Pavement Research, Design, and Prestressed Concrete

BENGT F. FRIBERG, *Consulting Engineer, St. Louis, Missouri*

THIS study is premised on the apparent possibility of greatly improved service of concrete pavements through basic improvement in their structural design. Inherent characteristics of prestressed concrete are particularly applicable to that purpose.

Pavement stresses are investigated. Combined stresses are appraised in the light of pavement research since 1935. Approximate stress prognostications for prestressed slabs from 400 to 800 ft. long are suggested.

Longitudinal prestress of 300 psi, applied to single-lane 6-in. slabs up to 600 ft. long, will apparently provide substantial structural improvement over conventional thicker pavements. It is indicated that prestressed construction might be developed to provide prestressed pavements at a cost substantially equal to that of conventional thicker pavements.

● CONCRETE pavements have been used on over 100,000 miles of highways. They are the most common high-type surfacing. Expenditures for surfacing on primary and secondary roads have been about 40 percent of construction funds for these highways, as compared to about 25 percent for grading and structures, each (*1*).

The average expected service life for concrete pavements is less than 30 years, (*2*), and much shorter than the 50-year expected service life for structures (*1*). Conditions of service should lead us to expect for concrete pavements at least equal service life to that shown by structures. Apparently less than optimum performance has been obtained in concrete pavements built up to this time. A major challenge for improvement of concrete pavements pertains to their basic design.

Concrete Pavement Types

Only two types of concrete pavements have remained in common use throughout the period of intensive highway construction up to the present: unreinforced pavements, with transverse joints closely spaced, generally 20 ft.; and pavements containing distributed steel, generally wire mesh, for crack control, with transverse joints up to 100 ft. apart. There has been no major improvement in these two designs up to the present time.

Concrete materials have improved, air entrainment in particular has improved performance in cold climates. Unsound aggregates have been largely eliminated. Sound air entrained concrete is equal to well over 50-year service in the United States' climates. The realization of longer pavement service life, therefore, is not blocked by material limitations.

The thicker pavements built in recent years for heavy traffic are not an assured design improvement. The concrete in them is as highly stressed by combinations of load and temperature as that in older thinner pavements. Design improvement by more effective means than thickness increase is a primary challenge.

Concrete Pavement Deterioration

Most recent concrete pavement failures are of structural nature, as differentiated from failures attributable to weakness or disintegration of the concrete itself (*3*). Pavement deterioration centers at transverse cracks and joints, apparent as progressive subgrade displacement and poor riding surface. In all pavement surveys cracking has been considered a primary indication of pavement deterioration. Closely spaced joints are not noticeably preferable to cracks.

A great number of pavements are resurfaced each year to halt deterioration temporarily and restore their riding surface (*7*, *8*), some at a comparatively early period in their life (*9*).

Unsatisfactory materials have been the cause for some pavement replacements, but they appear to have been of localized nature (*4, 5*), and not a major consideration for the increasing mileages of resurfacing. Even material failures seem to be peculiarly oriented near transverse cracks and joints (*4, 5*). The life of resurfacing is in itself limited by "reflection cracks" from the underlying slab (*7, 10, 13, 14*).

Poor subgrades cannot be disregarded as a continuing deteriorating influence. But, with the exception of localized frost heaves or unusual disturbance of soil equilibrium, subgrade instability appears to be serious exclusively at joints and cracks. Subgrade pumping, a major sign of deterioration of the pavement, has not been of noticeable consequence away from joints and cracks.

These conditions are a challenge to pavement design. Joints must be eliminated, cracks must be prevented in some positive manner by design. Cracks are the result of excessive concrete tension stress which therefore should be controlled by any practical means.

Prestress is specifically aimed at the prevention of tension stresses in concrete. It has become a widely accepted construction method in recent years, and its characteristics and materials have particular interest for consideration of use in concrete pavements.

PRESTRESSED-CONCRETE PAVEMENTS

Principles of Prestressed Concrete

Prestressing is the term applied to the imposition of compressive stress on concrete for the purpose of preventing or diminishing tension stresses in service. Prestressed concrete has been used with spectacular success in structures (*15*), but has not been applied to pavements, except in isolated experimental slabs. Prestressing of highway pavements depends upon the development of methods suitable for normal highway construction speeds, and designs which satisfy financial and service norms of this intensively standardized and competitive field.

Prestress may be imposed by external means, such as pressure cells in transverse joints, provided adequate abutments exist, or by internal highly stressed steel as used, exclusively, in structural prestressing. The steel is pre-tensioned if the concrete is placed around the steel, stressed by exterior means which are slacked off to transfer the force on the concrete; if small wires are used the stress can be transferred from steel to concrete by bond alone. The steel is post-tensioned if it is not stressed until the concrete has been placed. Commonly, open holes or tubes encase the steel in the concrete, and the concrete takes the pressure in tensioning the steel at its ends; the holes or tubes may be grouted later.

Other means for prestressing, such as expansive concrete held within firm abutments, the filling of cracks and joints with rigid material at low temperature, or the insertion of rigid wedges, have been suggested. The elimination of expansion joints may provide some prestress at high temperature. Pressurized joint cells of sufficient dimensions and pressure would provide compression at all temperatures. These prestress means would all require firm end abutments. Otherwise, progressive movements at pavement ends with loss of prestressed may be anticipated because of the low frictional resistance of the subgrade to seasonal slab movements (*16*). A compression stress of 1,000 psi. due to restraint of expansion may be realized at high summer temperature, equal to about 1,000 tons for a 24-ft. 6-in. slab, taxing any end abutment, yet such restraint prestress might be completely dissipated by a 30-F. temperature drop and concrete creep during dry seasons. The permanency of external prestress means would be conjectural. Contrary to internal bonded steel prestress which positively prevents buckling, external prestress means might contribute to blow-ups and loss of prestress. For these reasons, with pavement design improvement an urgent problem, and every need for positive and lasting prestress with long life expectancy, internal methods of prestress appear to deserve major attention for initial construction.

High-strength steel wire is most frequently used for prestressing and is particularly suited to long pavement slabs. Steel stress of 150,000 psi. is commonly used. Some decrease in prestress due to steel and concrete creep can be expected, but it is not certain that substantial concrete creep will occur for normal pavements on soil subgrades extending over several years. Prestressing steel of .15-sq.in. cross section per ft. width, equivalent to ½ lb. per sq.ft. commonly used as distributed reinforcement, would be sufficient for 200-psi. applied prestress in a 9-in., 260-psi. in a 7-in. and 360-psi. in a 5-in. pavement in one direction. This amount of compression would provide substantial relief of pavement stresses.

Pavement Prestressing Possibilities

Prestressing may be considered in effect the equivalent of increased concrete tension strength without corresponding increase in Modulus of Elasticity. Prestress up to a substantial part of concrete compressive strength is feasible. On the basis of concrete flexure alone, thin pavement slabs could be sufficiently prestressed to take wheel load stresses, but thin slabs would be subject to large elastic deflections under load because the elastic properties of concrete are not changed by prestressing. For instance, the bending stress in a 4-in. slab on a 200-k subgrade, loaded centrally with a 10,000-lb. wheel load, would be not much over 500 psi, and such tension stress may easily be eliminated by prestressing, but its deflection under load into the subgrade would be about .05 in. It is doubtful that a normal subgrade could take frequent repetition of such deflections without permanent displacement. The usable limit of prestress in pavements would seem to be secondary to the determination of usable pavement thickness, considering limits of elastic deflections of the subgrade or subsidence under the hammering of traffic.

Conventional pavement design is predicated on bending of unreinforced concrete and limited by its flexural strength. It would be feasible to eliminate all tension stresses in prestressed pavement design as has been done in prestressed structures. However, considering conventional pavement performance, the practical criterion for prestressed pavements should be the elimination of tension stresses higher than compatible with normal material considerations, and sufficient prestress to assure substantially monolithic action and pressure sealed cracks anywhere in the slab at all times. Highways are frequently opened to traffic when the concrete modulus of rupture is from 550 to 600 psi., with the strength at advanced age over 800 psi. On the basis of some safety against fatigue stresses for assumed concrete properties a maximum concrete stress of less than 350 psi. tension would appear desirable.

Two objectives appear attainable in prestressed pavements: firstly, the number of joints could be greatly reduced, and continuing crack failures could be eliminated; secondly, substantial improvement in cross section design would be realized with the least practical slab depth and with steel quantities in the general range employed as distributed reinforcement for crack control.

Pavement Prestress Investigations

Aside from questions of construction economy, which can hardly be satisfied without extended practical application, many design questions must be answered as a preliminary indication to the possibilities of prestressed pavements. This is a completely new type of design deserving considerations which have not normally been applied to conventional pavements. Details which might be neglected in limited-life construction may not be acceptable in designs for greatly extended service life, but improved details should not unduly burden the initial cost comparison. Suitability for mechanization, even though the equipment has not been developed, is pertinent to consideration of design features. Mechanization must be assumed for any cost and construction comparison with present practices, but without contingencies in equipment development, and its use, and in wisely conservative designs for initial exploration.

