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Special Report 78

Prestressed Concrete Pavements

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Prestressed Concrete Pavements

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Foreword

A Subcommittee on Prestressed Concrete Pavements was established in May 1959 under the jurisdiction of the Highway Research Board Committee on Rigid Pavement Design. Basically, the assignment of the Subcommittee was (1) to study and assemble pertinent information relative to the design and construction of prestressed concrete pavements, (2) to make this information available to those interested in this type of pavement, and (3) to develop recommendations on planning, design, and areas of engineering investigation and research.

This report contains the recommendations and suggestions of the Subcommittee based on the present knowledge and judgment of the members. Inasmuch as the "state of the art" in prestressed pavement design and construction is not highly developed, this report is subject to revision as more definitive information becomes available. Specific information on performance, now being accumulated by the Subcommittee for a number of experimental projects, is to be presented in a supplementary report. Attention is invited to the included bibliography, which consists of 195 references dating from 1946 through 1961.

The Committee on Rigid Pavement Design is deeply indebted to the Subcommittee for its efforts in the preparation of this report. The members of the Subcommittee are James P. Sale, chairman; Henry Aaron, Paul F. Carlton, Harry D. Cashell, and Gordon K. Ray.

William Van Breemen, Chairman
Committee on Rigid Pavement Design

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Prestressed Concrete Pavements

INTRODUCTION

In the past 15 years the possibility of using prestressed concrete for highway and airfield pavements has become of increasing interest to engineers in the United States and Europe. Consideration of this new paving concept results primarily from the possibility of gaining two basic advantages over conventional rigid pavements.

First, design investigations and limited testing of model and prototype slabs have indicated that prestressed pavements permit a more efficient use of construction materials in terms of required pavement thickness.

Second, prestressed pavements can be designed with fewer joints and with less probability of cracking than conventional rigid pavements, thereby promising extended pavement life and reduced maintenance requirements.

As with any new use of construction materials, considerable design and construction criteria development will be necessary to validate and permit evaluation of the potential advantages of prestressed concrete pavement. Performance data for a wide range of loadings, foundation and weather conditions, and construction methods, are needed to check existing design theories. Valid criteria must be developed for establishing dimensions, magnitude of prestressing, requirements for reinforcing, and properly accounting for various foundation conditions.

A particular design problem exists at the transverse joints between adjacent prestressed slabs. Substantial horizontal and vertical movements can develop at these locations. Problems may also be anticipated in design and construction at vertical and horizontal curves.

Generally, the methods employed in the construction of prestressed pavements now in service have been more complex than those required for conventional pavements. Therefore, to take full advantage of the potential savings in construction materials it will be necessary to develop simple and realistic construction methods.

BASIC CONCEPTS

To understand the behavior patterns of prestressed concrete pavements it is helpful to first review those of conventional concrete pavements. Design procedures for conventional rigid pavements assume that load stresses remain within the elastic range of the concrete. This in turn requires that the tensile stresses that develop in the extreme fibers of a slab be limited to a value less than the flexural strength of the concrete. Under this concept the major portion of the slab between its top and bottom fibers is not fully utilized to resist load stresses. Therefore, it can be argued from a theoretical standpoint that this situation represents an inefficient use of construction materials.

Furthermore, because concrete is a relatively brittle material, pavement deflections that occur within the elastic range are small. Consequently, it can also be argued that complete advantage cannot be taken of the support potential of the subbase and subgrade.

It is obvious that permanent compressive forces induced by prestressing may be utilized to increase the effective flexural strength of the concrete. This would permit somewhat thinner pavements for a given loading condition. If, however, the structural benefits derived from prestressing were limited merely to extending the elastic range

of the concrete, it is doubtful that prestressed pavements, as such, would receive serious consideration. Of particular interest is the fact that prestressed pavements may enter an elasto-plastic phase of behavior in which load-carrying capability is substantially increased.

In the elasto-plastic phase of behavior, tensile cracks occur in the lower portion of the pavement. Under an applied load these cracks serve as momentary or partial plastic hinges. When the load is removed, the force of the prestress closes the cracks and the pavement regains its rigidity. Prestressed pavements can be designed to carry traffic loadings in this phase of behavior well beyond the purely elastic range. This is the characteristic that gives prestressed pavements a potential structural advantage over conventional pavements.

DEFINITIONS

The preparation of complete definitions for all terms associated with the general field of prestressed concrete is beyond the scope of this report and is not attempted herein. However, a reasonably uniform interpretation of the nomenclature associated with prestressed concrete pavements is considered desirable. On this basis, a listing of brief definitions has been prepared, as follows:

Prestressed Concrete Pavement.—A pavement in which a permanent and essentially horizontal compressive stress has been induced prior to the application of live load.

Initial Prestress.—The compressive stress induced in the concrete to meet the requirements for traffic loadings, subgrade restraint, restrained temperature warping, and anticipated prestress losses associated with construction, creep, relaxation of the stressing tendons, and hygrothermal contraction of the pavement.

Design Prestress.—The compressive stress remaining in the concrete, after deduction of anticipated prestress losses, to meet the requirements for traffic loadings, subgrade restraint, and restrained temperature warping.

Net Prestress.—The lowest level of compressive stress in the concrete to meet the requirements for traffic loadings.

Tendons.—Tensile members, generally embedded in the concrete, used to induce and maintain compressive stresses in the pavement.

Pretensioning.—A method of producing the prestressed condition in which tendons are tensioned prior to concreting.

Posttensioning.—A method of producing the prestressed condition in which tendons are tensioned after the concrete has reached a specified strength.

Poststressing.—A method of producing the prestressed condition without tendons after the concrete has reached a specified strength.

Preliminary Stressing.—The application of a limited compressive stress in the slab, for the purpose of preventing contraction cracks.

Eccentricity.—The distance from the mid-depth of the slab to the center of the tendons in pretensioned and posttensioned systems.

Anchorages.—Mechanical devices or means employed to attach the ends of the tendons to the concrete.

Jacks.—Portable devices used to apply prestressing forces.

Abutments.—Peripheral structures, either fixed or elastic, used as reactions for developing the prestressing forces.

Buckling.—A failure condition resulting from the development of compressive forces of sufficient magnitude to cause an interior portion of a slab to move upward from its original position.

Curling.—An upward bending of the prestressed slab, at or near its boundary. Prestressed pavements have a definite tendency to curl. For this reason many of the experimental pavements constructed to date have been designed with end tie-downs to prevent this action.

Creep.—A shortening of the slab in the direction of the applied force. In pretensioned and posttensioned systems this action merely results in an increase in joint opening and the accompanying loss in net prestress is not significant. In poststressed systems the action tends to relieve the induced compressive stress, thus requiring a

reapplication of pressure at the boundary of the slab to maintain the design prestress.

Conduits.—Passages in the concrete (such as tubes, pipes, or channels) for encasing the tendons of a posttensioned pavement.

Grouting.—The filling of conduits with a fluid cement mortar after the tendons in a posttensioned system have been placed in tension.

Sleeper Slab or Subslab.—A structural member placed under the ends of adjoining slabs, to provide support for edge loading or to serve as an abutment.

LIMITATIONS

The potential advantages ascribed to prestressing will be realized only after a number of obstacles in design and construction have been overcome. To date, prestressed concrete pavements have tended to be considerably more complex to design and construct than conventional pavements. Certain problem areas already have been recognized and tentative solutions have been proposed. Unfortunately, the number of prestressed pavements currently in existence is not large. Thus, too little is known of their behavior and performance characteristics to be certain that design procedures, adopted or proposed, are adequate for extensive construction programs.

No attempt is made here to outline all of the limitations or disadvantages that can be associated with prestressed pavements. Such a listing would likely be quite misleading, because the influence of many factors may prove to be superficial when more is known of the performance of this type of pavement. However, a few possible problem areas are discussed, not as disadvantages but as considerations for further development work.

1. Complexity. Although several relatively simple design concepts have been advanced, it must be recognized that prestressed pavements are inherently more complex than conventional pavements. This is true because prestressed pavements usually incorporate all of the components of standard rigid pavements plus a system for inducing permanent compressive stresses. In effect, the quantity of materials can be reduced, but the number of construction items is increased. For example, one or more of the following will be necessary:

(a) Friction-reducing layers or media.
(b) Sleeper slabs.
(c) Placement of tendons and conduits.
(d) Abutments.
(e) Grouting.
(f) Jacking for preliminary and final stressing.

2. Special Jointing. It has been stated previously that fewer joints are required in prestressed pavements than in conventional pavements. However, this reduction in joints is accompanied by certain complex design and construction problems. At transverse joints (normally spaced at intervals ranging from 300 to 800 ft) there is a tendency for both curling and relatively large horizontal movements to occur. If nothing is done to limit or prevent these movements, the design of the joint from the standpoint of load transfer, riding quality and sealing requirements is quite complicated. On the other hand, if the movements are restrained a system of abutments and tie-downs becomes necessary.

3. Construction Equipment. Thus far the construction industry has geared its equipment to the construction of conventional pavements. Undoubtedly, new items of equipment that would greatly simplify the construction of prestressed pavements can be developed. However, a reluctance to invest in this development can be anticipated until prestressed pavements are proved feasible, and a considerable volume of work is forthcoming.

4. Familiarity. Prestressed pavement is a new concept in the United States. It therefore can be expected that construction costs will be high until such time as contractors become familiar with the operations and techniques involved.

5. Application of Theory. The performance of experimental sections of pretensioned and posttensioned pavements has established the validity of designing in

accordance with the elasto-plastic theory. Poststressed pavements, which do not incorporate tendons, should theoretically conform to the same pattern of behavior. However, the presence of a tendon system does, logically, act to limit the upward migration of cracks associated with plastic hinges. A tendon system therefore provides additional protection against erratic stress conditions that tend to trigger failures.

The validity of the elasto-plastic approach for poststressed pavement systems remains to be established. This can only be accomplished by means of experimental pavements. Pending the results of such experimentation, it may become necessary to limit the magnitude of design stresses in poststressed pavements to conform more closely to the purely elastic phase of behavior.

In addition to the problems previously presented, other limitations may develop. In spite of these anticipated difficulties, many engineers consider that the investigation and testing of prestressed pavements are worthwhile. It is conceivable that a prestressed pavement only 4 to 5 inches in thickness and requiring a minimum of joint and crack maintenance can be developed that will extend the life expectancy of modern highways. Any pavement with such potential is clearly worthy of active research and investigation.

PRESTRESSING SYSTEMS

Prestressed concrete pavements have been constructed in many countries during the past 15 years. These pavements have been stressed longitudinally, longitudinally-transversely, or diagonally, by the application of one or more of the following three systems of prestressing:

Pretensioning

In this prestressing system, tendons consisting of wires, strands or bars of high tensile-strength steel are placed at the mid-depth of the pavement, attached to anchors or abutments, and pulled by mechanical means until a predetermined stress has been attained in the steel. The concrete is then placed and after it has reached a specified strength, the tendons are released. The tensile stress in the tendons is then transferred as compressive stress to the concrete through bond. Several methods of pretensioning which have been devised are shown in Figures 1, 2 and 3.

