

# Recommendations for Designing Prestressed Concrete Pavements

Reported by ACI Committee 325

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*The load-carrying capacity of concrete pavement slabs can be significantly increased by prestressing. Prestressing induces compressive stresses in the concrete of pavements slabs. These stresses modify the structural behavior of these members and considerably improve their capacity to sustain bending deformations without cracking.*

*Given adequate consideration to the design of joints and the placement of reinforcement, long prestressed slabs with substantially smaller thicknesses than those of conventionally reinforced pavements carrying the same loads, can be constructed practically without cracks. Also, by capitalizing on the favorable distribution of the stresses caused by the effect of the difference in the moisture content from top to bottom across the thickness of the slab, the amount of prestressing forces required, and thus the prestressing reinforcement, may be reduced.*

*This report analyzes the factors influencing the design of prestressed concrete pavements and recommends methods for their layout and structural analysis.*

**Keywords:** concrete pavements; control joints; creep properties; post-tensioning; prestressed concrete; prestressing steels; shrinkage; slab-on-ground construction; structural analysis; structural design; thickness; warpage.

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# CHAPTER 1—PRESTRESSED CONCRETE PAVEMENTS

## 1.1—Introduction

It has long been known that transverse joints in plain and lightly reinforced concrete pavements are sources of structural weakness. Many of the problems in concrete pavements such as cracking, faulting, pumping, and spalling occur at the joints and adversely affect the riding quality of the pavement. In addition, most of the maintenance work is needed at the joints. Pavement maintenance is costly and causes interruption to traffic flow. One approach to limiting joint problems is to use pavements without transverse joints except at the extreme ends, which is the case in continuously reinforced concrete pavements (CRCP). Another approach is to use transverse joints spaced at greater distances, which is the case in prestressed concrete pavement.

Transverse cracks are an accepted part of CRCP performance, although the high amount of longitudinal steel reinforcement used in this type of pavements holds the cracks tightly closed. With time, spalling and sometimes faulting can occur if the cracks are relatively wide, thus reducing the riding comfort of the pavement.

A properly designed and constructed prestressed concrete pavement can provide a smooth surface free of cracks and with few transverse joints. In spite of these advantages, the use of prestressed concrete pavements has not been widespread in the United States for the following reasons:

- a. Not many pavement engineers are familiar with the methods of design and construction of prestressed concrete pavements.
- b. Since there are only a few prestressed concrete pavements in the U.S. and a scarcity of data, an adequate evaluation of the performance of this type of pavement under various load and environmental conditions is not available.
- c. The past use of relatively high magnitudes of prestressing forces, both in the longitudinal and transverse directions, has been expensive. This has discouraged the widespread use of prestressed concrete pavement. This is in spite of the economic advantages of this type of pavement as a result of its lesser thickness and of its potential for less maintenance as compared to nonprestressed pavements.

d. The repair of a crack in a prestressed concrete pavement is very difficult. A repair is described in Morris and Emery (1977).

e. Some engineers perceive a possible corrosion problem with the strands and joints. Corrosion protection has not been covered in this document. Techniques for providing protection can be found in the guidelines for constructing bridge decks, parking garages, etc. See documents by ACI Committees 201, 221, and 345.

The magnitudes of the prestressing stresses and the corresponding amounts of prestressing steel can be reduced considerably, as compared to the amounts that have been commonly used, if proper attention is paid to the following two important factors:

1. The use of low friction media or treatments between the pavement and the supporting media reduces the tensile stresses due to friction that develop during slab contraction when temperatures drop. The reduction of friction allows a similar reduction in the amount of the required prestressing forces.
2. The consideration of the favorable distribution of shrinkage stresses through the thickness of the slab due to the moisture differential between the bottom and top surfaces (away from the slab edges) reduces the stresses from vehicular loads. These residual stresses, which are compressive at the bottom of the slab, counteract a large part of the tensile stresses due to vehicular loads and thus reduce the amount of prestressing steel.

Thus, the objective of this report is to provide some guidance in designing prestressed concrete pavements in an economical manner. One chapter summarizes the procedure that could be followed to produce an economical design for prestressed concrete pavements and includes two examples to illustrate how the information and procedures given in the report can be used in an actual design.

## 1.2—Definitions

**1.2.1 Curling**—The distortion of an originally essentially linear or planar member into a curved shape such as the warping of a slab due to creep or to differences in temperature or moisture content in the zones adjacent to its opposite faces.