The following questions apply for a preliminary consideration of suitable pavement prestressing practice:

Should prestress be applied longitudinally, or transversely, or in both directions;

What is a suitable level and uniformity of prestress for highway slabs;

What will be suitable slab dimensions, especially slab length, considering effectiveness of prestress at various distances from free ends;

How should slab thickness be determined, considering pavement flexure and subgrade deflection?

The question of pavement thickness is of greater consequence for prestressed than conventional pavements. In conventional construction only the material cost enters into consideration of thickness; in prestressed slabs, not only is the cost of extra concrete involved, the increased steel requirements to impose a desired prestress add to the cost as well. The question of pavement deflections and their influence on subgrade performance has hardly been touched upon in pavement research.

Until representative prestressed pavement data become available, conventional pavement research gives the best clue to prestress requirements. An important preliminary requirement is the best possible design comparison between conventional and prestressed pavements, which must be a primary guide to extended exploration.

PAVEMENT RESEARCH AND DESIGN

In order to illustrate questions pertinent to the design of prestressed pavements, a few research and design data have been assembled to indicate typical stress conditions in concrete pavements. The full range of variables could not possibly be covered, but the most general conditions are indicated. The performance of existing pavements gives the most direct indication to primary prestress needs. However, as pavement thickness would be decreased below conventional practice, different stress conditions might become critical. Performance indications must be coordinated with design analysis.

PAVEMENT CRACK SURVEYS

Cracks in existing roads show directly the most common critical stress conditions in concrete pavements. Corner or diagonal cracks, transverse cracks, and longitudinal cracks have been recorded in some published concrete pavement surveys (*18*). Complete crack surveys were made for Road Test ONE-MD (*17*).

The data show the almost exclusive predominance of transverse cracks in pavements of one lane wide slabs, separated by longitudinal keyed joints. On 900 miles of Louisiana 6-in. thickened-edge pavement (*18*) with 42-ft. average joint spacing 86 percent of all cracks were transverse, corner cracks averaged less than one per mile, with 3200 ft. of transverse joints and cracks per mile of road. On Road Test one-MD, sections 1, 2, and 3, 98 percent of the cracks were transverse cracks near joints.

Longitudinal center cracks, common in pavements up to 1925, were completely eliminated by center joint construction, permitting relatively unrestrained transverse temperature warping of single-lane slabs. However, longitudinal cracks near the outside pavement edge, extending for a short distance from transverse joints, sometimes referred to as "infiltration cracks", appear to be increasingly common. A different type of longitudinal cracking occurred on Road Test One-MD, section 4 on pumping soil, subjected to heavy tandem-axle loading where 11 percent of the cracks were lontitudinal; all originated at transverse joints 4 to 5 ft. from the edge, and extended progressively further away, finally meeting at midlength of the 40-ft. slabs. This longitudinal cracking is an indication of critical transverse load stresses near transverse joints in connection with loss of subgrade support.

Clearly, pavement failures indicate a primary need for longitudinal prestress.

PAVEMENT STRESSES

General Assumptions

Conventional pavement design has been based generally on analytical methods of Westergaard (*19*), modified by experimental research of Teller and Sutherland (*20*), and others. Data pertinent to long slabs have been derived from research on continuously reinforced pavements (*21*). Conditions pertinent to axle loadings are obtained from Road Test One-MD (*17*).

Mathematical means for load stress and deflection determination are involved and require assumptions not met with in normal pavement dimensions and vehicle loadings. Slab stresses are the combined effect of loads and soil pressures which are dependent upon deflections and which may be quite different for axle loads and single wheel loads, so that stresses for axle loads derived at by methods of superposition from single wheel loads are not reliable.

In this appraisal of pavement load stresses the method of successive approximations, referred to as "Sector Analysis of Concrete Pavements" (*22*) has been employed. The method has been applied particularly to stress derivations for dual-tire imprints, for axle loads, and for comparison between stresses in longitudinal and transverse direction in single-lane slabs.

The design analysis has been limited to 12 ft. wide long pavement slabs from 5 to 9 in. thick on non-pumping subgrade. The concrete is assumed to weigh $\frac{1}{12}$ lb. per cu. in., to have a thermal coefficient of expansion of 0.000005, and modulus of elasticity for flexural stress of 5,000,000 psi. The assumed design load is a single axle load of 20,000 lb. on two dual-tire imprints spaced 6 ft. apart, each 20 in. wide and 10 in. long. All joints are assumed to have effective load transfer, sufficient to provide ⅓ load and stress relief for corner and joint edge loads in the loaded slab. Joints are assumed to provide no rotational resistance. Cracks held closed by prestress should provide perfect load transfer, but unless the prestress were considerable there would probably be little bending resistance across the crack.

Pavement Stress Components

Critical pavement stresses usually are a combination of stresses from two or three principal causes, exceeding the safe bending stress of the concrete, resulting in structural cracks of specific orientation.

Traffic *load stresses* result from the distribution of wheel and axle loads through the pavement to the subgrade over an area much greater than that covered by the wheel imprints, imposing flexural stresses.

Warping stresses are restraint stresses caused by variation in temperature and moisture from top to bottom of the slab, which cause nonuniform length changes and slab curling with change in subgrade support adjacent to free edges, so that flexural restraint stresses are induced opposed to the slab curling and eventually resulting in full restraint some distance from edges and ends.

Friction stresses are restraint stresses imposed by the frictional resistance of the subgrade to the free contraction and expansion of monolithic pavement slabs under changing average slab temperature. Insignificant in conventional length slabs, except for determination of steel requirements to keep cracks from opening wide, friction stresses may reach appreciable magnitude in much longer prestressed slabs.

In prestressed pavements, prestress of predetermined magnitude, variable to a degree depending upon manner of imposition, creep in the steel and concrete, is a fourth stress component. Load and warping stresses combine as flexural stresses. Friction restraint stresses and prestress may be considered as evenly distributed on the cross section. The critical stress would normally be a tension stress in top or bottom fiber; although at early age the direct tension without prestress may be equally critical considering the higher concrete modulus of rupture.

Both load and warping stresses are different in longitudinal and transverse directions; both directions are pertinent to the determination of needs for longitudinal and transverse prestress. However, major stress variables have not been found with sufficient accuracy to justify quantitative consideration of Poisson's ratio effect.

Warping stresses are a major stress component. The temperature warping stress varies between top fiber tension, during night-time loss of heat from the slab to the air, and fairly high bottom fiber tension stresses when the pavement surface is exposed to intense sunlight and increasing temperature. Moisture warping, because of differential shrinkage between dry surface concrete and that near a wet subgrade, or because of rain, may impose considerable restraint stresses in longitudinal direction. Predominant moisture warping, noticeable as high joints, would be exerted over long periods of time and subject to relief by plastic flow of the concrete to a greater degree than nightly temperature warping with which it compares. Variations in subgrade moisture and fluctuations in subgrade levels because of moisture must be given consideration in connection with moisture warping. Until more research is available, moisture warping stresses must be left to conjecture, recognizing that they may increase night warping stresses and decrease day warping stresses in longitudinal direction.

WARPING STRESSES

Day temperature warping is occasioned by rapid temperature pick up at the surface, night warping by the slower temperature loss from the slab. For normal highway slab thicknesses both temperature gradients through the slab are approximately linear, and for day warping may reach 3 F. per inch thickness increasing temperature toward the surface, for night warping seldom exceeds 1 F. decrease toward the surface (*6*).

For daytime the upwardly convex warping curvature concentrates subgrade support near edges, with corresponding lifting of slab portions somewhat further away, causing restraint stress of compression at top and tension at bottom surface perpendicular to the end and

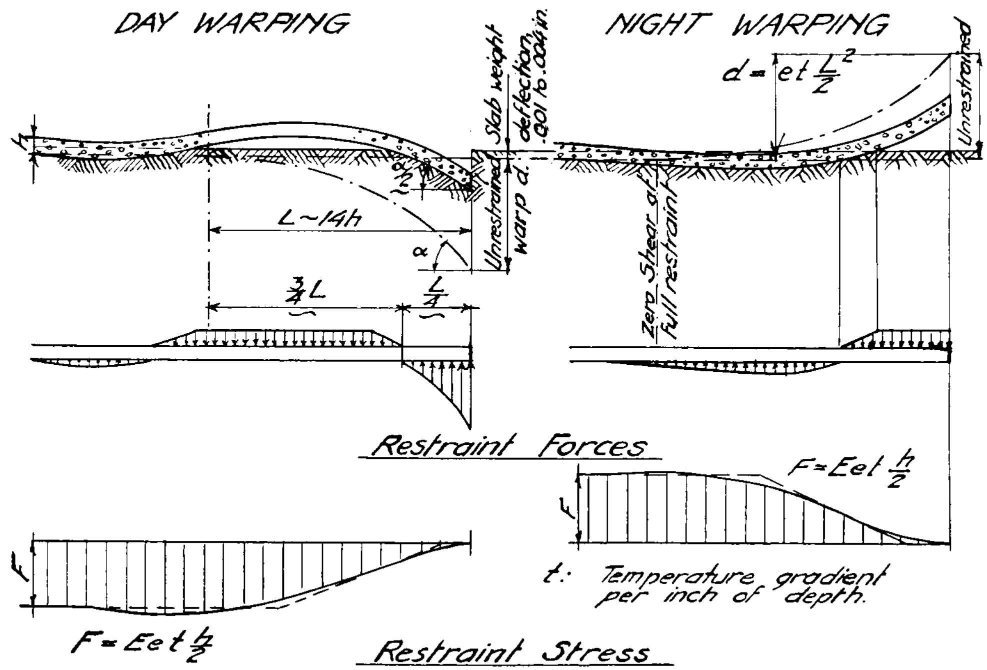


Figure 1. Temperature warping of ends of slabs for day-and-night-temperature differentials from top to bottom of slab, and approximate development of restraint stresses from end to full restraint in unloaded slabs.

edge. For night conditions the upwardly concave warping curvature lifts the slab edges off the subgrade causing restraint stress of tension in the top and compression in the bottom surface, Figure 1.

