenence, they must also meet conventional pavement construction costs.

Concrete Pavements, Conventional and Prestressed

In U. S. highway practice, three types of pavements with the following typical chacateristics and dimensions have been used extensively.

Short slab plain pavements, with transverse joints spaced about 15 to 25 ft. apart, 9 to 10 in. thick without any distributed steel reinforcement. Relative cost is about \$7.- per yd^2.

Steel reinforced pavements, with transverse joints 40 to 100 ft. apart, slabs 8 to 10 in. thick with wire mesh reinforcement weighing 5 to 8 lb per yd^2. The relative cost is about \$8.- per yd^2.

Continuously reinforced concrete pavements (CRCP), generally 8 in. thick, with 0.6 pct longitudinal steel, causing the characteristic closely spaced transverse cracks, which take the place of joints, steel weight about 20 lb per yd^2. Often transverse steel weighing 1 to 2 lb per yd^2 is used as well. The relative cost is about \$10.- per yd^2.

The three types of design have all been used extensively in various state highway departments as standard designs without serious deficiencies, but perhaps not in any case with lasting optimum performance. The substantial mileage of CRCP placed during the last 20 years, at cost clearly higher than the other two types, is an indication of recurrent design questions. Plain short-slab pavements have been troubled by faulting at transverse joints, to prevent which the Federal Highway Administration is calling for general use of corrosion resistant dowels, (Ref. 1). Conventional reinforced design pavements have been troubled by breakage of the distributed

steel and wide cracks, caused by rusting and by immobilizing of dowels across transverse joints. CRCP, while eliminating the joints and their associated difficulties, have been beset with failures where cracks occur too close together, and at construction joints where freshly placed concrete cannot follow the movements of adjacent older pavement, with resultant close crack spacing, large deflections and foundation deterioration.

Increasing concern over performance of the conventional standard designs, has led to the recent explorations of prestressed pavements in U. S. highway construction. Wide acceptance and economical construction of prestressed highways hinge on the perfection of simple and effective prestressing methods and procedures, construction practices which do not hamper paving speeds, and design details for lasting performance.

The prestressed highway pavements in U. S., over 160,000 yd^2, which have been placed or are in construction since 1970, have been 6 in. thick, with 400-ft. or longer slabs, prestressed in longitudinal direction only with post-tensioned steel. The pavements have been placed on friction reducing membranes on treated bases. Plastic encased strands have been used at 24-in. spacing, to produce over 200 psi prestress with 1/2-in. strand, or over 300 psi with 0.6-in. strand on one project with 600-ft. slab s. The 24-in. strand spacing has been chosen to fit 12 ft. wide lanes and the common 12-in. dowel spacing at transverse expansion joints.

The high-strength grease protected and plastic encased strand type, and numerous types of strand anchors are readily available, as are light single-strand post-tensioning jacks. All are widely used in building and bridge construction. These products have made post-tensioned strand prestressing the logical choice for pavements as well. Stainless surface sliding dowels can be used without prohibitive cost in the widely spaced expansion joints. The single or double joints are at post-tensioning gaps, which are filled in after initial period slab shortening movements.

Transverse prestress has not been used. As shown later, it is of doubtful structural value in 6-in. slabs. It would disproportionately increase the cost of the pavement.

Using prestressed pavement designs as outlined above, their construction cost is within the range of conventional highway designs, below the cost of CRCP by actual bid comparisons. The real advantage must be in performance. The transverse joints are in continuing development. Highway pavements have benefitted from fairly uniform load limits and design practices and extensive information on performance. For these reasons, the structural comparisons between prestressed and conventional pavements in this expose relate predominantly to highways. These comparisons give indications to performance advantages of long prestressed pavements.

Prestressed Airport Pavements.

In U. S. the few prestressed runway and taxiway pavements have been small exploratory projects for the Navy or the Army Corps of Engineers. Pavement thicknesses have been 6 to 9 in. with about 500-ft slabs, prestressed to some 400 psi with post-tensioned steel. The wide pavements, placed in three passes have been tied together with post-tensioned steel.

In European practice, prestressed pavements have been used more widely in airport construction during recent years. A slab thickness of 7 in. is common, with 400 to 500 ft. between transverse joints. Longitudinal and transverse prestress in the multiple lane pavements is 200 to 300 psi with -generally- post-tensioned steel.

Attempts have been made in Europe to use continuously prestressed pavements without transverse joints. The pavements have been placed between very solid project end abutments, and the longitudinal prestress fluctuates with concrete temperature and moisture content to high maximum

compression in summer. The method has apparently been very successful on one airport project with limestone aggregate. It has not been used successfully in highway or airport pavements with conventional concrete aggregates.

The great variation in maximum loads on airport pavements, up to 48 kip per tire of twin tandem gears with 4-ft. tire spacing and 5 ft. in tandem, requiring up to 14 in. thick slabs, does not permit great uniformity of design. While prestressing would seem to offer great potential advantages, comparisons with conventional runway and taxiway performance are not available in the literature. For these reasons, prestressed pavement applications in airport construction generally may come slower.

Material Conservation and Energy Savings

The base product cost comparison between concrete and bituminous pavements has changed drastically in recent years. From 1972 to 1976, portland cement concrete increased 25 pct in cost per yd^3, while asphalt cement concrete increased 75 pct, to about twice the cost of concrete. The increasing asphalt cost follows the scarcity of petroleum and can be expected to go higher. It is probable that concrete pavements will be increasingly used in all classes of pavements in future years.

The different standard designs of highway pavements show substantial differences among themselves in material and energy needs. Table 1 lists the comparative concrete and steel requirements for short-slab pavements with doweled joints, for reinforced pavements with doweled joints, and for CRCP, as well as for prestressed pavements with paired expansion joints 500 ft. apart.

As seen in Table 1, the amount of steel used in prestressed pavements is not significantly more than used for dowels and supports in joints alone 20 ft. apart, and very much less than used in other pavement designs. The saving in concrete is appreciable.

An approximate estimate of energy consumption in the basic materials for the different types of design is included in Table 1. It is based on energy consumption for production of steel and cement (Ref. 2), including aggregates, transportation and placement. The energy consumption figures listed indicate that the construction of prestressed pavements would save about 1/3 to 1/2 of the energy expended in conventional pavements.

TABLE 1. MAIN CONSTRUCTION MATERIAL REQUIREMENTS AND ENERGY CONSUMPTION IN CONCRETE PAVEMENTS.

Pavement design	Concrete		Steel requirement, lb / yd^2				Energy requirement, 10^6 Btu / yd^2		
	Thickness in.	yd^3/yd^2	Slab steel	Transv. joint	Long. joint	Total	Concrete	Steel	Total
Short-slab	9.5	0.26	-	3.0	0.2	3.2	0.79	0.06	0.8
Reinforced	9.0	0.25	6.0	1.0	0.2	7.2	0.75	0.15	0.9
CRCP	8.0	0.22	20+2	-	-	22	0.67	0.45	1.1
Prestressed	6.0	0.17	2.7+1	0.3	0.2	4.2	0.50	0.08	0.6

Energy requirement estimates: Concrete, $3.0 \cdot 10^6$ Btu / yd^3 in place,
Steel, 20,000 Btu / lb in place.

