Guide for Design of Jointed Concrete Pavements for Streets and Local Roads

Reported by ACI Committee 325

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This guide provides a perspective on a balanced combination of pavement thickness, drainage, and subbase or subgrade materials to achieve an acceptable pavement system for streets and local roads. Such concrete pavements designed for low volumes of traffic (typically less than 100 trucks per day, one way) have historically provided satisfactory performance when proper support and drainage conditions exist. Recommendations are presented for designing a concrete pavement system for a low volume of traffic and associated joint pattern based upon limiting the stresses in the concrete or, in the case of reinforced slabs, maintaining the cracks in a tightly closed condition. Details for designing the distributed reinforcing steel and the load transfer devices are given, if required.

The thickness design of low-volume concrete pavements is based on the principles developed by the Portland Cement Association and others for analyzing an elastic slab over a dense liquid subgrade, as modified by field observations and extended to include fatigue concepts.

Keywords: dowel; flexural strength; joint; pavement; portland cement; quality control; reinforced concrete; slab-on-grade; slipform; subbase; tie bar; welded wire fabric.

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CHAPTER 1—GENERAL

1.1—Introduction

The design of a concrete pavement system for a low traffic volume extends beyond the process of pavement thickness selection; it entails an understanding of the processes and the factors that affect pavement performance. It also encompasses appropriate slab jointing and construction practices that are consistent with local climatic and soil conditions.

Concrete pavements for city streets and local roads are often used in residential areas and business districts, and in rural areas to provide farm-to-market access for the movement of agricultural products. The term "low volume" refers to pavements subject to either heavy loads but few vehicles, or light loads and many vehicles. City streets and local roads also serve an aesthetic function because they are integrated into the landscape and architecture of a neighborhood or business district.

Concrete pavement performs well for city street and local road applications because of its durability while being continuously subjected to traffic and, in some cases, severe climatic conditions. Because of its relatively high stiffness, concrete pavements spread the imposed loads over large areas of the subgrade and are capable of resisting deformation caused by passing vehicles. Concrete pavements exhibit high wear resistance and can be easily cleaned if necessary. Traffic lane markings can be incorporated into the jointing pattern where the concrete's light-reflective surface improves visibility. Concrete pavement surfaces drain well on relatively flat slopes.

The major variables likely to affect the performance of a well-designed concrete pavement system for city streets and local roads are traffic, drainage, environment, construction, and maintenance. Each of these factors may act separately or interact with others to cause deterioration of the pavement. Due to the nature of traffic on city streets and local roads, the effects of environment, construction, and maintenance can play more significant roles in the performance than traffic. Nonetheless, complete information may not be available regarding certain load categories that make up the mixture of traffic carried on a given city street or local road.

1.2—Scope

This guide covers the design of jointed plain concrete pavements (JPCP) for use on city streets and local roads (driveways, alleyways, and residential roads) that carry low volumes of traffic. This document is intended to be used in conjunction with ACI 325.9R. References are provided on design procedures and computer programs that consider design in greater detail. This guide emphasizes the aspects of concrete pavement technology that are different from procedures used for design of other facilities such as highways or airports.

1.3—Background

The thickness of concrete pavement is generally designed to limit tensile stresses produced within the slab by vehicle loading, and temperature and moisture changes within the slab. Model studies and full-scale, accelerated traffic tests have shown that maximum tensile stresses in concrete pavements occur when vehicle wheel loads are close to a free or unsupported edge in the midpanel area of the pavement. Stresses resulting from wheel loadings applied near interior longitudinal or transverse joints are lower, even when good load transfer is provided by the joints. Therefore, the critical stress condition occurs when a wheel load is applied near the pavement's midslab edge. At this location, integral curbs or thickened edge sections can be used to decrease the design stress. Thermal expansion and contraction, and warping and curling caused by moisture and temperature differentials within the pavement can cause a stress increase that may not have been accounted for in the thickness design procedure. The point of crack initiation often indicates whether unexpected pavement cracking is fatigue-induced or environmentally induced due to curling and warping behavior. Proper jointing practice, discussed in Chapter 4, reduces these stresses to acceptable levels.

Concrete pavement design focuses on limiting tensile stresses by properly selecting the characteristics of the concrete slab. The rigidity of concrete enables it to distribute loads over relatively large areas of support. For adequately designed pavements, the deflections under load are small and the pressures transmitted to the subgrade are not excessive. Although not a common practice, high-strength concrete can be used as an acceptable option to increase performance.

Because the load on the pavement is carried primarily by the concrete slab, the strength of the underlying material (subbase) has a relatively small effect on the slab thickness needed to adequately carry the design traffic. Subbase layers do not contribute significantly to the load-carrying capacity of the pavement. A subbase, besides providing uniform support, provides other important functions, such as pumping and faulting prevention, subsurface drainage, and a stable construction platform under adverse conditions.

Thickness design of a concrete pavement focuses on concrete strength, formation support, load transfer conditions, and design traffic. Design traffic is referred to within the context of the traffic categories listed in Chapter 3. Traffic distributions that include a significant proportion of axle loads greater than 80 kN (18 kip) single-axle loads and 150 kN (34 kip) tandem-axle loads may require special consideration with respect to overloaded pavement conditions.

Like highway pavements, city streets and local roads have higher deflections and stresses from loads applied near the edges than from loads imposed at the interior of the slab. Lower-traffic-volume pavements are usually not subjected to the load stresses or the pumping action associated with heavily loaded pavements.

In most city street applications, concrete pavements have the advantage of curbs and gutters tied to the pavement edge or placed integrally with the pavements. Curb sections act to carry part of the load, thereby reducing the critical stresses and deflections that often occur at the edges of the slab. Widened lanes can also be used to reduce edge stresses in a similar manner. Dowel bars on the transverse joints are typically not required for low-volume road applications except, in some cases, at transverse construction joints; however, they may be considered in high truck-traffic situations where pavement design thicknesses of 200 mm (8 in.) or greater are required.

Roadway right-of-way should accommodate more than just the pavement section, especially in urban areas. The presence of utilities, sewers, manholes, drainage inlets, traffic islands, and lighting standards need to be considered in the general design of the roadway. Provisions for these appurtenances should be considered in the design of the jointing system and layout. Proper backfilling techniques over buried utilities also need to be followed to provide uniform and adequate support to the pavement.[1]

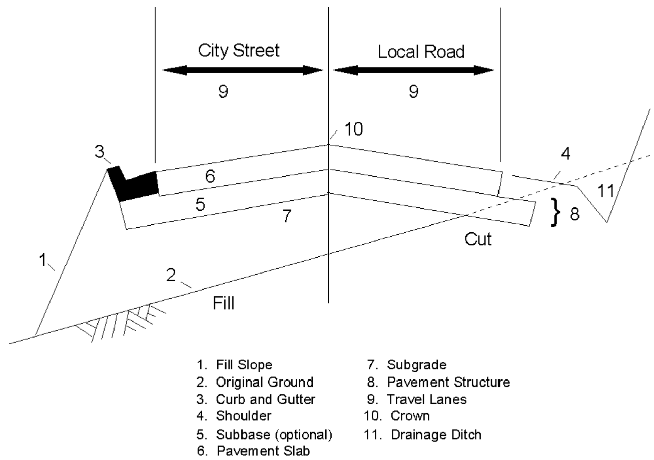


Fig. 1.1—Typical section for rigid pavement structure.

Intersections are a distinguishing feature contributing to the major difference between highways and local pavements. Intersection geometries need to be considered in the design of the jointing system and layout. Slabs at intersections may develop more than a single critical fatigue location due to traffic moving across the slab in more than one direction.

1.4—Definitions

The following terms are used throughout this document. A typical cross section in Fig. 1.1 is provided to facilitate the design terminology.

Average daily truck traffic—self-explanatory; traffic, in two directions.

Aggregate interlock—portions of aggregate particles from one side of a concrete joint or crack protruding into recesses in the other side so as to transfer shear loads and maintain alignment.

California bearing ratio (CBR)—the ratio of the force per unit area required to penetrate a soil mass with a 1900 mm^2 (3 in.^{2}) circular piston at the rate of 1.27 mm (0.05 in.) per min to the force required for corresponding penetration of a standard crushed-rock base material; the ratio is typically determined at 2.5 mm (0.1 in.) penetration.

Concrete pavement—this term is used synonymously with "rigid pavement."

Crack—a permanent fissure or line of separation within a concrete pavement formed where the tensile stress in the concrete has equaled or exceeded the tensile strength of the concrete.

Deformed bar—a reinforcing bar with a manufactured pattern of surface ridges that provide a locking anchorage with the surrounding concrete.

Dowel—(1) a steel pin, commonly a plain round steel bar, that extends into two adjoining portions of a concrete construction, as at a joint in a pavement slab, so as to transfer shear loads; and (2) a deformed reinforcing bar intended to transmit tension, compression, or shear through a construction joint.

Drainage—the interception and removal of water from, on, or under an area or roadway.

Equivalent single-axle loads (ESAL)—number of equivalent 80 kN (18 kip) single-axle loads used to combine mixed traffic into a single design traffic parameter for thickness design according to the methodology described in the AASHTO design guide.[2]

Expansive soils—swelling soil.

Faulting—differential vertical displacement of rigid slabs at a joint or crack due to erosion or similar action of the materials at the slab/subbase or subgrade interface due to pumping action under load.

Frost heave—the surface distortion caused by volume expansion within the soil (or pavement structure) when water freezes and ice lenses form within the zone of freezing.

Frost-susceptible soil—material in which significant detrimental ice aggregation occurs because of capillary action that allows the movement of moisture into the freezing zone when requisite moisture and freezing conditions are present.

Joint—a designed vertical plane of separation or weakness in a concrete pavement; intended to aid concrete placement, control crack location and formation, or to accommodate length changes of the concrete.

Construction joint—the surface where two successive placements of concrete meet, across which it is desirable to develop and maintain bond between the two concrete placements, and through which any reinforcement that may be present is not interrupted.

Contraction joint—a groove formed, sawed, or tooled in a concrete pavement to create a weakened plane and regulate or control the location of cracking in a concrete pavement; sometimes referred to as control joint.

Isolation joint—a joint designated to separate or isolate the movement of a concrete slab from another slab, foundation, footing, or similar structure adjacent to the slab.

Load transfer device—a mechanical means designed to transfer wheel loads across a joint, normally consisting of concrete aggregate interlock, dowels, or dowel-type devices.

Moisture density—the relationship between the compacted density of a subgrade soil to its moisture content. Moisture content is often determined as a function of the maximum density.

Modulus of rupture—in accordance with ASTM C 78, a measure of the tensile strength of a plain concrete beam in flexure and sometimes referred to as rupture modulus, rupture strength, or flexural strength.

Modulus of subgrade reaction (*k*)—also known as the coefficient of subgrade reaction or the subgrade modulus; is the ratio of the load per unit area of horizontal surface of a mass of soil to corresponding settlement of the surface and is determined as the slope of the secant, drawn between the point corresponding to zero settlement and the point of 1.27 mm (0.05 in.) settlement, of a load-settlement curve obtained from a plate load test on a soil using a 760 mm (30 in.) or greater diameter loading plate.

Pavement structure—a combination of subbase, rigid slab, and other layers designed to work together to provide uniform, lasting support for imposed traffic loads and the distribution of the loads to the subgrade.

Pavement type—a portland cement concrete pavement having a distinguishing structural characteristic usually associated with slab stiffness, dimensions, or jointing schemes. The major classifications for streets and local roads are:

1. Jointed, plain concrete pavement—a pavement constructed without distributed steel reinforcement, with or without dowel bars, where the transverse joints are closely spaced (usually less than 6 m [20 ft] for doweled pavements and 4.5 m [15 ft] or less for undoweled pavements).

2. Jointed, reinforced concrete pavements—a pavement constructed with distributed steel reinforcement (used to hold any intermediate cracks tightly closed) and typically having doweled joints where the transverse joints can be spaced as great as 13 to 19 m (40 to 60 ft) intervals.

Plasticity index (PI)—the range in the water content through which a soil remains plastic, and is the numerical difference between liquid limit and plastic limit, according to ASTM D 4318.

Pumping—the forced ejection of water, or water and suspended subgrade materials such as clay or silt, along transverse or longitudinal joints and cracks and along pavement edges. Pumping is caused by downward slab movement activated by the transient passage of loads over the pavement joints where free water accumulated in the base course, subgrade, or subbase, and immediately under the pavement.

Reinforcement—bars, wires, strands, and other slender members that are embedded in concrete in such a manner that the reinforcement and the concrete act together in resisting forces.

Resistance value (*R*)—the stability of soils determined in accordance with ASTM D 2844. This represents the shearing resistance to plastic deformation of a saturated soil at a given density.

Rigid pavement—pavement that will provide high bending stiffness and distribute loads to the foundation over a comparatively large area. Portland cement concrete pavements (plain jointed, jointed reinforced, continuously reinforced) fall in this category.

Shoulder—the portion of the roadway contiguous and parallel with the traveled way provided to accommodate stopped or errant vehicles for maintenance or emergency use, or to give lateral support to the subbase and some edge support to the pavement, and to aid surface drainage and moisture control of the underlying material.

Slab—a flat, horizontal or nearly so, molded layer of plain or reinforced concrete, usually of uniform, but sometimes variable, thickness supported on the ground.

Slab length—the distance between the transverse joints that bound a slab; joint spacing.

Spalling—a type of distress in concrete pavements that occurs along joints and cracks. It is associated with a number of failure modes, but is manifested by dislodged pieces of concrete in the surface along a joint or crack, typically within the limits of the wheelpath area.

Soil support (S) or (SSV)—an index number found in the basic design equation developed from the results of the AASHTO road test that expresses the relative ability of a soil or aggregate mixture to support traffic loads through a pavement structure.

Stabilization—the modification of soil or aggregate layers by incorporating stabilizing materials that will increase load-bearing capacity, stiffness, and resistance to weathering or displacement, and decrease swell potential.

Standard density—maximum dry density of a soil at optimum moisture content after compacting, according to ASTM D 698 or AASHTO T-99.

Subbase—a layer in a pavement system between the subgrade and base course, or between the subgrade and a portland cement concrete pavement.

Subgrade—the soil prepared and compacted to support a structure or a pavement system.

Swelling soil—a soil material (referred to as an expansive soil) subject to volume changes, particularly clays, that exhibit expansion with increasing moisture content, and shrinkage with decreasing moisture content.

Thornthwaite Moisture Index—the net weighted difference, over the course of a year, in the amount of moisture available for runoff and the amount of the moisture available for evaporation (less the amount stored by the soil) relative to the potential evapotranspiration.

Tie bar—a bar at right angles to, and tied to, reinforcement to keep it in place; a bar extending across a construction joint.

Warping (or curling)—a deviation of a slab or wall surface from its original shape, usually caused by temperature, moisture differentials, or both, within the slab or wall.

Welded wire fabric—a series of longitudinal and transverse wires arranged substantially at right angles to each other and welded together at all points of intersection.

Widened lane—a widening of the outer lane by positioning the shoulder lane stripe 0.3 to 0.6 m (1 to 2 ft) from the edge of the slab, creating an "interior load" condition and reducing the wheel load stresses in the slab from those created by an "edge load" condition.

Zip strip—a t-shaped form to support and position a removable plastic insert strip placed in the surface of a fresh concrete pavement surface to induce cracking along the edge of the plastic insert while the concrete is hardening.