**1.2.2 Deflection**—A variation in position or shape of a structure or structural element due to effects of loads or volume change, usually measured as a linear deviation from an established plane rather than an angular variation. (In pavements, this relates to vertical slab movements only.)

**1.2.3 Deformation**—A change in dimension or shape due to stress. Time-dependent deformation may be stressless, as in the cases of unrestrained shrinkage or temperature length change.

**1.2.4 Elongation and shortening**—Terms used to designate length changes.

**1.2.5 Frictional restraint**—The decrease in length change of a pavement caused by frictional resistance of

the subgrade to the movement of the pavement. In long slabs, remaining flat on the base, the frictional strains are assumed to be evenly distributed on the sections from top to bottom. The only regions without frictional restraint are freely moving slab ends.

**1.2.6 Gradient**—Term used for describing the variation, in the vertical direction, of temperature or moisture from top to bottom of the slab, as temperature gradient and moisture gradient.

**1.2.7 Post-tensioning**—A method of prestressing reinforced concrete in which tendons are tensioned after the concrete has hardened.

**1.2.8 Prestressed concrete**—Concrete in which internal stresses of such magnitude and distribution are introduced that the tensile stresses resulting from the service loads are counteracted to a desired degree; in reinforced concrete the prestress is commonly introduced by tensioning the tendons.

**1.2.9 Prestressed concrete pavement slabs**—Pavements into which compressive forces are applied to the concrete sections during construction for the purpose of decreasing tensile stresses in the concrete during service.

**1.2.10 Restraint**—Restriction of free movement of fresh or hardened concrete. (In pavements, it is the decrease in deformations caused by temperature or moisture changes as a result of forces arising with movements or deflections to produce stress-related strains.) Restraint can be internal or external and may act in one or more directions.

**1.2.11 Shrinkage**—Volume decrease caused by drying and chemical changes; a function of time but not of temperature or of stress due to external load.

**1.2.12 Strain**—Deformation of a material resulting from external loading, or the restrained portion of potential length and volume change resulting from internal causes.

**1.2.13 Sustained modulus of elasticity  $E_s$** —This term has been established to include both immediate elastic deformations and the deformations due to creep.

**1.2.14 Swelling**—Volume increase caused by wetting or chemical changes, or both; a function of time but not of temperature or of stress due to external load.

**1.2.15 Warping**—A deviation of a slab from its original shape, usually caused by temperature or moisture differentials or both within the slab. (In pavements, warping effects are specifically determined at zero temperature gradient conditions.)

### 1.3—Prestressed pavement capabilities

ACI Committee 325 has published two reports dealing with prestressed concrete pavements. The report of February 1959 reviewed experiences and tests prior to that time. It called attention to a substantial increase in load-carrying capacity of prestressed as compared with nonprestressed pavements. The report of April 1968 gave details for proposed experimental prestressed highway projects including procedures to determine length changes and frictional restraints to movements in long slabs.

After publication of the reports, several prestressed highways were built in the U.S.; the results of the evaluations support the validity of the concepts in the earlier reports. Investigations of prestressed concrete pavements have shown that a favorable prestress distribution can be used in slabs on grade to produce the high load-carrying capacities of these pavements (ACI Committee 325 1959).

Most of the methods of calculating stresses in concrete pavements are based on Westergaard's (1948) theoretical procedures or the empirical results of the AASHO Road Test (1986) developed in the early 1960s. Both are mainly concerned with determining a thickness adequate to carry wheel loads. Neither method incorporates directly the stresses resulting from restraint of movements or deflections caused by temperature and moisture variations. The resulting design thickness is, in most cases, sufficient to carry traffic loads. However, little attention has been directed toward preventing cracks in conventional pavement designs.

An extensive research program of concrete pavements was conducted by the Bureau of Public Roads during the 1930s, and reported by Teller and Sutherland in five papers from 1935 to 1937. This investigation covered the entire field of concrete pavement behavior on soil foundations, including temperature and moisture effects, in evaluating the Westergaard theoretical studies. The authors acknowledged the general importance and value of moisture-caused movements and restraints; however, they proposed no method of quantitatively incorporating the concept into designs.