Posttensioning

This system differs from the pretensioning system primarily in that the tendons, in an unstressed condition, are placed at the mid-depth of the slab in flexible or rigid conduits or are coated with a bond-breaking material. Usually the tendons are partially stressed before concrete placement, for alinement only. After the concrete has attained

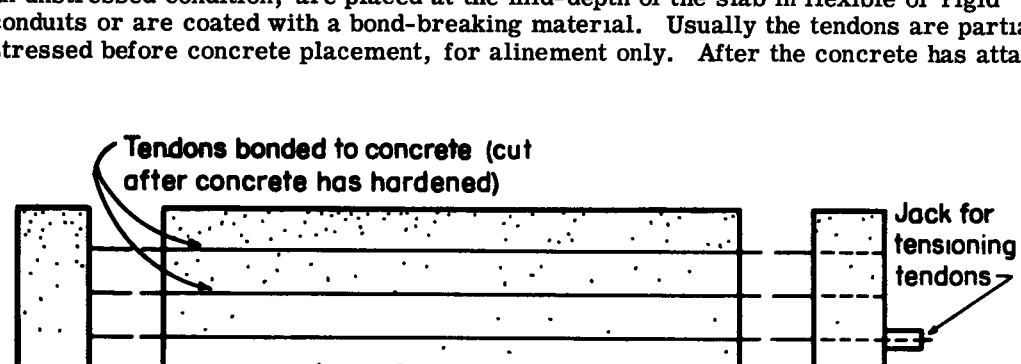


Figure 1. Pretensioning (transverse stressing can be accomplished by pretensioning or posttensioning).

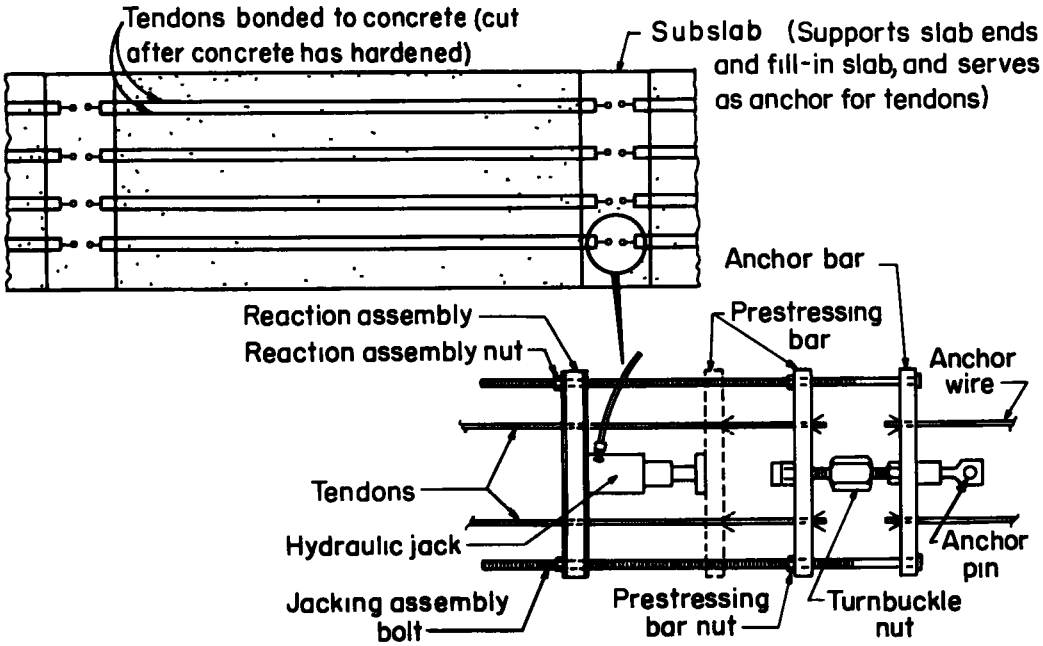


Figure 2. Pretensioning (transverse stressing can be accomplished by pretensioning or posttensioning).

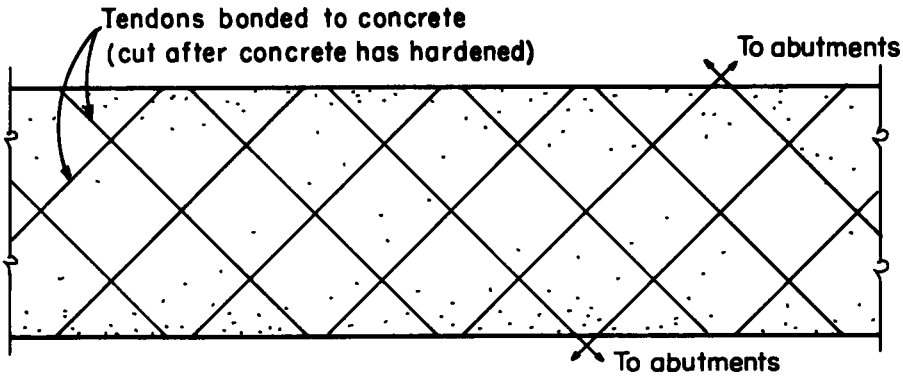


Figure 3. Diagonal pretensioning.

a specified strength, the tendons are stressed by jacking operations until the desired prestress is induced in the concrete. In a conduit system grout is subsequently pumped into the space surrounding the tendons to prevent corrosion and, in effect, to bond the tendons to the pavement.

One method of posttensioning consists of stressing the tendons by direct jacking at the boundary of the slab. After application of the jacking force the tendons are anchored in place.

Another method employs a system of jacks in a gap between two segments of a slab. Tendons, anchored in opposite ends of the slab, pass through the gap. After the concrete has reached a specified strength, the jacks are used to force the two segments of the slab apart, stressing the tendons and inducing compressive stress in the concrete.

When the tendons have been stressed to the proper degree, the gap is filled with concrete. After this concrete has attained sufficient strength the jacking force is released. The jacks may or may not be removed.

Some typical posttensioning methods used in past construction are shown in Figures 4, 5 and 6.

Poststressing

In this system, the prestressing of the concrete is accomplished without the use of tendons. Generally, a series of slabs is placed between two end abutments. When the concrete has attained sufficient strength, a force is applied at the joints between the slabs until a specified compressive stress has been induced in the concrete. In some cases the abutments are designed to provide an elastic-type reaction in order to prevent the development of excessive compressive stresses, and to maintain the pavement in a prestressed condition during slab contraction. Normally this system is used in the longitudinal direction only. Transverse prestress, where required, can be provided by either pretensioning or posttensioning. An example of poststressing is shown in Figure 7.

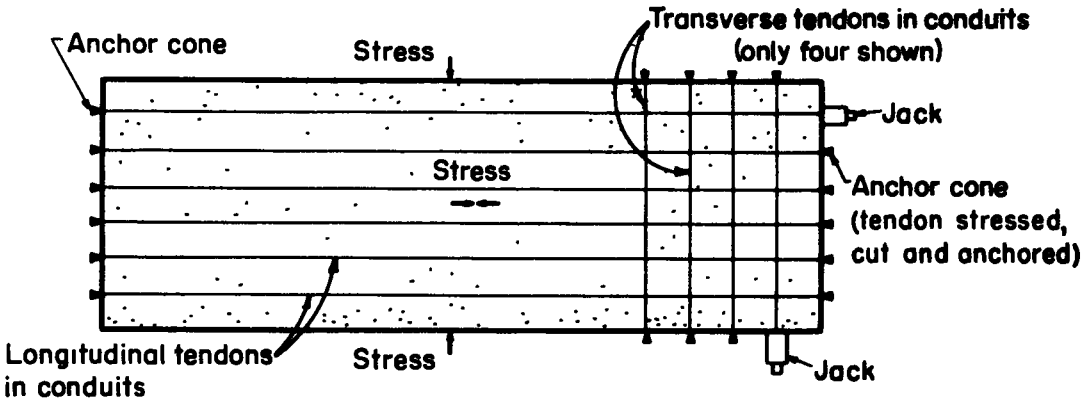


Figure 4. Posttensioning with end jacking.

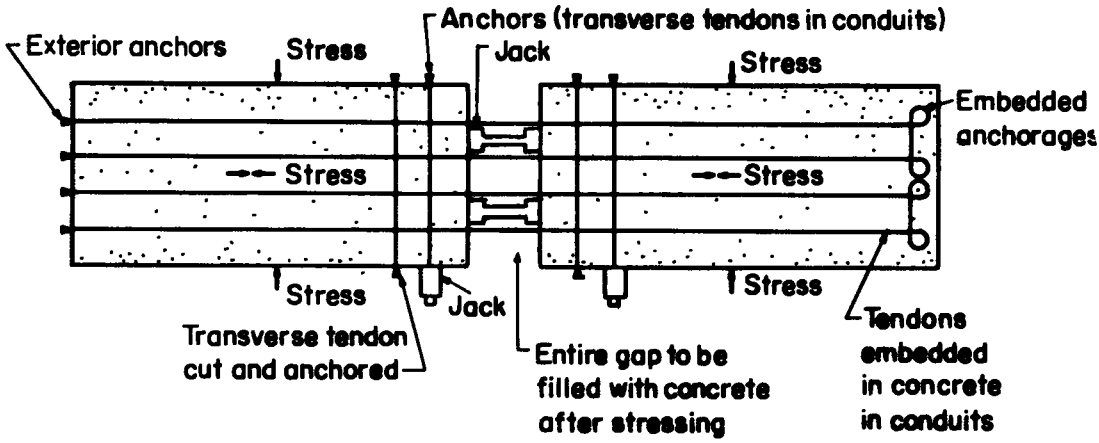


Figure 5. Posttensioning with gap jacking.

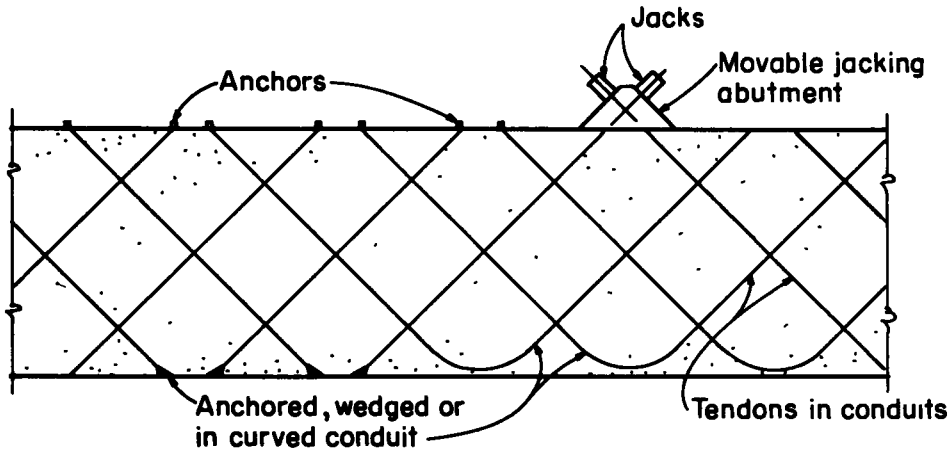


Figure 6. Diagonal posttensioning.