The timing of warping is pertinent to stresses in long slabs for combination with stress components due to contraction and expansion:

> Average slab temperatures vary from a minimum in the early morning hours near sunrise, to a maximum shortly after noon to as late as 4 pm.;
> Day warping commences from one to three hours after minimum average slab temperatures, and increases rapidly to a peak value near noon shortly before maximum average temperature is reached;
> Night warping commences 2 to 5 hours after maximum average temperature, and is approximately constant through the night hours.

It is evident that day warping should be considered only in connection with expanding slabs near maximum expansion, night warping only with contracting pavements at any time.

Restraint stresses for temperature warping of concrete pavements have been investigated on the assumption of vertical resistance proportionate to the restrained warping deflection (*23*). Experimental consideration of warping (*17, 20*) has been limited to unloaded slabs, in which case the maximum force against warping is the slab's unit weight over the raised portions.

In view of the importance of warping stresses, an appraisal under varying conditions of loads and subgrade support, longitudinally and transversly, is pertinent. The following symbols apply:

Concrete modulus of elasticity	E psi.
Concrete thermal coefficient	e
Concrete thermal gradient through slab	t F. per in.
Slab depth	h in.
Concrete stress	f psi.
Concrete stress for full restraint	F psi.
Distance from free edge	w in.
Distance from free end for full restraint	L in.
Vertical curvature of warped slab	d in.

Fully Restrained Warping for Longitudinal Direction Stress.

Some distance from ends and edges full restraint of warping is reached. Beyond that distance the difference in length due to differential temperature between top and bottom fibers, *eth*, is overcome by the flexural restraint strains, F/E, compression and tension, such that:

$$F = Eet\frac{h}{2} \quad (1)$$

Approximate conditions of warping restraint are illustrated in Figure 1. The change in subgrade support near the end, whether decrease as in night warping, or increase as in day warping, is counteracted over some distance immediately adjacent, with maximum stress, assumed equal to full restraint stress, existing at section of zero shear. The restraint stress increases at approximately linear rate, the warped end slope may be assumed to approximate one half of that for unrestrained warping. The curvature for unrestrained warping is circular, with change in elevation d over a distance w from a line of tangency:

$$d = et\frac{w^2}{2} \quad (2)$$

As seen, this unrestrained warp is independent of slab thickness.

The warped elastic line for unloaded slab end may be approximated by an end portion with linearly changing deflection and an inner curved portion. Upward pressure resisting warping is proportionate to deflection below the unwarped or neutral level, downward resistance is proportionate to pavement rise from neutral level, with its limit the slab weight, for any void below the slab. Under normal conditions of subgrade support the end portion will be between $L/4$ for day warping with the resistance of raised inner portions limited to the slab's own unit weight, to about $L/3$ for night warping, when the end of the slab is elevated over the subgrade. The distance from the end to the section of full restraint stress is 14 h for day warping at 3 F. temperature gradient, and about the same dimension for the lesser night warping with end restraint limited to the slab unit weight; points at any greater distance from the ends may be assumed to be subject to full restraint stress against temperature warping.

Stresses for fully restrained temperature warping are computed from equation (1). They are listed below for 5- to 9-in. pavement thicknesses, 5,000,000 psi. Modulus of Elasticity, and .000005 thermal coefficient.

	Slab thickness, in.				
	5	6	7	8	9
Day warped slabs, 3 F. temperature gradient, bottom tension, psi	190	225	260	300	340
Night warped slabs, 1 F. temperature gradient, top tension, psi	60	75	90	100	110

Moisture accumulation near the concrete bottom surface would have the effect of decreasing the tension near the bottom for day warping and increasing the tension in the top surface for night warped slabs.

Transverse Temperature Warping

The limited transverse slab dimensions are insufficient to provide full restraint of warping at the center of a 12-ft. lane for both day and night warping in 6-in. and thicker slabs.

Unrestrained warping curvature, per equation (2) would be: for 3 F. day temperature gradient .039 in. down; for 1 F. night temperature gradient .013 in. up, at the edge of a 12-ft. lane. The computed restrained warping conditions for unloaded slabs based on flat unwarped subgrade and slab, k of 200, are listed in Table 1. As seen full restraint stress is only reached in 5-in. night warped slabs.

TABLE 1

	Slab thickness, in.				
	5	6	7	8	9
	Maximum day warping				
Warping curvature	.012 in.	.017 in.	.021 in.	.026 in.	.030 in.
Edge down fr. flat	.009 in.	.012 in.	.015 in.	.017 in.	.018 in.
Center rise	.003 in.	.005 in.	.007 in.	.009 in.	.012 in.
Warping stress	140 psi	160 psi	140 psi	120 psi	100 psi
	Night warping				
Warping curvature	.003 in.	.004 in.	.006 in.	.007 in.	.008 in.
Edge rise	.002 in.	.003 in.	.004 in.	.005 in.	.006 in.
Center down fr. flat	.001 in.	.001 in.	.002 in.	.002 in.	.002 in.
Warping stress	60 psi	60 psi	60 psi	60 psi	50 psi

Warping of unloaded slabs has been observed on Arlington test slabs (*20*), and on Road Test One-MD (*17*). On Arlington 10 ft. wide 6-in. test slabs, an edge rise of .01 in. was observed for 1.1 F. night temperature gradient, corresponding to about .013 in. total warping curvature. The unrestrained warping curvature would be $.000005 \times 1.1 \times 60^2/2$ or .011 in. On the same slab a downward edge deflection of .024 in. was observed for 3¾ F. day temperature gradient, corresponding to about .035 in. warping curvature. The unrestrained warping curvature would be .038 in. On Road Test One-MD slabs observed edge movements were .015 in. up for 1 F. night temperature gradient, .029 in. down for 3½ F. day temperature gradient, corresponding to about .02 and .04 in. total curvature, respectively. The corresponding unrestrained warping curvatures of the 12-ft. lanes are .013 and .045 in. The transverse warping behaviors for night and day warping are illustrated in figure 2. The observed warping deflections, as seen, are much greater than the computed restrained values for both day and night warping, nearly equal to the unrestrained warping in either case. Deflections of the Arlington slab show center joint restraint to be negligible, which may be assumed to be the case also of the old Test Road pavement. The probable interpretation of the observed condition is that the subgrade adjusts itself to the small deflections of transverse warping, so that restraint stressed to not become noticeable. It is possible that normal subgrade levels along slab edges may be depressed somewhat; tension stresses would then exist in the top of unwarped slabs, actual top tension stress in night warped slabs would be changed very little and transverse day warping stresses would be correspondingly decreased. The transverse day-warping restraint stresses com-

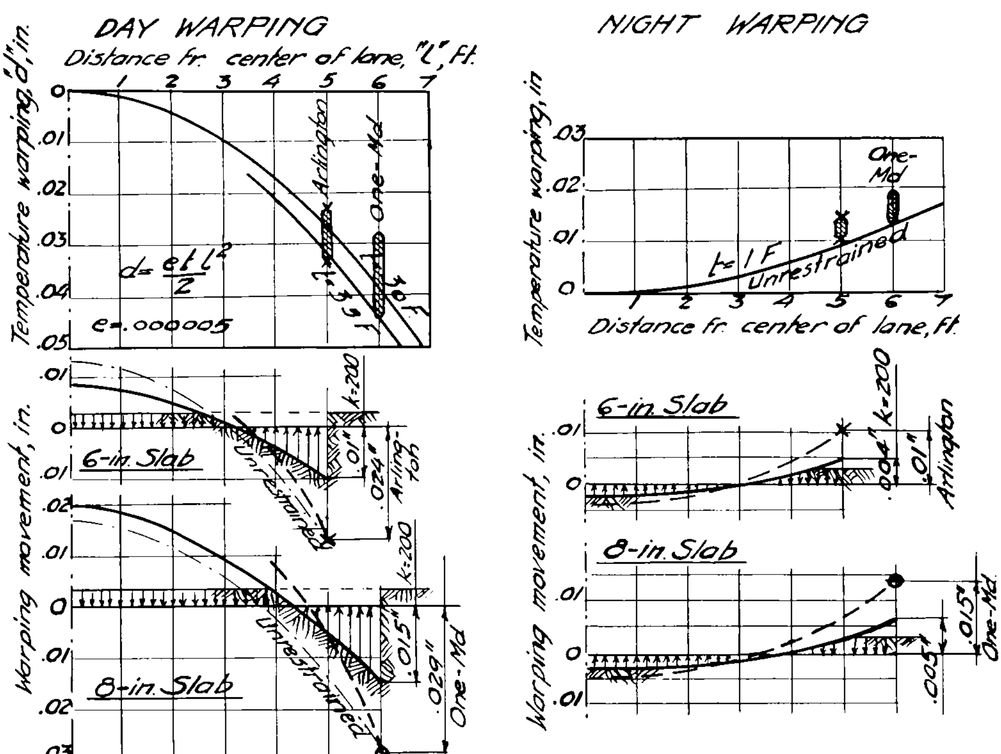


Figure 2. Transverse temperature warping of single-lane slabs for day- and night-temperature differentials from top to bottom of slab. Approximate warping of 6- and 8-in. slabs on uniform subgrade is shown, and compared with deflections observed on Arlington and Road Test One-Md slabs. Observed warping is incompatible with normal rate of subgrade reaction change (dashed lines) near slab edges.