Procedures for quantitatively determining the time-dependent gradient restraint stresses and their distribution on pavement cross sections evolved from the investigation of prestressed concrete for slabs at the University of Missouri at Rolla from 1956 to 1958, which was cosponsored by the FHWA and the Missouri State Highway Department (Friberg 1962).

The research included prestress to 500 psi (3.5 MPa) magnitude. The results indicate that creep deformations are lower at the bottom than at the top of the pavement. This information can be used to determine the restraints of slowly changing moisture warping, as well as deformations under prestress from an early age and thereafter. The resultant concentration of compressive stresses toward the bottom of prestressed pavements due to the combined effect of prestressing and differential shrinkage are valuable characteristics of prestressed pavements.

This finding makes it possible for the designer to consider the environmental stresses from temperature and moisture gradients as well as prestress in resisting traffic loads. This is especially true in the interior of prestressed pavements, which usually consist of large slabs cast over membrane sheets. While water can evaporate freely from the top surface of these slabs, the bottom surface is permanently covered and movement of water from this surface is restricted.

With proper attention to joint designs and steel placement in long slabs, the designer can develop

stressed pavements that are substantially thinner than nonprestressed pavements by considering the favorable moisture distribution.

#### 1.4—Historical background

**1.4.1 Developments to 1960**—Between the end of World War II in 1945 and 1960, nearly 60 prestressed concrete pavements were constructed; most of them were experimental sections of pavement totaling about 13 miles (21 km) of highways and 20 miles (32 km) of airport pavements of multiple width construction (ACI Committee 325 1959). Of this, one highway and six airport experiments were in the United States.

These early projects covered a wide range of prestressing methods and magnitudes. Individual slab lengths ranged from about 160 to 700 ft (50 to 210 m), with an average of about 400 ft (120 m). Post-tensioned pavements, constructed with flat jacks in transverse joints and heavy end abutments, were explored for fixed-length configurations in which the prestress was allowed to vary seasonally with the temperature and moisture. Longitudinally applied prestress in individual slabs ranged from 190 to over 700 psi (1.3 to 4.80 MPa). Transverse prestressing up to 400 psi (2.8 MPa) was used in about one-half of the highway and all airport projects. The pavement thicknesses averaged 5¾ in. (0.15 m) for highway and 6½ in. (0.17 m) for airport prestressed slabs.

In the U.S., very few prestressed airport pavements were built following the six experimental projects. In contrast, several prestressed runways and taxiways were constructed in Europe during the 1960s and continue to be constructed on major civilian as well as military airports, with excellent performance. Most of the prestressed airport pavements, totaling well over 4 million yd<sup>2</sup> (3.3 million m<sup>2</sup>) have been post-tensioned longitudinally and transversely with patented systems that use high-strength bars in grouted steel conduits.

For civilian airports, 7 in. (0.18 m) pavements have been used extensively. The projects include 830,000 yd<sup>2</sup> (680,000 m<sup>2</sup>) at Schiphol, Amsterdam's main airport, constructed from 1965 to 1978; 660,000 yd<sup>2</sup> (530,000 m<sup>2</sup>) at Cologne-Bonn airport, constructed from 1960 to 1968; and 700,000 yd<sup>2</sup> (560,000 m<sup>2</sup>) at Rio de Janeiro airport from 1972 to 1978. For military airports, over one million yd<sup>2</sup> (800,000 m<sup>2</sup>) of 5.5 in. (0.14 m) thickness, 600,000 yd<sup>2</sup> (500,000 m<sup>2</sup>) of 6.3 in. (0.16 m) runways and taxiways, and 200,000 yd<sup>2</sup> (170,000 m<sup>2</sup>) of 4¾ in. (0.12 m) thick overlay pavements have been put in place.

**1.4.2 Developments after 1960**—Industrial developments and research investigations during the 1960s improved the prospects for successful applications of prestressed pavements in the U.S. Among these are the increased use of plastic-encased grease-protected high-strength seven-wire steel strand on reels for structural prestressing. This has made available a convenient and economical post-tensioning tendon for long slabs. Also in widespread use are combined bearings and strand chucks that permit easy placement of the post-tensioned strand anchors that firmly grip the strand. The development of lightweight double-cylinder open-throat jacks has speeded up post-tensioning operations to the point where single-strand post-tensioning is a minor operation in slab prestressing.