PAVEMENT BEHAVIOR AND PRESTRESS EFFECTS

Environmental Influences

A pavement is a complex load-supporting structure. The stability of the supporting soil foundation is dependent on deflections and consolidations under repeated loadings. Any voids under the pavement, especially at edges and slab ends, may fill with water and subject the foundation to damage by water during traffic movements if it is suscepible to erosion.

The environment causes temperature and moisture variations in the pavement which induce concrete deformations, slab end deflections, and stresses throughout the slab length. These environmental stresses can be of the same order of magnitude as traffic load stresses. Without consideration of these large environmental influences, the design of the pavement structure for traffic loads becomes only an empirical exercise, of some value for minor dimensional variations and load repetitions, but not suitable for the greater dimensional variations possible in prestressed pavements.

The temperature and moisture gradients from top to bottom result in unit deformation gradients, which induce curvatures and vertical movements. These deformations and deflections can occur freely only at slab ends and edges. The vertical movements change the even support of the pavement on the foundation; the corresponding loads for vertical lifts are limited to the weight of the slab not in contact with the foundation. The loads result in moments, increasing from slab ends inward, with flexural stresses and strains opposed to the deformations gradients, increasing to equal the deformation gradients at some distance from the ends. All points further away from the ends, subjected to the same temperature or moisture deformation gradients, are fully restrained by the flexural restraint stresses, and remain flat on the base. The distance from the ends to full flexural restaint is comparatively short, with the remainder of long slabs fully restrained and under full flexural restraint stress. These restraint stresses may counteract completely the flexural traffic load stresses depending on the environment.

While flexural restraints increase parabolically from free ends, with all but a few feet near joints and cracks of long slabs at full flexural restraint stress, frictional restraints increase linearly from freely moving ends and at a much slower rate, so that full frictional restraint is not common several hundred feet away, for normal temperature changes. Friction resistance reverses direction in direct response to movements; however, in long slabs and on bases with shear-movement relationships of their own, the partial restraint stresses and corresponding strains away from slab ends decrease and reverse direction, without being reflected in proportionate slab movement, for several degrees of temperature change in the daily average concrete temperature cycle. The result is a characteristic hysteretic behavior of slab end movements in long slabs for the daily temperature cycles, (Ref. 3), with important information on elastic slab behavior awaiting further study.

Frictional forces, although at the bottom of the slab, do not involve flexural restraint additional to that already determined for warping, to equal the flat pavement profile. Frictional strains must also be equal from top to bottom; accordingly, frictional stress distribution on the cross section corresponds to the modulus of elasticity variation from top to bottom, for the daily stress cycles.

Moisture Warping

The existence of a moisture gradient in pavements, from the relatively dry surface concrete to the substantially saturated concrete at bottom of the impermeable slab, is natural and generally recognized. Dry concrete shrinks, rapidly at early age and at a decreasing rate throughout its life; moist concrete, by comparison, is subject to some slight swelling at mature ages, (Ref. 4). The relative shortening of the pavement top surface must result in upward warping of slab ends, and compression restraint stresses at bottom away from slab ends and edges. The upward warping of pavement ends, or the equivalent existence of voids under joints,is common for all concrete pavements and a cause for concern on non-draining foundations, (Ref. 5).

Warping movements and restraint stresses in concrete pavements are not easily determined, caused as they are by developing shrinkage gradients, with some seasonal fluctuations, and restrained by stresses with different stress-strain relations at top and bottom, and different creep behavior in the dry top and the moist bottom concrete.

Warping behavior and warping restraints of prestressed slabs have been investigated in a single experimental project at University of Missouri, Rolla, from 1956 to 1958, (Ref. 6). The significant and apparently extremely beneficial warping restraint stresses in longitudinal direction of long monolithic pavements, suggested by the following analytical data, have been derived from that research.

In the project, temperature gradients, length changes and curvatures were observed in $5\frac{1}{2}$- and 8-in. slab elements in normal highway locations with granular bases and shoulders, and with normal highway concrete, 25- by 222-in. long, eight slabs of each thickness. The slabs were under prestress of, nominally, 0, 100, 300, and 500 psi, uniformly distributed on the end sections by plates and held constant by heavy spring assemblies. Progressive and cyclic length, curling and warping changes were observed to two years age.

Progressive warping deformations as well as length changes increased with prestress. Figure 1 shows the unit deformations at top and bottom, for zero temperature gradient, a short distance in from the ends, where the stress distributions on the cross section were known. Figure 1 shows the deformations at one month in September, at 7 months in late winter, at 21 months in late spring, and at 2 years, early September. The measurements began during covered curing and before prestress application. The data give the total unit deformations near the ends, including swelling and shrinkage in unstressed slabs, plus deformation due to stress application and creep up to 480-psi compression, to the different ages shown. The general slopes of the lines show the sustained modulus of elasticity, effective modulus, E_a to each age for the top concrete and for the bottom concrete.

The observed pavement data are in qualitative agreement with the shrinkage and creep measurements of Ref. 4, on cylinders of different diameters, at different rates of moisture, and at different stresses. Fortunately those tests extended to over 20 years under stress, as a guide to behavior beyond the two year age. The data show longitudinal and creep behaviors to be expected in prestressed pavements near their ends, without Poisson's ratio effects.

The sustained modulus at bottom of a pavement should apparently be based on values for concrete in moist or saturated condition. The modulus at top may vary with climatic conditions, somewhat higher in moist climates than in dry ones. Accepting the Rolla data as typical, the sustained modulus value at top E_{aT} can be assumed to be one-half of the value at bottom E_{aB}. The sustained modulus values observed in the $5\frac{1}{2}$- and 8-in.

slabs are shown in Figure 2, extrapolated to 25 years (10^4 days), on the basis of trends in Ref. 4.

Flexural Warping Restraint Computations

In normal exposures, deformations can be assumed to vary linearly from top to bottom. Near the unrestrained ends, as shown in Figure 1, the deformation gradient from top to bottom is large. Away from the ends, in the flat slab portions, there can be no deformation gradient: the deformations at top and bottom must be equal. The large warping deformations at top must be decreased by tension strains. Compression strains arise near the bottom. The tension force near the top must equal the compression force near the bottom. The total unrestrained warping gradient D is divided between the top tension strain and the bottom compression strain, as follows:

Top tension strain $\frac{D}{\sqrt{\frac{E_{aT}}{E_{aB}}} + 1}$, Bottom compression strain $\frac{D}{\sqrt{\frac{E_{aB}}{E_{aT}}} + 1}$

The corresponding stresses are obtained directly. The distribution of full restraint strains and stresses in a $5\frac{1}{2}$-in. slab for 300 psi evenly distributed prestress, at 30 days, at 7 months and at 2 years age are illustrated in Figure 3. As shown by the stress distribution at right in Figure 3, in the fully restrained slab positions, the top surface stress is decreased to about 0, -100, and -50 psi, and the bottom stress is increased to about -600 psi or more from the 300 psi prestress at the ends.

