Prestressed Pavement Joint Designs

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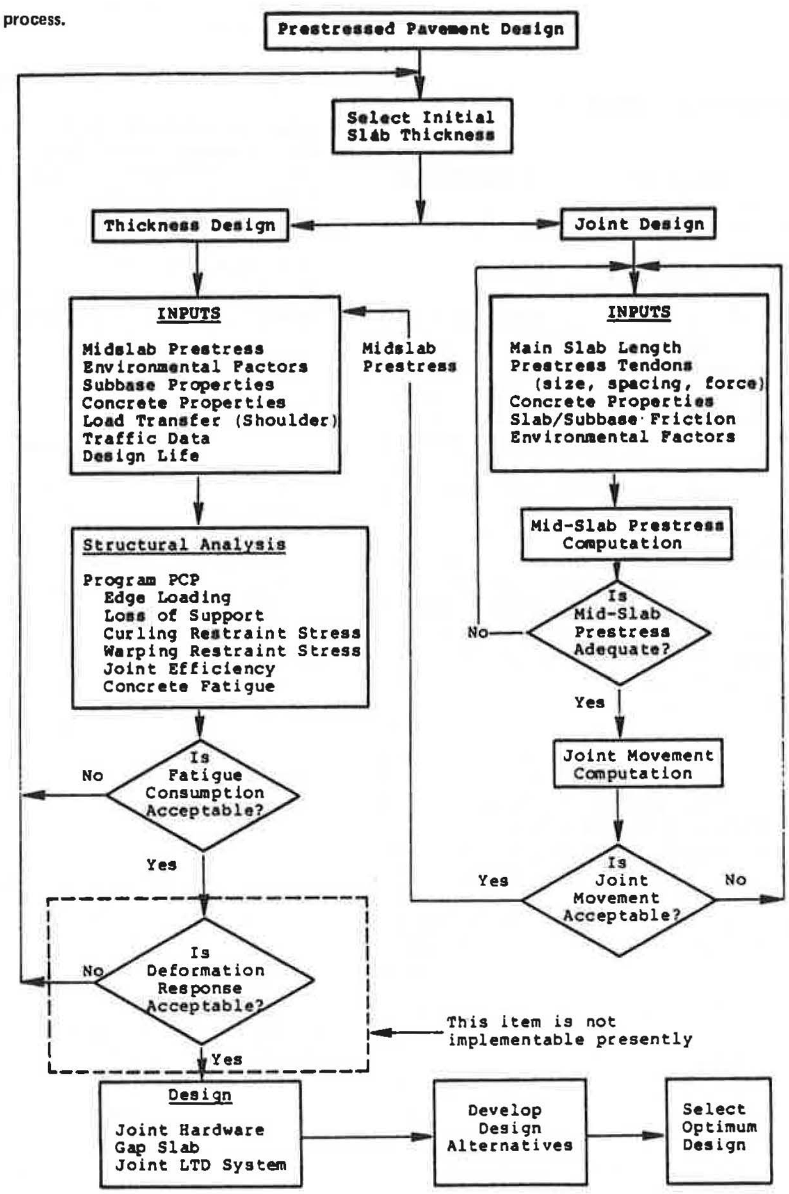
Four transverse joint designs for prestressed concrete pavements are presented. Items considered in developing the designs include slab length, tendon force, tendon size, tendon spacing, desired midslab prestress, allowable joint movement, and use of one or two active joints between adjacent main slabs. Proper attention must be given to joint hardware design because a large number of items such as anchors, strands, load-transfer devices, infiltration-prevention devices, reinforcement, and positioning bars are located within a few inches of the joint. Therefore, detailing of joint hardware is a critical element of design. Designs I, II, and III are for an 8-in-thick pavement with main slab lengths of 350 ft. A short prestressed gap slab and a single active joint are used between the main slabs. Design IV is for a 7-in-thick pavement with main slab lengths of 250 ft. A tied concrete shoulder is used. Gap slabs are 10 in thick, conventionally reinforced, with an active joint at each end.

The objective of the Federal Highway Administration (FHWA) Research Project 5E, Premium Pavements for Zero Maintenance, is to exploit modern materials and technology in developing zero-maintenance pavements for warranted use. As a portion of this research project, an investigation has been conducted by Construction Technology Laboratories, a division of the Portland Cement Association. The objective of the investigation was to develop design and construction techniques for prestressed concrete pavements.

Prestressed pavement design includes the determination of required pavement thickness and joint hardware. Joint hardware is determined based on anticipated slab movement and length. Figure 1 shows the basic steps involved in prestressed pavement design.

As shown in Figure 1, the prestressed pavement design process is iterative and involves the interaction of many factors. The process starts with the selection of an initial slab thickness. Then, for joint hardware design, trial main slab length and

Figure 1. Prestressed pavement design process.



prestress tendon size, spacing, and force are selected. Effective midslab prestress is computed. A minimum of about 50-psi midslab prestress should be obtained. If it is not obtained, slab length, tendon size, spacing, or force is varied until the desired midslab prestress is obtained.

When the midslab prestress criterion is satisfied, anticipated maximum joint movement is computed. Selection of an appropriate joint infiltration-prevention device such as a strip seal, compression seal, or steel cover plate depends on the magnitude of total joint movement. Total movement may be accommodated at one or two active joints between adjacent slabs. Slab length is varied until computed joint movement can be accommodated by the device selected.

After slab length, midslab prestress level, and joint hardware are established, a structural analysis is performed. This analysis requires a value of effective midslab prestress as an input. The structural analysis computes fatigue consumption due to edge stresses at midslab. If fatigue consumption is more than 100 percent, the design process is repeated by using a larger slab thickness.

This paper presents transverse joint designs for prestressed pavements. Further design details are given elsewhere (1).

JOINT DESIGN STEPS

Joint design for prestressed pavements involves the following steps:

1. Determination of required pavement thickness;
2. Selection of slab length;
3. Determination of prestressing tendon size, spacing, and force; and
4. Detailing of joint hardware.

Proper attention must be given to joint hardware design because a large number of items such as anchors, strands, load-transfer devices, infiltration-prevention devices, reinforcement, and positioning bars are located within a few inches of the joint. Detailing of joint hardware is, therefore, a critical element of design. Detailing requirements also put a limit on the practical minimum slab thickness that can be used for construction.

Prestressed pavement thickness is determined by using the computer program presented in Tayabji and others (2). This program considers the case of loads applied at or near a longitudinal edge. Bottom fiber stresses due to load, temperature differentials, moisture differentials, and midslab prestress are determined and summed for different magnitudes of traffic load. The resultant stress for each loading consumes a portion of the pavement's fatigue resistance. The design thickness is that for which fatigue consumption generally ranges between 60 and 100 percent. By using this procedure, a small compressive stress is maintained in the slab.

Thickness design is based on edge loading; consideration is given to stresses due to temperature, moisture, edge support loss, and the presence or absence of a tied concrete shoulder. On this basis, thickness requirements were 7 and 8 in for zero-maintenance pavements with and without a tied shoulder, respectively (2).

Selection of slab length and tendon force, size, and spacing is influenced by the desired minimum prestress level at midslab and the allowable joint movement. As noted previously, this selection process is iterative. Several trial selections are required before a satisfactory solution is achieved. A brief discussion of factors considered in computing midslab prestress and joint movement follows.

PRESTRESS REQUIREMENTS

End prestress must be sufficient to provide a minimum midslab prestress of about 50 psi after subtracting losses due to tendon friction, concrete shrinkage, concrete creep, steel relaxation, and subbase friction restraint. Equations for computing losses are given elsewhere (1).