CHAPTER 2—PAVEMENT MATERIAL REQUIREMENTS

2.1—Support conditions

Adequate subgrades are essential to good concrete pavement performance. Because of its rigidity, concrete pavement has a high degree of load-spreading capacity. The pressure below the pavement slab is low and spread over a relatively large area. Therefore, uniformity of support, rather than high subgrade strength, is a key factor in concrete pavement performance. Sufficient strength for anticipated construction traffic loads should be a consideration during the construction stages, particularly under poor drainage conditions.

Foundation-related factors that can contribute to pavement distress are:

- Nonuniformity of support caused by differences in subgrade soil strength or moisture;
- Nonuniform frost heave;
- Excessive swelling of expansive subgrade materials;
- Nonuniform compaction; or
- Poor drainage properties of the subbase or subgrade, which can enhance the potential for erosion under the action of slab pumping and lead to loss of support, and ultimately, faulting at the joints.

The effect of these factors can be minimized or eliminated through adequate design and construction of the subgrade soils by the use of positive drainage control and moisture control during compaction, as discussed in Section 2.1.1.[3,4]

Edge and corner support generally refers to the degree of load transfer provided along the longitudinal edge and corner of the pavement. Different types of edge or corner support will provide varying degrees of structural benefits. Several studies have shown that the critical fatigue point for jointed concrete pavement (JCP) is along the outer edge. The presence of adequate load transfer on the shoulder edge joint, a widened driving lane, a thickened edge, or a tied curb and gutter, will reduce edge stresses (Appendix A). In some climates, undoweled pavements on stiff, stabilized bases can develop cracks in the vicinity of the slab corners.[5,6] This type of cracking may also be important in thin slabs. Traffic loads applied at the corner yield the maximum deflections in the slab. Doweled joints may reduce slab deflections nearly 50%.[7-11]

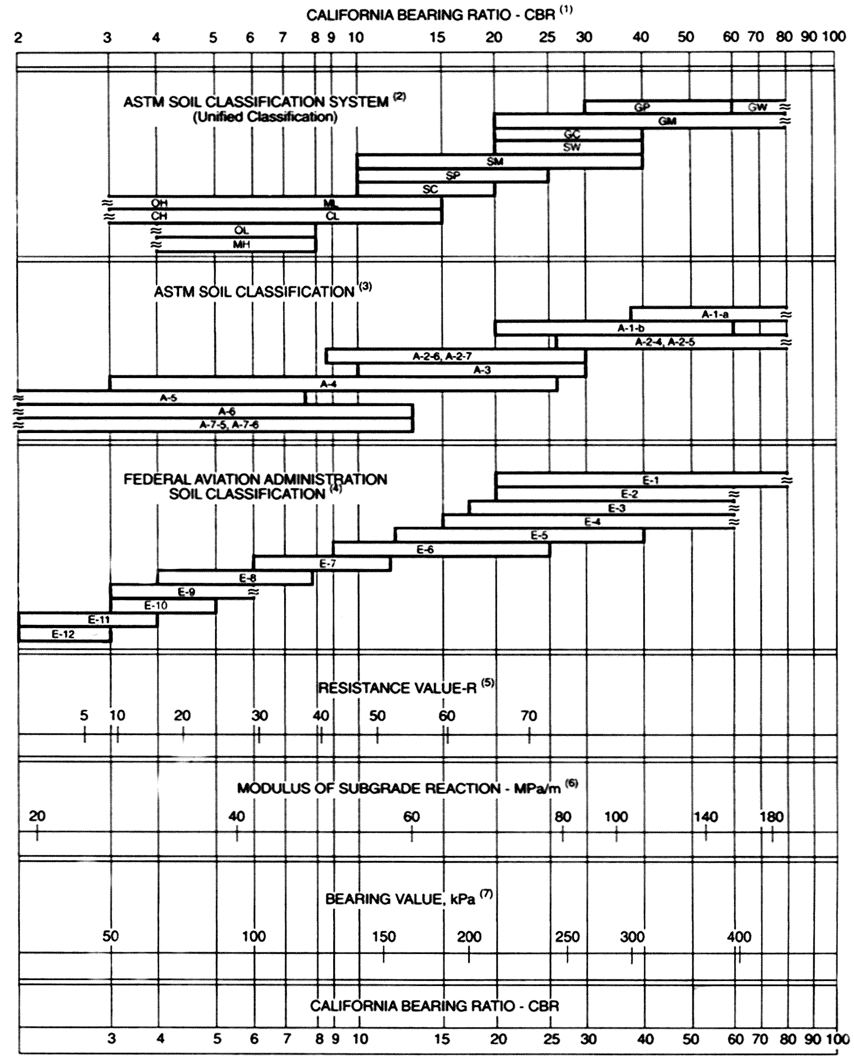
2.1.1 *Subgrade support*—The subgrade is the underlying surface of soil on which the roadway will be constructed. The subgrade should be examined along the proposed roadway location. The soil should be classified according to one of the standardized systems and its properties, such as liquid and plastic limits, moisture-density relationships, and expansion characteristics along with in-place moisture content and density, should be determined by standard tests. Either the modulus of subgrade reaction *k*, California Bearing Ratio (CBR), resistance value *R*, or soil support value (SSV) should be determined. When local requirements or the project scope does not warrant such extensive soil investigations, other possible sources of information regarding the nature of the subgrade include U.S. Department of Agriculture (USDA) soil survey reports and soils investigations from adjacent facilities.

Where subgrade conditions are not reasonably uniform, corrections are most economically and effectively achieved by proper subgrade preparation techniques such as selective grading, compaction, cross-hauling, and moisture-density control of the subgrade compaction. Obvious trouble spots, such as pockets of organic materials and large boulders, should be removed.[4] Areas where culverts or underground pipes exist deserve special attention as inadequate compaction of the backfill materials will cause pavement settlement.

For a subgrade to provide reasonably uniform support, the four major causes of nonuniformity should be controlled:

1. Variable soil conditions and densities;
2. Expansive soils;
3. Differential frost heave (and subsequent thawing); and
4. Pumping.

More detailed information on special subgrade problems can be found in Appendix B. Experience indicates that uniform support conditions are an important characteristic of well-performing low-volume roads.



(1) For the basic idea, see O. J. Porter, "Foundations for Flexible Pavements," Highway Research Board *Proceedings of the Twenty-second Annual Meeting*, 1942, Vol. 22, pages 100-136.
(2) ASTM Designation D 2487.
(3) "Classification of Highway Subgrade Materials," Highway Research Board *Proceedings of the Twenty-fifth Annual Meeting*, 1945, Vol. 25, pages 376-392.
(4) *Airport Paving*, U.S. Department of Commerce, Federal Aviation Agency, May 1948, pages 11-16. Estimated using values given in FAA *Design Manual for Airport Pavements.* (Formerly used FAA classification; United Classification now used.)
(5) C. E. Warnes, "Correlation between *R* Value and *k* Value," unpublished report, Portland Cement Association, Rocky Mountain-Northwest Region, October 1971 (best-fit correlation with correction for saturation).
(6) See T. A. Middlebrooks and G. E. Bertram, "Soil Test for Design of Runway Pavements," Highway Research Board *Proceedings of the Twenty-second Annual Meeting*, 1942, Vol. 22, page 152.
(7) See Item (6), page 184.

Fig. 2.1—Approximate interrelationships of soil classifications and bearing values.[12,13]

To give consideration to all factors that can affect the performance of the pavement, a careful study of the service history of existing pavements on similar subgrades in the locality of the proposed site should be made. Conditions that may cause the subgrade or subbase to become wetter over time, such as rising groundwater, surface water infiltration, high soil capillarity, low topography, rainfall, thawing after a freeze cycle, and poor drainage conditions also can affect the future support rendered by the subgrade. Climatic conditions such as high rainfall, large daily and annual temperature fluctuations, and freezing conditions can also adversely affect pavement performance. Soil properties may vary on a seasonal basis due to variations in the moisture levels.

The supporting strength of the foundation on which a concrete slab is to be placed is directly measurable in the field. The most applicable test for rigid pavements is the plate bearing test as described in ASTM D 1196 or AASHTO T-222. The procedure consists of incrementally loading a stiff 760 mm (30 in.) diameter plate while measuring the deflection of the plate. The results of the test are expressed as Westergaard's modulus of subgrade reaction (*k*-value), which is the pressure on the plate divided by its deflection, expressed in units of MPa/m (psi). The test is usually conducted until the plate deflection is 2.54 mm (0.1 in.) or a maximum plate pressure of 68.9 KPa (10 psi) is attained. It is recognized, however, that this test is seldom performed. Back-calculating *k*-values using falling weight deflectometer (FWD) data on existing pavements is typically a much more cost-effective approach to get an estimate of the *k*-value for various local soil types and conditions. The *k*-value also can be estimated from resilient modulus testing of laboratory soil samples, the use of the dynamic cone penetrometer (relative to the pavement thickness), or from other sound engineering basis, such as that shown in Fig. 2.1.[12,13] Some municipal agencies rely on experience and on approximate *k*-values for design purposes that can be obtained from Fig. 2.1 for various soil classifications systems or soil strength test results, that is, CBR. In using the material classification systems in Fig. 2.1 and the results from the laboratory tests, the designer should recognize that depth of soil, moisture content, and field density affect the *k*-value to be used in the field. The subgrade *k*-value will also vary with weather conditions throughout the year. Experience has indicated that thickness design is relatively insensitive to changes in *k*.

2.1.2 *Subbase properties*—A subbase is a layer of select material placed under a concrete slab primarily for bearing uniformity, pumping control, and erosion resistance. The select material may be unbound or stabilized. It is more important, however, that the subbase or subgrade be well-drained to prevent excess pore pressure (to resist pumping-induced erosion) than to achieve a greater stiffness in the overall pavement. With respect to pavement support, several design alternatives may be considered, which include unbound bases, widened outside lanes, thickened edges, or, in some cases, doweled joints, that is, a doweled or thickened edge on a gravel base versus an undoweled pavement on a stabilized base. The use of dowel bars or stabilized bases is typically not recommended for low-volume design applications. Design options such as unbound bases, thickened edges, widened outside lanes, or tied curb and gutters can be very cost effective.

Experience suggests that for pavements that fall into the light residential and residential classifications (see Chapter 3), the use of a subbase to increase structural capacity may or may not be cost effective in terms of long-term performance of the pavement.[14,15] For streets and local roads, the primary purpose of a subbase is to prevent mud-pumping if conditions for mud-pumping exist. (Appendix B contains information on mud-pumping.) Well-drained pavement segments that carry less than 200 ADTT (80 kN [18 kip] single-axle or 150 kN [34 kip] tandem-axle weights) are not expected to experience mud-pumping. With adequate subgrade preparation and appropriate considerations for surface and subgrade drainage, concrete pavements designed for city streets with surface drainage systems may be built directly on subgrades because moisture conditions are such that strong slab support may not be needed. Conditions warranting the use of a subbase constitute special design considerations discussed as follows. If included in the design, however, the percentage passing the 75 μm (No. 200) sieve size in granular subbase materials should be less than 8% by weight.

If used under a rigid pavement, a subbase may serve the purpose of:

- Providing a more uniform bearing surface for the pavement;
- Replacing soft, highly compressible or expansive soils;
- Providing protection for the subgrade against detrimental frost action;[16]
- Providing drainage; and
- Providing a suitable surface for the operation of construction equipment during adverse weather conditions.

When used, a minimum subbase thickness of 100 mm (4 in.) is recommended over poorly drained subgrades, unless stated otherwise in Table 2.1. For arterials or industrial pavements subjected to adverse moisture conditions (poor drainage), SM and SC soils (Table B.1) also may require subbases to prevent subgrade erosion due to pumping. The designer is cautioned against the use of fine-grained materials for subbases because this may create a pumping condition in wet climates where traffic levels are greater than 200 ADTT. Positive surface drainage measures such as 2 to 2.5% transverse surface slopes and adequate drainage ditches should be provided to minimize the infiltration of water to the subgrade, possibly trapping water directly beneath the pavement and saturating the underlying layers—a potentially erosive condition. Relative to surface drainage, many problems with support and durability of pavements can be averted by effectively draining surface water away from the pavement so that it does not pond on the surface or enter at the edges and joints. In particular, if an open-graded aggregate is used for the subbase, the lowest pavement section where the water will be exiting the system should be well drained. The necessity for adequate surface drainage cannot be over emphasized.

Table 2.1—Minimum recommended subbase thicknesses (mm) for poorly drained soils*

AASHTO climatic classification	CBR† classification		
	Low	Medium	High
Wet-freeze	100	100‡	100‡
Wet	100	100‡	None
Dry-freeze	None	None	None
Dry	None	None	None

*>200 ADTT, two-way, 1 in. = 25.4 mm, 1 psi/in. = 0.27 MPa/m.

†Low CBR: < 4 (*k* < 20 MPa/m); medium CBR: 4 to 15 (*k*: 20 to 63 MPa/m); high CBR: > 15 (*k* > 63 MPa/m).

‡Minimum subbase thickness of 100 mm may be eliminated from the design if the subgrade soils met the AASHTO Soil Drainage classification of fair to excellent.

Subbase thickness requirements are suggested in Table 2.1 as a practical means of securing the minimum thickness needed to minimize faulting of joints. As previously noted, a subbase serves many important purposes and in some cases may be used to provide a stable surface for construction expediency. This may be applicable in wet-freeze climates where the use of a stabilized subbase is recommended, because water can easily collect under a slab due to freezing-and-thawing action.

Low-strength subgrades can be stabilized to upgrade the CBR rating listed in Table 2.1 as a matter of economic consideration. A contractor may find it advantageous to use a subbase or a stabilized subgrade to provide a more stable working platform during construction. Although subbases are not generally used for local streets and roads, they can be effective in controlling erosion of the subgrade materials where traffic conditions warrant such measures.[16]

Typical values of *k* for various soil types and moisture conditions are given in Appendix B, but they should be considered as a guide only, and their use instead of the field-bearing test is left to the discretion of the engineer. In instances where granular subbase materials are used, there may be a moderate increase in *k*-value that can be incorporated in the thickness design. The suggested increase in *k*-value for design

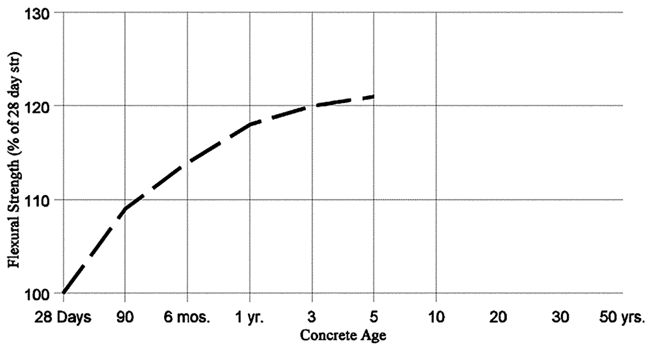


Fig 2.2—Flexural strength gain versus age.[12]

Table 2.2—Design *k*-values for granular subbases (1 psi/in. = 0.27 MPa/m)

Subgrade *k* value, MPa/m	Subbase thickness, mm	
	100	150
13.5	16.0	19.0
27	30.0	32.5
54	60.0	62.5
81.5	87.0	89.5

purposes is shown in Table 2.2. Usually, it is not economical to use a granular subbase for the sole purpose of increasing *k*-values or reducing the concrete pavement thickness.