In the developing market for prestressed pavements, the results of research on low-friction media or treatments between the supporting media and the pavement are of some importance. Low friction values have been obtained with double layers of thin plastic membranes of the low-friction type (Timms 1963). Such products are available commercially with a coefficient of friction measured in the laboratory according to ASTM D 2103 as low as 0.20. Such low friction values are not attainable in field practice due to construction variations in the subbase. However, subgrade friction values on the order of 0.50 are possible if the pavement is placed on two layers of polyethylene sheets on a relatively smooth surface. Even lower values might be possible with a friction-reducing agent (such as a thin layer of paraffin oil) between the polyethylene sheets (U. S. Department of Transportation 1983).

Confidence is growing in the use of prestressed pavements due to the performance of recently constructed projects in the U.S. (Gramling et al. 1983). A highway project incorporating the new ideas was constructed near Dulles International Airport, Va., in 1972 (Friberg and Pasko 1973b), using uniform 200-psi (1.4-MPa) prestress in 400 to 760 ft (120 to 230 m) long slabs. Three more full-scale highway projects were constructed: Pennsylvania in 1973 (Brunner 1975), Mississippi in 1975 (Albritton 1976), and Arizona in 1977 (Morris and Emergy 1977). More recently, Texas built prestressed overlays in 1985 (Burns and McCullough 1986) and Pennsylvania is planning a major project in 1988 (Gramling 1986). Some details on the design of an economical prestressed pavement system for highway pavements are shown in Chapter 5. These references also cover corrosion protection of the hardware in the pavements.

CHAPTER 2—TIME-DEPENDENT DEFORMATIONS AND RESTRAINT STRESSES IN PRESTRESSED PAVEMENTS

## CHAPTER 2—TIME-DEPENDENT DEFORMATIONS AND RESTRAINT STRESSES IN PRESTRESSED PAVEMENTS

### 2.1—Seasonal length changes of prestressed slabs

Changes in pavement length depend primarily on the temperature changes in the concrete, the swelling of the concrete that usually takes place during the cold season because of fluctuation in moisture content, and the restraints to movement due to subgrade friction. The coefficient of thermal expansion in concrete is mainly dependent on the thermal coefficient of the coarse aggregate, which varies from about  $2.5 \times 10^{-6}/^{\circ}\text{F}$  ( $4.5 \times 10^{-6}/^{\circ}\text{C}$ ) for high-grade limestone to about  $6.5 \times 10^{-6}/^{\circ}\text{F}$  ( $11.7 \times 10^{-6}/^{\circ}\text{C}$ ) for acceptable types of siliceous rocks (Emanuel and Hulsey 1977). Neat cement has a somewhat higher thermal coefficient. The measured value of thermal coefficient of concrete is also dependent on age, temperature, and moisture content.

Hence the thermal properties of a pavement undergo seasonal changes. These seasonal changes in thermal coefficients have an effect on the seasonal change in length. Ideally, the actual values of thermal coefficients should be determined for each project. Such an approach would be advantageous from the particular application standpoint as well as to accumulate data for future use. Where this is not possible, it is considered appropriate to use the thermal coefficient for fully saturated conditions for predicting the winter length changes, about  $1\frac{1}{2}$  times this value for predicting the summer length changes, and an intermediate value for the other seasonal length changes.

The minimum values of coefficients of thermal expansion for limestone aggregate concrete may be in the order of  $3 \times 10^{-6}/F$  ( $5.4 \times 10^{-6}/C$ ) and for siliceous aggregate concrete  $6 \times 10^{-6}/F$  ( $10.8 \times 10^{-6}/C$ ). For summer conditions in mature pavements, thermal coefficients may be  $4 \times 10^{-6}/F$  ( $7.2 \times 10^{-6}/C$ ) in limestone and  $7 \times 10^{-6}/F$  ( $12.6 \times 10^{-6}/C$ ) in siliceous aggregate concrete. The type of concrete and aggregate, in large measure, govern the fluctuations in expansion joint widths to be expected between prestressed pavement slabs.

The seasonal length changes of slabs due to temperature should be decreased by the amount of seasonal swelling (which is independent of the amount of prestress). The unit deformation of this swelling has not been observed to be less than  $100 \times 10^{-6}$ .