puted above for unloaded slabs are undoubtedly much greater than the actual warping stress.

Warping Restraint Stresses in Loaded Slabs

Loads which cause slab curvature the same direction 'as unrestrained warping at any given section have the effect of decreasing warping restraint stress at that section, and vice versa. F. i., corner load on a day warped slab would result in decreased warping stress near the corner, increasing the distance from the corner at which full restraint is reached; on a night warped slab it would increase the stress and decrease the distance to full restraint. Loads on slab portions fully restrained against warping combine directly with warping, toward increased total stress, as edge load stress and longitudinal day-warping stress, or decreased stress such as edge load stress and night-warping stress.

Normal traffic lane axle loads probably have the least possible influence on transverse warping stresses, compared to unloaded slabs; edge axle loads would result in transverse day-warping stresses lower than for unloaded slabs, and night-warping stresses near the edge higher than for unloaded slabs but probably not higher than at the center of the lane of unloaded slab. Single loads on slab interior would decrease night warping stress, and increase day warping stress although probably not to value for full restraint, especially considering the apparent lack of restraint to transverse warping.

Single wheel loads near lane center without an adjacent edge or corner depressed by the companion wheel are not common enough to warrant consideration of transverse day warping stresses above those for unloaded slab. But this condition could not be expected in pavement slabs over one lane wide.

In longitudinal direction full restraint stress is assumed to exist throughout long slabs under load. It should be recognized, however, that full night warping stress is unlikely at sections of maximum corner load stress (see Fig. 4).

LOAD STRESSES

The load condition of two wheels spaced transversely 6 ft. apart is defined by the term axle load. The normal position for axle load is each wheel 2 to 3 ft. from the nearest slab edge, referred to as Lane Axle Load. If one wheel is tangent with the outside edge the loading is an Edge Axle or Corner Axle. The load stresses for the different load positions, computed by means of successive approximation through sector analysis should not be considered exact but rather comparatively representative; further refinement of approximations could result in some adjustment of stresses in the thin slabs.

Figure 3 shows maximum flexural stresses in 5- to 9-in. slabs for wheel and axle loads in different possible critical positions, based on subgrade modulus of 400 psi. per in. deflection. Maximum tension in top fiber and in bottom fiber are shown in different groups of graphs, stress in longitudinal direction to the left, stress in transverse direction in the graphs to the right, and stresses for joint edge and corner load conditions are shown in separate graphs from those for loads elsewhere on the slabs. Significant longitudinal top tension does not occur for loads away from joints, nor longitudinal bottom tension for loads at joints.

Maximum top tension occurs for wheel or axle loads near the joint corner, at a distance from the corner of 20 to 40 in. from the end or edge, nearer in longitudinal than trans-direction, and varies from about 400 psi for 5- to 150 psi for 9-in. slabs. Some transverse top tension may occur for edge axle loads anywhere along the slab.

Maximum bottom tension stresses occur directly under a wheel in all instances, and are substantially greater in longitudinal than in transverse direction. The maximum varies from 500 psi for 5- to about 200 psi for a 9-in. slab, longitudinal edge stress. The transverse joint edge stress is substantially lower, especially for the normal lane axle load, when computed for dual tires on the basis of 33-percent joint load transfer and stress relief.

Wheel and Axle Loadings

Single wheel and axle loadings may produce substantially different stresses, as shown in figure 3, and either the wheel load or the axle load stress may be the greater. This finding is not surprising considering the very different deflections and subgrade pressure distributions under the two types of loads. This redistribution of subgrade pressures exerts a substantial influence on stresses in both longitudinal and transvese direction.

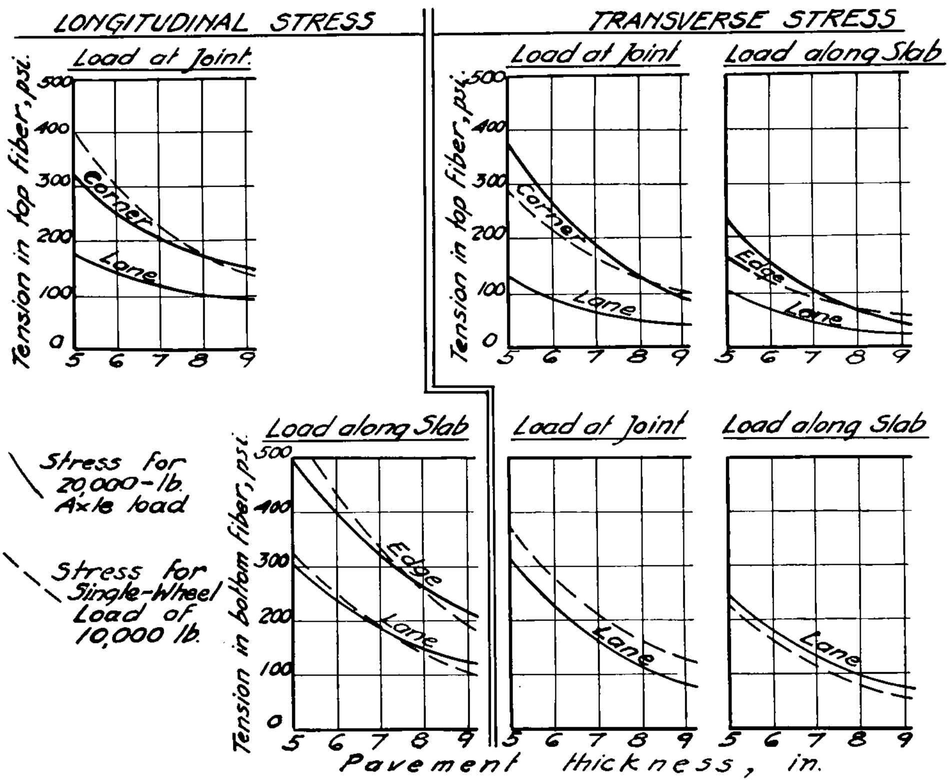


Figure 3. Maximum stresses for 20,000-lb. axle and 10,000-lb. wheel load on dual tires in 5- to 9-in. single-lane pavements, with the axle directly at the joint and elsewhere along the slab. Top-fiber tension stress graphs are shown above those for bottom-fiber tension; longitudinal stresses separately from transverse stresses. Significant longitudinal tension occurs only for load at joint in top fiber, for load away from joints in bottom fiber. Stresses shown for sub grade support 400 psi. per inch deflection.

Almost no research is available to verify the variation in stresses between single-wheel and axle loads, nor the comparison between stresses in longitudinal and transverse direction. The *maximum* stresses for loads on slabs on granular soil of Road Test One-MD are in general agreement with stresses illustrated in figure 3, and give support for the computed lower stresses in transverse direction.

Single wheel loads occur very rarely at outside edges and corners, more frequently at inner edges and corners where they are relieved by joint load transfer; the more common edge axle load is assumed for combined stresses in preference to single-wheel edge load.

Influence of Warping on Load Stresses

Night warping, by lifting slab ends and edges from the subgrade, tends to decrease soil support near corners and edges, with a resultant increase in stresses perpendicular to the edge. Day warping depresses slab ends and edges giving increased soil support near loads at these points. Moisture in the lower parts of the slab contributes to warping in the same direction as night warping, so that for normally wet subgrades voids near edges and ends may exist under pavements without temperature differential; day warping may then represent most nearly conditions of even subgrade support.

Night warping increases top tension stresses due to loads and increases the distance to the section of maximum load stress; as mentioned previously corner and edge loads also act to increase night warping stresses and move the section of full restraint against warping nearer the edge. Observed stresses for loads on night warped slabs would appear to include both of these effects. Loads near ends and edges on day warped slabs on the other hand would cause decreased load stress, decreased distance to the section for maximum load stress, and also decreased warping stress near the edge. Observed corner load stresses on day warped slabs would be lower than actual, those on night warped slab higher than actual; however, in no case should the difference between the observed and the actual stress be more than the stress for fully restrained warping.