The even distribution of prestress at the ends results in the relatively high warping deflections at the slab ends. In the observed $5\frac{1}{2}$- and 8-in. slabs (Ref. 6), warping deflections were twice as great in the slabs prestressed to 480 psi as in slabs without prestress, from 0.07 without prestress to about 0.15 inch. Obviously, the slab ends were not in contact with the foundation at those deflections.

End warping deflections will generally involve slab ends without ground support, with weight of the unsupported end contributing to the full restraint moment as the end support is shifted inward. The deflections in the supported portion will be distributed from the point of reactive support, x , in proportion to

$$e^{-\beta x} \cdot \sin \beta x \; ; \qquad \text{where} \qquad \beta = \sqrt[4]{\frac{k \cdot b}{4 \cdot E_a \cdot \frac{b \cdot h^3}{12}}}$$

The E_a value is the prorated values between top and bottom, k is the modulus of subgrade report, and h is the slab thickness. The horizontal tangent nearest the end is at a distance $\frac{1}{4}\pi/\beta$ into the reactive support length, where full restraint can be assumed to occur. The warping deflection can then be estimated from the unrestrained curvature, less the end deflection caused by the restraint moment. The procedure is illustrated in Figure 4, showing the accumulation of warping restraint moments in the $5\frac{1}{2}$-in. slab for a modulus of subgrade reaction of 100 pci at 7 months, in late winter, at least warping. The estimated warping deflection is 0.053 in., with 40 inches out of ground contact. Computed on the same basis, the end warping would be 0.096 in. at one month and 0.12 in. at two years.

Undesirably large warping deflections at the ends can be decreased by prestress concentrated below mid-depth, as illustrated in Figure 5, which shows estimated warping and warping restraints of a 6-in. slab with average prestress 200 psi, centered $\frac{1}{2}$ in. below mid-depth, 100 psi at top and 300 psi at bottom at the ends, at five years. The prestress distribution beyond the point of full restraint is +30 psi at top and -485 psi at bottom; the full restraint is about 65 in. from the slab end, and the warping deflection is 0.030 in. for the $1.7 \cdot 10^{-6}$ per inch warping curvature, for this maximum summer warping.

As a general rule, because of warping, the effective prestress at the slab bottom is about twice the average prestress in the fully restrained slab portions, irrespective of prestress distributions at the ends. The warping deflection at the ends is about one-half of the unrestrained warping taken from the point of horizontal tangent at full warping restraint. While for evenly distributed prestress at the ends the warping deflections are objectionable, by centering the prestress below mid-depth, the end warping can be reduced to insignificant amounts.

As shown by unit deformations in Figure 1 for slabs without prestress, swelling to $50 \cdot 10^{-6}$ at bottom and shrinkage to $150 \cdot 10^{-6}$ at top in two years, in both $5\frac{1}{2}$- and 8-in. slabs, the moisture influence in pavements appears not to change appreciably with thickness; the bottom becomes substantially saturated for any thickness.

Temperature Curling

Temperature gradients during the evening and nighttime heat loss periods at the surface do not exceed 2° F per in. depth. The daytime curling in full sun seldom exceeds 3° F per in. depth, equivalent to at most $20 \cdot 10^{-6}$ per in. unrestrained curling curvature at slab ends. Flexural curling restraints during night conditions involve slab end lift, adding to warping restraints. The daytime curling restraints involve downward slab end movements, counter to the warping lifts. Compared to the unrestrained warping curvatures during summertime of some $40 \cdot 10^{-6}$ per in., the warping and warping restraint stresses will only rarely be appreciably decreased by the temperature curling restraints.

The effective modulus for determination of curling restraint stresses is probably substantially higher than the sustained modulus for the continuing warping stresses. The curling is subject to a normal 24-hour cycle of reversing curling restraint stresses, for which creep tests are known. Lacking supporting data, the effective modulus for the cumulative reversing curling restraint computation might be based on sustained modulus for 1/4 of the age in Figure 2.

The temperature differences between top and bottom during curling increase with slab thickness; the curling restraint stresses must then increase proportionately. As the daytime effect is to cause curling restraint flexural tension at bottom, adding to traffic load tension at bottom, any decrease in thickness practical with prestressing is favorable. Furthermore, daytime frictional resistance to expansion causes increasing compression stresses away from slab ends, decreasing the combined friction and curling restraint tension in long slabs. These conditions combine to eliminate temperature curling from consideration in the appraisal of critical pavement stress conditions in this expose.

Structural Value of Prestress in Pavements

The value of all prestress applications rests on the axiomatic assumption that stresses resulting from prestress serve to counteract load stresses. In pavements, the prestress serves directly for this purpose at ends and at cracks. Additionally in pavements, the highly valuable flexural warping restraint stresses away from ends and cracks are a lasting environmental bonus of prestressing in long slabs, providing the most valuable distribution of compression stress on the pavement cross section. Load stresses can be appraised in relation to these natural combinations of stresses away from ends and cracks.

Good curing practice and early introduction of prestress are the principal means by which cracks during the early critical period can be prevented. A most important purpose of prestressing of pavements is to assure, to the greatest practical extent, the existence of these natural

and lasting valuable stress conditions in long slabs.

Near joints, load stresses can be appraised in relation to the joint construction, such as dowels or special supports, and to the existing distribution of prestress at the critical sections near the joint.

In pavements, cracks can be decreased by introduction of prestress and design; however, some transverse cracks caused by unforeseen foundation movements or an exceptional load cannot be economically prevented. At cracks, load stresses can be decreased below those at a free end only by firm aggregate interlock available across a closed crack. A second purpose of pavement prestress, then, is to assure that any crack in the pavement is under sufficient compression to remain effectively closed at all times.

Prestressed Pavement Length Changes

Prestressed pavements are subject to the normal average-temperature 24-hour cycles and seasonal cycles of conventional pavements of the same thickness. The daily cycles are restrained by reversing frictional stresses. The seasonal cycles would not seem to be restrained by subgrade friction; however, the seasonal cycles appear to be influenced by moisture pickup during the cold season equivalent to some $100 \cdot 10^{-6}$ unit deformation beginning in late fall and decreasing in effect from spring to late summer.

Progressive Length Changes

Progressive length changes caused by prestress could apparently be based on the average prestress without consideration of frictional tension decrease during night contraction, or frictional compression increase during the day, on the assumption that these effects balance each other along the slab. The progressive creep in long prestressed slabs should then be subject to equal unit deformations throughout.