Frictional restraints do not exert a major influence on the seasonal temperature movements, but friction stress is a major concern in the design of long slabs. The minimum required design value is 0.5 for the average friction coefficient under prestressed pavements of about 600 ft (180 m) maximum slab lengths. A friction coefficient of this magnitude is attainable by using a double layer of high-slip polyethylene (U. S. Department of Transportation 1983) under the concrete pavement. This high-slip polyethylene contains a friction-reducing agent between the two layers and should be placed on a well compacted and leveled subbase.

Friction on frozen subgrades can vary significantly (U. S. Department of Transportation 1983). On the Dulles Project (Friberg and Pasko 1973b), the first crack on the project near mid-length of the 760-ft (228-m) slab occurred after a drop in concrete temperature from 58 to 16 F (14 to  $-9$  C) on a frozen subbase. For this reason, a friction coefficient of not less than 0.7 should be considered at low temperatures (U. S. Department of Transportation 1983). If friction-reducing layers are not used under the pavement, higher values must be considered for the coefficient of friction. The appropriate value to be used should be obtained from investigations conducted on site.

## 2.2—Annual thermal-length change cycle in different pavements—Example

After obtaining the information on the thermal coefficients of concrete and their variations with aggregates, temperature, moisture, and age, appropriate

computations can be made for any project. An example based on assumed conditions approximating the conditions of observations by Teller and Sutherland (1935- 1937) is given in Table 2.2 as applied to 6 in. (0.15 m) thick pavement slabs 400 and 600 ft (120 and 180 m) in length.

The length changes are determined for average concrete temperatures. In the continental U.S., maximum air temperature very rarely exceeds 110 F (43 C), which may give about a 130 F (54 C) surface temperature.

Table 2.2 is based on 80 F (27 C) low summertime daily temperature. For extremely high air temperatures, a temperature gradient of 4 F/in. (0.09 C/mm) is possible. Friction restraints apply for the daily expansion above 80 F (27 C) at a friction factor equal to 0.5. At extremely low temperatures, minimum air temperatures are not easily predictable for any project. Extreme low air temperatures in the continental U.S. vary from about 0 F ( $-18$  C) in the gulf states to  $-50$  F ( $-45$  C) in some northern states (Anon. 1941). At these low temperature exposures, the surface will often be not more than 10 F (5 C) warmer than the air. A negative temperature gradient of 2 F/in. (0.045 C/mm) should be used for the extreme condition. The  $-20$  F ( $-29$  C) minimum surface temperature, or  $-30$  F ( $-34$  C) air temperature would be exceeded in some northern states.

The tabulated contraction-expansion for the annual cycle is for the full slab length. At each end, the annual cycle of movement of a slab end is about one half of the values given in Table 2.2.

## 2.3—Noncyclic length changes from shrinkage and prestress plus creep

The long-time total deformations from the prestress are assumed proportional to the average prestress on the cross sections of the pavement slab and proportional to the slab length. The prestress forces are decreased by the friction restraint stresses during the night contraction and are increased during the day expansion; accordingly, the nominal concrete prestress in the slab can be assumed to be active throughout the slab length. Sustained modulus of elasticity values at different ages suffice for computation of the total progressive length change due to prestress.

Longer slabs will generally be designed with higher prestress at the ends than the shorter slabs to maintain a specified minimum effective prestress at mid-length of the contracting slabs. If the prestressing is applied at the short gaps between the prestressed slabs, joint widths can be adjusted during the placement of the expansion joints for the drying shrinkage, prestress application, and creep that occur during the early age, up to about one month.

After casting, a concrete slab undergoes drying shrinkage and creep that reduce the prestress forces that are applied. Some typical values of shortening are illustrated in Fig. 2.3.1, which is based on the evaluation of different slab lengths, all with 200 psi (1380 kPa) prestress applied at the ends, placed at Dulles airport (Fri-