On the Arlington slabs (*20*) observed stresses for 10,000 wheel load at the corner day warped decreased 80 psi for 6- and 50 psi for 9-in. slabs, and night warped increased 40 psi for 6- and 20 psi for 9-in. slab, compared to stress for corner without temperature warp.

On Road Test One-MD (*17*), for load near a corner, the stress along the 9-in. edge decreased from 180 psi. for corner warped up to 60 psi. for corner warped down; for load near the edge the edge stresses were 180 and 130 psi., respectively. Along the edge the warping stress probably did not change materially, the decrease in stress for that load appears to represent change in load stress due to warping. By direct comparison 70 psi. of the observed change in corner load stress might be due to change in warping stress incident to load from night to day conditions.

Compared to full restraint against temperature warping, 225 and 340 psi. for 6- and 9-in. day warped slabs, 75 and 110 psi. for 6- and 9-in. night warped slabs, the change in load stress due to warping appears to be small. Top tension load stresses in night warped slabs would appear to be increased less than 40 psi. Bottom tension stresses for loads along depressed edges in day warped slabs, are assumed to be decreased between 90 psi. in 5-in. and 50 psi. in 9-in. edges.

COMBINED FLEXURAL STRESSES

Warping and load stresses combine to give maximum combination of flexural stress. For assumed design conditions, Figure 4 shows probable maximum combination of these stresses in 5- to 9-in. slabs for axle loads at transverse joints and elsewhere in most critical positions. Graphs showing top tension stresses, combined with night warping stresses, are grouped separately from graphs showing bottom tension stresses; longitudinal edge stress is shown for both night and day warped slabs. Load stresses have been adjusted for warped slab conditions.

Top-fiber tension stresses are for corner load or perpendicular to the edge for edge load; the combined stress, assuming full temperature warping restraint stress, is probably greater than can be expected as near to edges and ends as maximum load stress. Combined longitudinal bottom tension stresses, additive during day warping and compensatory during night warping, appear possible in long slabs except for loads closer than 14 times the slab depth from each end. The combined transverse bottom tension stresses for lane axles, assuming the theoretical warping stress that would occur near the center of unloaded slabs, is very probably higher than actual.

The maximum combined flexural stresses, which must be considered for relief by prestressing, are:

- Firstly: Longitudinal edge stress in day warped slabs, and in thin pavements also in night warped slabs.
- Secondly: Transverse corner stress, in thin slabs possibly also joint edge stress, and longitudinal corner stress.
- Lastly: Transverse stresses for loads anywhere else along the slab.

It is obvious that longitudinal prestress should receive primary consideration, possibly also transverse prestress along joint edges.

Combined longitudinal stresses approach concrete flexural strength. It is apparent that transverse cracks may be anticipated anywhere along conventional slabs. The excessive longitudinal edge stresses, occurring near times of maximum expansion from contracted length, would actually be relieved in some degree in central portions of long slabs by the simultaneous friction restraint stresses in compression, but not appreciably so in conventional slab lengths.

Frictional restraint stresses will be investigated for much longer pavement slabs.

SLAB MOVEMENTS AND FRICTIONAL RESTRAINT STRESSES

Length of conventional pavement slabs seldom exceeds 100 ft. between joints or cracks and frequently is much less. The length appears to be limited by concrete contraction at early age in conjunction with increasing warping stresses as the modulus of elasticity of the

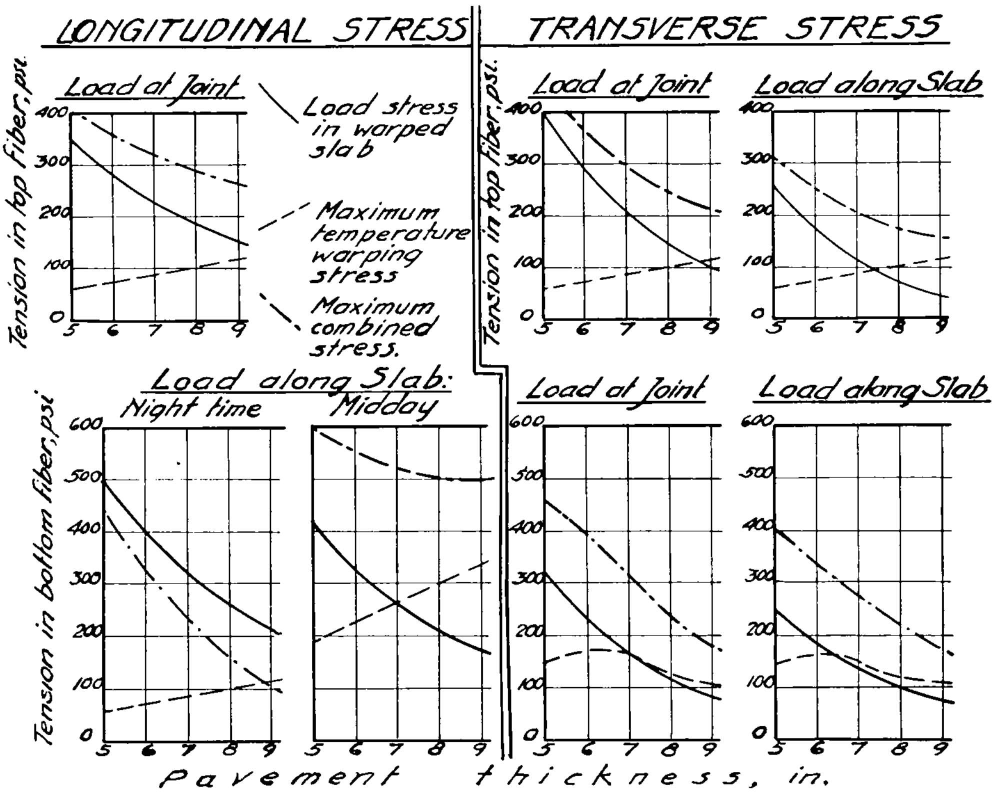


Figure 4. Combined flexural stresses longitudinally and transversely in 5- to 9-in. slabs for critical axle loads of figure 3 on warped slabs, plus probable maximum warping stresses, full restraint of longitudinal warping and transverse night warping, restraint equal to that computed in unloaded slabs for transverse day-warping.

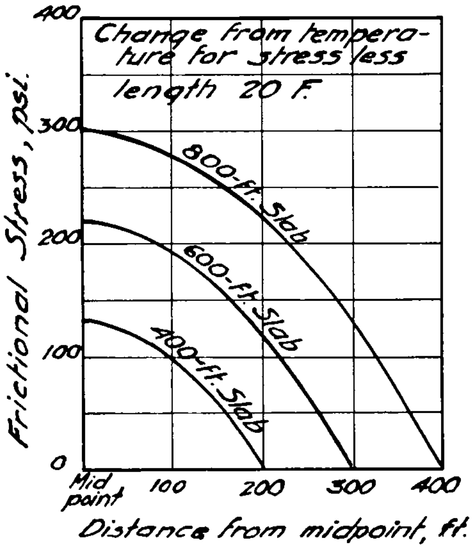
concrete increases. In transverse direction early warping stresses would appear to exceed the concrete strength almost always in pavements built more than one lane wide.

The free contraction and expansion of pavement slabs about their midpoint is restrained by friction on the subgrade. Tests have indicated that the friction force is proportionate to the square root of the movement, a, the modulus of friction varying from $7\sqrt{a}$ on adherent, rough and moist subgrades to $2\sqrt{a}$ on sandy, dry, and even subgrades, when a is in inches, and higher for small slab dimensions than for thick and long slabs. The upper limit of the modulus of friction is the coefficient of sliding friction, 1.5 or more on rough subgrades and between 1.0 and 1.5 on sandy even subgrades. For this study it will be assumed that the modulus of friction is $3\sqrt{a}$, and the coefficient of friction 1.5, applying to parts of slabs moving in excess of .25 in. A low frictional resistance is desirable for long prestressed slabs; the assumed friction modulus may require special subgrade treatment on some locations.

The presence of cracks alters drastically contraction and expansion characteristics of conventional pavements, if cracks are numerous even if the slabs are reinforced. However, if the precompression in prestressed pavements is sufficient any cracks will remain under pressure. On that assumption prestressed pavements should behave as monolithic uncracked slabs even if cracked.