Equations for computing prestress losses require the use of an end prestress value. This means an initial value is assumed and a final value is determined by an iterative process. One method of shortening this process is to make judgment assumptions regarding tendon diameter, spacing, and stress level. For example, if 0.6-in-diameter tendons are stressed to 70 percent of ultimate, the allowable tendon force is 41 000 lb. For tendons spaced at 18-in centers in an 8-in-thick pavement, initial end prestress is 285 psi. This procedure was used to compute losses for examples shown in Table 1. Coefficients and other values required for computations are listed in Table 2.

SLAB END MOVEMENTS

Slab end movements result from daily and seasonal temperature variations and concrete drying shrinkage and creep.

Temperature-Associated Movements

Temperature-associated movements are functions of the concrete coefficient of thermal expansion and local temperature variations. Movements are affected by seasonal as well as daily temperature effects. Seasonal movements take place over a long period of time; therefore, it is assumed that slab-to-subbase friction does not restrict movement (3). Daily movements due to temperature variation are affected by slab-to-subbase friction; therefore, daily

Table 1. Prestress calculations.

Item	General Calculations	
	Slab 7 in Thick	Slab 8 in Thick
Slab length (ft)	250	350
Strand diameter (in)	0.6	0.6
Strand force (kips)	41	44
Strand spacing (in)	24	18
End of slab prestress (psi)	244	306
Prestress losses (psi)		
Shrinkage	6	6
Creep	4	6
Relaxation	20	31
Strand friction	39	66
Subbase friction	100	140
Total	169	249
Midslab prestress (psi)	75	57

Table 2. Prestress loss computation coefficients.

Item	Magnitude
Tendon ultimate strength (psi)	270 000
Area, 0.6-in-diameter tendon (in^2)	0.217
Concrete creep coefficient	2.5
Concrete shrinkage strain (millionths)	150
Strand relaxation coefficient	
70 percent of ultimate stress	0.08
75 percent of ultimate stress	0.10
Wobble friction coefficient per foot	0.0014
Subbase friction factor	0.8
Modulus of elasticity of steel (million psi)	28
Modulus of elasticity of concrete (million psi)	5

movements are corrected for subbase frictional restraint.

During winter, slab concrete is more moist than in the summer. This results in a concrete coefficient of thermal expansion that is about 15 percent lower than that for concrete in a drier state (4). This factor is considered for computation of daily temperature-associated movements for winter months.

Seasonal slab movement is given by the following equation:

$$d_1 = \alpha(\Delta t)L \tag{1}$$

where

- d_1 = slab movement associated with seasonal temperature changes,
- α = coefficient of thermal expansion of concrete,
- Δt = seasonal variation in average concrete temperature, and
- L = slab length (ft).

Maximum daily slab movement during the summer months is given by the following equation:

$$d_2 = \alpha(\Delta t_s)L - d_f \tag{2}$$

where

- d_2 = slab movement associated with daily temperature variation during summer,
- Δt_s = summer maximum temperature less summer average temperature, and
- d_f = slab movement restrained by subbase friction, i.e.,

$$d_f = (\sigma_f/2E_c)L \tag{3}$$

where σ_f is the maximum subbase friction restraint stress, and E is the modulus of elasticity.

Maximum daily slab movement during the winter months is given by the following equation:

$$d_3 = 0.85\,\alpha(\Delta t_w)L - d_f \tag{4}$$

where d_3 is the slab movement associated with daily temperature variation during winter and Δt_w is the winter average temperature less winter minimum temperature.

Shrinkage

Shrinkage strain is influenced by amount of mixing water, water-cement ratio, aggregate type, and curing conditions. For concrete prisms drying from all faces, long-term shrinkage strain varies from 100 to 500 millionths (5). For slabs drying only from the top, a value of 250 millionths has been assumed. About 100 millionths of this strain takes place within the first month. Because gap slabs are not placed until about one month after main slabs are cast, only 150 millionths strain needs to be considered in computing future slab shortening.

Slab shrinkage is given by the following equation:

$$d_4 = \epsilon_s L \tag{5}$$

where d_4 is the slab shortening due to shrinkage and ϵ_s is the concrete shrinkage strain.

Concrete Creep

Creep is the long-term shortening of concrete subjected to sustained stress. The relation between concrete creep strain (ϵ_k) and elastic strain is expressed by the following equation (6):

$$\epsilon_k = C_u(f_{av}/E_c) \tag{6}$$

where f_{av} is the average prestress along the slab length (psi) and C_u is the ultimate creep coefficient.

Slab shortening due to creep (d_5) is then given by the following equation:

$$d_5 = \epsilon_k L \tag{7}$$

Creep magnitude varies with gradation of concrete aggregates, particle shape, aggregate type, cement content, water-cement ratio, concrete density, curing, age at loading, load intensity, and concrete element size. A creep coefficient of 2.5 is suggested for computing creep-associated shortening of prestressed pavements.

Two examples of slab end movement computations are presented for the four joint designs presented in this paper. Coefficients, weather information, and other factors used in the calculations are listed in Table 3.

Designs I, II, and III

Computations are for an 8-in-thick pavement with 350-ft-long main slabs. One active joint is used at the gap slab. The movements are as follows:

d_1 = 1.32 in,
d_2 = 0.38 in,
d_3 = 0.62 in,
d_4 = 0.64 in, and
d_5 = 0.32 in.

The total movement at an active joint equals $d_1 + d_2 + d_3 + d_4 + d_5$ = 3.28 in.

Design IV

Computations are made for a 7-in-thick pavement with 250-ft-long main slabs. Two active joints are used at the gap slab. The movements are as follows:

d_1 = 0.47 in,
d_2 = 0.14 in,
d_3 = 0.22 in,
d_4 = 0.22 in, and
d_5 = 0.12 in.

The total movement at each active joint equals $d_1 + d_2 + d_3 + d_4 + d_5$ = 1.17 in.

Knowledge of slab end movements is essential to setting the initial opening at active joints of gap slabs. It is also important in selecting the size of compression seals, width of cover plates, and ex-

Table 3. End movement computation coefficients.

Item	Magnitude
Modulus of elasticity of concrete (million psi)	5
Concrete creep coefficient	2.5
Coefficient of thermal expansion, summer (in/in/°F)	0.000 005 0
Coefficient of thermal expansion, winter (in/in/°F)	0.000 004 3
Concrete shrinkage strain (millionths)	150
Slab-to-subbase friction factor	0.8
Summer avg concrete temperature (°F)	93
Winter avg concrete temperature (°F)	30
Seasonal variation in avg concrete temperature (°F)	63
Summer maximum concrete temperature (°F)	114
Winter minimum concrete temperature (°F)	-8
Summer maximum temperature excess of avg (°F)	21
Winter minimum temperature less than avg (°F)	38
Avg slab prestress for 7-in-thick pavement (psi)	165
Avg slab prestress for 8-in-thick pavement (psi)	160

tensibility requirements of compressive and strip seals.

The average concrete temperature during placement of gap slabs is used to determine the initial width of active joints. From design I calculations, it is seen that a joint width set at 93°F would be expected to close 0.38 in due to daily summer temperature variation. Extrapolation shows that for a placement temperature of 72°F, closure would be 0.76 in. Thus, the joint width set for the latter condition would be double that required for the first.

Table 4. Joint design parameters.