2.2—Properties of concrete paving mixtures

Concrete mixtures for paving should be proportioned in accordance with ACI 211.1. They also should be designed to produce the desired flexural strength; to provide adequate durability and skid resistance; and to supply a workable mixture that can be efficiently placed, finished, and textured with the equipment the contractor will use. Paving mixtures should use a nominal maximum size aggregate of 38 mm (1.5 in.), where practical, to minimize the mixture water demand and reduce drying shrinkage. Mixtures with excessive fine aggregates should be avoided as these tend to increase the potential for uncontrolled shrinkage cracking. Properties of paving mixtures should be confirmed by laboratory trial mixtures.

2.2.1 *Strength*—While loads applied to concrete pavement produce both compressive and flexural stresses in the slab, the flexural stresses are more important because loads can induce flexural stresses that may exceed the flexural strength of the slab. Because concrete strength is much lower in tension than in compression, the modulus of rupture (MOR) (ASTM C 78, third-point loading) is often used in concrete pavement thickness design. It is calculated tensile stress in the extreme fiber of a plain concrete beam specimen loaded in flexure that produces rupture according to ASTM C 78. The results from this procedure are used to represent the flexural strength of a concrete slab.

Because concrete strength is a function of the type and amount of cementitious material (portland cement plus pozzolanic material) and the water-cementitious materials ratio (*w/cm*) selected for the mixture, water-reducing admixtures also can be used to increase strength while maintaining sufficient workability of the fresh mixture. Detailed information on portland cements and pozzolanic materials can be found in ACI 225R, 232.1R, 233R, and 234R. Aggregates should be clean to ensure good aggregate-to-paste bond and should conform to the quality requirements of ASTM C 33. Cubical-shaped coarse aggregates have been shown to have a beneficial effect on workability[17] that indirectly affects the flexural strength of the slab. Mixtures designed for high early strength can be provided if the pavement should be used by construction equipment or opened to traffic earlier than normal (that is, 24 h to 30 days versus 28 days).[18,19] Regardless of when the pavement is opened to traffic, the concrete strength should be checked to verify that the design strength has been achieved.

The design methods presented herein are based on the results of the third-point loading flexural test. Because the required thickness for pavement changes approximately 13 mm (0.5 in.) for a 0.5 MPa (70 psi) change in MOR, knowledge of the flexural strength is essential for economic design. The relationship between third-point loading and center-point loading values for MOR is:[20,21]

$$MOR_{1/3\ pt.} = 0.9\ MOR_{center-pt.} \qquad (2\text{-}1)$$

MOR values for 28- or 90-day strengths are normally used for design. The use of the 90-day strength can be justified because of the limited loadings that pavements receive before this early age and may be considered to be the long-term design strength. If the facility is not opened to traffic for a long period, later strengths may be used, but the designer should be aware of earlier environmental and construction loadings that may cause pavement stresses that equal or exceed the early strength of the concrete. For most streets and highways, the use of the 28-day strength is quite conservative, and the 90-day strength may be appropriate. Under average conditions, concrete that has an MOR of 3.8 to 4.8 MPa (550 to 700 psi) at 28 days is most economical. Figure 2.2 illustrates the average flexural strength gain with age as measured for several series of laboratory specimens, field-cured test beams, and sections of concrete taken from pavements in service. When other data are unavailable, the 90-day strength can be estimated based on a range of 100 to 120% the 28-day value, depending on the mixture. While design of concrete pavement is generally based on the tensile strength of the concrete, as represented by the flexural strength, it may be useful to use compressive-strength testing in the field for quality-control acceptance purposes and in the laboratory for mixture design purposes.

Although a useful correlation between compressive strength and flexural strength is not readily established, an approximate relationship between compressive strength (f_c') and flexural strength (MOR) is given to facilitate these purposes by the formula

$$MOR = a_1 \gamma_{conc}^{\ 0.5} f_c'^{\ 0.5} \text{ (ACI Committee 209)} \qquad (2\text{-}2)$$

where γ_{conc} is the concrete unit weight, and a_1 varies between 0.012 and 0.20 for units of MPa (0.6 to 1.0 for units of psi). If desired, however, a specific flexural-to-compressive

Table 2.3—Recommended percentage air content for air-entrained concrete (ASTM C 94)*

Nominal maximum size aggregate, mm	Typical air contents of non-air-entrained concretes	Recommended average air content for air-entrained concretes, %		
		Mild exposure	Moderate exposure	Severe exposure
9.5	3.0	4.5	6.0	7.5
12.7	2.5	4.0	5.5	7.0
19.0	2.0	3.5	5.0	6.0
25.4	1.5	3.0	4.5	6.0
38.1	1.0	2.5	4.5	5.5

*Tolerances: for average air content of 6% or greater, ±2%; for average air content less than 6%, ±1-1/2%.

Exposure conditions:
Mild exposure—Concrete not subject to freezing and thawing, or to deicing agents. Air may be used to impart some benefit other than durability, such as improved workability or cohesion.
Moderate exposure—Outdoor exposure in a cold climate where the concrete will be only occasionally saturated with water before freezing, and where deicing salts will not be used.
Severe exposure—Outdoor exposure in a cold climate where the concrete may be exposed to wet freezing-and-thawing conditions, or where deicing salts may be used.

strength correlation can be developed for specific mixtures. The strength of the concrete should not be exceeded by environmentally induced stresses (curling and warping), which may be critical during the first 72 h after placement.[19]

2.2.2 *Durability*—In frost-affected areas, concrete pavements should be designed to resist the many cycles of freezing and thawing and the action of deicing salts.[22] In these cases, it is essential that the mixture have a low *w/cm*, adequate cement, sufficient quantities of entrained air, plus adequate curing and a period of drying. The amounts of air entrainment needed for concrete resistant to freezing and thawing vary with the maximum-size aggregate and the exposure condition. Recommended percentages of entrained air are given in Table 2.3 and ACI 211.1.

In addition to making the hardened concrete pavement resistant to freezing and thawing, recommended amounts of entrained air improve the concrete while it is still in the plastic state by:

- Reducing segregation;
- Increasing workability without adding additional water; and
- Reducing bleeding.

Because of these beneficial and essential effects in both fresh and hardened concrete, entrained air should be incorporated into the mixture proportioning for all concrete pavements. Detailed information on the use of chemical admixtures in concrete can be found in ACI 212.3R.

The amount of mixing water also has a critical influence on the durability, strength, and resistance to freezing and thawing of hardened concrete. The least amount of mixing water with a given cementitious material content to produce a workable mixture will result in the greatest durability and strength in the hardened concrete. A low water content can be achieved by using the largest practical nominal maximum-size coarse aggregate, preferably 38 mm (1.5 in.). In addition, the coarse aggregate should be free of clayey coatings and as clean as possible. Experience also has shown the use of a minimum amount of mixture water, (*w/cm* ranging from 0.40 to 0.55, depending on materials and method of paving) no greater than that needed to meet the specified strength and workability criteria provides satisfactory results.

It is poor practice to indiscriminately add water at the job site because it can impair the durability characteristics of the concrete. Addition of water at the job site should not be prohibited, however. If ready-mixed concrete arrives at the job site at a less-than-specified slump, only the additional water needed to bring the slump within the required limits, as provided for in ASTM C 94, should be injected into the mixer to ensure that the design *w/cm* is not exceeded. Before discharging, the concrete should then be given the proper amount of additional mixing at a mixing speed as stipulated in ASTM C 94.

Aggregate selected for paving should be resistant to freezing-and-thawing deterioration (or D-cracking) and alkali-silica reaction (ASR). Coarse aggregate that meets state highway department requirements for concrete paving should provide acceptable service in most cases. Fly ash, particularly Class F, should serve as an effective mineral admixture to help prevent deterioration of concrete due to ASR.[23] Aggregate sources should be checked for durability with respect to past performance and freezing-and-thawing resistance.

High concentrations of soil sulfates also can cause deterioration and premature failure of concrete pavements. Where soils that may be in contact with the concrete pavement contain sulfates, the recommendations of ACI 201.2R should be followed.

2.2.3 *Workability*—Workability is an important consideration in selecting concrete for paving projects. Slump for slipform paving is usually between 15 and 40 mm (0.5 and 1.5 in.). Concrete to be placed by hand or with a vibratory or roller screed should have a higher slump, no greater than 100 mm (4 in.). Water content, aggregate gradation, and air content are all factors that affect workability. Recent developments in the research of aggregate gradations have led to improvements in workability-related properties of concrete mixtures.[24]

2.2.4 *Economy*—Economy is an important consideration in selecting the concrete to be used for paving. Well-graded aggregates, minimum cement content consistent with strength and durability requirements, and use of both mineral and liquid admixtures are all factors that should be considered in proportioning economical concrete. Mixtures proportioned with locally available materials are usually the most economical mixtures.

2.2.5 *Distributed and joint reinforcement*—Concrete pavements are usually classified as plain or reinforced, depending on whether the concrete contains distributed steel reinforcement. Plain pavements also may be divided into those with or without load transfer devices at the joints. Most low-volume pavement designs do not require dowels. The thickness design methods are the same for plain or reinforced pavements because the presence or lack of distributed reinforcement has no significant effect on the load-carrying capacity or thickness.

The use of reinforcement is only recommended for low-volume applications on a limited basis. These limited cases occur when irregular panel shapes are used or when joint spacings are in excess of those that will effectively control shrinkage cracking. Although reinforcing steel cannot be used to address cracking caused by nonuniform support conditions, distributed reinforcement steel may be included to control the opening of unavoidable cracks. The sole function of the steel is to hold together the fracture faces if cracks should form. The quantity of steel varies depending on joint spacing, slab thickness, coefficient of subgrade resistance, bar size, and the tensile strength of the steel. Refer to Chapter 4 for further details of pavement reinforcement design.

CHAPTER 3—PAVEMENT THICKNESS DESIGN

3.1—Basis of design

The most cost-effective pavement design is that which has been validated by road tests, pavement studies, and surveys of pavement performance. The most commonly used methods are the AASHTO design guide,[2] which was developed from performance data obtained at the AASHTO road test; and the Portland Cement Association's (PCA) design procedure,[12,13] which is based on the pavement's resistance to fatigue and deflection effects on the subgrade. The PCA procedure is recommended for use in instances of overload conditions that can yield design thicknesses beyond those provided in this chapter. Further explanations of design concepts suggested in the PCA design procedure can be found in Appendix A. A design catalog published by the National Cooperative Highway Research Program (NCHRP) may also provide useful design information.[25]

These thickness design methods can be used for plain or reinforced pavements because the presence or lack of distributed reinforcement has no significant effect on loaded slab behavior as it pertains to thickness design. If it is desired to use steel reinforcement, which is usually not necessary, it may be designed in accordance with Section 4.6. The use of those procedures along with good joint practice (as outlined in Chapter 4) should result in a satisfactory design for low-volume applications.

3.2—Traffic

The determination of a design thickness requires some knowledge of the range and distribution of traffic loads expected to be applied to the pavement over the design period. Although accurate traffic predictions are difficult to achieve, the designer should obtain some information regarding the types of trucks that will use the pavement, the number of each truck type, truck loads, and the daily volume anticipated over the design life. Passenger cars and pickup trucks typically cause little or no distress on concrete pavements and can be excluded from the design traffic. Precautions should be taken to account for overload traffic conditions that may be more appropriately accounted for by the PCA pavement design procedures. It should also be determined if loads over the 80 to 90 kN (18 to 20 kips) legal limit are in the distribution of traffic loads, although these should be rare in low-volume facilities.

The heaviest axle loads control concrete pavement thickness design and resulting pavement performance. Documented traffic data may contain some inaccuracies because the number and the magnitude of the heaviest axle load groups may not have been recorded. A few very heavy axle loads can play a critical role in the cracking and faulting performance of thin concrete pavements. The design engineer should determine the number and types of trucks that can use the facility in the future, particularly in regard to garbage trucks, concrete trucks, construction vehicles, or other heavy traffic that may have load exemptions within a certain travel radius. See Reference 26 for further information. The design engineer also can derive the gross and axle weights of the trucks, which can be done by assuming the loaded axles conform to state legal load limits, such as 80 kN (18 kip) for single axle, and 150 kN (34 kip) for tandem axle. Overloaded vehicles should be more carefully determined. These can then be projected into the future by forecasting the growth curve of the facilities to be serviced by the new pavement. The forecast can be based on curves constructed to parallel the trends in area population, utility growth, driver or vehicle registration, or commercial developments. For the purposes of the AASHTO design procedure,[2] truck traffic loading should be determined by vehicle classification data and 80 kN (18 kip) equivalent single-axle load (ESAL) factors.

Items to consider when predicting traffic include:

- Traffic volumes (ADT and ADTT) are usually expressed as the sum of two-directional flow and should be divided by two to determine a design value;
- Traffic flow for two-lane roadways seldom exceeds 1500 vehicles per hour per lane, including passenger cars, and may be less than 1/2 this value in rolling terrain or where roadside interference exists; and
- Where traffic is carried in one direction in multiple lanes—75 to 95% of the trucks, depending on traffic, will travel in the lane abutting the right shoulder.

3.2.1 *Street classification and traffic*—Comprehensive traffic studies made within city boundaries can supply necessary data for the design of municipal pavements. A practical approach is to establish a street classification system. Streets of similar character may have similar traffic densities and axle-load intensities. The street classifications used in this guide are:

Light residential—These are short streets in subdivisions and may dead end with a turnaround. Light residential streets serve traffic to and from a few houses (20 to 30). Traffic volumes are low—less than 200 vehicles per day (vpd) with a two to four ADTT for two-axle, six-tire trucks and heavier traffic in two directions (excluding two-axle, four-tire trucks). Trucks using these streets will generally have a maximum tandem axle load of 150 kN (34 kips) and a 80 kN (18 kips) maximum single-axle load. Garbage trucks and buses most frequently constitute the overloads on those types of streets.

Residential—These streets carry the same type of traffic as light residential streets but serve more houses (up to 300), including those on dead-end streets. Traffic generally consists

Table 3.1—Street classification[27]

Street classification	VPD or ADT, two-way	Heavy commercial vehicles (two-axle, six-tire, and heavier)	
		%	No. per day
Light residential	200	1 to 2	2 to 4
Residential	200 to 1000	1 to 2	2 to 4
Collector	1000 to 8000	3 to 5	50 to 500
Minor arterial	4000 to 15,000	10	300 to 600
Major arterial	4000 to 30,000	15 to 20	700 to 1500
Business	11,000 to 17,000	4 to 7	400 to 700
Industrial	2000 to 4000	15 to 20	300 to 800

of vehicles serving the homes plus an occasional heavy truck. Traffic volumes range from 200 to 1000 vpd with an ADTT of 10 to 50. Maximum loads for these streets are 98 kN (22 kip) single axles and 150 kN (34 kip) tandem axles. Thicker pavement sections may be required on established bus routes in residential areas.

Collector—Collectors serve several subdivisions and may be several miles long. They may be bus routes and serve truck movements to and from an area even though they are not through routes. Traffic volumes vary from 1000 to 8000 vpd with approximately 50 to 500 ADTT. Trucks using these streets generally have a maximum single-axle load of 115 kN (26 kips) and a 200 kN (44 kip) maximum, tandem-axle load.

Business—Business streets carry movements through commercial areas from expressways, arterials, or both. They carry nearly as much traffic as arterials; however, the percentage of trucks and axle weights generally tends to be less. Business streets are frequently congested and speeds are slow due to high traffic volumes but with a low ADTT. Average traffic volumes vary from 11,000 to 17,000 vpd with approximately a 400 to 700 ADTT. Maximum loads are similar to collector streets.