Frictional Restraint Stresses

Figure 5 shows frictional restraint stresses in 400-, 600-, and 800-ft. long slabs for 20 F. average temperature drop from unstressed condition, and the movement of all points



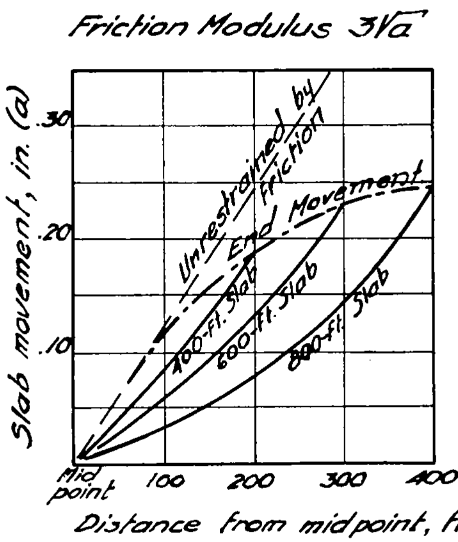


Figure 5. Theoretical longitudinal temperature movements and frictional restraint stresses in 400-, 600-, and 800-ft-slabs on low-friction subgrade, computed for a sustained temperature change of 20 F., and slabs assumed without stress at beginning of temperature change.

between the slab center and the ends. The modulus of elasticity has been taken at 4,000,000 psi. for these evenly distributed recurrent stresses. The restraint stress near midpoint is 130, 220, and 300 psi., respectively. The longitudinal prestress applied at the ends would have to exceed these amounts to assure compression on all slab sections. It is not anticipated that restraint stresses would develop differently in prestressed slabs; therefore the average stress on any section would be the prestress less the restraint stress for contracting slabs, and prestress plus the restraint stress for slabs in an equivalent state of expansion. The friction-stress strains at slab center at the end of a 20 F. temperature drop are equivalent to the elongation for about 7, 11, and 15 F. temperature change.

On reversal of temperature change length increase and friction reversal will occur first near slab ends, in central parts the restraint stress would decrease but no immediate expansion would be induced. Equilibrium must exist between restraint stress and frictional stress induced by slab movements to the slab ends. Compression may exist near the ends while tension still exists in central parts, and contraction movement might take place some distance from the end even though there is expansion at the slab ends. The movements and restraint stresses would gradually change to those for expansion throughout the slab length; however, to reach equal magnitude frictional restraint compression stresses as the tension stresses computed above for 20 F. temperature change from unstressed condition would apparently require 27, 31, and 35 F. total temperature change. The central friction stresses corresponding to a total 30-F. average temperature cycle in 400-, 600-, and 800-ft. slabs would be 150, 210, 260 psi., respectively, tension and compression.

Slab Movements and Joint Width Movements

The contraction at each end as shown in figure 5 is .19 in. for 400-, .23 in. for 600-, and .24 in. for 800-ft. slabs. The restraint in end movement amounts to .06, .13, and .24 in., respectively. Full restraint for 20 F. average temperature drop from unstressed condition is obviously reached near 400 ft. from the ends. Considering the strains due to friction stress which require temperature reversal for their dissipation, the above end movements would apparently correspond to 27, 31, and 35 F. temperature cycles. The end movement corresponding to 30-F. temperature cycle would apparently be about .22 in. for all three slab lengths.

The composite cyclic temperature movements and friction stresses have not been investigated beyond these approximations. The prognostications are in general agreement with observations on continuously reinforced slabs (*21*), for daily temperature cycles. A 30-F. average temperature cycle would seldom be exceeded in slabs of the depths considered (*6*). The daily change in joint width between successive slabs apparently would approximate ½ in.

It is indicated by the performance of long continuously reinforced and extensively cracked slabs (*21*) that 1,000-ft. and possibly longer slabs undergo the seasonal-average length change, consisting of many overlapping daily cycles, virtually without restraint. The seasonal joint width change then should correspond to the slab length change without restraint for the full seasonal drop in average daily slab temperature, which could be expected to exceed 50 F. only in climates of extreme yearly fluctuations (*6*). For 50 F. seasonal temperature change the joint width change would be 1.2, 1.8, and 2.4 in., and the over-all joint width change 1¾, 2¼, and 3 in. for 400-, 600-, and 800-ft. slabs. Seasonal changes in joint widths, rather than the daily variations, appear to be a major joint design consideration for long prestressed slabs.

PRESTRESSED PAVEMENTS

Longitudinal Prestress

Longitudinal prestress might be applied along slabs or from ends at transverse joints. Upon initial application of prestress it may be expected that the effective prestress on any section away from the point of application would be decreased by the amount of frictional restraint induced by slab shortening under prestress. These length changes would combine with temperature contraction and be opposed to temperature expansion; therefore, just as the seasonal length change is unrestrained, prestress could be expected to equal the applied prestress throughout the slab lengths under consideration after some daily temperature cycles at some median daily temperature, irrespective of distance to point of application.

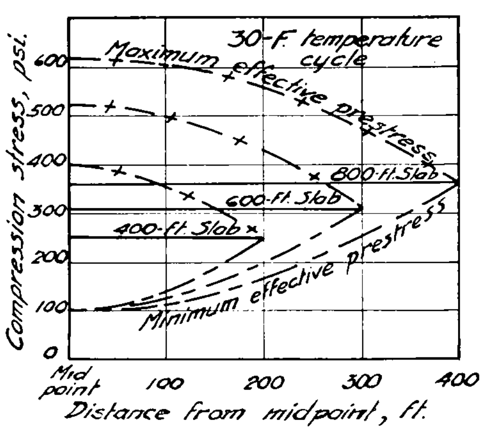


Figure 6. Approximate daily range of effective longitudinal prestress along 400-, 600-, and 800-ft. slabs as influenced by frictional restraint, decreased by tension for contracted slab, increased by compression for expanded slab, for 30-F. daily slab-temperature cycle, and based on 250, 310, and 360 applied median prestress, respectively, to maintain not less than 100-psi. effective prestress at midpoint of contracted slabs, on low-friction subgrade.

Concrete and steel have nearly equal coefficients of thermal expansion, the applied prestress therefore would not vary materially from summer to winter, nor daily, for internally steel prestressed slabs. These remarks are limited to such slabs. Externally prestressed slabs would require a very different analysis for temperature stresses.

Effective Prestress in Long Slabs

Prestressed slabs must be assumed to be subject to the same frictional restraints to free contraction and expansion for daily temperature cycles as non-prestressed slabs, and these restraint stresses will be opposed to the prestress for contracting slabs, but will act in the same direction as the prestress in expanding slabs.

Prestress and friction stresses may both be assumed to be evenly distributed on the slab cross sections. It will be assumed that the prestress is constant and uniform at some stress-less daily temperature and equal to the applied prestress; the average section stress along prestressed slabs, termed effective prestress, will then vary in 400-, 600- and 800-ft. slabs from 150, 210, and 260 psi. above at midday and to as much below applied prestress, effective at midpoint at night. The more nearly uniform are slab temperatures the less prestress variation may be expected.

It is undoubtedly desirable to have sufficient prestress to avoid tension stress throughout contracting slabs. If the prestress is chosen to maintain a minimum of 100 psi. compression at midpoint for normal daily fluctuation, the effective prestress range between day and night condition shown in figure 6, is obtained for 400-, 600- and 800-ft. slabs. The effective prestress values in figure 6 will be used for consideration of total combined stresses in prestressed slabs.

Maximum Stresses in Longitudinally Prestressed Slabs

Critical flexural tension stresses, as shown in figure 4, may be combined directly with simultaneous effective prestress compression, as shown in figure 6, to obtain maximum stresses in prestressed slabs. Maximum day warping stresses can only be expected in slabs near maximum expansion; on the other hand night warping stresses may not necessarily be present in slabs while still near minimum length. Figure 7 shows maximum combined stresses in night warped, unwarped, and day warped prestressed slabs 400-, 600-, and 800-ft. long, from 5 to 9 in. thick.

Near ends applied prestress is fully effective at all times, decreasing both corner stress and longitudinal edge tension to low values, as shown in the three graphs for loads at joints or along slabs near ends. In central portions of long slabs the maximum edge tension will