Item	General Parameters	
	Slab 8 in Thick	Slab 7 in Thick
Main slab length (ft)	350	250
Gap slab thickness (in)	8	10
Gap slab length (in)	59	59
Design condition	Free edge	Tied shoulder
No. of active joints	1	2
Tendon diameter (in)	0.6	0.6
Tendon spacing (in)	18	24
Tendon load (kips)	44	41
End of slab prestress (psi)	306	244
Midslab prestress (psi)	57	75
Movement at each joint (in)	3.3	1.2

JOINT DESIGNS

Four transverse joint designs are presented. Designs I, II, and III are for an 8-in-thick pavement with main slab lengths of 350 ft. A single active joint between adjacent main slabs is used for these designs. Design IV is for a 7-in-thick pavement with a tied concrete shoulder. Main slab lengths are 250 ft. Two active joints between adjacent main slabs are used for this design.

Gap spaces are left between ends of main slabs to accommodate posttensioning operations. Gap slabs are cast in these spaces approximately 30 days after

Figure 2. Design I, overall view.

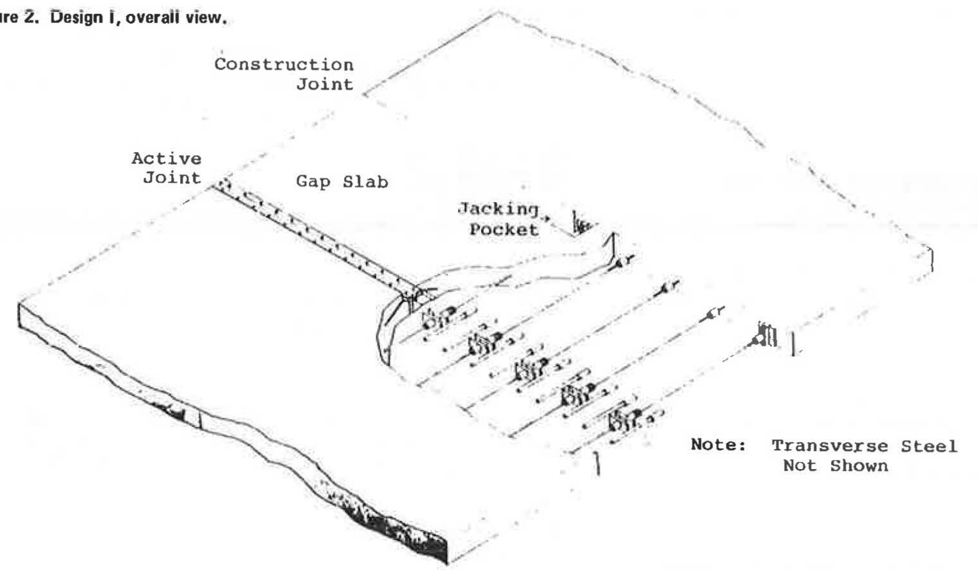
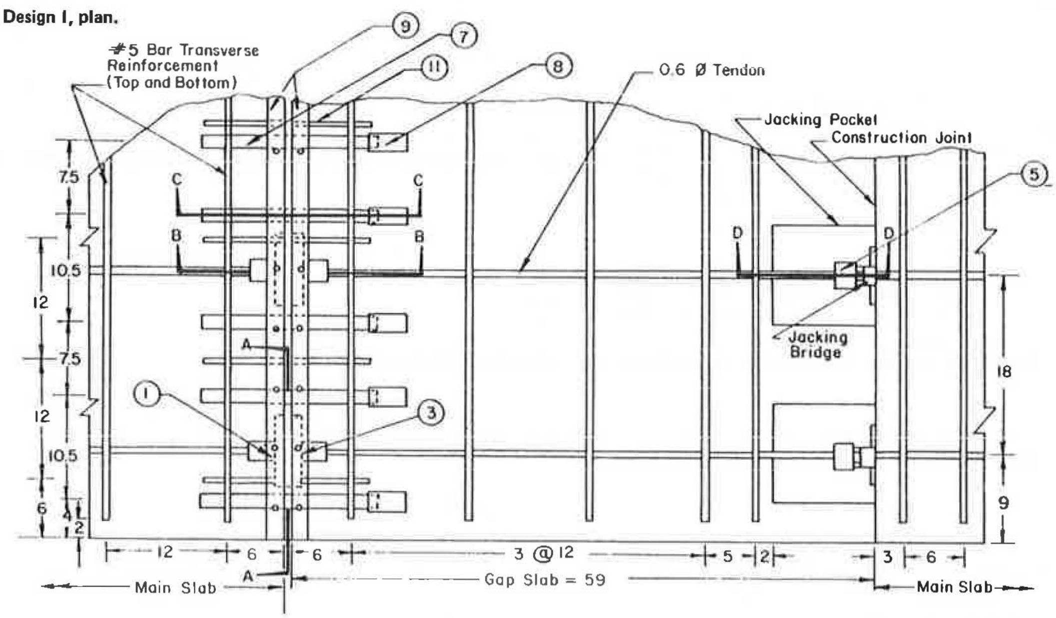


Figure 3. Design I, plan.



Dimensions in inches

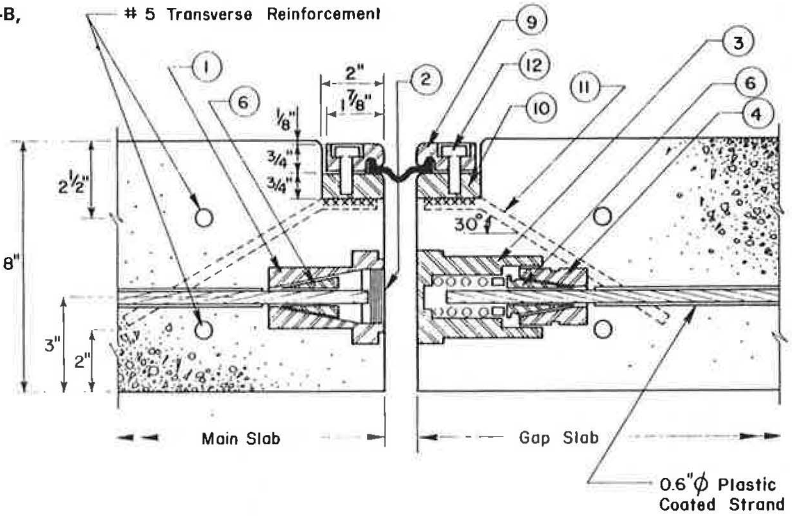


Figure 4. Section B-B, design I.

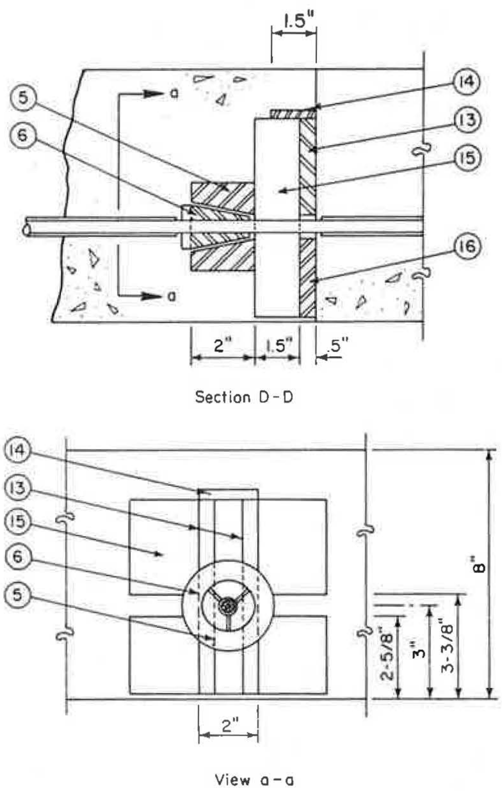


Figure 5. Section D-D, design I.