Arterials—Arterials bring traffic to and from expressways and serve major movements of traffic within and through metropolitan areas not served by expressways. Truck and bus routes, and state- and federal-numbered routes are usually on arterials. For design purposes, arterials are divided into minor arterial and major arterial, depending on traffic capacity and type. A minor arterial may have fewer travel lanes and carry less volume of total traffic, but the percentage of heavy trucks may be greater than that on a six-lane major arterial. Minor arterials carry 4000 to 15,000 vpd with a 300 to 600 ADTT. Major arterials carry approximately 4000 to 30,000 vpd with a 700 to 1500 ADTT. Maximum loads for minor arterials are 115 kN (26 kip) single axles and 200 kN (44 kip) tandem axles. Major arterials have maximum loads of 130 kN (30 kip) single axles and 230 kN (52 kip) tandem axles.

Industrial—Industrial streets provide access to industrial areas or parks. Total traffic volume may be in the lower range but the percentage of heavy axle loads is high. Typical vpd are around 2000 to 4000 with 300 to 800 ADTT. Truck volumes are not much different than the business class; however, the maximum axle loads are heavier—133 kN (30 kip) single axles and 230 kN (52 kip) tandem axles.

The street classifications outlined herein may or may not correspond to the classifications used in any metropolitan area. They are given to indicate, generally, the volumes and axle weights of traffic using streets. They are summarized in Table 3.1. The values are reasonable but should be tempered with knowledge of local traffic patterns. It is not likely that the last three classifications will fit within the previously established low-volume road traffic limits (<100 ADTT).

Concrete pavements can be designed for a given level of traffic and any life desired; however, future changes in traffic patterns and axle loads are often difficult to predict. For arterials and industrial roads and streets, future traffic can be of considerable influence on design.

3.3—Thickness determination

Proper selection of the slab thickness is a crucial element of a concrete pavement design. Inadequate thickness will lead to cracking and premature loss of serviceability. Suggested thicknesses for the design of low-volume concrete roads are listed in Table 3.2(a) and 3.2(b) as a function of subgrade support and concrete flexural strength (third-point loading). The thicknesses listed for a *k* value of 81.5 MPa/m (300 psi/in.) are considered to be minimum thicknesses for design. Pavement designs provided in these tables are assumed to be applicable to a 30-year performance period as long as minimal durability-related distresses occur. Pavement life can also be assessed from the standpoint of fatigue accumulation based on calculations illustrated in Appendix A.

Small changes in concrete thickness or an increase in concrete strength can have a significant effect on pavement fatigue life. For this reason, tolerances on pavement thickness are important. This is especially true in thinner pavements where small reductions in thickness represent a significant percentage of the thickness. In these instances, concrete strength and variability in strength are important.

For overload traffic and cases related to variable support conditions that may require the use of dowel bars at the joints, thickness designs should be developed from Chapter 4 of the PCA design manual for concrete highways and streets. This procedure is based on erosion and fatigue analysis and may dictate the use of a stabilized base.

The PCA design procedure determines a critical stress and a critical erosion for a pavement slab, assuming that environmentally induced stresses are minimized through appropriate jointing practice. By using detailed axle-load-distribution data, a reasonable estimate of fatigue and erosion damage can be estimated. A greater amount of detail with respect to this design process is provided in Appendix A.

3.4—Economic factors

Proper design of a pavement system includes an analysis of costs over the entire life cycle of the pavement. Different designs invariably have different predicted performance lives and therefore should be related through present worth, annual costs, or other generally accepted methods of engineering economics. Items included in this portion of the design process include maintenance and rehabilitation costs expected over the design life, in addition to initial construction costs of the design. Other items that may be considered are user costs,

Table 3.2(a)—Pavement thickness, mm,[27] with integral or tied curb and gutter or shoulders (supported edges)

k = 13.5 MPa/m					*k* = 27 MPa/m						
MOR MPa					MOR MPa						
3.4	3.8	4.1	4.5	4.8	3.4	3.8	4.1	4.5	4.8	Traffic classification	
150	150	150	125	125	150	125	125	125	125	ADTT = 3	Light residential
175	175	150	150	150	175	150	150	125	125	ADTT = 10	Residential
175	175	150	150	150	175	150	150	125	125	ADTT = 20	Collector
175	175	150	150	150	175	150	150	150	125	ADTT = 50	
200	200	175	175	175	200	175	175	150	150		
225	200	200	175	175	200	175	175	175	150	ADTT = 100	Minor arterial
225	200	200	200	200[*]	200	200	175	175	175	ADTT = 500	
225	200	200	200	200[*]	200	200	175	175	175	ADTT = 100	
225	225	200	200[*]	200[†]	225	200	175	175	175[*]	ADTT = 500	Major arterial
250	225	225	200	200[*]	225	225	200	200	175	ADTT = 400	
250	250	225	225[*]	225[†]	225	225	200	200[*]	200[†]	ADTT = 800	Business
275	250[*]	250[†]	250[‡]	250[§]	250	225	225[*]	225[*]	225[*]	ADTT = 1500	
225	200	200	175	175	200	200	175	175	150	ADTT = 300	
225	225	200	200[*]	200[†]	200	200	175	175[*]	175[*]	ADTT = 700	Industrial
250	225	225	200	200[*]	225	225	200	200	175	ADTT = 400	
250	250	225	225[*]	225[†]	225	225	200	200[*]	200[†]	ADTT = 800	—

k = 54 MPa/m					*k* = 81.5 MPa/m						
MOR MPa					MOR MPa						
3.4	3.8	4.1	4.5	4.8	3.4	3.8	4.1	4.5	4.8	Traffic classification	
125	125	125	100	100	125	125	100	100	100	ADTT = 3	Light residential
150	125	125	125	125	150	125	125	125	100	ADTT = 10	Residential
150	150	125	125	125	150	125	125	125	100	ADTT = 20	Collector
150	150	125	125	125	150	125	125	125	125	ADTT = 50	
175	175	150	150	150	175	150	150	150	125		
175	175	150	150	150	175	150	150	150	125	ADTT = 100	Minor arterial
200	175	175	150	150	175	175	150	150	150[*]	ADTT = 500	
200	175	175	150	150	175	175	150	150	150[*]	ADTT = 100	
200	175	175	175	175[*]	175	175	175	175[*]	175[†]	ADTT = 500	Major arterial
200	200	175	175	175	200	175	175	175	175[*]	ADTT = 400	
225	200	200	175	175[*]	200	200	175	175[*]	175[†]	ADTT = 800	Business
225	200	200	200[*]	200[†]	200	200	200[*]	200[*]	200[†]	ADTT = 1500	
175	175	175	150	150	175	175	150	150	150	ADTT = 300	
200	175	175	175[*]	175[†]	175	175	150	150	150[*]	ADTT = 700	Industrial
200	200	175	175	175	200	175	175	175	175[*]	ADTT = 400	
225	200	200	175	175[*]	200	200	175	175[*]	175[†]	ADTT = 800	—

Note: 1 in. = 25.4 mm; and 1 psi/in. = 0.27 MPa/m.

[*]If doweled, thickness can be decreased by 13 mm.
[†]If doweled, thickness can be decreased by 25 mm.
[‡]If doweled, thickness can be decreased by 38 mm.
[§]If doweled, thickness can be decreased by 50 mm.

energy costs, or any other economic considerations associated with each design option.[2,28]

CHAPTER 4—PAVEMENT JOINTING

Joints are placed in concrete pavements to control cracking and facilitate construction. They divide the pavement into practical construction increments, delineate traffic lanes, and accommodate slab movements. The three types that are commonly used in concrete pavements are contraction joints, construction joints, and isolation (expansion) joints. The first two joint types are used both transversely and longitudinally. Contraction joints are intended to control cracking. Construction joints allow for interruption during placement or occur at planned joint locations such as longitudinal separations between adjacent lanes. Isolation joints are used to allow relative movement between adjacent structures or pavements.

Table 3.2(b)—Pavement thickness, mm,[29] without curb and gutters or shoulders (unsupported edges)

k = 13.5 MPa/m					*k* = 27 MPa/m						
MOR MPa					MOR MPa						
3.4	3.8	4.1	4.5	4.8	3.4	3.8	4.1	4.5	4.8	Traffic classification	
175	175	150	150	150	175	150	150	150	125	ADTT = 3	Light residential
200	200	175	175	150	175	175	175	150	150	ADTT = 10	Residential
200	200	200	175	175	200	175	175	150	150	ADTT = 20	Collector
200	200	200	175	175	200	175	175	175	150	ADTT = 50	
250	225	225	200	200	225	200	200	175	175	ADTT = 50	
250	225	225	200	200	225	200	200	200	175	ADTT = 100	Minor arterial
275	250	225	225	200	250	225	200	200	200	ADTT = 500	
275	250	225	225	200	250	225	200	200	200	ADTT = 100	
275	250	250	225[*]	225[*]	250	225	225	200	200[*]	ADTT = 500	Major arterial
300	275	250	250	225	275	250	225	225	200	ADTT = 400	
300	275	275	250[*]	250[†]	275	250	250	225	225[*]	ADTT = 800	Business
300	300	275[*]	275[†]	275[‡]	275	250	250	250[*]	250[†]	ADTT = 1500	
250	250	225	225	200	225	225	200	200	175	ADTT = 300	
275	250	225	225	225[*]	250	225	225	200	200	ADTT = 700	Industrial
300	275	250	250	225	275	250	225	225	200	ADTT = 400	
300	300	275	250[*]	250[†]	275	250	250	225	225[*]	ADTT = 800	—

k = 54 MPa/m					*k* = 81.5 MPa/m						
MOR MPa					MOR MPa						
3.4	3.8	4.1	4.5	4.8	3.4	3.8	4.1	4.5	4.8	Traffic classification	
150	150	125	125	125	150	125	125	125	125	ADTT = 3	Light residential
175	150	150	150	125	150	150	150	125	125	ADTT = 10	Residential
175	175	150	150	150	175	150	150	150	125	ADTT = 20	Collector
175	175	150	150	150	175	150	150	150	125	ADTT = 50	
200	200	175	175	150	200	175	175	150	150	ADTT = 50	
200	200	175	175	175	200	175	175	150	150	ADTT = 100	Minor arterial
225	200	200	175	175	200	200	175	175	175	ADTT = 500	
225	200	200	175	175	200	200	175	175	175	ADTT = 100	
225	200	200	200	200[*]	225	200	200	175	175[*]	ADTT = 500	Major arterial
250	225	225	200	200	225	225	200	200	175	ADTT = 400	
250	225	225	200	200[*]	225	225	200	200	200	ADTT = 800	Business
250	225	225	225[*]	225[*]	250	225	225	225[*]	225[†]	ADTT = 1500	
225	200	200	175	175	200	200	175	175	175	ADTT = 300	
225	200	200	175	175	200	200	175	175	175[*]	ADTT = 700	Industrial
250	225	225	200	200	225	225	200	200	175	ADTT = 400	
250	225	225	200	200[*]	225	225	200	200	200	ADTT = 800	—

Note: 1 in. = 25.4 mm; and 1 psi/in. = 0.27 MPa/m.

[*]If doweled, thickness can be decreased by 13 mm.
[†]If doweled, thickness can be decreased by 25 mm.
[‡]If doweled, thickness can be decreased by 38 mm.
[§]If doweled, thickness can be decreased by 50 mm.

To effectively control cracking due to tensile stresses created by restrained shrinkage and temperature and moisture differentials, it is important to have the joints properly spaced. Proper joint spacing depends on pavement thickness, concrete strength, aggregate type, climatic conditions, and whether distributed steel reinforcement is used. Reinforcing steel is intended to hold tightly closed intermediate shrinkage cracks that can occur between joints. Synthetic fibers may have some effect on shrinkage cracking,[17] but do not affect joint spacing, while weather conditions at the time of construction can significantly affect crack development.

Load transfer across transverse joints is another important element of design. Contraction joints without dowels provide load transfer through aggregate interlock across the joint. Closely spaced joints usually result in small openings at the joints that result in increased aggregate interlock between panels. Short joint spacings result in minimal openings that help keep incompressible materials from getting into the joint and causing pavement blow-ups. Spreading the joints farther apart results in wider openings and diminished aggregate interlock and load-transfer capacity. Proper jointing of concrete pavements is essential to ensure good performance. Improper

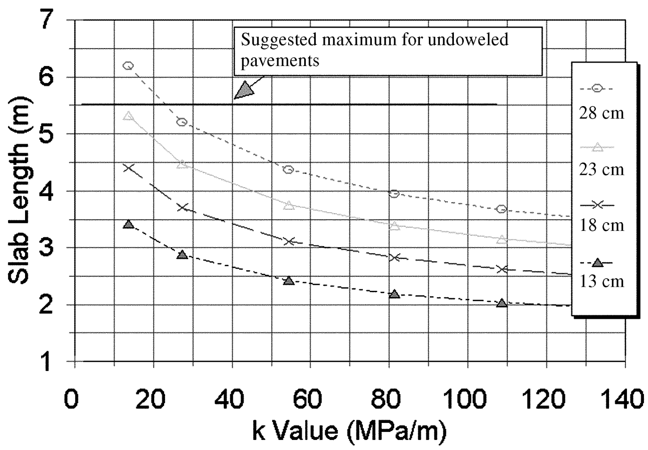


Fig. 4.1—Slab length-pavement thickness relationships.

jointing can lead to premature loss of serviceability, despite adequate thickness of the pavement.

Spacing of the initial drying shrinkage cracks varies from about 10 to 50 m (30 to 150 ft), depending on concrete properties, variations in subgrade friction, and climatic conditions during and after placement. Studies indicate that the spacing of cracks should naturally occur at intervals of 4 to 5 m (12 to 15 ft).[30] This distance is related to a characteristic term known as the ℓ-value, which is defined in Section 4.1 as a function of k value and slab thickness. The occurrence and interval of early cracks is important because this is the determining factor as to where joints should be located to control cracking. The anticipated crack-width opening should also be taken into consideration for proper joint sealing as well as for maintaining aggregate interlock.

In plain concrete pavements with joint spacing of 4 to 5 m (12 to 15 ft), cracks do not generally form beneath all joints for a few weeks to several months after the pavement is constructed. For joints spaced at 12 m (36 ft) or more, intermediate transverse cracks between joints may not develop for several months to several years after the pavements are opened to traffic. When intermediate cracks do occur, they are generally spaced at about 4 to 5 m (12 to 15 ft or approximately 4.4ℓ), and they are the result of the combined effect of restrained warping, curling, and load stresses.

In jointed pavements, the joint interval is either designed to provide for each expected crack at 3 to 5 m (12 to 15 ft) intervals (plain slab design) or spaced at greater intervals with adequate distributed steel in each panel (reinforced slab design) to provide good performance at the intermediate cracks. For reinforced slabs with their longer joint spacings, the joint openings are correspondingly larger, making load transfer by aggregate interlock less effective; therefore, dowel bars are needed. Some type of load transfer, either dowels or stabilized subbases, is required to minimize deflection at the joint and prevent faulting. For all undoweled slabs, the shrinkage of the concrete mixture should be minimized as much as possible through adequate curing. These options should be considered on the basis of the life-cycle benefit derived from them.