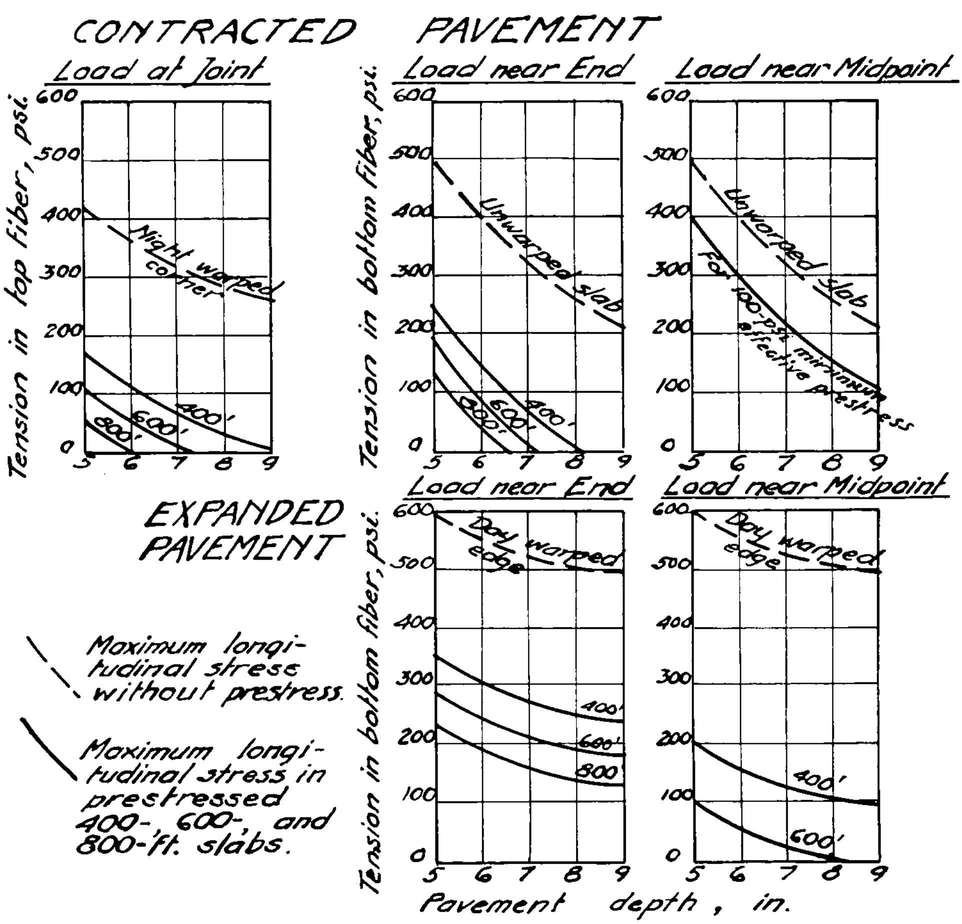


Figure 7. Combined longitudinal maximum-tension stresses in 5- to 9-in. prestressed pavements due to axle load stress, effective prestress in contracted and expanded slabs, and simultaneous temperature warping stress, based on 250-, 310-, and 360-psi. applied prestress at ends of 400-, 600-, and 800-ft. slabs. Stresses in non-prestressed slabs shown for comparison.

be decreased by the amount of minimum effective prestress as shown in the graph for load on unwarped fully contracted slab; usually fully restrained night warping may still be present in which case the edge tension under load would be from 60 to 110 psi. less than shown. Bottom tension stresses in day warped prestressed slabs for loads near slab ends are decreased by the applied end prestress, for loads near midpoint they are decreased still further by the amount of frictional restraint as well.

Maximum longitudinal edge tension stresses of 300 psi. are indicated in 6-in. prestressed slabs both near ends during the day and near midpoint at night. Longitudinal corner tension values in prestressed slabs are still lower. The assumed prestress apparently gives balanced end and midpoint design in 6-in. slabs 400 ft. long.

Transverse Prestress

It has been indicated that the presence of transverse warping stresses in single-lane slabs is subject to considerable question, so that the combined transverse flexural stresses shown in figure 4 probably would not be exceeded and very possibly may not be reached. Transverse flexural tension stress substantially over 300 psi. is indicated only for loads at joints in slabs thinner than 7 in. and away from joints thinner than 6 in.

Transverse prestress is accordingly not required in single-lane slabs away from transverse joints for balanced stresses longitudinally and transversely in 6-in. slabs with longitudinal prestress, but may be required along transverse joints.

Slabs built full 24-ft. width without center joint could be expected to have substantial transverse warping stresses and combined flexural stresses of about 400 psi. even along 9-in. slabs, and may crack longitudinally at early age, before prestressing. Transverse prestress would unquestionably be required to meet the design objectives. Transverse prestress other than at transverse joints in 6-in. or thicker slabs should therefore be considered in relation to the possible advantages of a pressure-closed longitudinal crack (or center joint) rather than for stress relief.

COMPARISION OF PRESTRESSED AND CONVENTIONAL DESIGNS

The possible combined longitudinal flexural stresses for loads anywhere along conventional pavements of practical slab lengths under the assumed design conditions are very close to the actual concrete strength at early age. No assurance exists against transverse cracking of conventional slabs anywhere, except that inherent in possibly lower modulus of elasticity than assumed at early age and inelastic deformations of the concrete. A very low safety factor is indicated by the great increase in transverse cracks on pavements with aggregates having slightly higher thermal coefficient of expansion or with some increase in early temperatures. Combined stresses in conventional highway pavements of any thickness may in any case exceed the concrete fatigue strength at mature age. These pavements lack essential strength prerequisites for unlimited heavy traffic intensities and long life without extensive cracking or very closely spaced joints.

By comparison, prestressed pavement stresses, even in relatively thin slabs, may apparently be held to reasonable maximum values with some safety against unforeseen pavement curvatures, and for normal design conditions less than assumed concrete fatigue strength. Prestressed concrete pavements accordingly offer possibilities for lasting structural improvement.

Pavement Deflections

Prestressing conveys no change in concrete modulus of elasticity, and would not be expected to induce different elastic load deflection characteristics to slabs of one depth. Cumulative deflections would be smaller by reason of fewer joints and cracks, less inelastic concrete deflections, and reduced deflections across pressure sealed cracks.

Inasmuch as prestressed pavements could be built without excessive stresses substantially thinner than conventional construction practice allowable pavement deflections give greater concern. Research on this subject is very limited; pumping data are inapplicable as loss of soil material in pumping does not appear to be related to deflection. On Arlington tests slabs (*20*) no measurable increases in .02-in. edge load deflections occurred for 80 repetitions of loads; and corner deflections in the range up to .05 in. increased up to .01 in. for 80 repetitions, relatively independent of initial deflection, and predominantly during the wet spring months.

On Road Test One-MD (*17*) for about 150,000 load applications, settlements at joints on granular soil for 18,000-lb. axle load, with .025-in. normal deflection of night warped slab corner, were one half of those for the 22,400-lb. axle load with only slightly greater load deflection. The observed corner deflections for load on day warped slabs were about .006 in. Deflections for edge loading were in each case about one-half of the corner deflections.

Observed load deflections were not very much greater for slabs placed on fine grained soils, and did not increase appreciably where pumping was absent.

Computed deflections for the slab designs analyzed in this study, approximate:

	Slab thickness, in.				
	5	6	7	8	9
For corner, in.	.04	.025	.020	.018	.017
For edge axle load, in.	.02	.014	.012	.010	.008

The computed corner deflections increase rapidly for pavement depths under 6 in.; however, the computed deflections for subgrade k 400 psi. per in. deflection are much greater than observed for load alone on day-warped slabs on granular subgrade in Road Test One-MD. It is indicated that 6-in. slab thickness may be satisfactory at joints over consolidated granular subgrades and would undoubtedly be satisfactory along slab edges on most subgrades.

On fine-grained soils positive means to prevent loss of subgrade through pumping near joints, appear to be a primary requisite irrespective of pavement thickness and deflection. Transverse joints in prestressed pavements are spaced so far apart that such measures may involve little expense.

PRESTRESSED PAVEMENT PROGNOSTICATIONS

The structural sufficiency of concrete pavements made possible by the use of relatively low values of prestress, warrants careful consideration of the possibilities for construction of longitudinally prestressed pavements at reasonable cost.

Bettered service life from 30 to 40 years would justify about 18 percent first cost increase, and from 30 to 50 years about 30 percent, assuming stable construction costs and a fixed annual charge, but even greater increase in first cost would be justified for increasing costs of construction. These percentages show the maximum additional costs justified for commensurate improvement in construction, against which the possible cost increase of prestressed pavements must be appraised. The applicable construction cost can only be confirmed after extensive construction experience with adequately developed equipment. On preliminary studies only elementary comparisons with present practice can be made. Operational details can be indicated only to the extent of stimulating constructive thought and give initial ideas of practicability and costs.

Prestressed Pavement Construction

Highway construction practices have been developed through the years by competitive pressure to high efficiency and correspondingly economical operations. Hourly progress of 200 to 300 ft. of 24-ft. pavement would have to be made with prestressing operations to fit into accepted construction speed with the mixer on the shoulder, and ultimately greater speed considering the faster rate of concrete placing in thinner slabs. Longitudinal steel installation, hole or enclosure forming for post-tensioning cables, and any pre-fabrication or assembly are susceptible to full mechanization employing powered equipment riding the side forms. Joint preparation and prestressing operations would require manual skill to a greater extent, favoring the use of long slabs.

The problem of transverse joint sealing, and drainage may attend long prestressed slabs in less degree than it has shorter slabs. Adequate drainage and subgrade preparation could be provided more economically under joints spaced far apart, but fillers or seals within the joints would probably not be practical for the large daily and seasonal movements. Principal attention may instead be directed toward exclusion of obstructions and/or easy cleaning of joints. Open joints between two and three inches in width at low temperature present unknown conditions, but may be found acceptable. Load transfer devices for these joint widths would be a problem for quantitative design rather than development.

It is not possible to predict which prestressing method may ultimately become most widely used for pavements; initial work would probably follow established methods which give the greatest assurance of lasting efficiency. The necessary product and equipment developments for post-tensioned construction do not appear unduly complicated or costly for standardized, high-production highway construction. From present experience, post-tensioned cables in grouted holes, and precast joint elements appear to involve the simplest and most reliable method for immediate development.