Table 5. Joint hardware for design I.

Item	Description	Dimension
1	Combined chuck anchor bodies (Figure 6)	For 0.6-in strand
2	Stainless-steel caps to fit anchor body (Figure 4)	
3	Automatic seating anchors (Figure 7)	For 0.6-in strand
4	Externally threaded chucks	For 0.6-in strand
5	Barrel chucks for temporary prestressing and stress transfer (Figure 5)	2.75x2 in long
6	Three-jawed wedges (Figure 4)	For 0.6-in strand
7	Stainless-steel dowels (Figure 3)	1.25 in thick, 18 in long
8	Dowel caps (Figure 3)	1.3125 in inside diameter by 4 in
9	Extrusions for upper portion of seal holder with holes for bolts (Figure 4)	6 ft long, 0.75x1.875 in
10	Extrusions for lower portion of seal holder drilled and tapped (Figure 4)	6 ft long, 0.75x2 in
11	No. 3 deformed bars welded to lower seal holder extrusion (Figure 4)	9 in long[a]
12	Bolts (Figure 4)	0.5 in
13	Steel plates (Figure 5)	6.25x2.75x0.5 in
14	Steel plates (Figure 5)	2x1.5x0.25 in
15	Steel plates (Figure 5)	6x3x0.5 in
16	Steel plates (Figure 5)	6x2.5x0.5 in

[a]Bent as shown in Figure 6.

main slab placement. Prestressed pavement construction details are given elsewhere (7). Joint design parameters used for this paper are listed in Table 4.

Design I: Strand Prestressed Gap Slab

An overall view of a joint designed for an 8-in-thick pavement with main slab lengths of 350 ft is shown in Figure 2. For clarity of viewing, the transverse steel located near the ends of main slabs and in the gap slab is not shown.

In this design, main slab prestress is applied at construction and active joint faces. Tendons from the construction joint face are continued to anchorage devices located at the active joint. Jacking pockets are provided at the construction joint for posttensioning the gap slab. Gap slab tensioning is accomplished by using a jacking system that grasps the construction joint chuck and advances the tendon into the anchorage device. The anchorage device automatically grips the strand as it is advanced. A more descriptive account of each step in the process, together with details concerning jacking equipment and procedures, is given in the construction manual (7).

A plan view of design I is shown in Figure 3. Additional details of joint hardware locations and dimensions are shown in Figures 4 and 5 for sections B-B and D-D. Circled numbers on the drawings refer to the parts that are listed (with dimensions) in Table 5.

Tendon anchors, load-transfer devices, and methods of preventing infiltration are major joint hardware. These items are discussed separately.

Anchors

Two types of permanent anchors were designed for use at active joints. One type, which is located in the main slab, combines the anchor body and chuck into one casting. Bearing is provided close to the joint

Conventional anchors are used in jacking pockets located at the construction joint face. Tendons and anchors are positioned below slab middepth to reduce upward warping of slab ends. Tendon centers are located 5 in below the slab surface.
face. Tendons and wedges are protected from corrosion by a stainless-steel cap threaded into the anchor after completion of tensioning. A sectional view of this anchor is shown in Figure 4. Details are shown in Figure 6.

The second type of permanent anchor is located at the active joint face of the gap slab. The anchor body is threaded internally to accept an externally threaded chuck. Anchors are provided with springs to prevent wedges from moving toward the joint face during gap slab prestressing. Sufficient space is provided within the anchor body to permit strand extension during prestressing operations. These springs also provide positive seating of wedges. A sectional view of this anchor is shown in Figure 4. Details are presented in Figure 7.

Load Transfer

Stainless-steel dowels 1.25 in in diameter are located on each side of the anchors. Transverse spacing is shown in Figure 3. Dowels are embedded in the concrete of the main slabs at active joint ends. That portion of the dowel that extends into the gap slabs are greased, and caps are placed over dowel ends to assure unrestrained slab end movements.

Infiltration Prevention

Premolded nylon-reinforced neoprene-strip seals are used to prevent joint infiltration. Strip-seal holders consist of upper and lower steel extrusions, as shown in Figure 4. Dimensions of top elements are 1.875x0.75 in. One side is shaped to hold the longitudinal edge of the strip seals. The tops of the extrusions are set 0.125 in below the concrete surface for protection from snowplow blades.

Top extrusions are drilled and countersunk to recess 0.5-in bolts used for clamping the upper seal-holder extrusion to the lower extrusion. Bolt spacing is 6 in on centers. The lower extrusion is drilled and tapped at spacings to match those in the upper extrusion. The lower extrusion is anchored in the slab by No. 4 deformed bars.

Several different diaphragms or strip seals can be used with this joint design. Generally, diaphragm or strip seals are premolded extruded neoprene or natural rubber folds that extend the length of the joint. They are mechanically anchored to each side of the joint. Normally, 0.125- to 0.375-in-thick neoprene is used. The neoprene is usually reinforced with fibers to provide tensile strength and resist puncturing.

Design II: Rod Prestressed Gap Slab

An overall view of design II is shown in Figure 8. This design is for an 8-in-thick pavement with main slab lengths of 350 ft. Rods and nuts are used to prestress the gap slab from jacking pockets. Splice chucks located in these pockets join tendons and rods. Jacking in the pocket advances the rod into the anchor. The rod nut located at the gap slab active joint face is tightened to maintain prestress. This system eliminates the need for the temporary jacking bridge used at the construction joint face of the main slab in design I. In addition, the specially designed anchors used at active joints in design I are not required. Dowels are used at the active joint to transfer load. Additional details of joint hardware locations and dimensions are given elsewhere (1).

Figure 6. Permanent anchor.

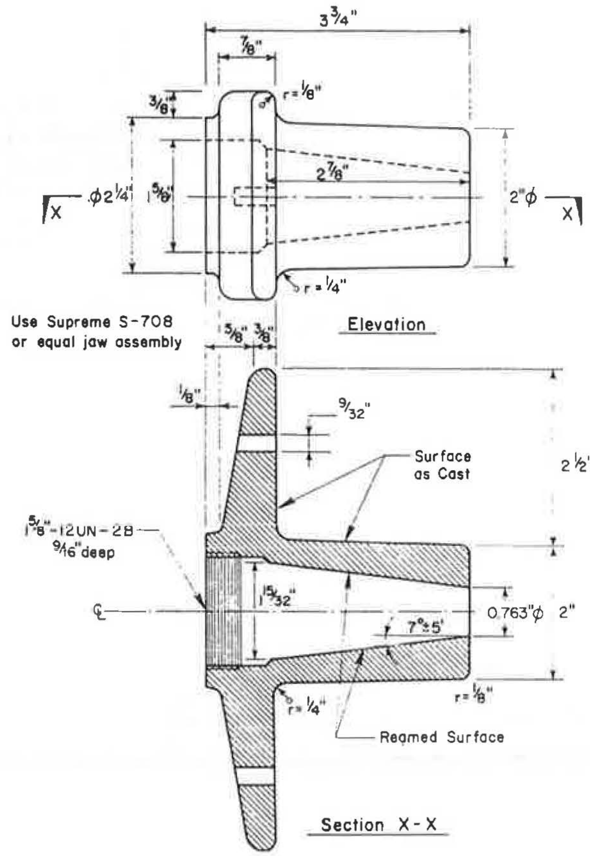


Figure 7. Automatic seating anchor.