4.1—Slab length and related design factors

Studies have shown that pavement thickness, base stiffness, and climate affect the maximum anticipated joint spacing beyond which transverse cracking can be expected.[31] Research indicates that there is a general relationship between the ratio of slab length L to the radius of relative stiffness ℓ and transverse cracking. The radius of relative stiffness is a term defined by Westergaard to quantify the relationship between the stiffness of the foundation and the flexural stiffness of the slab. The radius of relative stiffness has a lineal dimension and is determined by the following equation:

$$\ell = [Eh^3/12k(1-\mu^2)]^{0.25} \tag{4-1}$$

where

ℓ = radius of relative stiffness, mm;
E = concrete modulus of elasticity, MPa;
h = pavement thickness, mm;
μ = Poisson's ratio of the pavement (≈ 0.15); and
k = modulus of subgrade reaction, MPa/m.

Experience indicates that there is an increase in transverse cracking when the ratio L/ℓ exceeds 4.44. Using the criterion of a maximum L/ℓ ratio of 4.44, the allowable joint spacing would increase with increased slab thickness but decrease with increased (stiffer) foundation support conditions. The relationship between slab length, slab thickness, and foundation support for a L/ℓ ratio of 4.44 is shown in Fig. 4.1. Methods are available to take the effect of the subbase into account in determination of the k-value.[7,32] Figure 4.1 is recommended in lieu of the general rule that slab length (in feet) should be about 2 to 2.5 times the slab thickness in inches (maximum 5 m [15 ft]).

4.1.1 *Load transfer*—Load transfer across a contraction joint is effectively developed by:

- Aggregate interlock (the interlocking action of aggregate particles at the faces of the joint);
- The stiffness of supporting layers, such as the addition of a stabilized subgrade or a subbase; or
- The addition of mechanical devices across the joint, such as dowel bars.

4.1.1.1 *Aggregate interlock*—The irregular faces of the cracks that form at the tip of the grooves or sawcut notches delineating joint locations play a key role in creating a shear mechanism in which to transfer load from one side of the crack to the other side. The degree of load transfer depends on the aggregate interlock provided by the interlocking faces. The degree of aggregate interlock depends on the width of cracks and the spacing between the joints. Joint spacing should be maintained at minimum intervals, but those suggested in Fig. 4.1 represent practical limits. To maintain minimal crack openings, expansion of isolation joints should be avoided except at fixed objects and in symmetrical intersections. Caution should be exercised when placing joints in the vicinity of isolation joints to ensure against wide openings.

Aggregate interlock alone will furnish enough load transfer to give good joint performance for roads and streets with lighter traffic. To ensure adequate load transfer and the least loss in effectiveness of these joints due to traffic loads, joint intervals should be kept in accordance with Fig. 4.1; foundation support should be reasonably uniform, and concrete aggregates should be sound and hard. In special cases where the ADTT is more than about 100, it may be necessary to improve load transfer with the use of stabilized subgrades, dowels, or thicker pavements[15] to reduce deflections and prevent faulting. Faulting is manifested as a small vertical displacement relative to the direction in which the traffic moves where the leading edge of the joint raises above the opposite or following edge of the joint.

4.1.1.2 *Doweled joints*—Dowels or other mechanical load transfer devices are not needed for most city streets and low-volume road conditions, particularly when transverse joint spacings are 5 m (15 ft) or less. They may be economically justified under soft subgrade support ($k \leq 20$ MPa/m) or heavy truck traffic conditions. Generally, pavements less than 200 mm (8 in.) thick are not doweled to provide load transfer due to lower design traffic levels.

Smooth dowels across contraction joints in pavements also may be used to increase the design joint spacing while providing sufficient load transfer. This practice should be used with caution, because more pronounced warping and curling effects and larger joint movements are associated with longer joint spacings. It is usually more economical to keep joint spacing close, using the benefit of aggregate interlock and thickening the pavement slightly if necessary to reduce deflections.

Dowels are beneficial and often used in pavements that will carry a significant number of heavy trucks. In general, one can relate the need for dowels to the required pavement thickness. If the design thickness is less than about 200 mm (8 in.), dowels are not needed. If the design thickness is 200 mm (8 in.) or greater, largely dictated by truck traffic, then dowels are often required to reduce slab pumping and faulting.

In such situations, dowels are used to supplement the load transfer produced by aggregate interlock and stabilized layers. They transfer shear loads across the joint and help to reduce deflections and stresses at the joint. The dowels should be plain, round bars equivalent to ASTM A 615, and corrosion protection should be provided. Corrosion protection can be provided by epoxy or plastic coating (in accordance with ASTM B 117) in areas where deicing salts are used. Other options for corrosion are available but may be cost-prohibitive. Before delivery to the job site, at least 1/2 of each bar should be covered with a suitable debonding agent to prevent dowel lock-up. Dowels should be able to move longitudinally in their slots to allow free joint movement from expansion or contraction of the concrete.

Dowel bars should be sized according to the pavement thickness. For pavements less than 250 mm (10 in.) thick, dowel bars should be 32 mm (1.25 in.) in diameter. For pavements 250 mm thick (10 in.) and greater, 38 mm (1.5 in.) dowels should be used. All dowels should be 460 mm (18 in.) long and placed at 300 mm (12 in.) spacings centered on the joint and at middepth of the slab. A minimum diameter of 25 to 38 mm (1.0 to 1.5 in.) is needed to control faulting for heavily loaded pavements. Induced bearing stresses under dowel bars can cause the concrete matrix to deteriorate and elongate the dowel sockets, which reduces the effectiveness of the dowels and their load-transfer capabilities.[33,34] The bearing area under the dowel bar at the face of the joint is most critical. Consolidation of the concrete around the dowel at this location is extremely important for long-term performance.

The traditional method of placing dowels to ensure their stability has been by means of fabricated-steel supporting units or baskets. These units should be sturdy and placed so that the dowels are properly aligned and parallel to the centerline. Dowel bar inserters can install dowel bars within acceptable tolerances (within 6.35 m [0.25 in] of parallel axis).[35] A 150 mm (6 in.) minimum embedment length is needed for a dowel to be 100% effective. Dowels placed in hardened concrete should be drilled and epoxy grouted in place.

4.1.1.3 *Stabilized subgrades or subbases*—Stabilized subbases or subgrades (when warranted, see Table 2.1) are another way to improve the performance of plain and reinforced jointed pavements. Stabilized subbases reduce potential joint deflection, improve and maintain longer effectiveness of the joint under repetitive loads, and provide an all-weather working platform for the paving contractor. This type of subbase may be warranted in areas that do not drain well or in which poor drainage conditions exist. Caution should be exercised when using stabilized subgrades or subbases to ensure proper subbase drainage, that is, permeable subbase materials or edge drains to allow water to be removed from the pavement structure. Stabilized subbases and subgrades should be extended 0.7 m (2 ft) beyond an unsupported slab edge when used.

To serve these functions, cement-treated subbases are made with granular materials in AASHTO Soil Classification Groups A-1, A-2-4, A-2-5, and A-3. These materials contain not more than 35% passing the 75 µm (No. 200) sieve size, have a plasticity index of 10 or less, and may be either pit-run or manufactured materials. The greater the traffic, the greater the percent of cement added to make the subbase nonerodible.[25]

4.2—Transverse joints

The purpose of a contraction joint is to control cracking caused by restrained drying shrinkage and thermally induced movements of the concrete, and by the effects of curling and warping. Concrete, while drying, may shrink almost 1.5 mm for every 3 m (0.06 in. for every 10 ft) of length. This shrinkage may develop a tensile stress in excess of the early tensile strength of the concrete, leading to cracking in the concrete. Due to the induced restraint inherent in a jointed concrete pavement, contraction joints should be spaced in accordance with Fig. 4.1. Joint spacing requirements can vary due to the subgrade characteristics, the concrete coarse aggregate type, concrete strength, type of subbase support, and curing practice.[7,32]

4.2.1 *Transverse contraction joints*—Joints are optimally created at selected locations and intervals by a plane of weakness formed in the pavement by a variety of methods. Depending on the method used, the planes of weakness may be induced while the concrete is still in the early hardening stages or after a certain amount of hardening has taken place.

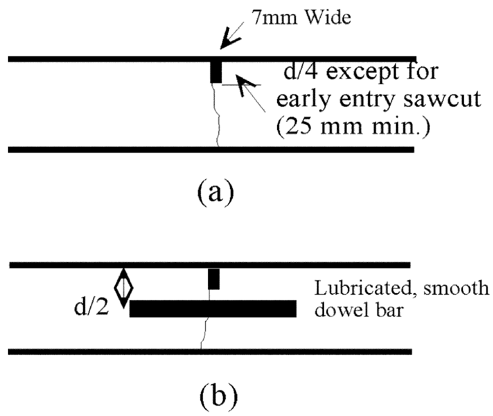


Fig. 4.2—Transverse contraction joint types.

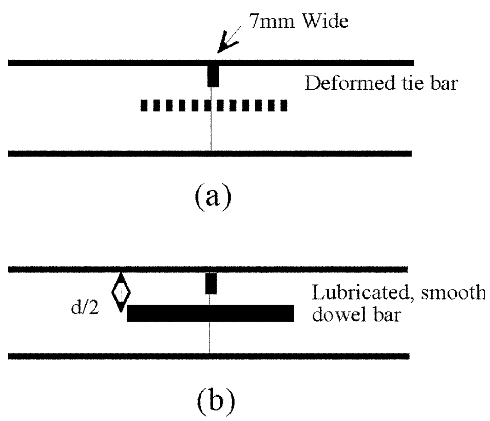


Fig. 4.3—Transverse construction joint with different types of drilled and epoxied load-transfer devices.

Some of the more common methods to induce a plane of weakness are:

- Conventional saw cutting;
- Early-entry saw cutting;
- Use of a grooving tool; and
- Use of a remolded filler strip.

When using saw-cutting techniques to control cracking, the timing of the cut is very important to the control of cracking, particularly if the early-entry method is used. The time of cutting required to control cracking depends on the strength of the concrete and the depth of the cut or the notch as well as the weather conditions at the time of construction and the stiffness of the subbase. Because early-entry saw cut methods only notch the surface of the pavement 25 to 38 mm (1 to 1.5 in.) in depth, it is important to use this method before final setting of the concrete to ensure crack initiation. Conventional cutting methods, because the depth of cut is nominally *d*/4 or *d*/3, are used at ages much later than final setting of the concrete (12 to 24 h), but not until the concrete has attained sufficient strength to resist spalling and raveling damage. The time of early sawing usually ranges from 2 to 6 h after placing, depending upon temperature (ACI 302.1R, Reference 19). All joints should be sawed in successive patterns to control random cracking and minimize nonuniform joint openings. Early saw cutting is important on hot, windy days, particularly on stabilized bases (due to increased curling and warping stress), to prevent random slab cracking; however, all sawcutting operations, whether early, late, or in between, should be accomplished at sufficient depths to initiate cracking.

Planes of weakness may be created while the concrete is still plastic by using a grooving tool or by inserting a premolded filler strip. The width of the groove will depend on whether the joint is to be sealed. Joints that are to be sealed should have joint wells at least 7 mm (1/4 in.) wide to provide a reservoir for the sealant, as discussed in Section 4.7. The choice of a crack initiation method should be based on experience, local conditions, and weather conditions at the time of construction. Plastic zip-strips can be used for thinner slabs placed directly on subgrade. Sawcutting is preferred to this method to minimize random cracking.

Whenever possible, the contraction joint pattern should divide the pavement into panels that are approximately square. The length of a panel may be 25% greater than the width. Joint patterns across adjacent lanes should be continuous. Joints should extend through integral and tied curbs. Two types of transverse contraction joints are shown in Fig. 4.2. Suggested reservoir dimensions, sealant properties, and application are discussed under Section 4.7.

4.2.2 *Transverse construction joints*—Transverse construction joints provide the interface between slabs of concrete placed at different times during the course of construction. These joints are usually butt-type, but can be keyed in some instances and may be doweled or restrained by use of a deformed tie bar. Butt-type joints do not provide load transfer, but load transfer is not usually required for city streets and low-volume roads serving light vehicles. The need for load transfer should be considered under heavy traffic conditions.

Transverse construction joints (Fig. 4.3) are used for interruptions in paving operations, such as those that occur at the end of the day, for bridges and intersections, or when placing should be stopped 30 min or more for weather or equipment breakdown. Whenever a cold joint is caused by interrupted work, a construction joint should be used, but be located at a designated joint location in the jointing pattern, as illustrated in Fig. 4.4. The type of transverse construction joints generally referred to are those placed at planned contraction joint locations (Fig. 4.4). Certain events, such as lack of materials, sudden changes in weather, or equipment breakdowns, may occur during construction, requiring the need for an emergency construction joint, a planned construction joint, or a combination thereof. In these circumstances, the construction joints should be placed where contraction joints are planned to ensure that excessive joint openings do not occur in adjacent slabs. (This may require partial slab removal.) Use of deformed tie bars will restrict opening of the joint, which may be a desirable effect in some instances.

Figure 4.4 shows typical details for construction joints in pavements where one or more abutting lanes of a roadway are involved and are formed at normal joint locations. These are butt-type joints that may require dowels because there is no aggregate interlock to provide load transfer. Dowel size and spacing are the same as indicated in Section 4.1.1.3. If they were not precoated, dowel ends extending through the

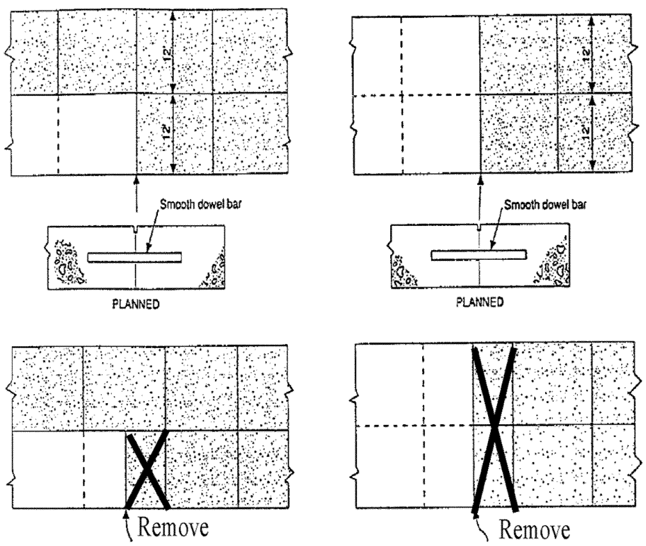


Fig. 4.4—Planned and emergency construction joints.[33]

butt joint should be lubricated on the exposed end before paving is resumed to prevent both corrosion and bond. Dowel misalignment should be held to a minimum.

Transverse construction joints falling at planned locations for contraction or isolation joints are built and sealed to conform to the specifications for those joints. Construction joints should be properly maintained and sealed to prevent infiltration of incompressible materials that may eventually affect long-term pavement performance.

4.3—Longitudinal joints

Longitudinal joints control irregular longitudinal cracks that would otherwise occur under panel widths that exceed the limits recommended in Fig. 4.1. Such cracks normally develop from the combined effects of load and restrained warping after pavements are subjected to traffic.

The following criteria are useful guides for the spacing of longitudinal joints:

- A spacing of 4 to 5 m (12 to 15 ft) serves the dual purpose of crack control and lane delineation. Longitudinal joints on arterial streets also should be spaced to provide traffic-and parking-lane delineation. On these streets, it is customary to allow 3 to 3.5 m (10 to 12 ft) for parking that can also be used as a travel or turning lane; and
- Longitudinal joints are usually required for crack control on one-way ramps where the slab width is 5 m (15 ft) or more.