In Figure 6, the progressive length changes in $5\frac{1}{2}$-in. slabs at Rolla are shown, from 10-day age to 2 years, with straight line extrapolation to 10^4 days, or about 25 years, on the logarithmic scale. The one-year age is shown, with 10-month length changes extrapolated to 12 months in good agreement.

The data in Figure 6 have been used to estimate the total progressive shortening of prestressed slabs. No significant shortening is indicated in unprestressed pavements after the first month. For slabs prestressed during the first week, the estimated shortening to 30 days is 0.10, 0.14, 0,18, 0.22 and 0.25 in. per 100 ft., and the progressive shortening from 30 days to about 25 years is indicated to be not over 0.05, 0.10, 0.16, 0.20, and 0.22 in. per 100 ft. of slab length, for 100, 200, 300, 400, and 500 psi lasting prestress, respectively, in a 6-in. pavemnt. A 400-ft. slab under 200 psi average prestress could accordingly be expected to shorten about 0.4 in. after the first month of shortening of about 0.5 in., based on the Rolla tests.

The seasonal moisture-induced fluctuation in length is apparently independent of prestress, about $100 \cdot 10^{-6}$ as shown in Figure 6. For a 400-ft. slab, the cold-season swelling is about 0.5 in. in late fall, with a corresponding seasonal shrinkage in late spring. Assuming this seasonal fluctuation occurs yearly, in the mature 400-ft. pavement at 200-psi prestress the progressive shortening would vary from about 7/8 in. during summer to 3/8 in. for late winter measurements.

Thermal Contraction And Expansion

Superimposed on the progressive length changes are the temperature move-

ments in individual slabs. They are directly related to the concrete coefficient of thermal expansion, with a range from $7 \cdot 10^{-6}$ to less than $3 \cdot 10^{-6}$ per degree F. depending primarily on the coarse aggregate. The thermal coefficient has been found to be higher for low than for high temperatures, changing from $7 \cdot 10^{-6}$ at 10° to $5 \cdot 5 \cdot 10^{-6}$ at 100° F. in gravel aggregate concrete (Ref. 7). At the same time, the coefficient has been found to be maximum at about 70% relative humidity, decreasing to 100% saturation, from about $7 \cdot 10^{-6}$ to $6 \cdot 10^{-6}$ in quartz aggregate, and from $3 \cdot 5 \cdot 10^{-6}$ to $2 \cdot 5 \cdot 10^{-6}$ in limestone aggregate concrete, all per degree F. (Ref. 8).

Seasonal temperature cycles in prestressed pavements, in the U.S., may range from 50° F. in the south to 100° F. in the north, with the seasonal movements assumed to occur without frictional resistance. The corresponding seasonal length change would be from 0.2 to 0.7 in. per 100 ft. length, depending on the concrete and the location.

Added to the seasonal length variations are the nighttime contraction at low and the daytime expansion at high temperature, both of which are restrained to some extent by frictional stresses, varying with slab length, from 0.07 in. in 400- to 0.12 in. in 600-ft. slabs. Including the daily cycles, the temperature length changes in prestressed pavements for the total yearly temperature cycles may be from 0.3 to 0.9 in. per 100 ft. of slab length. In any case, these temperature-related length changes from maximum summer to minimum winter temperature are partially compensated for by the cold season swelling of the concrete. During the life of a pavement, the total range of joint width increase between 400-ft. slabs may be about 2 in. to about 4 in., depending on concrete aggregate primarily.

TRAFFIC LOAD STRESSES AND DEFLECTIONS

General Assumptions

At present, the design of a prestressed pavement is based on the assumption that it behaves elastically under traffic loads identically to the the same pavement without prestress. Prestress, properly distributed on the cross section, can then be added directly to the cross-section flexural stresses determined for a conventional pavement of equal thickness and width.

Traffic load stresses and deflections have been computed for a pavement slab not less than 4 in. thick under a single 20-kip axle in the usual governing locations for design. The concrete has been assumed to have $5 \cdot 10^6$ psi elastic modulus. The foundations have been assumed to have 100, 200, and 400 pci modulus of subgrade reaction. No Poisson's ratio effects have been included.

The iterative process Sector Analysis has been used (Ref. 9), for computations of stresses and deflections. In this method, elemental sectors, loaded by tire pressure from above and by subgrade reaction from below, are analyzed to determine the elastic lines and subgrade reaction distribution in each element and between the differently oriented elements, from which the radial flexural stresses and deflections are obtained directly. The combined effect of two wheels is obtained by superposition. The wheel centers have been assumed 71 in. apart; the wheel load imprints have been assumed to be 18 in. wide and 12 in. long away from joints; however, at the transverse joint 9 in. length has been used.

Tandem axles do not increase stresses significantly; however, deflections under tandem axles may be appreciable larger than under a single axle with the same load per individual axle.

Axle Loads Away From Transverse Joints

Figure 7 shows stresses in longitudinal and transverse direction for the single axle in normal tracking on a 12 ft. wide lane. The maximum flexural tension stresses are at bottom under each wheel in longitudinal direction. In 6=in. and thicker pavements, the transverse direction stress is less than one half of the longitudinal stress.

Figure 8 shows the flexural stresses and deflections for an axle with one wheel at the longitudianl edge on on 4- to 10-in. slabs. For this placement, the maximum flexural tension at the bottom along the edge and the edge deflection are much greater than for an axle in normal tracking on the 12-ft. lane. The transverse direction maximum tension is at top, 24 to 35 in. from the edge, and much lower than in longitudinal direction.

The maximum flexural stresses are quite high in the thinnest slabs; in a 5-in. slab 400 to 500 psi effective prestress would be required to bring maximum tension stress below about 300 psi; however, even in a 5-in. slab, the maximum tension in transverse direction is below 300 psi. Transverse prestress would not seem to be needed. The maximum edge deflections under the single axle decrease with increase in foundation modulus much more than the stresses which do not change significantly in transverse direction for 100- to 400-pci foundations.

Axle Load at Transverse Joint.

The critical position for the axle at a joint edge is with one wheel load at the slab corner of an open joint. In this position, the axle may be partially over the open joint, with increase concentration of wheel loads on one joint edge. In Figure 9, stresses and deflections have been analyzed, along the joint edge and along the longitudinal pavement edge, for a joint open 3 in. with $1\frac{1}{4}$- in. round dowels spaced 12 in. for load transfer. The dowels serve to unload the joint edge carrying the axle, placing an equal portion of the axle load on the far side of the joint.

Round dowels for load transfer have been investigated, (Ref. 10) and their design outlined (Ref. 11). To avoid high bending stresses in dowles crossing wide joints, larger than usually proportioned dowels are needed. The computed rate of dowel deflection for $1\frac{1}{4}$-in. dowel crossing a 3 in. wide joint is 0.006 in. per kip dowel shear (Ref. 11).