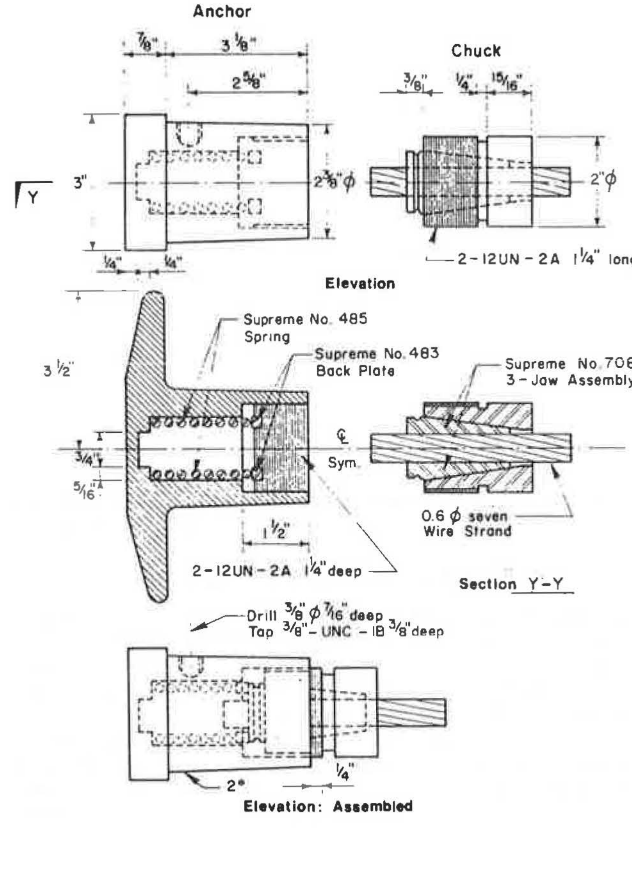


Figure 8. Design II, overall view.

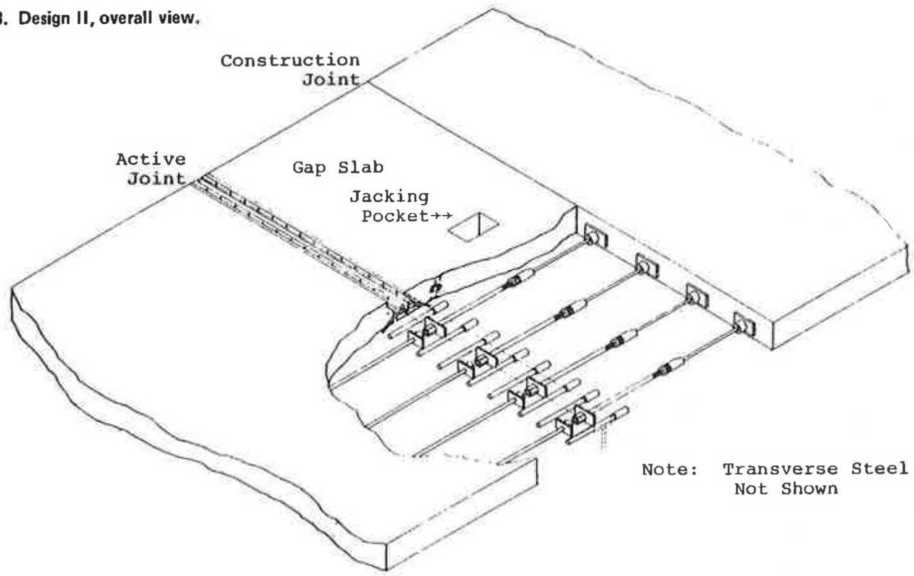
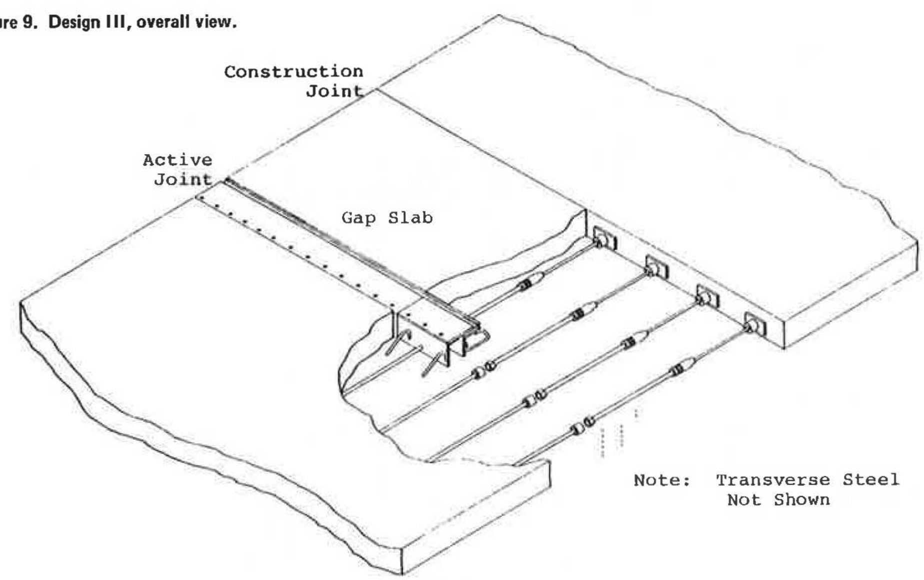


Figure 9. Design III, overall view.



Design III: Cover Plate Joint

An overall view of design III is shown in Figure 9. This design, which is for an 8-in-thick pavement with main slab lengths of 350 ft, also uses a rod-and-nut system to prestress the gap slab. However, posttensioning is accomplished by manual torquing of the nut located at the active joint face. Thus, jacking pockets are not required. The steel cover plate joint serves as bearing for tensioning tendons and nuts at the active joint. In addition, cover plates contribute to load transfer.

Additional details of joint hardware locations and dimensions are given elsewhere (1).

Design IV: Compression Seal Joint

An overall view of design IV is shown in Figure 10. This design is for a 7-in-thick pavement with main slab lengths of 250 ft. Main slab pavement thickness is reduced because a tied concrete shoulder is used. Prestressing is terminated at main slab ends. Gap slabs are 10 in thick and are conventionally reinforced. An active joint is provided at each end of the gap slab. Dowels provide load transfer at active joints.

A plan view of design IV is shown in Figure 11. Additional details of joint hardware and dimensions are shown in Figures 12 and 13. Items designated by circled numbers are described in Table 6.

As shown in Figure 12, a compression seal is used at the active joint. Seals must accommodate an anticipated joint opening of 1.2 in. Concrete shoulders prevent downward seal movement. Stainless-steel dowels spaced at 12-in centers are located 4 in below the slab surface. Tendon anchors are "off-the-shelf" models. Anchor faces are recessed to provide space for grout corrosion protection.

SUMMARY

Four joint designs for use with prestressed pavements are presented. Details are provided for 7- and 8-in-thick pavements. These thicknesses are computed to be satisfactory for zero-maintenance designs developed for heavily trafficked freeways. For less-heavy traffic, smaller thicknesses may be

Figure 10. Design IV, overall view.