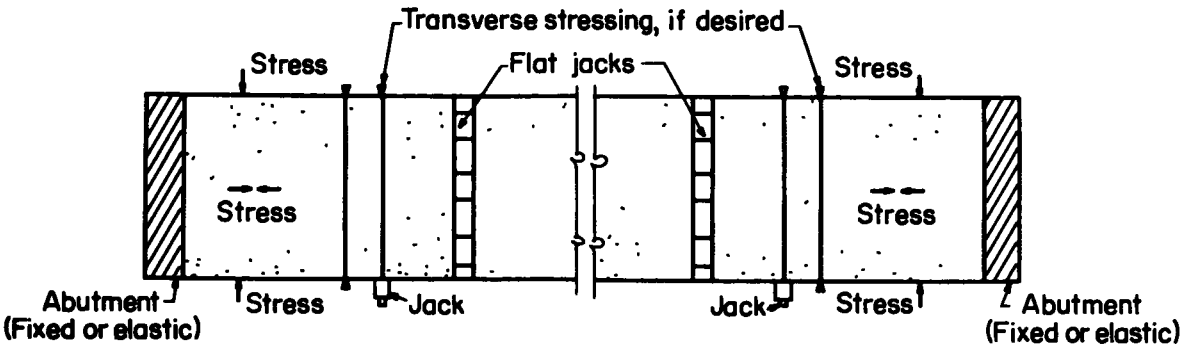


Figure 7. Longitudinal poststressing.

An important characteristic of poststressing systems is that small orders of hygrothermal contraction and creep in the concrete can seriously reduce the compressive stresses in the pavement. For this reason jacking systems are often designed to permit periodic reapplication of prestress. In pretensioning and posttensioning systems, which incorporate tendons, the losses due to contraction and creep in the concrete do not seriously affect the compressive stresses because only a small percentage of the tension in the tendon is relieved.

The methods of prestressing shown in Figures 1 through 7 simply demonstrate the basic principles involved in pretensioning, posttensioning and poststressing systems. It is not intended that these should take precedence over any other existing or proposed methods.

CONSTRUCTION REVIEW

Tables 1 and 2 list prestressed concrete pavements that have been constructed in various parts of the world, and reported in technical publications. Although these tabulations are not all inclusive, the projects listed are representative of worldwide construction.

As shown, pretensioning was used on two highway projects in the Netherlands and one in Italy, an airport project in Austria, and an experimental test slab in the United

TABLE 1

PRESTRESSED CONCRETE HIGHWAY PAVEMENTS

Country	Date	Location	Bibl. Ref.	Pavement Dimension			Prestress (psi)		Prestressing System
				Length (ft)	Width (ft)	Thickness (in.)	Long.	Trans.	
Austria	1956	Vienna		427	24	8	228	107	Posttensioned both directions.
	1958	Strosshof		164	37	6	235	142	Poststressed longitudinally, posttensioned transversely.
	1958-9	Anif-Saltzburg		2625	25	6.3	1138	None	Poststressed with BBRV wedges.
				2625	25	8	995	do.	Poststressed with Leonhardt wedges.
Belgium	1959	Between Zwartberg and Meeuwen	183	11,484	23	3.2, 4, 4.7	284, 427, 569	107, 273	Poststressed longitudinally with flat jacks, posttensioned transversely with steel strands.
Gt. Britain	1950	Crawley, Sussex	17, 25, 36, 38, 39, 44, 46, 51, 69, 92, 128	404	24	6	212	23	Posttensioned diagonally with cables at 18 ½° to CL of pavement.
	1951	St. Leonards, Hampshire	42, 50, 69, 75, 92, 128	1200 (3 400' slabs)	24	6	280 (nominal)	13	Posttensioned both directions with cables.
	1951	Wexham Springs, Buckinghamshire	25, 51, 67 92, 128	110	10	6	190	None	Posttensioned longitudinally with cables.
				130	10	6	90	None	
				190	11 ½	6	245	None	
	1951	John Laing's, Ltd.		3000 (15 180' slabs)	12	10	410	None	Posttensioned longitudinally with cables.
				(2 150' slabs)	14 ⅔	6	300	None	
	1952	Basildon, Essex	51, 67 92, 128	660 (4 165' slabs)	18	6	280	None	Posttensioned longitudinally with cables.
	1952	Woolwich	92, 128	3350	18-24	6	250	28	Posttensioned diagonally with cables.
	1954	Port Talbot, S. Wales	92, 128	1500 (5 300' slabs)	22	6	220-320	0-35	Posttensioned longitudinally with cables, diagonally with cables, and one slab gap jacked.
	1954	South Benfleet, Essex	128, 183	330	20	4	550	50	Poststressed longitudinally with flat jacks, posttensioned transversely with wires.
France	1946	Luzancy	92, 128	66, 81	19 ⅔	6.3 edges 7.9 CL	242-300	242-300	Posttensioned diagonally with cables at 45° to CL of pavement.
	1949	Esbly	92, 128	160	19 ⅔	5.9	228	228	Posttensioned diagonally with cables at 45° to CL of pavement.
	1953	Bourg-Servas	58, 71, 92 97, 128	984	23	4.7	585 Avg. (initial)	Variable	Poststressed longitudinally with flat jacks, posttensioned transversely with cables, reinforcing

					24.5	(thickened edges)			longitudinal prestress applied by 11 different methods.
Germany	1953	Heidenheim	92, 128	365 365 365	28 28 28	6 6 6 at CL 8 at edges	300 240 374	128 43 125	Posttensioned both directions with cables. Posttensioned diagonally with cables at 30° to CL of pavement.
	1954	Speyer		558	20	8	85-341	None	Posttensioned longitudinally with Baur-Leonhardt cables.
	1954	Montabaur		460	25	3.35	460	460	Posttensioned both directions with steel bars.
	1954	Margelstetten	183	788	25	6	299	29-142	Posttensioned longitudinally with Baur-Leonhardt cables, and transversely with Bauer system.
				394	25	6	370	128	Posttensioned diagonally with Wayss and Freytag system.
	1957	Wolfsburg		5906	30	6.3	356-498	185	Posttensioned both directions with cables.
	1959	Dietersheim	174	2953 (6 492' slabs)	25	6.3	455-654	213	Posttensioned both directions with Held and Froneke system.
Netherlands	1957	The Hague	146	3 slabs 312-377	24	4.7	230	None	Pretensioned longitudinally with wires, reinforced transversely with mild steel bars.
	1960	The Hague		328	28 ½	4.7	384	None	Pretensioned longitudinally with strands.
Italy	1957	Cesena	183	1641	24.5	3.2	355 at 20°C	355 at 20°C	Pretensioned both directions with steel cables.
Japan	1958	Osaka City	162	197	18	6	495	108	Posttensioned longitudinally with cables, transversely with bars.
	1958	Osaka City	162	134	36	6	426	158	Posttensioned diagonally with cables at 30° to CL of pavement.
Switzerland	1955	Naz		1641, 1096	8.2	4.7	None at 0° C	-	Poststressed longitudinally with Freyssinet jacks, posttensioned transversely with steel strands.
	1957	Moricken-Brunegg	158	6575 (200'-400', 600' slabs)	18	5	840-1330	None	Poststressed longitudinally with transverse wedges.
	1960	Boudry		4265	34.5	6	None at 10° C	None	Poststressed longitudinally with flat jacks.
United States	1956	Pittsburgh, Pa. (Jones and Laughlin Steel Co., for tests only)	121, 123, 124 138, 139	400 100 30	12	5	450	None	Posttensioned longitudinally with wire strands by gap-jack method.

TABLE 2

PRESTRESSED CONCRETE AIRPORT PAVEMENTS

Country	Date	Location	Bibl. Ref.	Pavement Dimension			Underlying Material	Prestress (psi)		Prestressing System
				Length (ft)	Width (ft)	Thickness (in.)		Long.	Trans	
Algeria	1954-5	Maison Blanche Algiers	77, 78, 86 89, 109, 128	8000 7700	197 82	7.1 7.1	Kraft paper on asphalt topping on 4" crushed limestone on 8" gravel.	250 (net) 250 (net)	250 (net) 250 (net)	Poststressed longitudinally with flat jacks, posttensioned transversely with cables.
Austria	1954	Schwechat, Vienna	182, 189	656	197	8	¾" sand on 12" subbase on 11" base.	213	107	Posttensioned both directions with cables.
	1959	Schwechat, Vienna	182, 189	3280 3609 1425	147 ½ 74 172	6 6 6	Waterproof paper on 1¼-in sand asphalt on gravel subbase.	227 by pretensioning 427 by post-stressing (initial)	142 142 142	Pretensioned longitudinally with wire strands, then poststressed with flat jacks. Posttensioned transversely with wire strands.
Belgium	1947	Melsbroek, Brussels	110, 144, 148, 183	243	164	6.3	--	--	--	Precast slabs posttensioned both directions with cables
	1958	Melsbroek, Brussels	177	1148	75	4	12" compacted sand subbase	620 (center area), 810, 935 (edge area)	470	Precast pretensioned slabs in form of parallelograms, posttensioned transversely with cables
	1959	Melsbroek, Brussels	183	10,820	148	7 (12 at active joints)	Kraft paper on 4" sand on 4" stone subbase.	--	--	Poststressed longitudinally with flat jacks, posttensioned transversely with cables.
England	1949	London	11, 41, 48, 92	343	120	6 5	Bituminous paper on sand on gravel or brickearth.	550	550	Precast square slabs divided into triangular pavement sections by diagonal joints, posttensioned transversely with cables, longitudinally by reaction
	1956	Finningley		200	200	6	Grade beams	250	250	Precast slabs 30' × 9', posttensioned both directions with cables.
	1958	Gatwick	187	290	230	5	Waxed paper on 3" concrete.	300-350	250	Posttensioned both directions with cables
	1959	Gatwick	187	150	132	6 5	Paper on 1" sand on 4" concrete.	100+ (net)	100- (net)	Posttensioned both directions with steel bars.
France	1946-47	Orly, Paris	1, 3, 5, 6 7, 8, 15 22, 23, 25	1312	197	6.3	Asphalt paper on 2" fine sand on 14" prepared subbase	470	470	Precast square slabs divided into triangular pavement sections by diagonal joints, posttensioned transversely with cables, longitudinally by reaction.