The dowel shear acts as loads on the slab ends, upward on the loaded side, downward on the far side. The rates of deflection of the slab ends can be determined , considering the dowel as loading a pavement strip, one dowel spacing wide, in longitudinal direction at the end. Knowing the deflection of the joint edge without dowels, and the rates of deflection of the dowel across the joint and the slab ends under dowel loading, the dowel loads and dowele joint edge deflections and stresses can be determined.

The pavement strips are analyzed by beam on elastic foundation methods. For 6 in. pavement thickness h, and concrete elastic modulus E, 12 in. dowel spacing b, and 200-pci foundation modulus k, we obtain:

$$\beta = \sqrt[4]{k \cdot b / 4 E \cdot b h^3/12} = \sqrt[4]{k / 4 E h^3} = 0.0272.$$

The deflection at the slab end for 1000 lb load in $100 / 2\beta^3 E bh^3/12$, giving a rate of deflection of 0.023 in. per kip load. The total cross-joint deflection is (2· 0.023 + 0.006) per kip dowel shear, giving the dowel load at each dowel to equal the slab end deflection without dowels. The dowel shears, so determined are shown in Figure 9. The stresses and deflections for the edges without dowels were determined by sector analysis, with the inside wheel 80 in. from the edge. Tire sector dimensions and distributed sector loadings are shown. The total dowel shear across the 12-ft. joint is 5.6 kip, 28 pct of the axle load. The dowel 6 in. from the edge is loaded to 1.15 kip. The deflection of the loaded joint corner is about 0.04 in.

Along the joint, the doweled joint deflections are proportionate to the deflections without dowels; the stresses along the joint egde are then decreased in the same proportion. At the most heavily loaded corner dowel the joint edge deflection is decreased from 0.06 in. by 1.15 · 0.023 , or 0.026 in., to 0.034 in. The dowel relief for joint edge stress is accordingly about 43 pct.

Along the longitudinal edge, the moments and stresses in the 12 in. wide beam, loaded with 1.15 kip at the end, are determined by elastic support methods. For the case in Fig. 9, the maximum top tension without dowels is about 530 psi; the maximum flexural stress of the dowel relief load is 200 psi amximum 25 in. from the end. The dowel stress relief is about 36 pct. , the maximum sector stress being nearly the same distance from the corner.

The procedure is illustrated in Fig. 9 is some detail, because it is not known to have been published earlier. Deflections and stresses are effectively decreased by the dowels. The individual dowel shears are lower than conventionally assumed. The stiffness of the dowels can be neglected in comparison with the stiffness of the 12 in. wide slab strips. The maximum moment in the 1¼-in. dowel across a 3-in. joint is about 3300 in.lb. and the flexural stress in the dowel about 17 ksi. The concrete bearing stress at the face of the joint is about 3 ksi. The large dowels are needed across the joint near the edges, to keep dowel bending stresses and concrete bearing stresses within acceptable limits across wide joints between prestresses pavement slabs.

Prestress and Pavement Design Criteria

The primary purpose of prestress in pavements is to counteract the flexural traffic load stresses, and to prevent, to the greatest practical extent, transverse cracks in long slabs. Prestress, if applied at early age, may actually increase the flexural strength of the concrete, by preventing interior micro-cracking.

A limiting flexural stress of 350 psi for traffic loads is frequently used in pavement design, to avoid fatigue cracking in pavements with 700 psi st engtth. The flexural stress in longitudinal direction may reach 550 psi, fig. 8. for edge load axle on a 6-in. pavement on 200-pci foundation. A bottom prestress of 200 psi should suffice to bring the flexural stress within acceptable limits anywhere along the slab at any time, and generally to a much lower maximum stress, about 150 psi for 200 psi average cross section prestress. Fatigue stress considerations probably do not apply for 6-in. prestressed pavements.

Transverse direction stresses, as shown in Figures 7 and 8, are much lower than the longitudinal direction stresses away from transverse joints. It is doubtful that transverse prestress could be economically justified along highway pavements. Parallell to transverse joints, some prestress could be useful to protect the joint face and assure satisfactory dowel performance.

Prestressed Pavement Deflections.

The maximum edge deflection under a single 20-kip axle could reach 0.025 in. in a 6-in. pavement on a 200pci foundation. At a transverse joint corner, the deflection could reach 0.04 in. (Fig. 9). In either case, the deflection under two 20-kip axles in tandem placement could be appreciably greater. These deflections may not be acceptable on pavements carrying intensive heavy traffic. The solution, in that case, is to use a base with a higher modulus of reaction, or a thickened pavement end at transverse joinst. The construction of prestressed pavements with short thickened ends is practical, thanks to the prestress, using closed cell compressible fillers at the offset.

Allowable deflections in concrete pavements under traffic loads is a not adequately researched subject. On very stiff bases and on structural foundations, apparently very thin prestressed pavements might be acceptable, without exceeding either stress or deflection limits. On normal subgardes, deflections under load may be more critical for pavement performance than stresses.

At the AASHO Road Test, Ref. 5, edge deflections were measured for truck loadings , with the nearest wheel centered 20 in. from the edge. Where the edge deflection was less than 0.015 in. the probability of the pavement section withstanding the full test on the 100-pci foundation, was better than 90 pct. The single-axle deflection of 0.015 in. as measured, corresponds to 0.027-in. deflection for edge loading as shown in Figure 8. The failures on the test road were almost completely throuh loss of base and subgrade material by pumping at transverse joints and edges. Where the base is of a non-eroding type, such failures should not occur. Larger edge and joint delfections should then be acceptable.

Concrete pavements have traditionally been placed with vertical edges. In slip-formed pavement construction, this requirement is by no means essential. A 30- to 40-degree slope of the edge could improve the pavement construction, and would add appreciably to the available support for edge loads. The sloped-edge construction would permit better sealing between the pavement and the shoulder.

A maximum edge deflection of 0.025 in. under a 20-kip axle on a 6-in. pavement, would require a 200-pci or better foundation. At joints, as outlined in Figure 9, a 0.025-in. limiting deflection would require a foundation with 400 pci modulus of support. Prestress centered below mid-depth decreases the normally existing voids at transverse joints significantly, decreasing the deflections under loads as well. To that extent, greater load deflections ca be tolerated under prestressed pavement ends.

Equal limitation on pavement deflections apply to transverse cracks and joints. Aggregate interlock across closed cracks is generally superior to dowels for load transfer. Prestress must be sufficient to maintain compression across cracks under all conditions of climatic changes, anywhere in long prestressed slabs, throughout the life of the pavement.

CLOSURE

The recent prestressed pavement projects in the U. S. have given clear indications of economical construction. Research studies and observations have demonstrated , in addition to the amount of prestress, its very great additional values in preserving naturally existing favorable stresses in concrete pavements and full utilization of of the concrete as a material for ground supported long pavements. These findings give promise of wide use of prestressed pavements in highway and airport construction.