Table 2.2 — Example of calculated annual length change of pavement slabs

| Slab thickness, in. (m)                                                      |  | 6 in. (0.15 m)                 |                   | Calculations for 400 ft section                                                                                                                             |
|------------------------------------------------------------------------------|--|--------------------------------|-------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Slab Length, ft (m)                                                          |  | 400 (120)                      | 600 (180)         |                                                                                                                                                             |
| Restrained temperature expansion above 80 F (27 C)                           |  |                                |                   |                                                                                                                                                             |
| 1. Average temperature                                                       |  | + 118 F (48 C)                 |                   | $130^{\circ} - \frac{6 \text{ in.} \times 4^{\circ}/\text{in.}}{2} = 118^{\circ}$                                                                           |
| 2. Unrestrained expansion, in.                                               |  | + 1.094                        | + 1.642           | $(118-80)^{\circ} (6 \times 10^{-6}) (400 \times 12) \text{ in.} = 1.094$                                                                                   |
| 3. Friction stress, mid-length                                               |  | psi<br>kPa<br>+ 100<br>+ 690   | + 150<br>+ 1035   | $\frac{(0.5) (200 \text{ ft} \times 1 \text{ ft} \times \frac{1}{2} \text{ ft} \times 144 \text{ lb/ft}^3)}{(12 \times 6 \text{ in.}^2)} = 100 \text{ psi}$ |
| 4. Friction restrained each end, in.                                         |  | - 0.04                         | - 0.09            | $\frac{(100 \text{ psi}) (400 \times 12)}{2 \times 2} = 0.04 \text{ in.}$<br>$3 \times 10^6$                                                                |
| 5. Restrained expansion for full length                                      |  | in.<br>mm<br>+ 1.014<br>+ 25.8 | + 1.462<br>+ 37.1 | from 2, 1.094-2(.04)                                                                                                                                        |
| Restrained contraction below + 20 F (- 7 C)                                  |  |                                |                   |                                                                                                                                                             |
| 6. Average temperature                                                       |  | - 14 C (- 26 C)                |                   | $- 20^{\circ} + \frac{6 \times 2^{\circ}/\text{in.}}{2} = - 14^{\circ}$                                                                                     |
| 7. Unrestrained contraction                                                  |  | in.<br>- 0.653                 | - 0.979           | $(- 20-14) (4 \times 10^{-6}) (400 \times 12) = - 0.653$                                                                                                    |
| 8. Friction stress, mid-length                                               |  | psi<br>KPa<br>+ 140<br>+ 966   | + 210<br>+ 1449   | $\frac{(0.7) (200 \times 1 \times \frac{1}{2} \times 144)}{12 \times 6} = 140$                                                                              |
| 9. Friction restrained each end                                              |  | in.<br>+ 0.056                 | + 0.126           | $\frac{(140) (400 \times 12)}{2 \times 2} = 0.056$<br>$3 \times 10^6$                                                                                       |
| 10. Restrained contraction for full length                                   |  | in.<br>mm<br>- 0.541<br>- 13.7 | - 0.727<br>- 18.5 | - 0.653 + 0.112 = 0.541                                                                                                                                     |
| Unrestrained seasonal length change for + 20 to + 80 F (- 7 to 27 C) average |  |                                |                   |                                                                                                                                                             |
| Temperatures between 20 and 80 F                                             |  |                                |                   |                                                                                                                                                             |
| 11. $5 \times 10^{-6}/^{\circ}\text{F}$                                      |  | in.<br>+ 1.44                  | + 2.16            | $(80-20) \times 5 \times 10^{-6} \times (400 \times 12) = 1.44$                                                                                             |
| 12. Moisture @ $100 \times 10^{-6}$                                          |  | - 0.48                         | - 0.72            | $(100 \times 10^{-6}) (400 \times 12) = 0.48$                                                                                                               |
| 13. Adjusted length change                                                   |  | + 0.96                         | + 1.44            | $1.44 - 0.48 = 0.96$                                                                                                                                        |
| 14. Surface temperature between 80 and 130 F                                 |  | + 1.01                         | + 1.46            | from 5                                                                                                                                                      |
| 15. Surface temperature between - 20 and + 20 F                              |  | + 0.54                         | + 0.73            | from 10                                                                                                                                                     |
| 16. Total annual length change                                               |  | in.<br>mm<br>2.51<br>64        | 3.63<br>92        | from 13, 14, 15<br>$0.96 + 1.01 + 0.54 = 2.51$                                                                                                              |