										versely with cables.
Germany	1956	Memmingen	183	1135	98	5.5	Paper on ½" sand layer on granular subbase.	--	--	Posttensioned both directions with cables.
	1959	Wunstorf	183	8104	98	6	Paper on bituminous leveling course on old concrete	165	165	Posttensioned both directions with cables
	1959	Diepholz		6234	98	6	Double layer of paper on ¾" fine sand on 17" stone subbase	--	--	Posttensioned both directions with steel bars.
	1959	Hopsten	183	9810	98	5.5	Double layer of paper on ¾" fine sand on 17" stone subbase	165	165	Posttensioned both directions with cables.
	1960	Nordholz	183	9810	147	6	Double layer of paper on dune sand subbase.	165	165	Posttensioned both directions with cables.
	1960	Wahn, Cologne	190	12,468 12,468	197 75	7.1 (interior) 7.9 (ends) 7 1	Double layer of paper on compacted gravel subbase.	284 (slab ends) 214 (slab center)	--	Posttensioned both directions with cables
Netherlands	1951	Schiphol	128	1140 (5 92' slabs) (5 136' slabs)	136	5.5	Bitumen coat on 2" concrete on 18-24" of sand subbase.	510-570	510-570	Posttensioned both directions with cables.
New Zealand	1958	Woodbourne	119, 136	450 (3 150' slabs)	150	6	--	305	305	Posttensioned both directions with cables
United States	1953	Patuxent Naval Air Station, Md. (Special tests only)	65, 90, 99	500	12	7	Paper on 1" sand on 4" sand-clay subbase on 2'-6" sand-clay and gravel mix.	690	Only in areas.	Posttensioned longitudinally with cables
	1955	San Antonio, Texas	106, 114, 164	80 80	75 75	4 4	Asphalt leveling course on old concrete.	425 175	425 175	Posttensioned both directions with cables.
	1955	Sharonville, Ohio, Corps of Eng. (Special tests only)	117, 143	65	60	4	Waterproof paper on concrete base.	340	310	Pretensioned both directions with wires.
	1957	Sharonville, Ohio, Corps of Eng. (Special tests only)	186	500	50	9	Waterproof paper on sand layer.	200-400	200-400	Posttensioned both directions with steel bars
	1959	Biggs Air Force Base, Tex.	179, 184	1500 (3 500' slabs)	75 (3 25' slabs)	9	Polyethylene sheeting on ½" sand on 6" stabilized aggregate.	350	175	Posttensioned both directions with cables
	1959	Le Moore Naval Air Station, Calif.		568	75	6 thickened to 9 at outside edges.	2 layers of polyethylene sheeting on 6" soil-cement on 12" gravel.	--	--	Posttensioned both directions with cables.

States. An airport taxiway in Belgium was constructed of precast, pretensioned slabs joined together by posttensioning on the site. All the other pavements were either posttensioned or poststressed.

Highways

To date, the pretensioning system of prestressing has been used in the construction of only two sections of highway pavement. Posttensioning, on the other hand, has been accomplished by a variety of methods, including stressing in the longitudinal direction only, a combination of longitudinal and transverse stressing, and by diagonal stressing. In each of these posttensioning methods, tendons have been located near the mid-depth of the slab, either in conduits or coated with a bond-breaking material. Poststressing with both fixed and elastic abutments has been used on several highway projects.

Examples of highway pavements which illustrate different methods of prestressing are as follows:

Pretensioning. In 1957 three slabs, 312 to 377 ft long, approximately 24 ft wide, and 4.7 in. thick, were pretensioned on a main highway near The Hague, Netherlands. Longitudinal prestressing was accomplished by means of 60 wires, each 0.2 in. in diameter, stressed to approximately 146,000 psi. The wires were tensioned within a framework consisting of steel pipes placed longitudinally alongside the slab and prestressed beams placed transversely. Transverse reinforcement consisted of mild steel bars, 0.4 in. in diameter and spaced 12 in. apart, laid on top of the longitudinal wires. Transfer of stress from the steel to the concrete was effected at 6 days.

Posttensioning. On Route 48 near Dietersheim, West Germany, a posttensioned, prestressed pavement 2,953 ft long, 25.0 ft wide and 6.3 in. thick, was constructed in 1959. This project consists of a series of 6 slabs, each 492 ft long, with expansion joints between them. The slabs rest on a 6-in. stabilized base on a 16- to 24-in. gravel subbase, with a layer of friction-reducing paper between the slabs and the base. The concrete had a compressive strength of approximately 6,500 psi. in 28 days.

The pavement was prestressed both longitudinally and transversely. The longitudinal prestress was accomplished by tensioning tendons, each composed of seven 0.3-in. steel bars. These were anchored at one end of the slab and the jacking force was applied at the other end. The initial longitudinal prestress was approximately 650 psi at the jacking ends of the slabs, with a minimum allowable of about 450 psi. In the transverse direction, steel tendons on 30-in. centers were also tensioned by jacks, resulting in an initial prestress of about 210 psi.

A test pavement constructed near Pittsburgh, Pa., by Jones and Laughlin Steel Corporation, illustrated the gap-jacking method for posttensioning. This pavement, placed in 1956, is 530 ft long, 12 ft wide and 5 in. thick. It consists of a primary slab 400 ft long, flanked on one end by a 100-ft slab and on the other by a 30-ft slab. These flanking slabs provided a means for a limited study of the expansion joint problem. The slabs rest on a 5-in. granular subbase covered with a 1-in. sand layer and building paper to reduce friction.

The pavement was prestressed in the longitudinal direction only. The tendons, installed at the mid-depth of the slab and spaced 2 ft apart, extended the full length of the 400-ft slab and through a 5-ft 2-in. gap at its center. The strands were formed into loops at the terminal ends of the slab to provide anchorage. Each tendon was composed of four $\frac{7}{16}$-in. diameter strands placed in a $1\frac{1}{2}$-in. diameter flexible steel conduit.

When the concrete attained proper strength, jacks were placed in the gap and the half slabs were jacked apart, stretching the tendons about 2 ft and stressing the concrete at the gap to about 600 psi and at the slab ends to about 400 psi. A specially designed holding frame, set in place straddling the gap, was used to maintain the prestress and permit removal of the jacks. The gap was filled with concrete, and 72 hr later the holding frame was removed. After removal of the frame the prestress in the concrete at the gap was about 450 psi. The conduits were subsequently grouted. This pavement is not a part of a highway system. It was subjected initially to a program of static load tests with only a limited number of moving loads included. Recently this

pavement was subjected to a comprehensive program of moving load tests.

In 1958 a posttensioned pavement was constructed near Osaka, Japan, using diagonal stressing. This pavement is 134 ft long, 36 ft wide and 6 in. thick, with the pavement thickened to 8 in. at the sides and ends. Each tendon consists of 12 high-strength steel wires, 0.2 in. in diameter, sheathed in a 1.38-in. diameter mild steel tube. These tendons were spaced 5.64 ft apart at an angle of 30^0 with the centerline of the pavement. High-strength steel bars, 1 in. in diameter, were substituted for the tendons at the corners. One end of each tendon was anchored and a jack was used at the other end. When stressing was completed, the conduits were grouted.

Poststressing. In 1957 a $1\frac{1}{4}$ mi portion of the Moricken-Brunegg Road in Switzerland was constructed as a prestressed pavement. This pavement, consisting of 200-, 400- and 600-ft slabs, is 18 ft wide and 5 in. thick. Prestressing was obtained by using transverse wedges between the slabs, in conjunction with end abutments. The pavement had one horizontal curve with a radius of 1,150 ft and a length of 500 ft. On the outer edge of this curve, a horizontal abutment was constructed to prevent buckling.

The coefficient of friction between the wedges and the slabs was reduced to 0.16 by using graphite grease. Initial longitudinal prestress varied from 840 to 1,330 psi at the various slab ends.

In 1959 more than 20 experimental prestressed concrete slabs were included in a 1.5-mi length of the Fontenay-Tresigny bypass near Paris, France. The slabs were grouped in four separate sections, each built by a different contractor. Longitudinal prestress was applied by eleven different methods.

About 1,600 ft of one section, with fixed abutments at opposite ends, contains three types of elastic joints to stress a series of four slabs longitudinally. The slabs are 24.5 ft wide and 4.7 in. thick, except for their longitudinal edges which are thickened to 7.1 in. over a distance of 7.8 in. The longest slab is 520 ft.

In the first elastic joint, the prestress was applied by tensioning external cables anchored at the transverse boundary edge of a sleeper slab and attached to a narrow transverse concrete slab abutting the road slab overlying the sleeper-slab edge in question. This arrangement was duplicated for each of the two road slabs forming the joint. In the second joint, steel springs were used to apply and maintain the prestressing force. In the third joint, a delta-shaped concrete wedge, tensioned transversely by means of a small abutment alongside the slab edge, was employed to apply the longitudinal thrust. Each of the elastic joints induced a prestress in the concrete of about 285 psi.

Airports

Prestressed concrete pavements have been constructed at a number of airports in the United States and abroad. As in the case of prestressed highway pavements, most of the airfield pavements have been posttensioned. To illustrate the various methods of prestressing, brief details of several prestressed projects are as follows:

Pretensioning. At Vienna, Austria, the Schwechat Airport has a runway extension, a primary taxiway and a parking apron of 6-in. thick prestressed concrete pavement totaling approximately 8,300 linear ft. The runway and taxiway were divided into 24-ft 7-in. wide paving lanes and 400-ft long slabs. These two pavements were pretensioned and poststressed longitudinally and posttensioned transversely. The apron was pretensioned longitudinally and posttensioned transversely. Construction was completed in 1960.

Lane-width grade abutments, spaced at intervals of about 810 ft, were used to anchor longitudinal tendons at 30-in. centers. A subslab was placed midway between the abutments. Tendons 400 ft long were anchored to one abutment, coupled at the subslab with other 400-ft tendons, then tensioned at and anchored in the opposite abutment. The concrete was next placed and the prestress gradually transferred to it as bond developed between the concrete and the tendons.

After the major part of the shrinkage and creep had taken place, flat jacks were used in the joints at the subslabs to induce additional prestress in the concrete. The initial longitudinal prestress induced in the concrete from pretensioning was about 225 psi and

that from poststressing was about 425 psi. Transverse tendons in flexible conduits provided normal posttensioning after the pavement had been stressed longitudinally.

A taxiway at Brussels National Airport near Melsbroek, Belgium, was constructed of prestressed concrete in 1958. The pavement, 1,148 ft long, 75 ft wide, and 4 in. thick, was comprised of longitudinally pretensioned, precast slabs in the shape of parallelograms. These slabs, approximately 39 ft long and 5 ft wide, were pretensioned at the plant to stress levels of either 620, 810, or 935 psi. The taxiway was assembled on a 12-in. compacted sand subbase. The slabs having the lowest prestress were used in the edge areas; those with the highest prestress, in the central area.