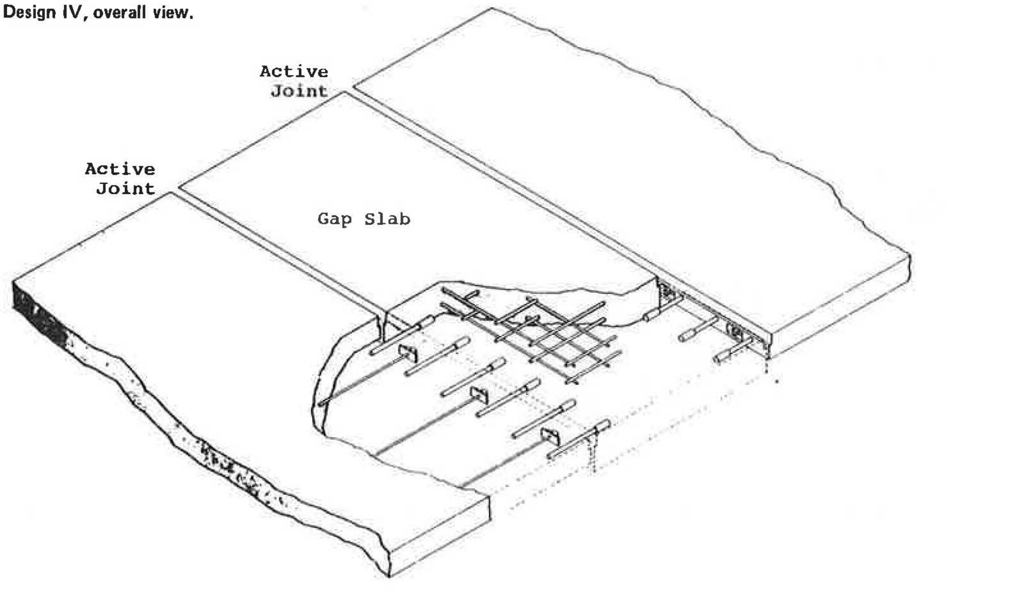


Figure 11. Design IV, plan.

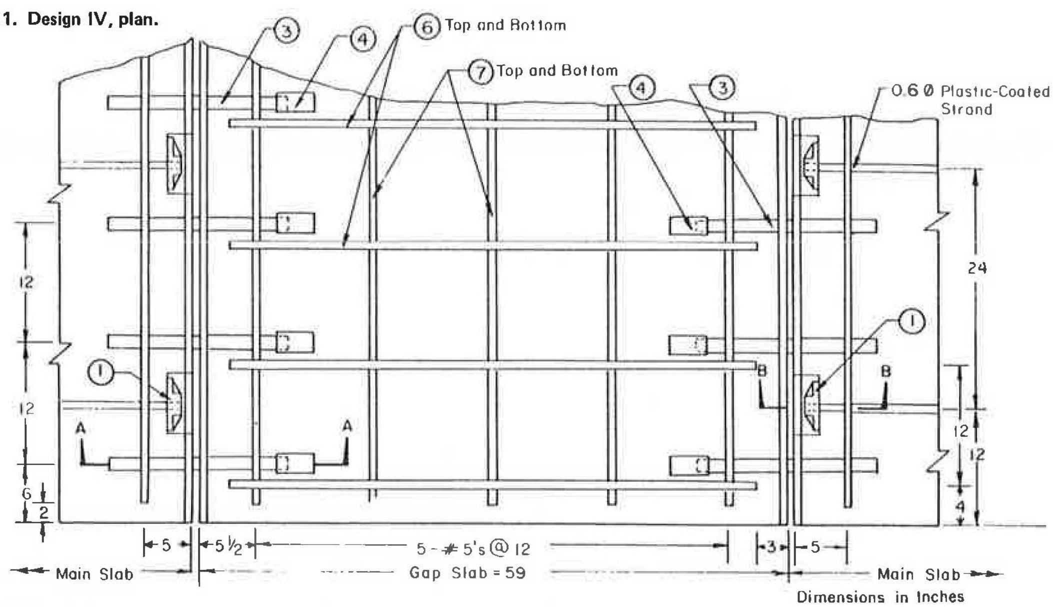
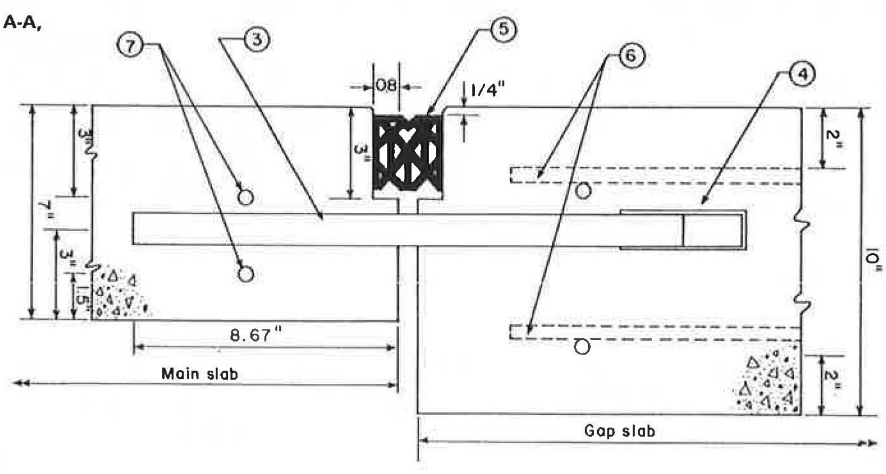


Figure 12. Section A-A, design IV.



ciated with these neoprene strips since their installation in 1975, including the design for fastening the edges to the slabs.

4. The method of posttensioning the gap slab in design I is the same concept as was used in the design and construction of the prestressed pavement near Harrisburg, Pennsylvania, in 1976. This method is presented in the PCA report (8). The valuable research information and knowledge obtained from this first-of-its-kind method constructed in the United States identified ways to improve the procedural techniques for posttensioning the gap slab. Joint design II merely presents another procedural technique for performing this posttensioning operation.

5. The use of the cover plate in design III for the 8-in, 350-ft slab is the same concept used in the two German airfield pavements in 1959 and 1960 (8, Figures 26 and 27, pp. 51-52).

6. The paper states that the length of the pavement slab is varied until the computed joint movements can be accommodated by the joint device selected. This is contrary to the procedure practiced heretofore by well-known designers and contributors who first determine (or select) the length of the pavement slab and then design the joint to accommodate the predesigned slab. The paper offers no explanation or reason as to why it recommends this reversal in design procedure from current practice.

7. In the discussion of joint design IV, it is stated that a 7-in pavement thickness can be used because the pavement is tied to the shoulder. The paper does not explain how this partial transfer of the vehicle load to the shoulder is to be achieved or, equally important, how this tie with the shoulder may influence the slab end movements and the design of the gap slab.

8. The paper states that tendons and anchors are positioned below slab middepth to reduce upward warping of slab ends. But yet no explanation is given as to how this eccentric prestressing, as recognized and used in current practice, will influence or effect the design of the slab.

9. The paper states that the design process starts with the selection of an initial slab thickness based on a minimum midslab prestress of only 50 psi. Other designers and contributors to prestressed pavement technology claim and substantiate their midslab prestress of 200 psi or more can be maintained in slab lengths of 400-500 ft. For the two slab thicknesses of 7 and 8 in, the paper presents slab lengths of only 250 and 350 ft, respectively.

10. The paper does not give any explanation or rationale as to why only one active joint is proposed for the longer slab but two active joints are proposed for the shorter slab, wherein the joint must accommodate end movements due to half of the slab length only.

11. In the section on slab end movements, the paper discusses long-term creep but does not discuss the seasonal effects of moisture. Among others, the potential benefits of moisture effects were substantiated in previous work conducted in 1956-1959 at the University of Missouri at Rolla. The potential benefits of moisture effects are reported in the literature by Teller and Sutherland (9), Friberg (10), and Kelley (11). Application of these findings indicates that the slab end movements presented in the paper may be reduced by as much as 1 in.