## NOTE:

1. Summer conditions: temperature gradient 4 F/in. (0.09 C/mm); maximum surface temperature 130 F (55 C); thermal coefficient  $6 \times 10^{-6}/^{\circ}\text{F}$  ( $11 \times 10^{-6}/^{\circ}\text{C}$ ); frictional coefficient above 80 F (27 C), 0.50 average.
2. Winter conditions: temperature gradient +2 F/in. (0.044 C/mm); maximum surface temperature -20 F (-29 C); thermal coefficient  $4 \times 10^{-6}/^{\circ}\text{F}$  ( $7 \times 10^{-6}/^{\circ}\text{C}$ ); frictional coefficient below +20 F (-7 C), 0.70 average. Summer-winter moisture length change is  $100 \times 10^{-6}$  in./in.
3. Calculations are for Pavement with -20 to 130 F surface temperature cycle (-29 to 55 C), with friction restraint above 80 F (27 C) and below +20 F (-7 C) at an elastic modulus of  $3 \times 10^6$  and a concrete weight of 144 lb/cf.

berg and Pasko 1973b). The total shortening of each of the different slabs reflects the combined effect of shrinkage and creep, both of which depend on the length of the prestressed slabs. Fig. 2.3.2 shows the unit length changes for the Dulles slabs (Friberg and Pasko 1973a).

Values of creep up to one month and beyond are shown in Table 2.3. The break at 30 days is assumed to be about the time when final tensioning would be adjusted and the expansion joints placed with the design joint gap dimensions. The values are shown for a 6 in. (0.15 m) thick slab using a sustained modulus of elasticity of  $3.7 \times 10^6$  psi (25.2 GPa) for 30 days, and  $1.7 \times 10^6$  psi (11.7 GPa) for the long term movements to about 20 to 30 years. A typical computation for the

progressive length change in a 400 ft (120 m) slab under prestress of 200 psi (1380 kPa) is: to one month,  $(400 \times 12 \times 200)/3.7 \times 10^6 = 0.26$  in. (6.6 mm); and to full life of  $10^4$  days,  $(400 \times 12 \times 200)/1.7 \times 10^6 = 0.56$  in. (14.2 mm). Similar computations can be made for the different prestress values and slab lengths. For 8 in. (0.2 m) pavements, slightly higher sustained modulus values are suggested, as shown in Table 2.3, since slabs with a larger volume of concrete contain more total moisture than thinner slabs.

To obtain the total noncyclic progressive length change in a prestressed slab, it is necessary to adjust the stress-related length changes for the drying shrinkage during the first month (about  $80 \times 10^{-6}$  from Fig. 2.3.1), and a probable growth thereafter of about  $50 \times$

$10^{-6}$  to the mature age of the pavement. In the lower part of Table 2.3, for drying shrinkage of  $80 \times 10^{-6}$  and a slow expansion thereafter of  $+50 \times 10^{-6}$ , the total strain for length change to mature age from construction is  $-30 \times 10^{-6}$ . The change after 30 days is relatively small; the continued creep, shown at a lower

sustained modulus, is to a great extent cancelled by an equivalent slow swell.

For a 200 psi (1380 kPa) prestress level in a 400-ft (120-m) slab, the calculated total shortening at the age of one month is 0.64 in. (16.3 mm), as indicated in Table 2.3 for a 6 in. (0.15 m) thick slab. For comparison, the observed shortening at one month is about 0.64 in. (16.3 mm) on Fig. 2.3.1 from the Dulles project. Mea-

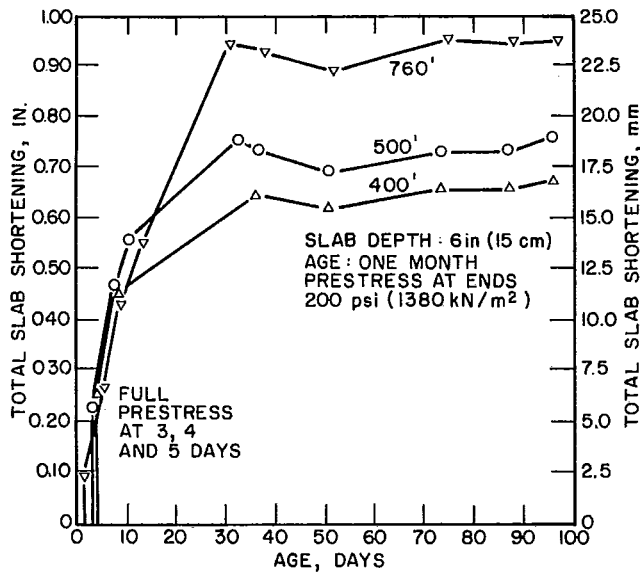


Fig. 2.3.1—Progressive length changes to 100 days; highway pavements placed in December for project at Dulles International Airport (Friberg and Pasko 1973b)