The slabs were placed with their long sides parallel to the longitudinal axis of the taxiway, their short sides or ends making about a 45° angle with this axis. The slabs were so placed that their angled ends did not form a continuous joint. All joints were caulked with mortar and a transverse prestress of about 470 psi was applied by tensioning cables threaded through preformed ducts in the slabs. Because of the parallelogram shape of the slabs, the transverse prestress caused compression across the joints formed by the angled ends, as well as across the longitudinal joints.

Posttensioning. One of the first prestressed pavements of any size was built in 1947 at the Orly Airport in Paris, France. It was basically 1,312 ft long, 197 ft wide and 6.3 in. thick. The pavement consisted of precast slabs 1 m square, laid on a 14-in. prepared base course covered with a friction-reducing layer of 2 in. of fine sand topped with asphalt paper. These slabs were assembled in rows with their abutting edges making continuous longitudinal and transverse joints.

The pavement was divided into triangular sections by diagonal joints containing ¾-in. vertical rollers on 1-in. centers. Odd-shaped, precast segments of slabs were used in forming the diagonal joints. Transverse prestress was applied by tensioning tendons consisting of 30¼-in. diameter wires inserted in the transverse joints. These tendons extended the full width of the pavement and were spaced 1 m apart. After tensioning was completed and the tendons were anchored, the transverse joints were filled with a sand-cement mortar.

Because of the triangular shape of the runway sections formed by the roller-bearing joints, the prestressing force applied in the transverse direction induced prestress in the longitudinal direction. Restraint in the longitudinal direction was provided by abutments at the ends of the paved strip. These abutments were elaborate structures, extending to a depth of about 26 ft below the pavement surface.

In 1959 a portion of an operational taxiway at Biggs Air Force Base, El Paso, Tex., was prestressed longitudinally and transversely. This portion consisted of three slabs, each 500 ft long, 75 ft wide, and 9 in. thick. Three 25-ft paving lanes were included in the 75-ft width. The slabs were constructed on 12 in. of selected clay-sand subgrade material plus a 6-in. stabilized aggregate subbase covered with ½ in. of sand and polyethylene sheeting as a friction-reducing layer. Their ends rested on subslabs covered with polyethylene sheets.

Each longitudinal tendon consisted of twelve ¼-in. wires encased in a flexible conduit. These were spaced approximately 24 in. apart. The transverse tendons consisted of six ¼-in. wires encased in rigid conduits on 27-in. centers. Electrically controlled hydraulic jacks, jacking against steel plates embedded in the slab, were used to apply the prestress.

An initial tensioning force of 10,000 psi was applied to align the longitudinal tendons. When the concrete reached a compressive strength of 900 psi the tendons were stressed to 20,700 psi. When the concrete attained a strength of 4,000 psi the tendons were briefly tensioned to 192,000 psi at the jacking points and then anchored at a final tensile stress of 168,000 psi. The transverse prestress was applied to all three lanes as a unit, the tendons being stressed to 168,000 psi and then anchored. All tendons were grouted. A design prestress in the concrete of 350 psi longitudinally and 175 psi transversely was obtained. A similar project was constructed at Le Moore Naval Station, Calif.

In 1960 a prestressed concrete runway 2⅜ mi long, and a taxiway of the same length, were constructed at Wahn Airport near Cologne, Germany. The runway was about 200 ft wide and the taxiway was about 75 ft wide. The pavement was divided into 395-ft

long slabs, which were placed on bituminous-treated paper over a gravel subbase. Pavement thickness was 7.1 in. for the runway interior and the taxiway. Runway ends were 7.9 in. thick. The pavement was posttensioned both longitudinally and transversely by tendons encased in conduits. The magnitude of the longitudinal prestress was 284 psi at the ends and 214 psi at the center of each slab.

A 1-m gap was left between adjacent slabs to provide a working area for posttensioning operations and for grouting the tendons. Subslabs 64 in. wide and 9 in. thick were placed at these gaps prior to paving. After the prestressing operations the gaps were filled with reinforced concrete, leaving 2.4-in. wide unsealed open transverse expansion joints at their centers. These joints were formed by two steel angle plates.

Poststressing. In 1954, at the Maison Blanche Airport, Algiers, Algeria, prestressed pavements were constructed consisting of a runway and a parallel taxiway of similar design. The runway pavement was approximately 8,000 ft long, 200 ft wide and 7.1 in. thick; and the taxiway was about 7,700 ft long, 80 ft wide and 7.1 in. thick.

Longitudinal prestressing was accomplished with flat jacks and elastic and abutments. The jacks, which were made of flat flexible metal tubing that extended nearly the width of a 20-ft paving lane, could be expanded by filling with water, oil, or cement grout. Active jacking joints were constructed at 1,000-ft intervals with two intermediate temporary jacking joints. Compression was applied gradually at the temporary joints as the concrete hardened. Jacking at the active joints did not start until the full paving strip was completed. Pressure adjustments were made at these joints during a minimum period of four months. Prior to placing the active joints in operation, the flat jacks were removed from the temporary joints and concrete was rammed into the vacant space. A tie-down system was used at the active jacking joints to prevent curling of the slab ends.

The elastic end abutments were curved prestressed concrete slabs approximately 186 ft long and about 6 in. thick throughout most of their length. These abutments were buried beneath the pavement, with one end joining the end of the pavement at ground level and the other end about 10 ft in the ground.

Transverse prestress was achieved by posttensioning 12-wire tendons in 2-in. diameter metal tubes spaced 4.36 ft apart. Prestress was applied simultaneously to both ends of the tendons by means of double-acting jacks. The conduits were grouted after completion of the prestressing operations. A second runway of similar design was constructed in 1960-61.

In 1959-60 a prestressed runway pavement was constructed at Brussels National Airport, near Melsbroek, Belgium, using poststressing longitudinally and posttensioning transversely. This pavement, 10,820 ft long, 148 ft wide, and 7 in. thick, was constructed on a 4-in. stone subbase blanketed with a friction-reducing layer of 4 in. of sand covered with kraft paper. Active jacking joints were spaced at 1,080-ft intervals with two intermediate temporary joints for initial prestressing. The pavement was thickened to 12 in. at the active joints, with the slab ends being tied down to prevent upward curling.

Longitudinal prestress was achieved through a system of flat jacks and friction abutments. The active jacking joints were located over access and utility tunnels, which permitted inspection and adjustment of the prestressing force. Transverse prestressing was accomplished by steel tendons, in conduits, anchored at one pavement edge and jacked at the other.

DISCUSSION OF DESIGN VARIABLES

1. Subgrade and Subbase. Experience has shown that the strength of the supporting foundation affects the performance of conventional rigid pavements in two ways: (1) the stress produced in the pavement by a given load decreases as foundation strength increases, and (2) the ability of the pavement to withstand repetitive loading increases as foundation strength increases.

With few exceptions, the prestressed pavements in Europe and the United States have been constructed on relatively high-strength foundations, with the modulus of subgrade reaction being generally 200 pci or higher. There is nothing, however, in pres-

ently accepted design procedures that limits the use of prestressed pavements to high-strength foundations. Pavement designers have simply been unwilling to risk constructing prestressed pavements, with their relatively large load deflections, directly on low-strength foundations, even though the results of limited model and full-scale traffic testing have indicated that such foundations may represent a favorable condition, provided pumping can be prevented.

Generally, the quality of the supporting foundation for prestressed pavements has been increased by compacted granular subbases. The thickness of these subbases has varied widely, ranging from as little as 4 in. to as much as 18 in. More commonly, subbase thickness has ranged from 6 to 12 in. Methods of improving foundation strength have included bases of soil-cement and bituminous concrete.

2. Pavement Thickness. Selection of pavement thickness is dependent on such factors as foundation strength, concrete strength, magnitude of prestress, and anticipated traffic loads. The thickness may be as little as 40 to 50 percent of that required for conventional concrete pavements. Pavement thickness for highways is more likely to be determined on the basis of providing the minimum permissible cover for the stressing tendons, rather than on the basis of load-carrying considerations.

Thicknesses of existing prestressed pavements generally range from 4 to 6 in. for highways, and from 5 to 9 in. for airfields. Where pavements have been subjected to interior loadings only, pavement cross-sections generally have been uniform in thickness. Where edge loadings are frequent, some pavement cross-sections have been of the thickened-edge type.

3. Slab Length and Width. The length of the prestressed pavement slab is associated closely with the design of the prestressing system. Slab lengths in excess of 1,000 ft have been constructed in Europe, whereas the maximum slab length has been 500 ft for the limited number of prestressed pavements built in the United States. The average slab length appears to be in the order of 400 ft. Some engineers contend that this average length reflects a reasonable compromise between the cost of additional prestress to offset the increase in subgrade restraint occasioned by longer slabs and the cost of providing additional transverse joints for shorter slabs.

In this discussion, slab length refers to the spacing between active or free transverse joints. Usual European practice has been to construct intermediate, inactive compression joints at intervals of 300 to 500 ft where the slab length exceeds 600 to 800 ft.

It is anticipated that in most cases the width of a paving lane will be dictated by the capabilities of the construction equipment, rather than by design considerations. The maximum width of paving lane that can be constructed by present-day equipment is approximately 25 ft. If the width of pavement exceeds 25 ft, some means of load transfer should be provided for the resulting longitudinal joint. This may be accomplished by using either a compression joint or a free joint with thickened edges, or a subslab. There should be no need for longitudinal expansion joints for pavement widths less than 600 to 800 ft. For pavement structures exceeding this width, considerations in determining the spacing of longitudinal expansion joints would be the same as for transverse expansion joints.

4. Magnitude of Prestress. As with pavement thickness, determination of the design prestress is related directly to other design features. Pavements prestressed to more than 1,000 psi have been reported in Europe. The maximum prestress induced in a prestressed pavement in the United States has been 700 psi.

Results of field tests on full-scale pavements, supplemented by data from laboratory tests on small-scale models, have indicated that structural benefits do not increase in proportion to an increase in prestress. Because of this finding, the magnitude of the design prestress in more recent construction has been in the order of 150 to 300 psi longitudinally, and 0 to 200 psi transversely.

The basic requirement for the longitudinal design prestress is that it be large enough to sustain the momentary plastic hinge action that may occur in the slab during the passage of a load. To accomplish this, the prestress must be sufficiently high to overcome stresses induced by subgrade restraint and restrained temperature warping of the slab, thus making available at all times a net prestress adequate to insure slab stability under traffic loading.

It is possible that transverse prestress may not be required for highway pavements. However, data now available indicate that considerable structural advantage is gained by this prestress. Additional investigative studies are needed to ascertain the relative merits of prestressed highway pavements constructed with and without transverse prestressing.

5. Spacing of Tendons. The spacing of the stressing tendons is determined largely by tendon size, magnitude of the prestress, allowable bearing stress at the anchorages, and maximum anchoring stress permitted in the tendons. For bars and stranded cables, tendon spacing has varied from a minimum of twice the slab thickness to a maximum of eight times the slab thickness. Typical spacing has been two to four times slab thickness for longitudinal tendons and three to six times this dimension for transverse tendons.