Longitudinal joints, contraction or construction, serving as lane-dividing or centerline delineations, are shown in Fig. 4.5. An intermediate, longitudinal contraction joint (shown at the bottom of Fig. 4.5) is used where two or more lanes are paved at a time. This type of joint is normally sawed and sealed. Under certain conditions, such as rapidly dropping air temperature during the first night, longitudinal cracks may occur early. In such cases, early sawing of the longitudinal joint is required. As with transverse joints, early sawing is preferable with longitudinal joints.

The keyed construction joint shown at the top of Fig. 4.5 is used for lane-at-a-time construction. For pavement thickness greater than 150 mm (6 in.), however, butt joints

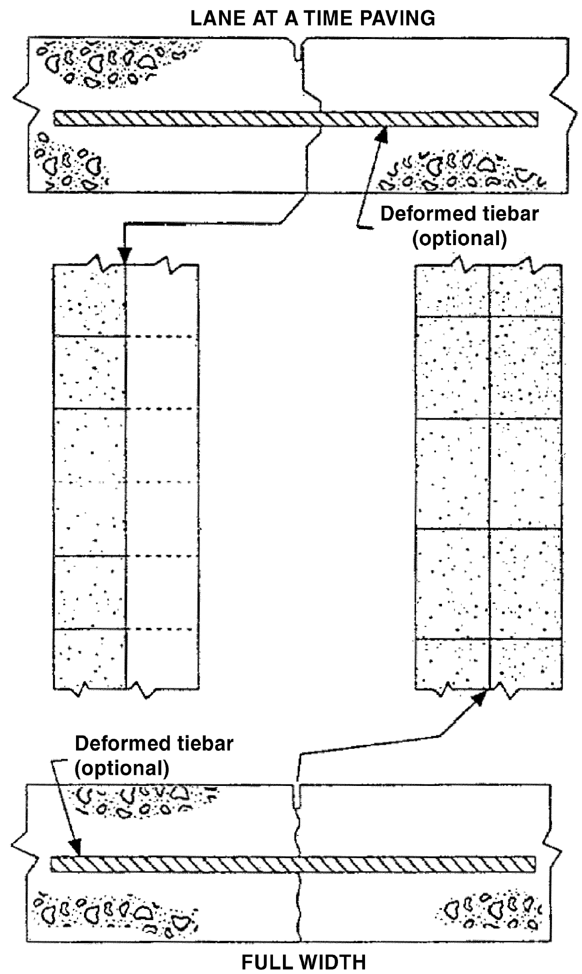


Fig. 4.5—Longitudinal joints.[33] *(Note: use butt joint with tie bar for pavements 150 mm [6 in.] thick or less.)*

are recommended for most applications. A similar recommendation applies for multilane pavements where the full width is not paved in one pass and for ramp connections to mainline pavements.

Both types of longitudinal joints serve as a hinge via the effect of the deformed tie bar that tends to promote load transfer through aggregate interlock to maintain structural capacity and serviceability. On most pavements, lateral movement is prevented by deformed steel bars (tie bars or tie bolts).

In slipform construction, deformed tie bars or tie bolts are inserted before the end of the trailing form or are inserted behind the paver pan. Insertion of straight (unbent) tie bars has been accomplished successfully with recent innovations in slipform equipment.

Curbs may be constructed monolithically with pavement slabs (Fig. C.1) for edge support, but they can be constructed separately and tied to the pavement to provide edge support. Curb and gutter sections are sometimes constructed first and then used as side forms for the pavement slabs. In this case, tie bars should be used to tie pavement lanes to the curb and gutter to benefit from the added structural edge support.

Depending on local experience, tie bars may not be required in the interior joints of city streets and low-volume roads if these are confined by a curb and gutter. Wide paved areas,

Table 4.1—Tie bar dimensions and spacings (commonly Grade 60)*

Slab thickness, mm	Tie bar size × length, mm	Tie bar spacing, mm Distance to nearest free edge or to nearest joint where movement can occur			
		3.0m	3.7 m	4.3 m	7.3 m
130	13M × 600	760	760	760	700
150	13M × 600	760	760	760	580
180	13M × 600	760	760	760	500
200	13M × 600	760	760	760	430
230	16M × 760	900	900	900	600
250	16M × 760	900	900	900	560
280	16M × 760	900	900	860	500
310	16M × 760	900	900	780	460

*Corrosion protection should be used in an area where deicing salts are used on the pavement on a regular basis.

whether or not confined by a curb and gutter, should be tied together in groups of no more than three lanes at a time. Tie bars should be used on center line joints of two-lane pavements where no curb and gutter exists to keep the slabs from separating. Longitudinal construction joints should be tied into the adjacent curb and gutter to use the structural benefit of the edge support.

Tie bars are designed to overcome the resistance of the subgrade or subbase to horizontal movement when the slab is contracting. This resistance is developed over the distance between the tied joint and the nearest free edge. The required cross-sectional area of tie bar per meter joint length is given by the following formula

$$A = \frac{bC_f wh}{f_s} \cdot 1000 \quad (4\text{-}2)$$

in which

A = cross-sectional area of steel required per meter length of joint, mm^2/m;

b = distance between the joint and the nearest untied joint or free edge, m;

C_f = coefficient of subgrade (of subbase) resistance to slab movement, taken at 1.5 or greater depending on the type of subbase;[36]

w = density of concrete, kg/m^3 (2400 kg/m^3 for normal-weight concrete);

h = slab thickness, cm; and

f_s = allowable working stress in steel, MPa (usually taken as approximately 2/3 of the yield strength).

Tie bars should be long enough so that the anchorage on each side of the joint will develop the allowable working stress of the tie bar. In addition, an allowance of about 70 mm (2.5 in.) should be made for inaccurate centering of the tie bar. Expressed as a formula, this becomes

$$L_t = \frac{f_s \times d_b}{4.826 \times 10^6} + 70 \quad (4\text{-}3)$$

where

L_t = length of tie bar, mm;

f_s = allowable working stress in steel, MPa (same as in Eq. (4-1)); and

d_b = diameter of tie bar, mm.

Recommended tie bar dimensions are 600 mm (24 in.) 15M bars placed on 760 mm (30 in.) centers, as a minimum. Other tie-bar spacings are listed in Table 4.1. In any case, no more than three lanes should be tied together.

The width of sawed longitudinal joints is commonly 3 to 6 mm (1/8 to 1/4 in.). Sawing should be done early enough to control cracking—within 4 to 12 h. Joints should be sawed before any heavy equipment or vehicles are allowed on the pavement.

After sawing, the joints should be flushed out, dried, and sealed, if required, to eliminate a second cleaning. Joints sawed with dry cutting blades can be cleaned with compressed air. Some sealants require that the new concrete be cured for 7 days before placement of the sealant.

4.4—Isolation joints and expansion joints

Isolation and expansion joints allow anticipated differential horizontal and vertical movements (if no dowels are used) to occur between a pavement and another structure. Because pavement performance can be significantly affected by the planned use and location of these joints, much care should be taken in the design process. Though the terms are often used interchangeably, isolation joints are not the same as expansion joints. Although both joints use full-depth joint filler material, rarely is it needed for expansion.

Performance studies have indicated that expansion joints are only necessary at relatively fixed structures such as a light pole footing and drop inlet boxes. In the past, designers placed transverse expansion joints to relieve compressive forces in the pavement and to limit blowups. In many cases, however, the expansion joints allowed too much opening of adjacent transverse contraction joints, which led to loss of aggregate interlock and sealant damage. By eliminating unnecessary expansion joints, adjacent contraction joints will remain tight and provide good load transfer and joint effectiveness.[37]

Isolation and expansion joints may be as much as 19 to 25 mm (0.75 to 1.0 in.) wide (Fig. 4.6). A preformed joint filler may be used to occupy the gap between the subbase or subgrade and the joint sealant. The filler is recessed 25 mm (1 in.) below the surface and should extend the full depth and width of the slab. Joint filler material should allow 50% compression and be nonshrinking, nonabsorbent, nonreactive, nonextruding, and flexible.[37]

The joint sealant is installed on top of the preformed filler. The sealant inhibits the infiltration of incompressible material and keeps the filler in place. It is essential to recess the sealant 6 mm to protect it from the damaging effects of traffic. The sealant and preformed filler material should be compatible. Some sealant manufacturers recommend a tape or rod bond breaker between sealant and filler materials. Regular maintenance inspections will be necessary to evaluate the performance of the expansion joint sealing materials.[37]

4.4.1 *Isolation joints*—Concrete slabs should be separated from fixed objects within or abutting the paved area to accommodate differential horizontal or vertical movement; however, use of dowels across the isolation joint will inhibit vertical displacement relative to the fixed objects. Isolation joints are used around light standard foundations, area drains, manholes, catch basins, curb inlets; between the pavement and sidewalks; and between the pavement and buildings.

Isolation joints are also used at asymmetrical intersections and ramps where joint grids are difficult to align. In these locations, load-transfer dowels should not be used so differential horizontal movements can occur without damaging the abutting pavement. Isolation joints (Fig. 4.6) are produced by inserting premolded joint fillers before or during the concreting operations. The joint filler should extend all the way to the subgrade and not protrude above the pavement. If vehicles are to pass over isolation joints along slab edges, consider using a thickened-edge joint. The pavement edge should be thickened by approximately 20% (at least 50 mm [2 in.] min.) and tapered to the required thickness over a distance of six to 10 times the pavement thickness, as shown in Fig. 4.6.[38]

4.4.2 *Expansion joints*—Studies of pavements in service have shown that expansion joints are not needed, except where a concrete slab is placed next to a bridge that is not subjected to the same temperature and moisture movements as the pavement. Pavements in slabs less than 200 mm (8 in.) thick with expansion joints should have thickened edges with no dowels, as discussed for isolation joints. Expansion joints in slabs 200 mm (8 in.) or thicker should be doweled.

In transverse expansion joints, at least one end of each dowel should be equipped with an expansion cap. The expansion cap allows the pavement to move freely as the joint expands and contracts. The cap should be long enough to cover at least 50 mm (2 in.) of the dowel and should provide a watertight fit. The cap should be equipped with a stop that prevents the cap from slipping off of the dowel during placement. A good stop location will provide a minimum dowel coverage by the cap equal to 6 mm (0.25 in.) more than the expansion joint width (typically 32 mm [1.25 in.]). The capped end of the dowel is also lubricated to prevent bond.

The same dowel placement and alignment requirements used for doweled contraction joints apply to doweled expansion joints. The dowels are typically placed at middepth, spaced 300 mm (12 in.) apart (on center), and have a diameter of 32 mm (1.25 in.) for 200 to 225 mm (8 to 9 in.) slabs and 38 mm (1.5 in.) for 250 mm (10 in.) or greater slabs. Epoxy coating for corrosion resistance is recommended for harsh climates when deicer salts are used. A bond breaker such as form oil is essential on the dowel bar.

An expansion basket supports and aligns the dowel bars while also supporting the preformed filler material. The filler should extend the entire width of the slab and fit snugly into the basket frame. Alignment of the dowel bar basket is important to allow for joint movement.

Transverse contraction joints within 20 to 30 m (65 to 100 ft) of transverse expansion joints should be thickened for pavements less than 200 mm (8 in.) thick and doweled for pavements 200 mm (8 in.) or thicker. The expansion joint may allow adjacent contraction joints to open more than other

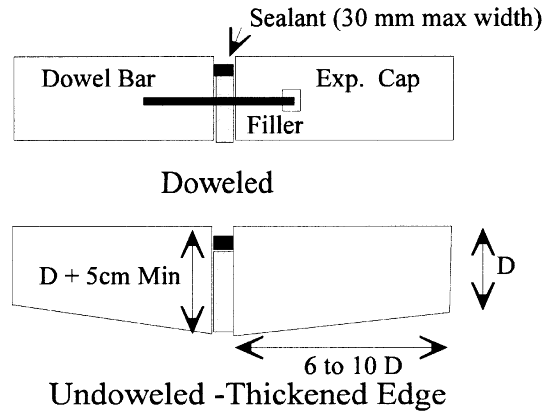


Fig. 4.6—Expansion and isolation joints (using a doweled or thickened-edge joint).

contraction joints. If not doweled, adjacent contraction joints would lose load transfer.[38]

4.5—Slab reinforcement

For most normal applications, distributed steel or wire mesh is not necessary in low-volume concrete pavements for roads and streets if joint spacings are kept short. The use of reinforcing steel will not add to the load-carrying capacity of the pavement nor compensate for poor subgrade preparation or poor construction practices. Embedded reinforcement may minimize deterioration of any cracking over the pavement service period if a possibility exists for cracking to occur due to poor soil support, settlement (from utility cuts, for example), frost heave, and swelling soils.

4.6—Irregular panels

In otherwise unreinforced city streets and low-volume roads, steel reinforcement should be considered for odd-shaped panels. An odd-shaped panel is considered to be one in which the slab tapers to a sharp angle, when the length-to-width ratio exceeds 1.70:1, or when a slab is neither square nor rectangular. At certain intersections where contraction joints are placed along radius lines to the edge of pavement, it can be difficult for a contractor to determine the precise location of odd-shaped panels before paving and sawing. Elimination of the reinforcement is acceptable in these circumstances.

Distributed steel is similar to joint reinforcement (in accordance with Section 4.3) in that it holds fracture faces together if cracks form. As pointed out previously for joint reinforcement, the quantity of steel varies depending on joint spacing, slab thickness, coefficient of subgrade resistance, and the tensile strength of the steel. A properly supported wire mesh should function adequately for most low-volume slab designs. Deformed wire mesh has performed significantly better than smooth wire mesh under greater traffic levels.

Because contraction joints should be free to open, distributed steel is interrupted at the joints. Because increased spacing between joints will increase joint openings and reduce aggregate interlock load transfer, thicker pavements with a wide joint spacing and carrying significant truck traffic may require load-transfer dowels. Distributed steel

Table 4.2—Joint sealant materials[31]

Hot-pour sealants	Specification	Properties
Polymeric asphalt-based	AASHTO M 0173	Self-leveling
	ASTM D 3405	
	SS-S-1401 C	
	ASTM D 1190	
Polymeric	ASTM D 3405	
Low modulus	Modified	
Elastomeric	SS-S-1614	
Coal tar, PVC	ASTM D 3406	
Cold-pour sealants/ single components		
Silicone	ASTM D 5893	Self-leveling, nonsag, low to ultra-low modulus
Nitrile rubber	No specifications currently exist	Self-leveling, nonsag
Polysulfide		Self-leveling, low modulus
Preformed polychloroprene elastomeric (compression seals)		
Preformed compression seals	ASTM D 2628	20 to 50% allowable strain
Lubricant adhesive	ASTM D 2835	

should be supported on chairs or precast concrete blocks to hold it in position, usually about 50 mm (2 in.) below the top of the slab.

4.7—Contraction joint sealants

The role of joint sealants is to minimize infiltration of surface water and incompressibles into the pavement joint. Incompressible materials cause point bearing pressures, which can lead to spalling. For low-volume roads and city streets with short joint spacings, the amount of joint opening and closing is small. Although opinions vary, the effectiveness of joint sealing for low-volume roads and city streets is not as critical as it is for long joint spacings and for highway pavements with high truck volumes, and it should be used only where local experience has shown a benefit. Joint sealants may not be cost-effective in dry climates.

Joint movement in pavements is influenced by factors such as the volume-change characteristics of the concrete, slab temperature range, friction between the slab and the subbase or subgrade, and slab length. A mathematical formulation[31] may be used to predict the joint opening.