In this paper emphasis is given to the determinations of the favorable stress conditions in long pavement slabs. Traffic load stresses and deflections of importance for appraisal of various choices in the design of prestressed pavements have been included. The data support the general design of the most recent highway projects.

Construction details are not included, because continuing development in techniques and pavement details occasioned by these projects might render such information quickly obsolete. With greater assurance of a wider market, new and old prestressing techniques can be perfected and introduced. The design of pavement ends and joints will be rationalized, and their construction simplified, to assure continuing excellent performance.

E - N - D.

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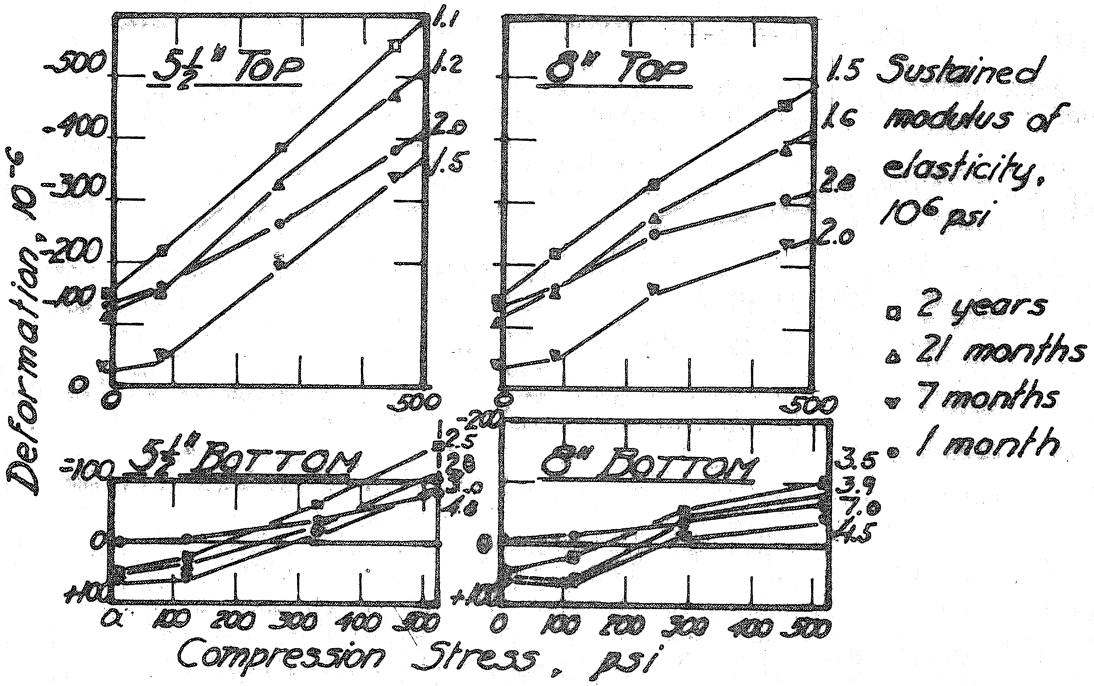


Figure 1. - Observed top and bottom stress deformations at 30-day to 2-year age in 5½- and 8-in. pavement slab elements, for August construction and prestressing.

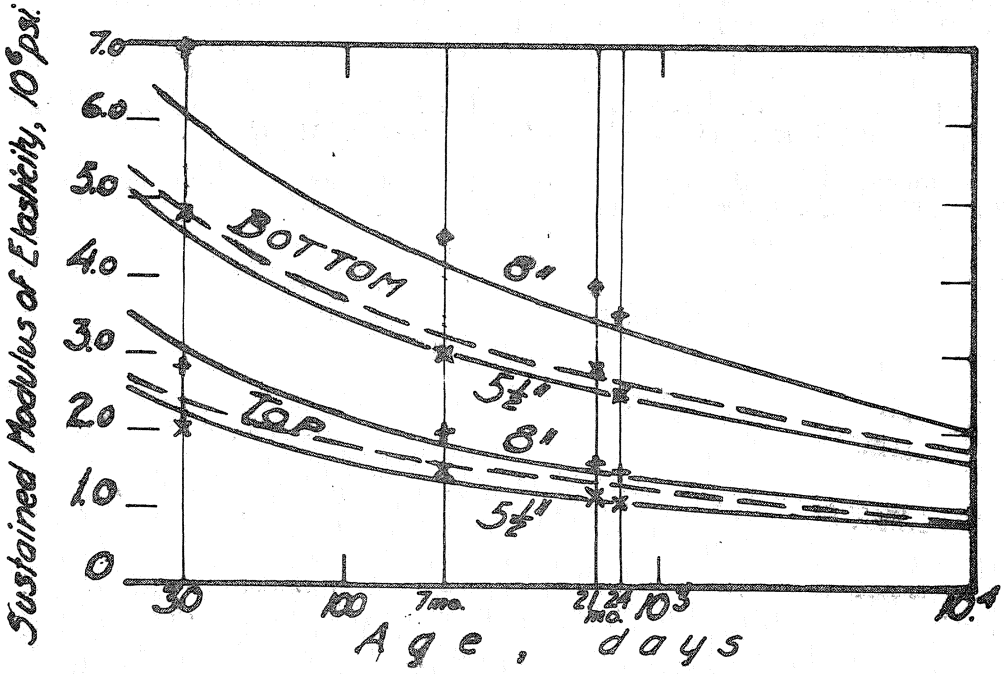


Figure 2. - Sustained effective modulus at top and bottom for pavement prestress, based on observed 5½- and 8-in. slabs. Modulus at top one half of modulus at bottom indicated for 6-in. prestressed pavement by dashed lines.

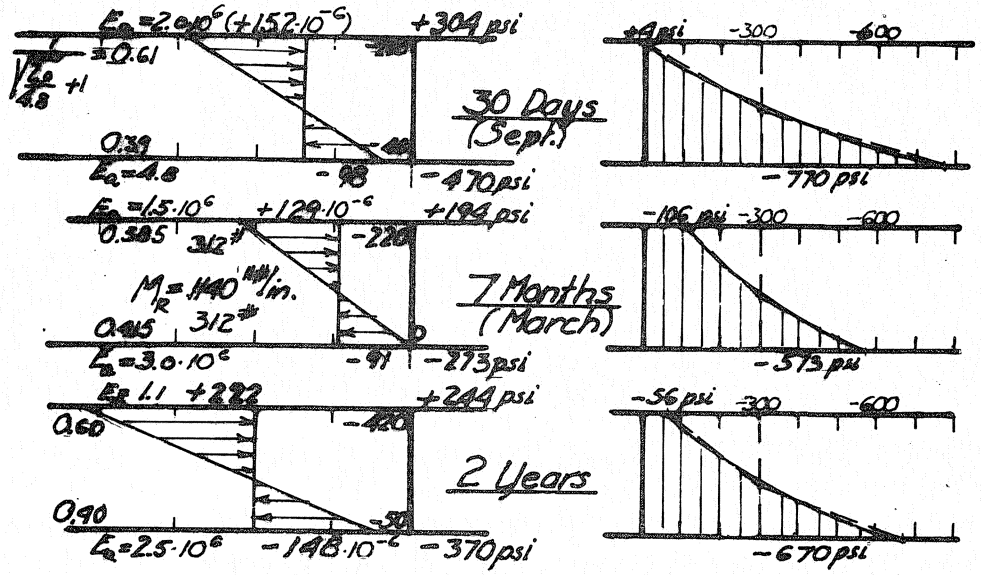


Figure 3. - Top and bottom warping deformations in $5\frac{1}{2}$-in. slab for 300 psi prestress at ends, flexural warping restraint, and actual prestress distribution in flat slab portions, to two years age.