6. Jointing. In the existing literature the types of longitudinal and transverse joints in prestressed concrete pavements are defined by such terms as "active", "inactive", "elastic", and "non-elastic", with the intent that the function or behavior of the joints be more or less indicated. In reviewing this general terminology, it is apparent that considerable confusion can develop unless more functional descriptions are given.

For the purpose of this report, the various types of joints and their functions are as follows:

(a) Free Joints. These are working joints between pretensioned or posttensioned prestressed slabs in which no provision is made for the transmission of compressive forces from one slab to the other. In order to adequately carry the design loads, these joints normally require some form of supplementary structural strengthening, such as subslabs, edge thickening, or load-transfer devices. The joints must be designed to provide for width changes of appreciably greater magnitude than those that occur at joints in conventional concrete pavements. The design of the joint should also take into account the tendency of prestressed pavements to curl at their boundaries.

(b) Partial Compression Joints. These are working joints between pretensioned or posttensioned prestressed slabs in which provision is made for the transmission of compressive forces during warm seasons, but in cold seasons they function as free joints. This type of joint, although designed to restrict in some degree the large end movements of the adjacent slabs, is subject to the same requirements for structural strengthening that apply to a free joint. The joint results in the development of relatively high compressive stresses in the pavement during the hottest season of the year, and may require some type of abutment at the terminal ends of the pavement to prevent permanent outward movement.

(c) Compression Joints. These may be either working or non-working joints which permanently transfer compressive forces from one slab to another. Non-working compression joints may contain flat jacks or grout jacks that are immobilized in place after application of the prestressing forces. To overcome prestress losses, some designs of grout jacks make provision for reapplication of the jacking forces. Another type of non-working compression joint is formed by continuing the stressing tendons through a construction joint.

Working compression joints are designed to maintain either a constant compressive force or some minimum compressive force on the slab ends, regardless of the magnitude of joint opening. This may be accomplished by installing either a constant-pressure hydraulic jacking system or a system of compression springs in the joint. End abutments must be used in conjunction with compression joints.

Several types of joints have been installed in existing prestressed pavements. Due to the limited information currently available, it is reasonable to consider all of these types as experimental. A brief description of some of the joints that have been tried or proposed is given in the following paragraphs.

A mechanical expansion-type device has been developed which may be used to form either a free or a partial compression joint. This is a prefabricated, accordion-like unit consisting of a series of vertical steel plates, which are covered and held in place with neoprene rubber. A subslab must be used in conjunction with the device. This type of joint has been installed in two prestressed pavements in the United States and in one pavement in Germany. Performance has been reported as satisfactory.

Other types of free joints have been tried in Europe. These include plate-type and finger-type designs similar to those used as expansion joints for highway bridges. Free joints of the gap type have proved unsuccessful because of difficulties associated with sealing.

Experimental partial compression joints were installed in the prestressed taxiway at Biggs Air Force Base, El Paso, Tex. These joints were installed during the winter months when the width of joint opening was maximum. A reinforced filler slab supported by a subslab was constructed in the gap between adjacent 500-ft prestressed slabs. Because the prestressed slabs underwent daily length changes in the order of ½ in., a ¼-in. thick premolded fiberboard was placed for the full depth of slab at each joint. This permitted the filler slab to cure without being overstressed by compressive forces resulting from the daily movement. Pavement adjacent to the ends of the 1,500-ft prestressed section acted as abutments and prevented outward movement during the summer months. The performance of these "immobilized" joints has been excellent over a two-year period.

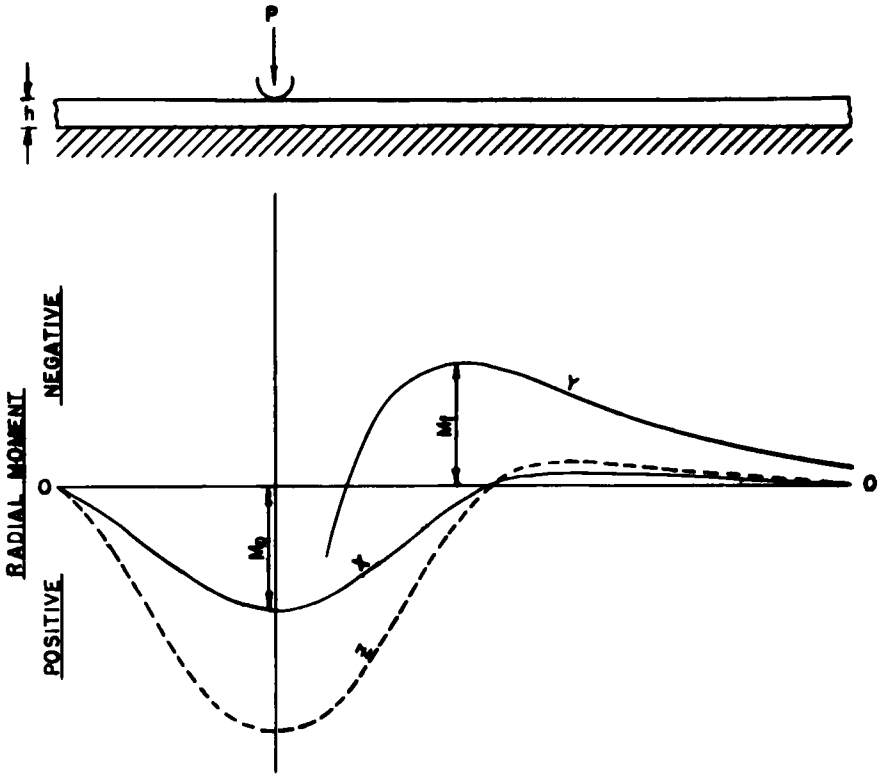
Regardless of the method of prestressing, compression joints have been used in lieu of free or partial compression joints in a number of prestressed pavements constructed in Europe. Slabs ranging in length from 300 to 500 ft are constructed with short gaps of several feet between adjacent slabs. These gaps are at concrete subslabs, which extend several feet under the end of each adjoining prestressed slab. Flat jacks are placed at intervals along the length of the gap, and the area between the jacks and the adjoining slabs is filled with concrete. After this concrete has attained sufficient strength, the jacks are expanded and the space resulting from the jacking is filled with a high-strength concrete. No detailed information is available as to the performance of these joints, although general indications are that no particular trouble has been experienced. Some joint designs permit reactivation of the jacks for subsequent stressing to overcome losses in prestress.

A longitudinal compression joint was incorporated in a 500-ft length of experimental prestressed pavement constructed by the U. S. Army Corps of Engineers at Sharonville, Ohio. The transverse stressing tendons were carried through the joint, and the compressive force across the joint was established at 200 and 400 psi. Three different methods were used to provide for load transfer across the joint. These included a doweled joint, a keyed joint, and a butt-type joint in which the face of the joint was sandblasted and washed with a neat cement grout prior to placing the adjacent slab.

The 9-in. thick pavement was subjected to gear loads up to 265,000 lb on a 4-wheel twin-tandem configuration. Accelerated traffic testing produced failures in 14 of 18 test items. In no case did any of the failures occur at the longitudinal compression joint, nor did its presence appear to have any significant influence on the overall performance of the pavement. The excellent performance of butt-type compression joints has been verified by small-scale laboratory model tests.

DISCUSSION OF FACTORS AFFECTING DESIGN

1. Elasto-Plastic Approach to Design. Engineers generally recognize that it is unduly conservative to design prestressed pavements on the basis of purely elastic behavior. Designs based on the elastic theory fail to take advantage of the potential increase in load-carrying capacity provided by the redistribution of moments which occurs with the formation of partial plastic hinges in the pavement. The general redistribution of the critical moments in a prestressed pavement is diagrammed in Figure 8, in which the maximum values for radial moment in the purely elastic phase of behavior are indicated by curve X. The maximum positive moment caused by load P_o is indicated by M_o. A further increase in load produces tensile cracking in the bottom of the slab and results in radial moments similar to those shown by curve Y. With increasing load the maximum negative radial moment, M_f, caused by load P_f becomes equal to the maximum positive moment, M_o. At this point a further increase in load produces tensile cracking in the top of the slab. Curve Z represents hypothetical values for radial moment had the slab remained elastic in behavior under load P_f. The relation between the maximum positive elastic moment and the moment associated with



P = WHEEL LOAD
h = SLAB THICKNESS
X = MAXIMUM RADIAL MOMENT DUE TO P_0
M_0 = MAXIMUM POSITIVE MOMENT DUE TO P_0
P_0 = MAXIMUM LOAD PRODUCING ELASTIC BEHAVIOR
Y = RADIAL MOMENT FOR ELASTO-PLASTIC BEHAVIOR DUE TO P_f
M_f = MAXIMUM NEGATIVE RADIAL MOMENT DUE TO P_f
P_f = LOAD PRODUCING ELASTO-PLASTIC BEHAVIOR ($P_f > P_0$)
Z = HYPOTHETICAL RADIAL MOMENT EQUAL TO $\frac{P_f}{P_0} \times X$

Figure 8. Load-moment relationships for prestressed pavements.

increasing the load from P_0 to P_f has been used in the development of design procedures for prestressed pavements (see pp. 212-213 and 232-233, 1961 HRB Proceedings).

2. Effect of Load Repetition. The design requirements for prestressed pavements will be influenced by the volume of traffic loads that must be carried by the pavement during its anticipated life. Obviously, the higher the number of repetitions of a given traffic condition, the greater must be the overall strength of the pavement. For highway pavements with large volumes of traffic, design factors for repetitive loading will necessarily be higher than those for repetitive loading on airfield pavements.

Load-repetition factors in the order of 2.0 to 2.25 have been used for airfield pavements where the design has been based on the elasto-plastic approach (see pp. 230-232, 1961 HRB Proceedings). Similar factors are not available for prestressed highway pavements. However, extrapolation of data being developed for prestressed airfield pavements indicates that load-repetition factors for highway pavements may be in the order of 2.75 to 3.0.

Currently, it would appear prudent to assign conservative values to the load-repetition factor in view of the limited information now available on the relationship between load repetition and design requirements. Furthermore, it has been demonstrated that there is little advance warning accompanying load failures of prestressed pavements. The additional traffic required for an underdesigned pavement to progress from a state of initial signs of distress to a state of complete failure is very small.

It is presently indicated that the relationship between load repetition and design requirements is influenced by the strength of the supporting foundation. In general, the load-repetition factor decreases with an increase in foundation strength. There is, however, need for considerable additional research in this area, particularly where the number of load repetitions exceeds one million.

3. Subgrade Restraint. Prestressed pavements tend to undergo length changes as a result of hygrothermal changes within the concrete, and as a result of the elastic shortening which occurs during application of the prestress. Such length changes result in a differential movement of the pavement relative to the subgrade. These movements are resisted by the friction between the pavement and the subgrade, thus inducing restraint stresses in the pavement. The restraint stresses are additive to the design prestress during increases in pavement length. Conversely, decreases in pavement length produce restraint stresses that are subtractive from the design prestress.