There are many acceptable materials available for sealing joints in concrete pavements. Sealants are most simply classified as liquid (field molded) and preformed (compression). Liquid sealants may be hot- or cold-poured, single- or two-component, and self-leveling or toolable. They assume the shape of the sealant reservoir and depend on long-term adhesion to the joint face for successful sealing. Preformed sealants are shaped during manufacture and depend on long-term compression recovery for successful sealing. Table 4.2 lists specifications for most available sealants. Sealing materials have been successfully applied directly into 3 to 6 mm (1/8 to 1/4 in.) wide contraction joints with short joint spacing. For low-volume concrete roads and streets with short joint spacing, it may be determined that it is unnecessary to seal the joints, although as previously noted, opinion may vary on this issue. For long panels, however, a second saw cut, to provide a widened reservoir, will enable the sealant to form a suitable shape. In this case, reservoir dimensions should reflect the sealant properties, local environmental conditions, and service records of sealants and pavements similar to the project being designed. For best results, follow the sealant manufacturer's recommendations for reservoir dimensions that suit their product.

In general, the joint sealants that are most effective in maintaining bond to the face of the joint are those that are placed with a 1-to-1 width-to-height ratio, that is, a shape factor of 1.0. Low-modulus sealants, however, can maintain good bond strength even when placed at ratios of 1-to-2. With field-molded sealants, a stiff self-adhering strip, coated paper, or metal foil is applied to the bottom of the sealant space to prevent bond between the sealant and bottom of the reservoir (Fig. 4.7). The bond breaker also supports the sealant so that it does not sag into the joint. Frequently, cord or rope is used as a bond breaker in the reservoir. In that case, the reservoir should be deeper by an amount equal to the cord diameter so the proper shape factor is maintained for the sealant (Fig. 4.7). The joints should be filled to about 6 mm (0.25 in.) below flush with the pavement surface.

Before sealing, the joint openings should be thoroughly cleaned of curing compound, residue, laitance, and any other foreign material. Joint face cleanliness directly affects the adhesion of the sealant to the concrete. Improper or poor cleaning reduces the adhesion of the sealant to the joint interface, which significantly decreases the life and effectiveness of the sealant. Cleaning can be done with sandblasting, water, compressed air, wire brushing, or a number of other ways, depending on the joint surface condition and sealant manufacturer's recommendations. See ACI 504R for additional information on joint sealing.

4.7.1 *Low-modulus silicone sealants*—The newer low-modulus silicone sealants have properties that allow them to be placed with a shape factor (depth-to-width) of 0.5 or slightly lower (twice as wide as deep). This should be done only with the low-modulus silicones. They should not be placed any thinner than 1/2 the width of the joint with a minimum thickness of 13 mm (0.5 in.). These sealants have bonding strength in combination with a low modulus, however, that allows them to be placed thinner than the normal sealants. These recommendations should be cross-checked with the sealant manufacturer to ensure proper performance. Usually, the supplier of the sealant will provide minimum dimensions for width and depth for their material. Silicone sealants require a separate operation to produce a uniform surface and ensure bonding with the sidewall. They should be tooled by drawing a specially shaped tool over the surface of the silicone sealant, which forces the sealant into contact with the sidewall at the top of the sealant and forms the correct shape for the sealant. If this is not done, the bond will be incomplete, resulting in infiltration at the edge of the sealant and premature adhesive failure. Recent studies have indicated improved bond of these types of sealants to concretes containing limestone coarse aggregate when primers are used.[39]

4.7.2 *Polymer sealants*—Thermo-plastic polymer sealants are hot-poured and harden as they cool to ambient temperature in the joint reservoir. Silicone sealants, cold-applied solvent sealants, and the two-component polymer sealants require a curing period to gain strength. Two-component polymer-type sealants require that two components be thoroughly mixed in exact proportions as the material is being placed in the joint. These sealants require special application equipment. Accurate temperature control for the polyvinyl chloride (PVC)-type tar polymers is critical for proper curing and development of beneficial properties.

Before sealing, the joint surfaces should be dry, clean, and free of curing compound, residue, laitance, and any other foreign material. Cleaning can be done by water or compressed air, wire brushing, sand blasting, or high-pressure-water blast, depending on the joint surface condition and sealant manufacturer's recommendations. Proper cleaning is essential to obtain a joint surface that will not impair bond or adhesion with the field-molded sealant. The surfaces should be dry when the sealant is placed in the joint well.

4.7.3 *Compression sealants*—Preformed compression seals are compartmentalized or cellular elastomeric devices that function between the joint faces in a compressed condition at all times. The preformed compression seals should remain compressed approximately 15% at maximum joint opening to maintain sufficient contact pressure for a good joint seal and to resist displacement and generally not more than 55% at maximum closing of the pavement joint to prevent overcompression.[31] A properly selected preformed seal takes into account the specified compression range, installation temperature, width of the formed opening, and expected slab movement. The seals should be installed about 6 mm (0.25 in.) below the surface of the pavement. This dimension may vary in relation to local environmental conditions and the service record of joints under similar service conditions. For specific products, seal size recommendations and availability should be obtained from the manufacturer or supplier.

Preformed compression seals require the application of a lubricant/adhesive to the reservoir side walls. While the lubricant/adhesive used during installation has some adhesive qualities, its primary function is to provide lubrication during installation. Its adhesive qualities should not be considered in design. The size of the reservoir is chosen to ensure that the seal remains in compression at all times. During installation, care should be taken to avoid twisting and to avoid stretching the sealant more than 3%.

4.7.4 *Hot-applied, field-molded sealants*—When the sealant is hot-applied, the safe heating temperature should not be exceeded, and the manufacturer's instructions should be followed carefully. Failure to follow such instructions may result in a chemical breakdown of the sealant and render the sealant useless. Because most of the hot-poured sealants are asphalt-based, they are potential fire hazards, and safety precautions should be taken. Proper melting units or kettles should be used to ensure proper control of the sealant temperature. For liquid sealants, the surfaces should be dry and the sealant should not be placed during cold weather. Good workmanship should ensure that the sealant material is not spilled on the exposed surfaces of the concrete.

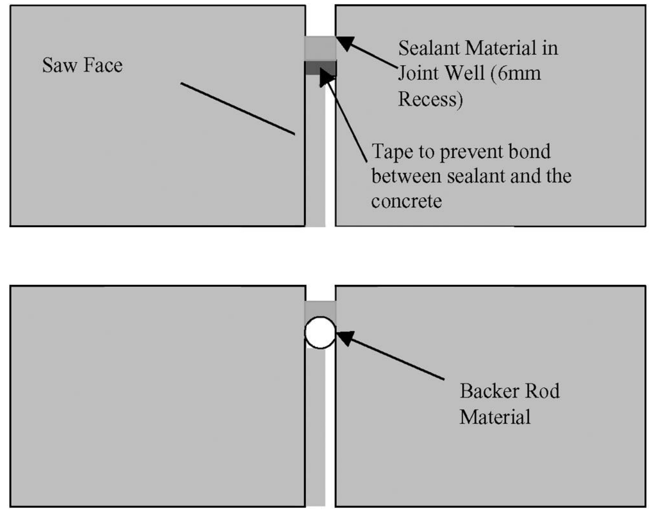


Fig. 4.7—Joint sealant reservoir.

4.7.5 *Cold-applied, field-molded sealants*—Most of the single-component cold-applied joint sealants are provided in small cartridges and can be applied with a caulking gun. For a two-part or multipart sealant, the components should be mixed in the proportion as specified by the manufacturer. For these types of sealants, the mixing is an essential and important part of the process and may require a specific type of mixer for large projects. If the pot life (the maximum time after initial mixing when the sealant can still be placed without adverse effects) of the sealant is long, the sealant can be mixed at a place other than the site. This is sometimes done to achieve more complete mixing than can be done on-site.

CHAPTER 5—SUMMARY

Certain considerations are essential to ensure the successful performance of a concrete pavement design. Concrete pavements for low-volume road applications should be constructed with short joint spacing patterns that result in small openings at the joints. This is key to maintain adequate load transfer over the design life. Induction of a successful joint pattern implies control of random cracking and minimization of uncontrolled cracking. Cracks of this nature will ultimately degrade the performance life of the pavement. Good surface drainage is also critical to long-term, maintenance-free performance. Drainage features should be well-designed and planned to adequately remove surface runoff from the pavement section. Finally, slab thickness needs to be well-chosen to carry the intended load distributions.

CHAPTER 6—REFERENCES

6.1—Referenced standards and reports

The standards and reports listed as follows were the latest editions at the time this document was prepared. Because these documents are revised frequently, the reader is advised to contact the proper sponsoring group if it is desired to refer to the latest version.

American Concrete Institute (ACI)
201.2R Guide to Durable Concrete
209R Prediction of Creep, Shrinkage, and Temperature Effects in Concrete Structures
211.1 Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete
212.3R Chemical Admixtures for Concrete
225R Guide to the Selection and Use of Hydraulic Cements
232.1R Use of Raw or Processed Natural Pozzolans in Concrete
233R Ground Granulated Blast-Furnace Slag as a Cementitious Constituent in Concrete
234R Guide for the Use of Silica Fume in Concrete
302.1R Guide for Concrete Floor and Slab Construction
304R Guide for Measuring, Mixing, Transporting, and Placing Concrete
305R Hot Weather Concreting
306R Cold Weather Concreting
308R Guide to Curing Concrete
325.9R Guide for Construction of Concrete Pavements and Concrete Bases
330R Guide for Design and Construction of Concrete Parking Lots
504R Guide to Sealing Joints in Concrete Structures

American Standards for Testing and Materials (ASTM)
A 185 Standard Specification for Steel Welded Wire Fabric, Plain, for Concrete Reinforcement
A 497 Standard Specification for Steel Welded Wire Fabric, Deformed, for Concrete Reinforcement
A 615 Standard Specification for Deformed and Plain Billet-Steel Bars for Concrete Reinforcement
A 616 Standard Specification for Rail-Steel Deformed and Plain Bars for Concrete Reinforcement
A 617 Standard Specification for Axle-Steel Deformed and Plain Bars for Concrete Reinforcement
A 706 Standard Specification for Low-Alloy Steel Deformed and Plain Bars for Concrete Reinforcement
B 117 Standard Practice for Operating Salt Spray (Fog) Apparatus
C 33 Standard Specification for Concrete Aggregates
C 78 Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)
C 94 Standard Specification for Ready-Mixed Concrete
C 150 Standard Specification for Portland Cement
C 260 Standard Specification for Air-Entraining Admixtures for Concrete
C 309 Standard Specification for Liquid Membrane-Forming Compounds
C 494 Standard Specification for Chemical Admixtures for Concrete
C 595 Standard Specification for Blended Hydraulic Cements
C 618 Standard Specification for Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete
C 672 Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals
C 685 Standard Specifications for Concrete Made by Volumetric Batching and Continuous Mixing
C 989 Standard Specification for Ground Iron Blast-Furnace Slag for Use in Concrete and Mortars
C 1157 Standard Performance Specifications for Blended Hydraulic Cement
D 698 Test Method for Moisture-Density Relations of Soils and Soil-Aggregate Mixtures, Using a 5.5 lb Rammer and 12 in. Drop
D 994 Standard Specification for Preformed Expansion Joint Filler for Concrete (Bituminous Type)
D 1190 Standard Specification for Concrete Joint Sealer, Hot-Applied Elastic Type
D 1196 Standard Test Method for Nonrepetitive Static Plate Load Tests of Soils and Flexible Pavement Components, for Use in Evaluation and Design of Airport and Highway Pavements
D 1751 Standard Specification for Preformed Expansion Joint Filler for Concrete Paving and Structural Construction (Nonextruding and Resilient Bituminous Types)
D 1752 Standard Specifications for Preformed Sponge Rubber and Cork Expansion Joint Fillers for Concrete Paving and Structural Construction
D 2487 Test Method for Classification of Soils for Engineering Purposes
D 2628 Specification for Preformed Polychloroprene Elastomeric Joint Seals for Concrete Pavements
D 2835 Standard Specification for Lubricant for Installation of Preformed Compression Seals in Concrete Pavements
D 2844 Standard Test Method for Resistance R-Value and Expansion Pressure of Compacted Soils
D 3405 Joint Sealants, Hot-Poured for Concrete and Asphalt Pavements
D 3406 Standard Specification for Joint Sealant, Hot-Applied, Elastometric-Type, for Portland Cement Concrete Pavements
D 4318 Test Method for Liquid Limit, Plastic Limit, and Plasticity Index of Soils
D 5893 Standard Specification for Cold Applied, Single Component, Chemically Curing Silicone Joint Sealant for Portland Cement Concrete Pavements

American Association of State Highway and Transportation Officials (AASHTO)
T-222 Nonrepetitive Static Plate Load Test of Soils and Flexible Pavement Components, for Use in Evaluation and Design of Airport and Highway Pavements
M-0173-60 Hot Poured Elastic Type

Federal
SS-S-1401 C Sealing Compound, Hot-Applied, for Concrete Asphalt Pavements

SS-S-1614 Sealant, Joint Jet-Fuel Resistant, Hot-Applied, for Portland Cement and Tar Concrete Pavements

These publications may be obtained from the following organizations:

American Concrete Institute
P. O. Box 9094
Farmington Hills, MI 48333-9094

ASTM
100 Barr Harbor Drive
West Conshohocken, PA 19428-2959

AASHTO
444 North Capitol Street Northwest, Suite 225
Washington, DC 20001

Business Service Center
General Services Administration
7th and D Streets SW
Washington, DC 20407

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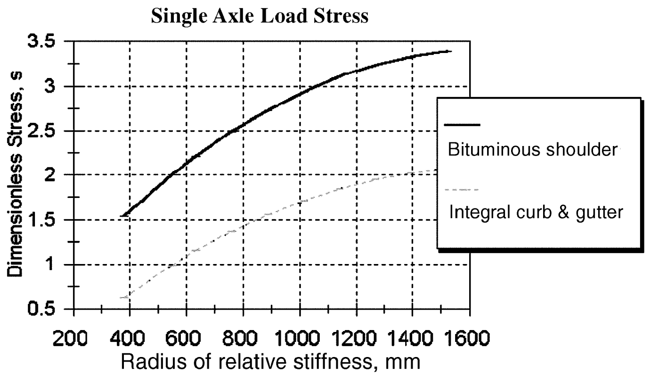

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APPENDIX A—PAVEMENT THICKNESS DESIGN CONCEPTS

A.1—Load stresses and fatigue calculations

The purpose of this appendix is to provide the design engineer some background into the development of the design table given in Chapter 3. The primary distress considered in this development is midslab cracking; although, other forms of distresses, such as faulting, and other forms of roughness joint spalling, can affect the performance of a concrete pavement subjected to low-traffic volumes. The design period is the theoretical life of the pavement with respect to midslab cracking due to critical edge stresses, before it requires either major rehabilitation or reconstruction. Therefore, the design process should represent the actual life of the pavement to the extent that slab cracking affects the performance of the pavement. The design thicknesses listed in Chapter 3 are based upon design traffic levels distributed over a 30-year period. Other design periods may be considered using the method described as follows. Each street category listed in the thickness table shown in Chapter 3 includes a multiplying factor that applies an arbitrary level of reliability with regard to overloads, low concrete strength, or thin pavement sections. The multiplying factors are:

- Light Residential: 1.0;
- Residential: 1.0;
- Collector: 1.1;
- Business: 1.1; and
- All Others: 1.2.

Axle load stresses can be found from a dimensionless stress parameter illustrated in Fig. A.1 and A.2. These graphs are provided on the following page to determine the stress σ as a function of slab thickness, *k*-value, and load:

$$\sigma = \frac{sP}{h^2}$$

where

σ = wheel load stress, MPa;

s = dimensionless stress (from Fig. A.1 or A.2);

P = single axle or tandem axle divided by 2, N; and

h = slab thickness, mm.