(Note: This discussion paper reflects my views only and does not necessarily reflect the official views or position of FHWA.)

Authors' Closure

We thank Stanek for his review of the paper. We are pleased that he acknowledges our appreciation of the fine pioneering work done in prestressed pavements by other researchers. A detailed review of this pioneering work is included in our first report on the project (8).

As Stanek states in his comments 1-5, we were guided by the past work of others in developing joint systems that are engineered to provide the required levels of performance.

The approach we used in determining the design slab length for the examples presented in the paper was based primarily on two considerations. First, the commercial availability of joint seals that can accommodate large joint movements influences the allowable magnitude of joint movement, and thus slab length. Second, the maximum joint opening is limited to about 3-4 in to prevent tire ingress into joints. This procedure is not a reversal from current practice. It is the established practice for joint designs that involve large openings.

With regard to provisions for a tied shoulder, we recommend use of a prestressed tied shoulder. Main-line lanes and the shoulder are cast in the same paving operation and prestressed at the same time. Thus, differential length changes between main-line pavement and shoulder are avoided. A weakened-plane longitudinal joint is provided between the outside lane and the shoulder.

Although additional prestressing is developed due to eccentric placement of tendons, this effect exists only at slab ends. As a simple analysis of a semi-infinite slab on elastic foundation shows, the effect of the moment developed due to tendon eccentricity dissipates rapidly away from slab ends. Therefore, although tendon eccentricity reduces upward-warping deformation at slab ends, it does not contribute to stresses in the interior portion of the slab.

Our approach to prestressed pavement design is not to provide as much midslab prestress as possible. It is rather to provide a minimum level of prestress to ensure that early cracks that may develop remain tightly closed. We do not object to the use of higher prestress levels, but we believe that higher prestress should be used to increase slab lengths or to provide an added factor of safety. However, unless satisfactory slab deformation response is assured, higher midslab prestress should not be used just to reduce slab thickness.

It should be noted that the calculated design midslab prestress level for the Arizona demonstration project was 42 psi (12). In addition, the measured midslab prestress at the Mississippi demonstration project, immediately after final prestressing, was 60 psi for sections that incorporated two layers of polyethylene under the slab (13).

Single active joints between main slabs are used to reduce the number of active joints. For design IV, use was made of shorter slab lengths and two active joints to permit use of compression seals. Design IV illustrates an economical option for joint hardware.

With regard to the influence of moisture effects, we believe that slab lengthening during winter months is not substantial at the slab surface. The reason the slab top does not lengthen as much as the bottom is due to drying shrinkage at the surface. This drying shrinkage is not fully recoverable and, in addition, slab shortening due to temperature is greater at the pavement surface.

Figure 13. Section B-B, design IV.

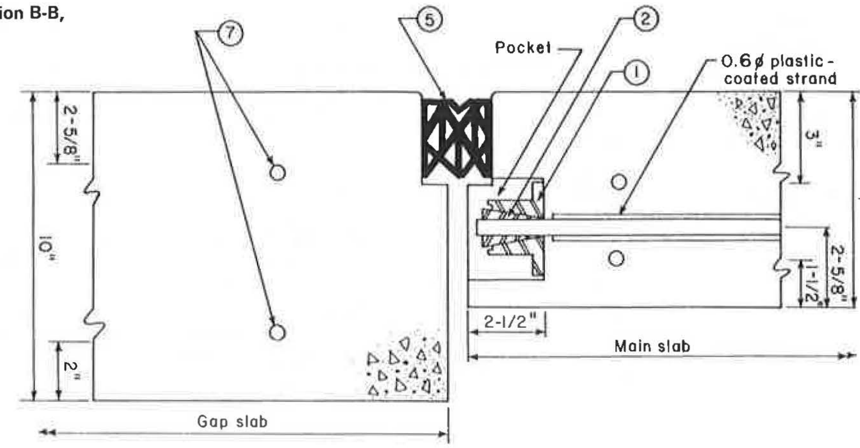


Table 6. Joint hardware for design II.

Item	Description	Dimension
1	Standard anchors (Figure 11)	3x5.25 in for 0.6-in strand
2	Three-jawed wedges (Figure 13)	For 0.6-in strand
3	Stainless-steel dowels (Figure 12)	18 in long, 1.125 in
4	Dowel caps (Figure 12)	4 in long to fit over 1.125-in dowel
5	Compression seal ACMASEAL (K-400) (Figure 12)	36 ft long, nominal uncompressed 2.5 in high, 3.4 in wide
6	No. 5 bar longitudinal reinforcement (Figure 12)	54 in long
7	No. 5 bar transverse reinforcement (Figure 11)	35 ft long

satisfactory. Joint design details in this paper can be easily adapted to other thicknesses by making the necessary dimensional changes.

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Bengt F. Friberg acted as a principal consultant and contributed to all phases of the study. His participation is gratefully acknowledged. In addition, Wolfgang Krahl also served as a consultant and contributed to many phases of the study. T.F. McMahon and W. Kenis of FHWA provided technical coordination. Their cooperation and suggestions are gratefully acknowledged.

The opinions and findings expressed or implied in the paper are ours. They are not necessarily those of FHWA.

Discussion

Floyd J. Stanek

The comments in this discussion paper were formulated from information received while I served as technical monitor and coordinator for two studies of prestressed pavements sponsored by the Office of Research, FHWA. One study was a coordinated study by three state highway agencies to conduct an on-site inspection for the study, Performance of Prestressed Pavements in Four States. The representative members of this inspection team are Wade L. Gramling, Pennsylvania Department of Transportation (DOT); Gene Morris, Arizona DOT; and T. Paul Teng, Mississipi State Highway Department.

The other study was a follow-up research study of the Prestressed Pavement Demonstration Project, which was constructed in 1971-1972 near Dulles International Airport, Loudoun County, Virginia. This study was conducted by Bengt Friberg, one of the principal contributors to the original design and construction of this project. I served as monitor of this project for the Office of Research, FHWA, since 1972 and was closely associated with Friberg during the past 18 months for the completion of this study. A research report for each of these two studies is scheduled for future publication by FHWA.