The magnitude of the restraint stress is a function of the coefficient of subgrade friction and the dimensions of the slab. This stress is maximum at the mid-section of the slab and, for concrete weighing 144 pcf, is expressed mathematically as:

$$R_f = \frac{L\,F}{2} \tag{1}$$

in which:

R_f = maximum subgrade restraint stress, in psi;
L = length of slab, in ft; and
F = coefficient of subgrade friction.

Coefficients of subgrade friction as high as 1.5 have been reported for slabs placed directly on granular subbases. It is an accepted practice to construct prestressed pavements on some type of friction-reducing layer such as sand and building paper, or sand and polyethylene sheeting. Use of a friction-reducing layer generally will result in coefficients of subgrade friction ranging from 0.50 to 0.75.

4. Prestress Losses. To maintain the required degree of prestress during the service life of the pavement, it is necessary that some additional prestress be applied initially to compensate for certain stress losses that will occur during and following construction. Assuming careful construction practices, such losses may approximate 15 to 20 percent of the design prestress for pretensioned and posttensioned systems. In the case of poststressed systems the entire prestress may be lost unless proper provision is made. Factors contributing to loss of prestress include:

1. Elastic shortening of the concrete.
2. Creep in the concrete.
3. Shrinkage of the concrete.
4. Relaxation of the stressing tendons.
5. Slippage of the stressing tendons in the anchorage devices.
6. Friction between the stressing tendons and the enclosing conduits.
7. Hygrothermal contraction of the pavement.

All of these sources of prestress loss, with the exception of items 2, 4 and 7, occur during construction. For pretensioned and posttensioned systems, the prestress losses are expressed in terms of loss of stress in the steel tendons. Thus, the initial prestress applied to the pavement in such systems must be sufficient to offset the total computed stress losses that occur because of natural adjustments in the construction materials during and following construction.

In poststressed systems, which do not incorporate tendons, the sources of prestress

loss are those listed in items 1, 2, 3 and 7. Some designers of poststressed systems have made provision for additional application of prestress by reactivating the jacking system as necessary during the service life of the pavement, rather than establishing a high initial prestress.

The following paragraphs present discussions of accepted procedures for establishing the magnitude of prestress losses.

(a) Elastic Shortening. The stress loss due to the elastic shortening of the concrete under the compressive force of the prestress is a function of the modular ratio of the steel and concrete (E_s/E_c), the magnitude of the prestress, and the degree of subgrade restraint. For pretensioned systems, the stress loss in the steel tendons due to elastic shortening of the concrete is equal to

$$f_s = (E_s/E_c)(R_p - R_f/2) \tag{2}$$

in which:

f_s = stress loss in the tendons, in psi;
E_s = modulus of elasticity of the steel, in psi;
E_c = modulus of elasticity of the concrete, in psi;
R_p = prestress in the concrete, in psi; and
R_f = maximum subgrade restraint stress, in psi.

Inasmuch as the stress loss in the tendons is inversely proportional to the modulus of elasticity of the concrete, it may be reduced by deferring application of the prestress until the concrete has attained appreciable strength.

For those posttensioned systems in which the tendons are stressed individually, the stress loss due to elastic shortening is approximately one-half that which occurs in a pretensioned system. Obviously, the simultaneous stressing of all tendons in a posttensioned system would eliminate any losses due to elastic shortening, because the shortening would occur as the stress is applied.

In poststressed systems, where no stressing tendons are used, the prestress loss in the concrete due to elastic shortening is also eliminated by the simultaneous application of the stressing force along the joint.

(b) Creep. The stress loss due to creep in the concrete is similar to the loss due to elastic shortening, in that both are the result of strains induced in the concrete. Unlike elastic shortening, which occurs instantaneously, creep is a function of the length of time during which the concrete is stressed. That portion of the strain which is in addition to the immediate elastic strain is defined as creep or "deferred strain."

The total deferred strain under a constant stress is proportional to the elastic strain. Various tests have indicated that the ratio of deferred strain to elastic strain ranges from 1.33 to 2.0. Therefore, depending on the modulus of elasticity of the concrete and the strain ratio, the deferred strain will be in the order of 3×10^{-7} to 6×10^{-7} in./in. for each psi of prestress.

For both pretensioned and posttensioned systems, the stress loss in the steel tendons due to the deferred strain in the concrete is equal to

$$f_s = \epsilon_d R_p E_s \tag{3}$$

in which:

f_s = stress loss in the tendon, in psi;
ϵ_d = deferred strain, in in./in.;
R_p = prestress in the concrete, in psi; and
E_s = modulus of elasticity of the steel, in psi.

As in the case of elastic shortening, the magnitude of the deferred strain can be reduced by delaying application of the prestress until the concrete has attained appreciable strength.

(c) Shrinkage. The amount of shrinkage which occurs in concrete is dependent upon

the physical properties of the raw materials, the proportioning of these materials, the method of placing and curing the concrete, the ambient temperatures during and soon after concrete placement, and the size of the slab.

Various tests have indicated that the coefficient of length-change due to shrinkage may be as little as 0.0001 in./in. or as much as 0.0007 in./in. In pretensioned systems, all of the shrinkage takes place after the tendons are stressed and tendon shortening of 0.0004 to 0.0005 in./in. may result. In posttensioned or poststressed systems, at least one-half the ultimate shrinkage usually occurs prior to stressing, in which case the shortening may only be in the order of 0.0002 in./in.

The stress loss in the tendons due to shrinkage in the concrete is equal to

$$f_s = \epsilon_s E_s \tag{4}$$

in which:

f_s = stress loss in the tendons, in psi;
ϵ_s = shrinkage, in in./in.; and
E_s = modulus of elasticity of the steel, in psi.

(d) Relaxation in the Steel. Tendons subjected to stresses in excess of 50 percent of the ultimate strength of the steel undergo a relaxation of stress which is due to creep in the steel. The amount of relaxation is a function of the magnitude of tensile stress in the steel, as related to the ultimate strength, type, and method of fabrication of the steel. In the case of high-strength "stress-relieved" steel, typical relaxation losses range from 0 to 3 percent at an anchorage stress of 0.50 f'_s, 4 to 6 percent at 0.60 f'_s, and 7 to 8 percent at 0.70 f'_s.

(e) Anchorage Losses. Some slippage of the tendons will occur in most prestressing systems when the load is released from the jacks and transferred to the anchors. The slippage of wires before being firmly gripped by friction wedges has been reported to be in the order of 0.1 in. The reduction in length of the tendons, in the case of direct-bearing anchorages, has been given as 0.03 in. This value may be reduced to as little as 0.01 in. by the use of shims. Large forces in the end fixtures may result in some slippage of the wires where heavy strands are used. The amount of such slippage will depend on the type of anchorage and size of the strands, and has been reported to be as much as 0.2 in.

The degree to which the slippage in the anchorage affects the stress loss in the tendons is directly proportional to the length of the tendon. Stress loss due to this slippage is equal to

$$f_s = \frac{\Delta L \, E_s}{L} \tag{5}$$

in which:

f_s = stress loss in the tendons, in psi;
ΔL = slippage in the anchorage, in in.;
E_s = modulus of elasticity of the steel, in psi; and
L = length of the tendon, in in.

(f) Tendon Friction in Posttensioned Systems. In posttensioned systems some loss in prestress will result from the friction developed between the tendons and their enclosures. This friction results from distortion and misalignment of the enclosure during construction, or from intentional bending of the enclosure due to changes in grade of the pavement. The frictional resistance thus created is a function of the angle-change of the enclosure, the magnitude of clearance between the tendon and the enclosure, and the type of materials used for the tendon and the enclosure.

The stress loss at any given distance from the jack may be approximated from

$$P_x = P_o \, e^{-(f_d X + f_f \phi)} \tag{6}$$

in which:

P_x = force in tendon at X distance from jack, in lb;
P_o = jacking force, in lb;
X = distance from jack, in ft;
ϕ = angular change in enclosure, in radians;
e = base of natural logarithms;
f_d = distortion coefficient; and
f_f = coefficient of friction between tendon and enclosure.

The actual values for f_d and f_f may vary considerably and should be determined in the field for the particular prevailing conditions. Typical values for f_d and f_f have been reported for the following conditions:

Type of Tendon	Type of Enclosure	f_d	f_f
High-strength bars	Bright metal	0.0001 - 0.0005	0.08 - 0.30
Galvanized strand	Bright metal	0.0005 - 0.0020	0.15 - 0.30
Wire cables	Bright metal	0.0005 - 0.0030	0.15 - 0.35

The general construction procedure is to apply an initial temporary overtensioning of the tendons to compensate for stress loss due to enclosure friction. Many specifications set the maximum value of this temporary overstress at 0.80 f'_s. Soon after the overstress is applied it is relaxed to the maximum value of the anchorage stress, which is usually in the order of 0.70 f'_s.

(g) Hygrothermal Contraction. For pretensioned and posttensioned systems of prestressing, which rely on the use of steel tendons to develop the prestress, the loss in prestress due to hygrothermal contraction is determined in accordance with Eq. 1. For poststressed systems of prestressing, which rely on externally applied forces to develop the prestress, the loss in prestress is equal to

$$R_t = \epsilon_t E_c t \tag{7}$$

in which:

R_t = prestress loss, in psi;
ϵ_t = coefficient of thermal expansion for the concrete, in in./in./°F;
E_c = modulus of elasticity of the concrete, in psi; and
t = temperature change, in °F.

5. Buckling. As discussed previously, prestressed pavements tend to undergo length changes as a result of hygrothermal changes within the concrete. Normally, the tendency for the pavement to expand is beneficial because of accompanying increases in prestress. There is, however, the factor of buckling, which must be considered during periods of expansion.

Both theoretical analysis and experimental studies have indicated that buckling is not a serious problem in pretensioned or posttensioned prestressed pavements. In these pavements, the stressing tendons within the slab act to resist buckling, thus the force required to buckle the slab becomes substantially greater than the compressive forces produced by hygrothermal changes. In the case of poststressed pavements, however, there are no stressing tendons to assist in resisting buckling from excessive compressive forces. Consequently, buckling becomes a particular problem in those cases where the joints are completely immobilized by concrete, grout, or some other type of rigid filler.

The mechanism of pavement failure due to buckling is complex, involving the physical properties of the concrete and foundation material, the dimensions of the pavement, the magnitude of the temperature change, and the degree of restraint at the ends of the pavement. Although some investigative work has been done in this field, there is clearly a need for additional research on both the magnitude of the

induced compressive forces and the magnitude of the compressive forces required to produce buckling under various conditions. Additional study is also warranted in evaluating the relative effects of daily temperature cycling as compared with long-term seasonal temperature changes.