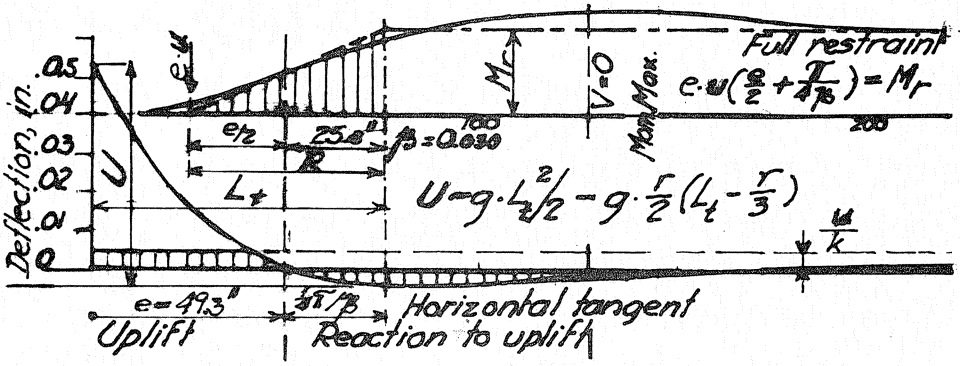


Figure 4. - Warped end deflection, based on full restraint moment of unsupported slab end at section of maximum ground support. Procedure shown for 300 psi prestress $5\frac{1}{2}$-in. slab, winter warping.

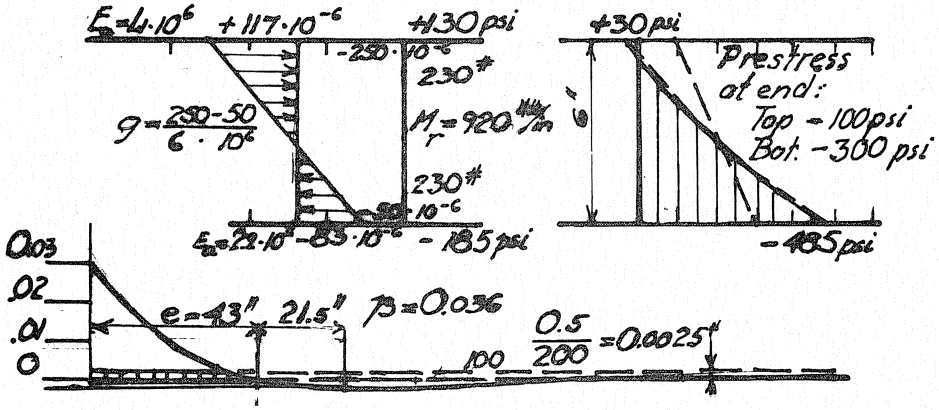


Figure 5. - Prestress below mid-depth decreases end warping. Shown for 6-in. slab on 200-pci base at 2000 days and summer warping.

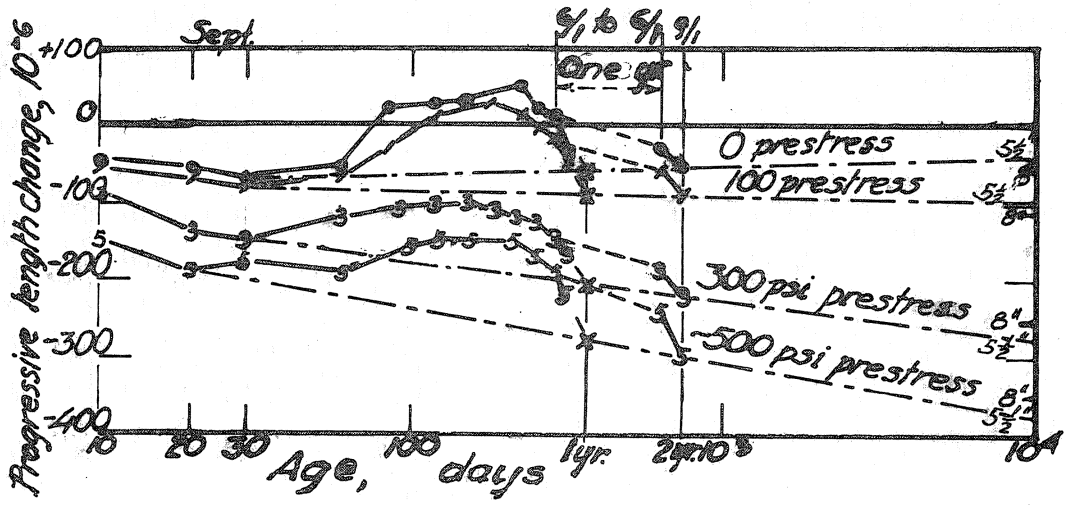


Figure 6. - Progressive length change in pavements prestressed to 500 psi, as observed in 5½-in. slabs to two years age, and projected to 27 years, with values for 8-in. slabs indicated. The gradual cold-season swelling is illustrated.

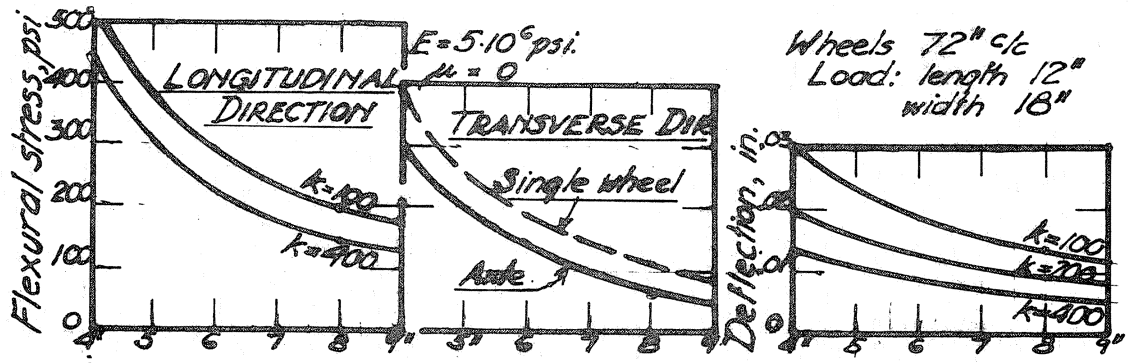


Figure 7. - Maximum flexural stress and deflection in 4- to 9-in. pavements under 20-kip axle at normal tracking on 12-foot lane over 100- to 400-pci base, showing also increased stress in transverse direction under single wheel away from an edge.