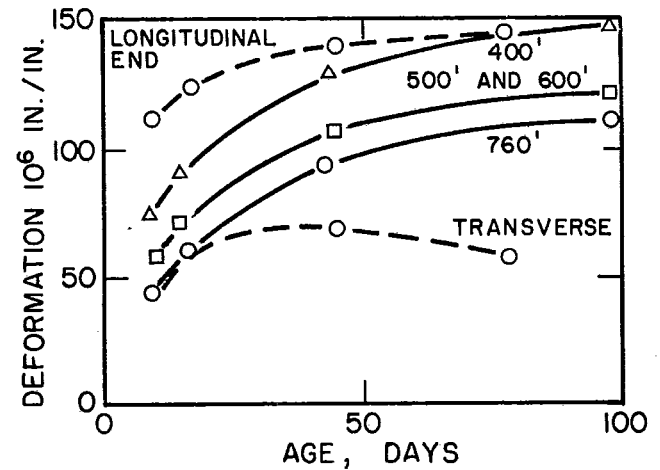


Fig. 2.3.2—Unit shortening of main slabs compared to end and transverse length changes independent of temperature (Friberg and Pasko 1983a)

**Table 2.3 — Total estimate of progressive length change of prestressed pavements at one month and at 10<sup>4</sup> days, in in., for concrete\* used at dulles airport**

| Pavement depth                                                           |                         |                                    |                                  | 6 in. (0.15 m) |                                              |                                              | 8 in. (0.20 m) |                                              |                                              |
|--------------------------------------------------------------------------|-------------------------|------------------------------------|----------------------------------|----------------|----------------------------------------------|----------------------------------------------|----------------|----------------------------------------------|----------------------------------------------|
| Time from construction                                                   |                         |                                    |                                  | One month      | 20 yr. +                                     | Difference, prestress applied at 1 month age | One month      | 20 yr. +                                     | Difference, prestress applied at 1 month age |
| Sustained modulus $E_{st}$ ,<br>10 <sup>6</sup> psi (GN/m <sup>2</sup> ) |                         |                                    |                                  | 3.7(25.5)      | 1.7(11.7)                                    |                                              | 4.4(30.4)      | 2.0(13.8)                                    |                                              |
| Length change from prestress alone                                       |                         |                                    |                                  |                |                                              |                                              |                |                                              |                                              |
| Slab length                                                              |                         | Prestress                          |                                  | in. (mm)       |                                              |                                              |                |                                              | in. (mm)                                     |
| ft                                                                       | m                       | psi                                | kPa                              |                |                                              |                                              |                |                                              |                                              |
| 400                                                                      | 120                     | 200                                | 1380                             | -0.26          | -0.57                                        | -0.31 (7.9)                                  | -0.22          | -0.48                                        | -0.26 (6.6)                                  |
| 600                                                                      | 180                     | 300                                | 2070                             | -0.58          | -1.28                                        | -0.70 (17.8)                                 | -0.49          | -1.08                                        | -0.59 (15.0)                                 |
| Length change from shrinkage and swell                                   |                         |                                    |                                  |                |                                              |                                              |                |                                              |                                              |
|                                                                          | Shrinkage to 30 day     | Swelling 30 to 10 <sup>4</sup> day | Total length change in pavements |                |                                              |                                              |                |                                              |                                              |
| Slab length, ft                                                          | ( $80 \times 10^{-6}$ ) | ( $50 \times 10^{-6}$ )            | One month                        | 20 yr. +       | Difference, prestress applied at 1 month age | One month                                    | 20 yr. +       | Difference, prestress applied at 1 month age |                                              |
|                                                                          | in.                     | in.                                |                                  |                |                                              |                                              |                |                                              |                                              |
| 400                                                                      | -0.38                   | +0.24                              | -0.64                            | -0.71'         | -0.07' (1.80)                                | -0.60                                        | -0.62          | -0.02 (0.50)                                 |                                              |
| 600                                                                      | -0.58                   | +0.36                              | -1.16                            | -1.50          | -0.34 (8.6)                                  | -1.07                                        | -1.30          | -0.23 (5.8)                                  |                                              |

\*Other concretes may have different values.

<sup>1</sup>-0.57-0.38+0.24 = -0.71.

<sup>2</sup>-0.71+0.64 = -0.07.