PLANNING AND DESIGN OF EXPERIMENTAL HIGHWAY PAVEMENTS

Scope of Research

Thus far, no prestressed pavement has been constructed on any highway in the United States. Therefore, it seems logical that a rather broad research coverage of principal design variables should be included in the first experimental projects. Variables recommended for study, and the suggested limits within which the study should be made, are as follows:

1. Subbase—various treatments, minimum thickness of 4 in.

Experience with concrete pavements of conventional design has shown that the tendency for edge pumping and accompanying loss of foundation support increases as pavement thickness decreases, other conditions being constant. Consequently, prestressed pavements, because of their lesser thickness and resulting greater deflection under traffic loads, may require subbases of higher quality than are needed for conventional pavements. In order to develop substantial information on this point, cement-treated and bituminous-treated subbases should be tried in conjunction with those conforming with the standard of the State.

2. Pavement thickness—range 4 to 7 in., uniform cross-section.

This range should serve to develop criteria for pavements subjected to a large volume of heavy truck loads. It is expected that the presence or absence of longitudinal cracking will assume a major role in this development. Experience indicates that such cracking in prestressed pavements is associated primarily with (a) planes of weakness formed by tendons and encasing conduits and (b) loss of foundation support due to edge pumping. Consequently, concrete cover over the tendons and the quality of the supporting foundation appear to be the controlling factors in determining thickness.

3. Slab length—range 400 to 800 ft.

This range should provide data essential to the establishment of a practical slab length. Present knowledge indicates that the cost of developing sufficient prestress to offset the loss resulting from subgrade restraint may be prohibitive for slabs longer than 800 ft. The number of transverse joints required for pavements with slab lengths less than 400 ft would, however, detract from one of the basic advantages of prestressed pavements. Therefore, in the final selection of a practical slab length, consideration must be given to arriving at a balance between the cost and performance of transverse joints and the cost of providing for subgrade restraint forces.

4. Magnitude of longitudinal design prestress—see table for range.

Currently, many engineers contend that the magnitude of the design prestress need be only slightly greater than the direct tensile stress resulting from subgrade restraint. Based on an analysis of this stress-producing factor, and information developed by field and laboratory studies, the following range in longitudinal design prestress is suggested:

Pavement Thickness (in.)	Slab Length (ft)	Range in Longitudinal Design Prestress (psi)
4	400	200 - 375
	600	275 - 450
	800	350 - 525
5	400	200 - 350
	600	275 - 425
	800	350 - 500
6	400	200 - 325
	600	275 - 400
	800	350 - 475
7	400	200 - 300
	600	275 - 375
	800	350 - 450

For pretensioned and posttensioned systems, the initial prestress should be sufficient to provide for (a) the selected design prestress and (b) the pertinent prestress losses discussed under Subsection 4 in the preceding section of this report. As indicated therein, this initial prestress should be about 15 to 20 percent greater than the design prestress, provided the pavement is carefully constructed.

For the poststressed system, the initial prestress should also be sufficient to provide for (a) the selected design prestress, and (b) certain prestress losses as previously discussed. In this system, compressive stress in the pavement is generally maintained by several reapplications of a relatively low prestressing force. If sufficient prestress were induced initially to overcome all anticipated losses it could result, under certain temperature conditions, in the application of a unit force exceeding the design prestress by more than 1,000 psi.

5. Magnitude of transverse design prestress—range 0 to 200 psi.

Whether or not transverse prestress is needed for highway pavements is a matter of speculation. Longitudinal cracking, particularly over tendons, has been reported in some pavements constructed without this prestress. Undeniably, certain structural benefits would be derived from its use. However, in the final appraisal of the value of prestressed pavements, the cost of transverse prestress must also receive consideration.

A study to determine the need for transverse prestress should include (a) no prestress or reinforcing steel, (b) reinforcing steel only, (c) combinations of prestress and reinforcing steel, and (d) several magnitudes of prestress within the suggested range.

6. Spacing of tendons—range 2 to 6 times pavement thickness.

This range should provide pertinent information on pavement performance as related to the spacing of tendons. Information will also be provided on the size of the tendons, inasmuch as size varies with variations in spacing, other conditions being equal.

7. Transverse joints—intensive study of various designs.

The large horizontal movements that occur at the ends of long prestressed slabs constitute a major problem in design that must be resolved before prestressed pavements can be considered practical. Various jointing methods have been tried, but none has proved entirely satisfactory from the standpoint of simplicity and cost. Studies in this area should include free, partial-compression, and compression joints.

8. Collateral studies.

In addition to studies of the foregoing design variables, other features of design merit consideration in experimental projects. The following are suggested for investigation:

(a) Strengthening of the longitudinal free edges. Because these edges are potential sources of weakness, some means of strengthening should be tried. Most promising are edge thickening and extra-width pavement, with the additional width being used as part of the shoulder.

(b) Boundary reinforcement. The benefits derived from the use of reinforcing steel at certain critical locations should be studied. This would include experiments to determine the proper amount and placement of reinforcing steel for jacking and anchorage locations, and for slab corners.

(c) Friction-reducing mediums. Various mediums should be tried, including sand, plastic sheeting, bitumen coatings, and combinations thereof.

(d) Longitudinal conduits. Obviously, in posttensioned systems, the larger the conduit the greater will be the tendency for longitudinal cracking. On the other hand, the smaller the conduit the greater will be the prestress loss resulting from friction between the conduit and the tendon. Therefore, it would be desirable to determine the most practical size and type of conduit.

It is recommended that methods of providing for the large horizontal movements that occur at the ends of prestressed slabs be studied in all experimental projects. It is further recommended that only one or two of the other major design variables discussed in the foregoing be incorporated in any one project. Collateral studies should be so planned that they will not influence the basic study.

Controls

The information now available on prestressed pavements, together with experience in general, suggest the following controls for experimental projects:

1. In order to accelerate appraisal of the design selected, it is desirable that the test pavement be constructed where the volume of heavy truck loads tends to be most severe in a particular State.
2. The concrete should conform with the standards of the State, as concerns its composition and method of placing and curing. However, (a) the maximum size of coarse aggregate should not exceed one-fourth of the pavement thickness and (b) full-width pavement vibration should be employed to permit the use of low-slump concrete and to adequately consolidate the concrete around the embedded elements.
3. The pavement should be constructed full width in one operation. If transverse prestress is omitted, the pavement should have a longitudinal center joint containing tie-bars.
4. A friction-reducing layer should be placed between the pavement and its foundation.
5. The prestressing tendons should be placed at mid-depth of the pavement slab.
6. The prestressing tendons should consist of either wires or strands having a minimum ultimate strength of 240,000 psi, or bars having a minimum ultimate strength of 145,000 psi.
7. The initial stress induced in the prestressing steel should not exceed 80 percent of ultimate at the jacking points, and 70 percent of ultimate at the anchorage points.
8. The unit jacking force (total force divided by the cross-sectional area of the slab) should not exceed one-fifth of the compressive strength of the concrete, as determined by test cylinders.
9. Each end of a slab should be provided with a tie-down system to prevent permanent upward curling.
10. The length of a section of test pavement of any given design should include not less than three consecutive slabs of that design.
11. Station numbers should be imprinted in the pavement surface at intervals of 100 ft.
12. An appreciable length of the State's standard pavement should be included in the experimental project, preferably in the same traffic lane, for purposes of comparison.

RECOMMENDED MINIMUM TESTS AND OBSERVATIONS FOR EXPERIMENTAL HIGHWAY PAVEMENTS

To correlate properly the results of research, certain basic information must be developed for all experimental highway projects. Minimum tests and observations believed essential are as follows:

Construction Phase

1. Daily maximum and minimum air temperature, obtained at test site.
2. Mid-depth temperature of the concrete, obtained just prior to final finishing, at intervals of 200 ft.
3. Mechanical tests on samples of subgrade soil and subbase material, in-place densities, and standard plate-bearing tests, obtained after completion of fine-grading, at random points not to exceed 1,000 ft. A minimum of three sets of tests should be obtained for each project.
4. Concrete data, to consist of information obtained by (a) standard tests of the State highway department, (b) compressive tests on concrete cylinders used to establish the time of prestressing, and (c) special tests of flexural strength and modulus of elasticity at 7 and 28 days.
5. Prestressing steel data, to consist of information obtained by mill tests and standard tests of the State.
6. Close inspection of construction, with notes of any unusual conditions that may

affect performance. Particular emphasis should be placed on alignment of tendons, end anchorages, abutments, jacking arrangements, grouting operations, and curing.

7. Photographic coverage of important operations.

Prestressing Phase

1. Simultaneous incremental measurements of jacking force, compressive strain in concrete, and strain in tendons, for one slab of each variation in design. Measurements of strain in concrete and tendons taken at (a) one end of slab, (b) one quarter-point of slab, and (c) mid-point of slab.

2. Measurements of the elastic shortening of one slab of each variation in design. Initial readings to be taken immediately prior to the application of jacking force. Subsequent readings to be obtained immediately after the application of jacking force.

3. Measurements of the mid-depth temperature of the slab.

4. Photographic coverage of jacking operations and instrumentation.

Post-Construction Phase

1. Annual range in air temperature and yearly rainfall, obtained from a nearby weather station.

2. Intensive condition survey of the pavement, including recording of cracks and photographs of any significant developments, made quarterly during first year after construction and each spring and fall thereafter.

3. Measurements of the changes in width of all transverse joints and cracks. Initial readings to be taken as soon as possible after prestressing operations. Subsequent readings to be obtained during hottest and coldest part of each year thereafter.

4. Recordings of the mid-depth temperature of the pavement, plus recordings of the ambient temperature, for correlation purposes. Readings to coincide with measurements of changes in joint width.

5. Transverse profiles every 100 ft of one slab of each variation in design, taken (a) before application of jacking force, (b) immediately after prestressing, (c) quarterly during first year after construction, and (d) each fall thereafter.

6. Measurements of load deflections of the outer pavement edge at the quarter-points and mid-length of one slab of each pavement thickness, obtained between daybreak and 2 hr following daybreak of a spring day, with an 18,000-lb single-axle load moving at creep speed. The vehicle should so track that the outside edge of the contact area of the outside tire is 6 in. from the pavement edge.

7. Surface roughness indexes or accurate longitudinal profile, obtained before pavement is opened to traffic and at 6-month intervals thereafter.

8. Traffic counts, axle-load weights, and frequencies, obtained soon after pavement is opened to traffic and at intervals of not more than two years thereafter.

9. Cores for pavement thickness determination. (Three cores for each variation in design.)

10. Pertinent observations and measurements on the State's standard pavement, to provide comparative data. (Includes surface roughness indexes.)

The preceding research program is general and may need some modification to apply to a particular prestressing system or a specific construction method. It is again noted that the listed tests and observations provide only minimum information for correlation purposes and are not intended to discourage more comprehensive investigations. Special observations of concrete creep, curling of the ends of pavement slabs, subgrade resistance, and residual compressive stresses in the pavement would be appropriate.

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