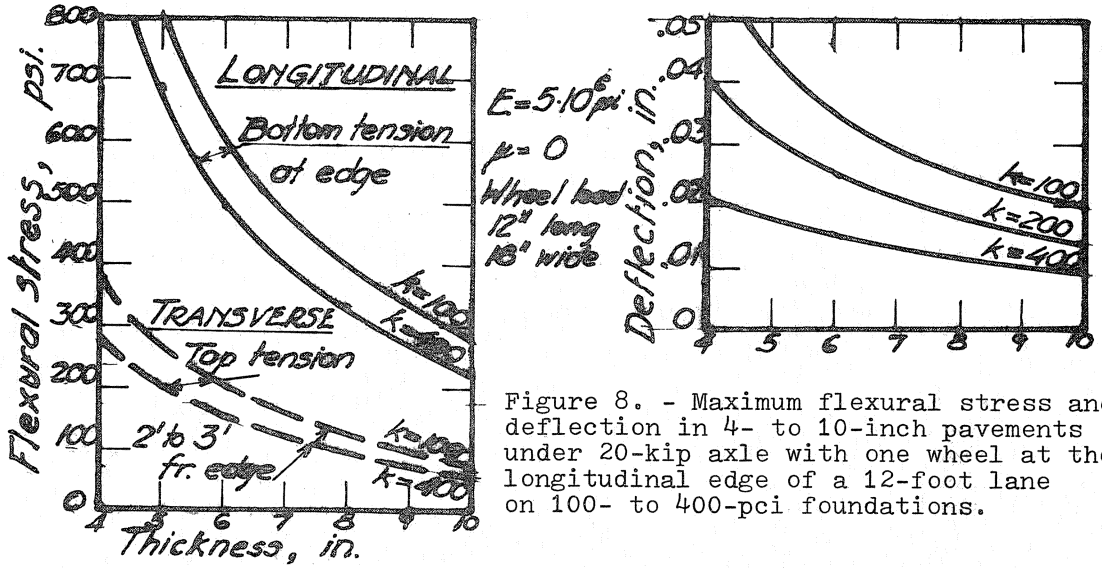


Figure 8. - Maximum flexural stress and deflection in 4- to 10-inch pavements under 20-kip axle with one wheel at the longitudinal edge of a 12-foot lane on 100- to 400-pci foundations.

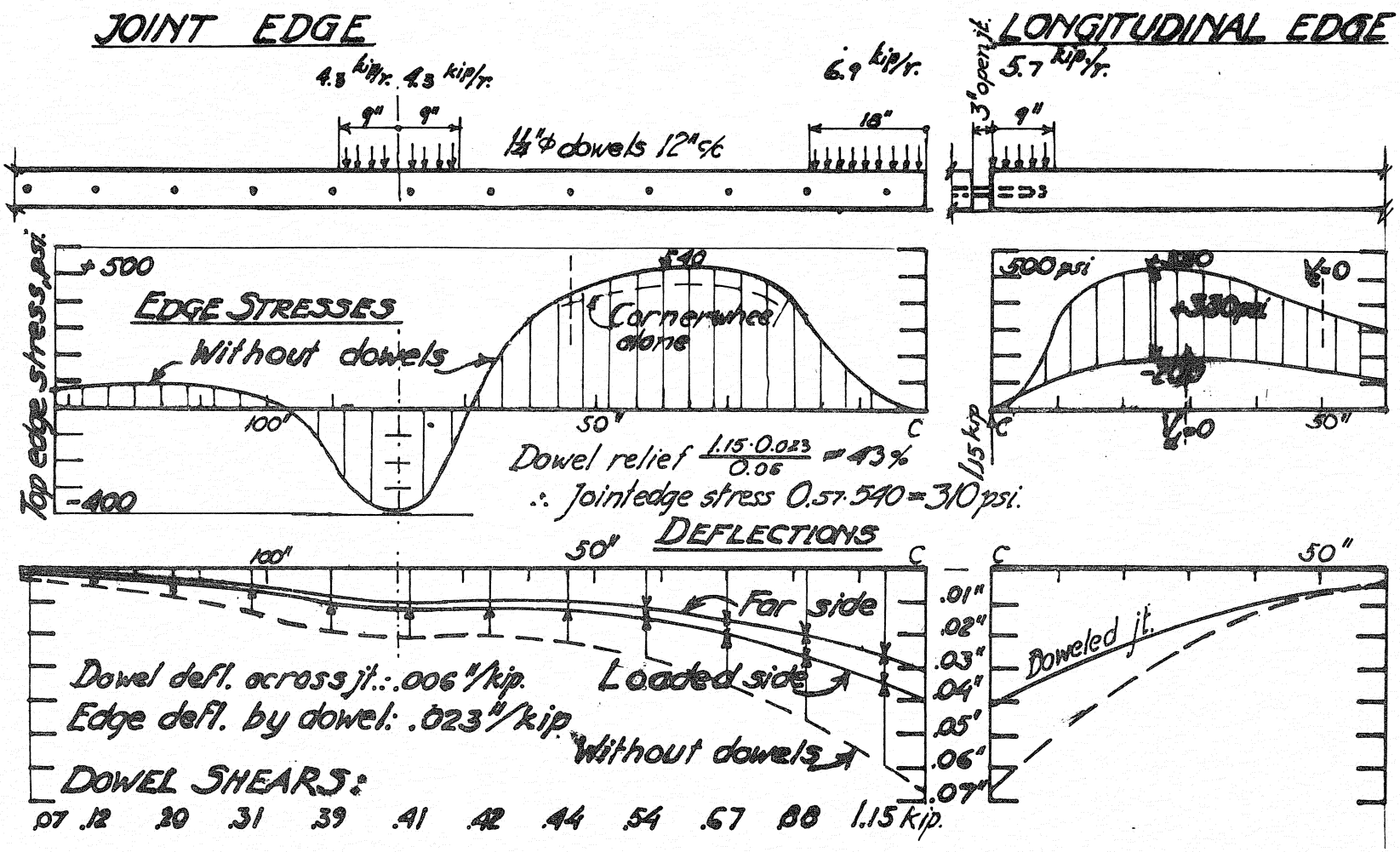


Figure 9. - Stresses and deflections at a transverse joint for 20-kip axle on 6-in. slab with 200-pci foundation modulus without dowels, and dowel effect with 1¼-in. dowels spaced 12 in. across 3 in. open joint.