The spacing of prestressing cables would depend upon the acceptable concentration of compression on the concrete at points of application. Transversly prestressed and precast joint slabs, containing anchorage devices, joint doweling, and joint closures, may simplify joint installation, permit prestress through cables spaced two to four ft., and give even distribution of pressure on the pavement at the earliest practical age, and protect the pavement during manual operations. Early prestress would appear to be especially effective in conjunction with procedures protecting the fresh slab against rapid loss of heat in curing. High-strength steel wire has become a standard material. Hydraulic prestressing jacks have been developed to meet common needs involving much greater forces than appear necessary for highway cables but requiring adaptation to pavement dimensions and for long extensions; a 500-ft. wire tensioned to 150,000 psi. would elongate more than 30 in., although a 500-ft. pavement slab prestressed to 300 psi. would shorten only about ⅝ in.

TABLE 2

	Slab length		
	400 ft.	600 ft.	800 ft.
Applied prestress, psi	250	310	360
Steel area per ft. width, sq. in.	.12	.15	.18
Prestressing cable weight, lb.	54,000	66,000	76,000
Total steel, inc. enclosures, anchors, joint dowels, etc	68,000	79,000	88,000
Estimated cost of steel items	$13,000	$14,000	$15,000
Estimated cost of steel placement, joint devices, stressing, and grouting	$5,000	$3,500	$3,000
Equipment costs, overhead, etc	$6,000	$6,500	$7,000
Probable cost of prestressing steel, transverse joints, and prestressing operations	$24,000	$24,000	$25,000

Prestressed Highway Costs

Prestressed concrete structures have become increasingly economical with experience. Prestressed pavement costs would in still greater degree be dependent upon continued experience and perfection of procedures. Preliminary cost data for comparative appraisal purposes must assume availability and efficient use of equipment; construction costs may appear high for highly standardized operations, but unforeseen refinements of design may require inclusion on the other hand.

Only items of specific reference to a comparison between prestressed and conventional construction will be discussed. Slab lengths for longitudinally prestressed 6-in. pavements will first be considered (Table 2); all items refer to one mile of 24-ft. highway.

If the above appraisal of mechanical and manual cost relations is correct, joint spacing over 400 ft. does not influence costs greatly. Shorter slabs would be expected to increase costs rapidly as well as slow down operations. The data in Table 2 indicate little to be gained by stepped application of prestress along the slabs, as compared to full prestress applied at transverse joints. A slab length between 400 and 600 ft. is indicated by these preliminary cost figures as most economical.

For comparison, corresponding pertinent costs of conventional pavements are given below, based on 9-in. slabs, the average thickness presently used by state highway departments in primary highways, with transverse doweled joints spaced 60 ft., and .6 lb. per sq. ft. of distributed reinforcement (*18*); a concrete cost of $12 per cu. yd. is assumed:

Concrete cost, 3,500 cu. yd. per mile	$42,000
Distributed steel, transverse joint dowels and installation devices	$12,000
Conventional pavement, compara-items cost	$54,000

This cost would be equalled by prestressed 6-in. pavement outlined above as shown below:

Concrete cost, 2,350 cu. yd. @ $12.80	$30,000
Prestressing steel items and installation	$24,000
Prestressed pavement, comparative items cost	$54,000

If 7-in. prestressed pavements were found advisable, the prestressing steel items could be expected to increase about $2,000, concrete costs would increase by about $4,000; prestressed highway costs would then be about 10 percent above the conventional pavement cost.

REMARKS

This discussion has been limited exclusively to highway pavements. Structural advantages of prestressing in thicker and more heavily loaded airport pavements could be expected to be even greater, but such pavements are far less subject to standardization and lack the possibilities for comparative study and research which has been the aim of this presentation. The quest for developments to fit the stringent operational demands of highway construction is a primary challenge; equipment and prestressing procedures suitable for highways could be applied more easily to heavier construction than the reversed.

Prestressed concrete would seem to offer sufficient possibilities for improvement of highway pavements to make thorough exploration of prestressed pavements a national responsibility.

REFERENCES

1. F. B. Farrel and H. R. Patrick, "The Capital Investment in Highways", Highway Research Board Proceedings, Vol. 32 (1953).
2. F. B. Farrel and H. R. Patrick, "Life Characteristics of Highway Surfaces", Highway Research Board Proceedings, Vol. 28 (1948).
3. W. van Breeman, "Current Design of Concrete Pavement in New Jersey", Highway Research Board Proceedings, Vol. 28 (1948).
4. C. W. Allen and J. F. Barbee, "Pavement Performance Surveys", Highway Research Board Proceedings, Vol. 26 (1946).
5. L. V. White and R. L. Peyton, "Condition of Concrete Pavements in Kansas as affected by Coarse Aggregate", Highway Research Board Proceedings, Vol. 25 (1945).
6. J. H. Swanberg, "Temperature Variations in a Concrete Pavement and the underlying Subgrade", Highway Research Board Proceedings, Vol. 25 (1945).
7. W. R. Woolley, "Some Observations on Resurfacing Portland Cement Concrete Pavements with Bituminous Mixtures", Highway Research Board Proceedings, Vol. 26 (1946).
8. Vernon G. Gould, "Salvaging old Pavements by Resurfacing", Highway Research Board Proceedings, Vol. 29 (1949).
9. G. R. Hanes, "Some Practices used by Ohio in the Salvaging of Old Pavements", Highway Research Board Proceedings, Vol. 27 (1947).
10. A. J. Bone, L. W. Crump and V. J. Roggeveen, "Control of Reflection Cracking in Bituminous Resurfacing over old Cement Concrete Pavements", Highway Research Board Proceedings, Vol. 33 (1954).
11. "Missouri does more Concrete Resurfacing", Engineering News Record, October 28, 1954.
12. D. W. Lewis, "The Performance of Concrete Resurfacing in Indiana", Highway Research Board Proceedings, Vol. 30 (1950).
13. O. L. Kipp, "Minnesota Practices on Salvaging Old Pavements by Resurfacing", Highway Research Board Proceedings, Vol. 30 (1950).
14. S. E. Roberts, "Cracks in Asphalt Resurfacing affected by Cracks in Rigid Base", Highway Research Board Proceedings, Vol. 33 (1954).
15. C. Dobell, "Prestressed Concrete in Highway Bridges and Pavements", Highway Research Board Proceedings, Vol. 32 (1953).
16. B. F. Friberg, "Frictional Resistance under Concrete Pavements and Re-

straint Stresses in Long Reinforced Slabs", Highway Research Board Proceedings, Vol. 33 (1954).
17. Highway Research Board Special Report 4, "Road Test One-MD", (1952).
18. B. F. FRIBERG, "Some Observations on the Use of Reinforcing Steel in Concrete Pavements", American Concrete Institute Proceedings, Vol. 47 (Sept. 1950).
19. H. M. WESTERGAARD, "Stresses in Concrete Pavements Computed by Theoretical Analysis", Public Roads, April 1926.
20. L. W. TELLER AND E. C. SUTHERLAND, "The Structural Design of Concrete Pavements", Public Roads, October 1935, November 1935, December 1935, September 1936, October 1936, April-May-June 1943.
21. H. D. CASHELL AND S. W. BENHAM, "Experiments with Continuous Reinforcement in Concrete Pavements", Highway Research Board Proceedings, Vol. 29 (1949).
22. B. F. FRIBERG, "Sector Analysis of Concrete Pavements, An Analysis of Pavement Load Stresses and Deflections", American Society of Civil Engineers (in course of Publication).
23. H. M. WESTERGAARD, "Analysis of Stresses in Concrete Roads Caused by Variations of Temperature", Public Roads, May 1927.

Velocity Distribution in a Street or Similar Channel

G. S. TAPLEY, *Civil Engineer*
Bureau of Engineering, City of Los Angeles

Manning's formula already has been applied to the determination of velocity distribution in the form $v = Gy^{2/3}$, where v is the velocity in a vertical element of water cross section, y is the depth of the element, and G is a constant depending on the roughness of channel surface and the channel slope. In the region affected by a curb or vertical side wall, however, this relationship gives irrational results, since the magnitude of velocity at the wall actually must be zero, whereas the equation above yields a finite value.

Differentiation of Manning's formula, on the other hand, gives an equation representing a locus of rational form for the region nearer the side wall. This locus and that of the equation given above, applied to the portion of the channel more remote from the side wall, forms a combined locus which agrees approximately with experimental results. The discrepancy is systematic, however, and is attributed to the neglected shear between water elements.

● FOR uniform flow in an open channel the gravitational and frictional forces are equal, so that

$$\tau PL = -wSLA^{1} \qquad (1)$$

where τ is the frictional drag per unit of area of channel surface, P is the wetted perimeter of water cross section, L is the length of channel, w is the weight of a cubic unit of water, S is the longitudinal slope of the channel, and A is the area of the water cross-section. From (1) it follows that the hydraulic radius R commonly employed in Manning's formula and elsewhere represents the ratio of unit drag to unit gravitational force; for, by (1)

$$R = \frac{A}{P} = -\frac{\tau}{wS}\,. \qquad (2)$$

[1] See for example, "Elementary Mechanics of Fluids," Rouse, p. 215.