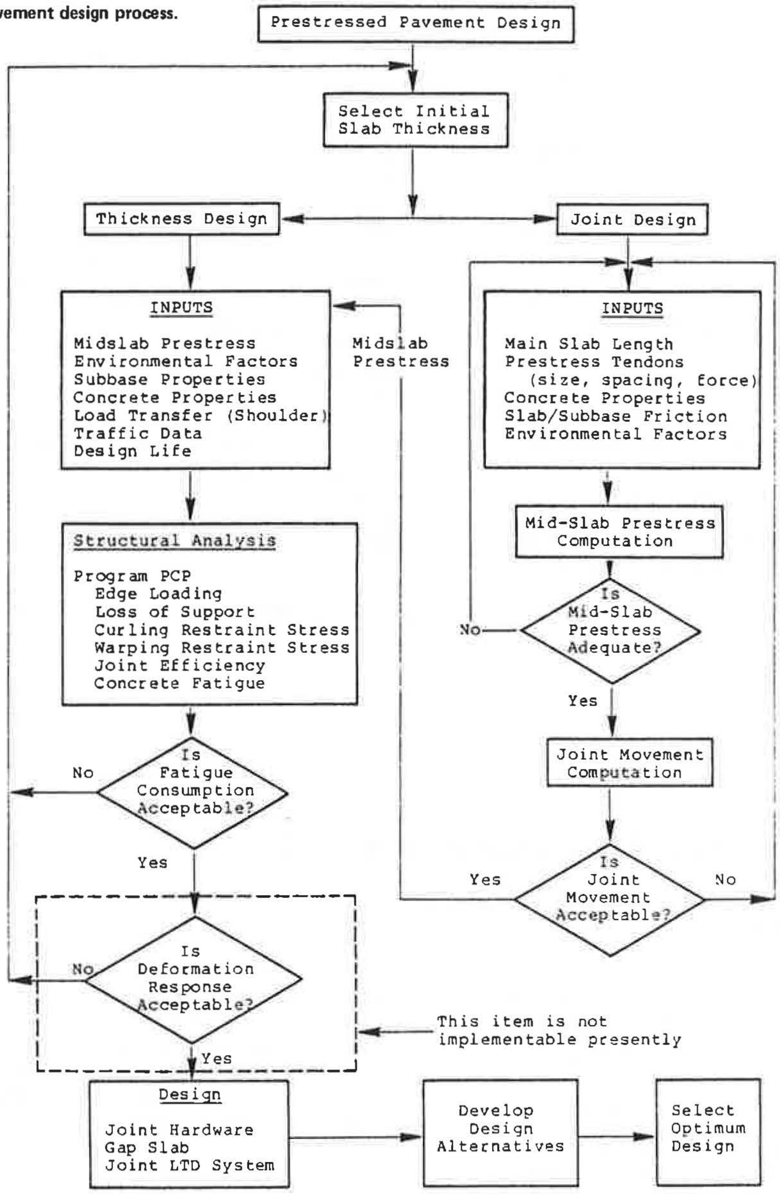
For proper assessment, the subject paper, Prestressed Pavement Joint Design, should be viewed in the context of the following specific comments.

1. Several designs of previous contributors are presented in a report by the Portland Cement Association (PCA) (8). This report gives a summary account of the expansion joints used in the prestressed pavement demonstration projects constructed in the early 1970s in Virginia and Pennsylvania and also of the joints in roadways and airfield pavements constructed in Germany during the 1950s.

2. The design of the load-transfer mechanism for joint design I for an 8-in, 350-ft slab is similar to the dowel design in the 6-in-thick prestressed pavement constructed near Dulles International Airport. This dowel design is shown in the PCA report (8, Figure 33, p. 61). Stainless-steel dowels were not available during the scheduled construction of this project. The initial dowels of ordinary steel were replaced with stainless-steel dowels in 1975. The valuable research information and knowledge obtained from this demonstration project support the recommendation that stainless-steel dowels should be used.

3. Similarly, except for the technique of fastening the edges to the pavement slab, the neoprene-strip seals in design I are the same as those initially recommended for the design of the Dulles Prestressed Pavement Demonstration Project. At the time of construction during the winter of 1971-1972, there was some question of long-term reliability of the particular design proposed for fastening the edges to the pavement slab. Polyurethane foam was installed initially, but it was later replaced with neoprene strips. There has been no problem asso-

Figure 1. Prestress pavement design process.



of effective midslab prestress as an input. Alternatively, a minimum level of the midslab prestress value may be assumed for the structural analysis. Structural analysis computes fatigue consumption due to edge stresses at midslab. If fatigue consumption is more than 100 percent, the design process is repeated by using a larger slab thickness.

It is assumed that fatigue consumption or damage is additive and that calculated fatigue consumption of 100 percent or more would result in structural failure of the slab. In practice, structural failure (i.e., cracking) in the slab does not result in immediate functional failure. Concrete pavements continue to provide satisfactory performance even if cracked. However, because of the zero-maintenance requirements of prestressed concrete pavements, the stringent criterion of 100 percent fatigue consumption is used to define failure.

This paper presents a thickness design procedure for prestressed concrete pavements. Factors considered in developing the procedure include traffic loading; temperature and moisture variations in the concrete slab; loss of subbase support; properties of concrete, subbase, and subgrade; and effective midslab prestress.

DESIGN PROCEDURE

A computerized program for thickness design of prestressed pavements is presented. Required pavement thickness is a function of stresses that result from traffic loads, temperature and moisture variations, loss of subbase support, and midslab effective prestress. The summation of these stresses is balanced against fatigue consumed to obtain a pavement designed to resist bottom flexural cracking.

An acceptable criterion for a design based on deflection is not available. Therefore, deflections are not computed. However, it is recognized that prestressed concrete pavements are thinner than conventional concrete pavements. For this reason, it is recommended that high-quality stabilized subbases be specified for use with prestressed pavements.

Procedures used for computing stresses and decisions regarding inputs for the computer program are briefly discussed. A detailed discussion, a program user's manual, and a program listing are presented elsewhere (1).

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Prestressed Pavement Thickness Design

S.D. TAYABJI, B.E. COLLEY, AND P.J. NUSSBAUM

A computerized procedure for thickness design of zero-maintenance prestressed concrete pavements is presented. Factors considered in developing the design procedure include traffic loading, temperature and moisture variation in the concrete slab, loss of subbase support, properties of concrete, properties of subbase, properties of subgrade, and effective midslab prestress. The procedure is based on flexural stress analysis and prevention of bottom transverse cracking that may initiate from the longitudinal edge of the slab in the vicinity of midslab. Inputs for the computer program include number and magnitude of axle loadings, wheel placement, traffic volume distribution during a 24-h day, temperature data, load transfer effectiveness, and effective prestress at midslab. Program output is in terms of total fatigue consumption at the end of design life. If fatigue consumption is less than 100 percent, then the thickness meets design criteria. A design example is presented for a rural four-lane highway in Illinois.

The objective of the Federal Highway Administration (FHWA) Research Project 5E, Premium Pavements for Zero Maintenance, is to exploit modern materials and technology in developing zero-maintenance pavements for warranted use. As a portion of this research project, an investigation has been conducted by Construction Technology Laboratories, a division of the Portland Cement Association. The objective of the investigation was to develop design and construction techniques for prestressed concrete pavements.

Conventional concrete pavements are designed on the basis of concrete's relatively low modulus of rupture without effectively using the natural advantage of its high compressive strength. In prestressed pavements, precompression in the concrete due to prestressing increases allowable stress in the flexural zone. Precompression causes the reduction or elimination of cracking and a large decrease in the number of transverse joints. Consequently, a more comfortable riding surface is provided and maintenance costs are reduced.

Prestressed pavement design includes the determination of required pavement thickness and joint hardware. Joint hardware is determined based on anticipated slab movement and length. Figure 1 shows the basic steps involved in prestressed pavement design.

As shown in Figure 1, the design process is iterative and involves the interaction of many factors. The process starts with the selection of an initial slab thickness. Then, for joint hardware design, trial main slab length and prestress tendon size, spacing, and force are selected. Effective midslab prestress is computed. A minimum of about 50-psi midslab prestress should be obtained. If it is not obtained, slab length, tendon size, spacing, or force is varied until the desired midslab prestress is obtained. A minimum prestress is desirable to ensure that the early shrinkage cracks that may develop remain tightly closed. Thus, load transfer across possible cracks is improved due to aggregate interlock.

When the midslab prestress criterion is satisfied, anticipated maximum joint movement is computed. Selection of an appropriate joint infiltration-prevention device such as a strip seal, compression seal, or steel cover plate depends on the magnitude of total joint movement. Total movement may be accommodated at one or two active joints between adjacent slabs. Slab length is varied until the computed joint movement can be accommodated by the device selected.

After slab length, midslab prestress level, and joint hardware are established, a structural analysis is performed. This analysis requires the value