The dimensionless stress *s* depends on the radius of relative stiffness ℓ, which is defined as

$$\ell = \sqrt[4]{\frac{1000 \cdot Eh^3}{12(1-\nu^2)k}} \qquad \text{(A-1)}$$

where
ℓ = radius of relative stiffness, mm;
E = elastic modulus of the concrete, MPa;
h = pavement thickness, mm;
k = subgrade reaction, Mpa/m; and
ν = Poisson's ratio.

For a given ℓ-value, the corresponding dimensionless stress can be determined. This translates into an axle load stress that can be used in the thickness determination.

A stress ratio can be found by dividing the axle load stress by the concrete modulus of rupture (MOR). This stress ratio can be used with either curve noted in Fig. A.3 to determine the total number of loads that can be applied or allowed before the slab is considered to be cracked. The estimated number of load applications is divided by the number of allowable loads to represent the amount of fatigue consumption accumulated within the slab. This process is repeated for all anticipated axle loads, and the amount of fatigue life that has been used is summed for all load applications. A slab is considered to have satisfactory thickness if less than 100% of the fatigue is used.

The MOR usually has been obtained by testing a small beam (150 x 150 x 500 mm [6 x 6 x 20 in.] is common) in flexure using midpoint or third-point loading arrangements. ASTM C 78 is used for midpoint and third-point loading tests, respectively. The MOR is calculated with the beam formula for stress in the extreme tensile fiber at the critical section.

$$\text{MOR} = \frac{Mc}{I} = \text{Stress}$$

where
M = failure moment, N-mm;
c = distance from the neutral axis to the extreme tensile fiber, 1/2 the depth of the beam, in mm; and
I = moment of inertia at the critical section, for a rectangular beam is width x (depth)^3/12, mm^4.

The 28-day, third-point loading MOR is used as the design strength for pavements, which is approximately 0.9 MOR obtained from a center point test. While design of pavement is generally based on flexural strength of concrete, it may be more practical to use compressive strength testing in the field for acceptance due to quality-control issues associated with flexure beam test specimens. This will require the development of a job-specific correlation between flexure beam strength and compressive strength. The relationship between compressive strength f_c' and flexural strength can vary depending on aggregate type, admixtures used, and age of the concrete. If local data are not available, an approximate relationship between compressive strength f_c' and flexural strength can be computed by the following formula

$$\text{MOR}_{1/3} = a_1 \gamma_{conc}{}^{0.5} f_c'^{\,0.5} \qquad \text{(A-2)}$$

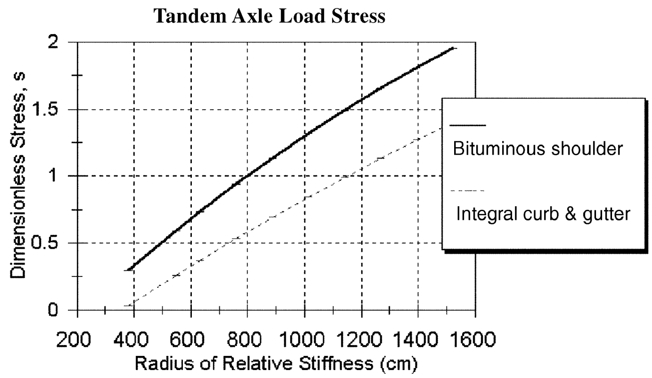

Fig. A.2—Tandem axle dimensionless stress versus ℓ-value.

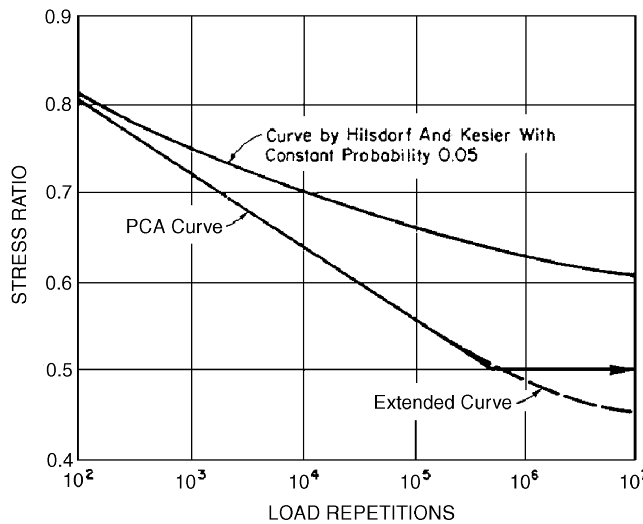

Fig. A.3—Fatigue relationships.[12]

where γ_{conc} is the concrete density, and a_1 varies between 0.012 and 0.020. This procedure is illustrated by the following example:

An industrial driveway with a curb and gutter is to be built to carry two delivery trucks per day for 20 years. Each truck is expected to have a front single axle with a load of 57.8 kN and a tandem rear axle of 213.5 kN. The subgrade is clay with k = 27 MPa/m.

Step 1: Determine the number of applications.

Two trucks per day for 20 years = 2 × 20 × 365 = 14,600 repetitions.

Step 2: Determine the dimensionless wheel load stress (s) from Fig. A.1 or A.2.

The inputs for determining the wheel load stress are:

- Concrete compressive strength (use f_c' = 33.8 MPa);
- k-value (use k = 27 MPa/m);
- Poisson's ratio (υ = 0.15); and
- Slab thickness (use h = 200 mm).

From Eq. (A-1), the value of ℓ can be calculated. The modulus of elasticity of concrete E_c can be determined from

$$E_c = 4733(f_c')^{1/2}$$

Table A.1—Growth projection data

Yearly rate of traffic growth, %	Projection factor, 30 years	Projection factor, 40 years
1	1.2	1.2
1.5	1.3	1.3
2	1.3	1.5
2.5	1.4	1.6
3	1.6	1.8
3.5	1.7	2.0
4	1.8	2.2
4.5	1.9	2.4
5	2.1	2.7
5.5	2.2	2.9
6	2.4	3.2

Table A.2—Typical axle-load distributions for low-volume design applications[27]

Axle load, kN	Axles per 1000 trucks			
	Category LR	Category 1	Category 2	Category 3
Single axles				
18	846.15	1693.31	—	—
27	369.97	732.28	—	—
36	283.13	483.10	233.6	—
44	257.60	204.96	142.70	—
53	103.40	124.00	116.76	182.02
62	39.07	56.11	47.76	47.73
71	20.87	38.02	23.88	31.82
80	11.57	15.81	16.61	25.15
89	—	4.23	6.63	16.33
98	—	0.96	2.60	7.85
107	—	—	1.60	5.21
116	—	—	0.07	1.78
125	—	—	—	0.85
133	—	—	—	0.45
Tandem axles				
18	15.12	31.90	—	—
36	39.21	85.59	47.01	—
53	48.34	139.30	91.15	—
71	72.69	75.02	59.25	99.34
89	64.33	57.10	45.00	85.94
107	42.24	39.18	30.74	72.54
125	38.55	68.48	44.43	121.22
142	27.82	69.59	54.76	103.63
160	14.22	4.19	38.79	56.25
178	—	—	7.76	21.31
196	—	—	1.16	8.01
214	—	—	—	2.91
231	—	—	—	1.19

in which, for $f_c' = 20$ MPa, $E_c = 21.1$ MPa. Using these inputs and Fig. A.1 ($\ell = 480$ mm), $s = 0.8$.

Step 3: Determine the wheel load stresses and stress ratios.

Under the front axle using $\sigma = P \bullet s/h^2 = 57.8 \bullet 0.8/0.20^2$ is found to be 1.15 MPa. Using a concrete unit weight of 2300 kg/m^3 and a value of a_1 of 0.012, the MOR can be determined from Eq. (A-2) as 2.57 MPa.

The stress ratio (single axle):

$$\frac{\text{stress}}{\text{MR}} = \frac{1.15}{2.57} = 0.45$$

Following the same process for rear axle except using Fig. A-2 (s = 0.18), the stress under the rear axle is found to be 0.96 MPa.

$$\text{The stress ratio (tandem axle): } \frac{0.96}{2.57} = 0.37$$

Step 4: Determine the allowable load repetitions.

From Fig. (A-3) (using the curve labeled ‘Integral Curb and Gutter’), allowable load repetitions for single axles equal 10^7 and for the tandem axles an infinite amount.

Step 5: Determine the amount of fatigue consumption.

$$\text{Fatigue consumption: } \frac{\text{expected loads}}{\text{allowable loads}}$$

$$\text{Fatigue consumption, single axles: } \frac{14{,}600}{1 \times 10^7} = 0.15\%$$

$$\text{Fatigue consumption, tandem axles: } = 0.0\%$$

Total fatigue consumption is less than 1%. The 200 mm pavement with an integral curb and gutter is acceptable, but a thinner section could be considered. Other thicknesses could be investigated for greater amounts of fatigue consumption, but note that a minimum thickness of 125 mm would ultimately control if the fatigue consumption was below 100%, because 125 mm is the minimum recommended slab thickness. The wheel load stresses are small for the curb and gutter configuration. The effect of tied concrete shoulders or curb and gutters is accounted in the design based on the degree of load transfer provided by the shoulder across the longitudinal joint. The effect of the degree of load transfer can be approximated by considering that a bituminous shoulder represents 0% load transfer and that a integral curb and gutter represents approximately 100% transfer. The stress conditions resulting with a tied concrete shoulder can be estimated in proportion to these two limits with respect to the expected load transfer efficiency provided over the design life.

This design method uses the average daily truck traffic in both directions (ADTT) to model the loads on the concrete pavement. For design purposes, this traffic is assumed to be equally distributed in each of the two directions, that is, 50% each way. The ADTT value includes only trucks with six tires or more and does not include panel and pickup trucks and other four-tire vehicles.

Because the ADTT value represents the average daily traffic over the life of the pavement, the designer should adjust the present ADTT to anticipate any future growth of traffic. Table A.1 may be used to multiply the present-day ADTT by an appropriate projection factor to arrive at an estimated average daily truck count.

Table B.1—Soil characteristics pertinent to roadway pavements (ACI 330)

<table>
<tr><th colspan="2">Major divisions</th><th>Letter</th><th>Name</th><th>Value as foundation when not subject to frost action</th><th>Potential frost action</th><th>Compressibility and expansion</th><th>Drainage characteristics</th><th>Compaction equipment</th><th>Unit dry weight, kg/m^3</th><th>Field CBR</th><th>Subgrade modulus k, MPa/m</th></tr>
<tr><td rowspan="10">Coarse-grained soils</td><td rowspan="5">Gravel and gravelly soils</td><td>GW</td><td>Gravel or sandy gravel, well graded</td><td>Excellent</td><td rowspan="3">None to very slight</td><td rowspan="3">Almost none</td><td rowspan="3">Excellent</td><td rowspan="2">Crawler-type tractor, rubber-tired equipment, steel-wheeled roller</td><td>19.6 to 22.0</td><td>60 to 80</td><td rowspan="4">81 or more</td></tr>
<tr><td>GP</td><td>Gravel or sandy gravel, poorly graded</td><td>Good to excellent</td><td>18.9 to 20.4</td><td>35 to 60</td></tr>
<tr><td>GU</td><td>Gravel or sandy gravel, uniformly graded</td><td>Good</td><td>Crawler-type tractor, rubber-tired equipment</td><td>18.1 to 19.6</td><td>25 to 50</td></tr>
<tr><td>GM</td><td>Silty gravel or silty sandy gravel</td><td>Good to excellent</td><td rowspan="2">Slight to medium</td><td>Very slight</td><td>Fair to poor</td><td>Rubber-tired equipment, sheepsfoot roller, close control of moisture</td><td>20.4 to 22.8</td><td>40 to 80</td></tr>
<tr><td>GC</td><td>Clayey gravel or clayey sandy gravel</td><td rowspan="2">Good</td><td>Slight</td><td>Poor to practically impervious</td><td>Rubber-tired equipment, sheepsfoot roller</td><td>18.9 to 21.1</td><td rowspan="2">20 to 40</td><td rowspan="6">54 to 81</td></tr>
<tr><td rowspan="5">Sand and sandy soils</td><td>SW</td><td>Sand or gravelly sand, well graded</td><td rowspan="3">None to very slight</td><td rowspan="3">Almost none</td><td rowspan="3">Excellent</td><td rowspan="3">Crawler-type tractor, rubber-tired equipment</td><td>17.3 to 20.4</td></tr>
<tr><td>SP</td><td>Sand or gravelly sand, poorly graded</td><td rowspan="2">Fair to good</td><td>16.5 to 18.9</td><td>15 to 25</td></tr>
<tr><td>SU</td><td>Sandy or gravelly sand, uniformly graded</td><td>15.7 to 18.1</td><td>10 to 20</td></tr>
<tr><td>SM</td><td>Silty sand or silty gravelly sand</td><td>Good</td><td rowspan="2">Slight to high</td><td>Very slight</td><td>Fair to poor</td><td>Rubber-tired equipment, sheepsfoot roller, close control of moisture</td><td>18.9 to 21.2</td><td>20 to 40</td></tr>
<tr><td>SC</td><td>Clayey sand or clayey gravelly sand</td><td>Fair to good</td><td>Slight to medium</td><td>Poor to practically impervious</td><td>Rubber-tired equipment, sheepsfoot roller</td><td>16.5 to 20.4</td><td>10 to 20</td></tr>
<tr><td rowspan="6">Fine-grained soils</td><td rowspan="3">Low compressibility (LL < 50)</td><td>ML</td><td>Silts, sandy silts, gravelly silts, or diatomaceous soils</td><td rowspan="2">Fair to poor</td><td>Medium to very high</td><td>Slight to medium</td><td>Fair to poor</td><td>Rubber-tired equipment, sheepsfoot roller, close control of moisture</td><td rowspan="2">15.7 to 19.6</td><td rowspan="2">5 to 15</td><td rowspan="4">27 to 54</td></tr>
<tr><td>CL</td><td>Lean, sandy, or gravelly clays</td><td rowspan="2">Medium to high</td><td>Medium</td><td>Practically impervious</td><td rowspan="5">Rubber-tired equipment, sheepsfoot roller</td></tr>
<tr><td>OL</td><td>Organic silts or lean organic clays</td><td>Poor</td><td>Medium to high</td><td>Poor</td><td>14.1 to 15.9</td><td rowspan="2">4 to 8</td></tr>
<tr><td rowspan="3">High compressibility (LL > 50)</td><td>MH</td><td>Micaceous clays or diatomaceous soils</td><td>Poor</td><td>Medium to very high</td><td rowspan="3">High</td><td>Fair to poor</td><td>12.5 to 15.7</td></tr>
<tr><td>CH</td><td>Fat clays</td><td rowspan="2">Poor to very poor</td><td rowspan="2">Medium</td><td rowspan="2">Practically impervious</td><td>14.1 to 17.3</td><td rowspan="2">3 to 5</td><td rowspan="2">13 to 27</td></tr>
<tr><td>OH</td><td>Fat organic clays</td><td>12.5 to 16.5</td></tr>
<tr><td colspan="2">Peat and other fibrous organic soils</td><td>Pt</td><td>Peat, humus, and other</td><td>Not suitable</td><td>Slight</td><td>Very high</td><td>Fair to poor</td><td>Compaction not practical</td><td colspan="3">—</td></tr>
</table>

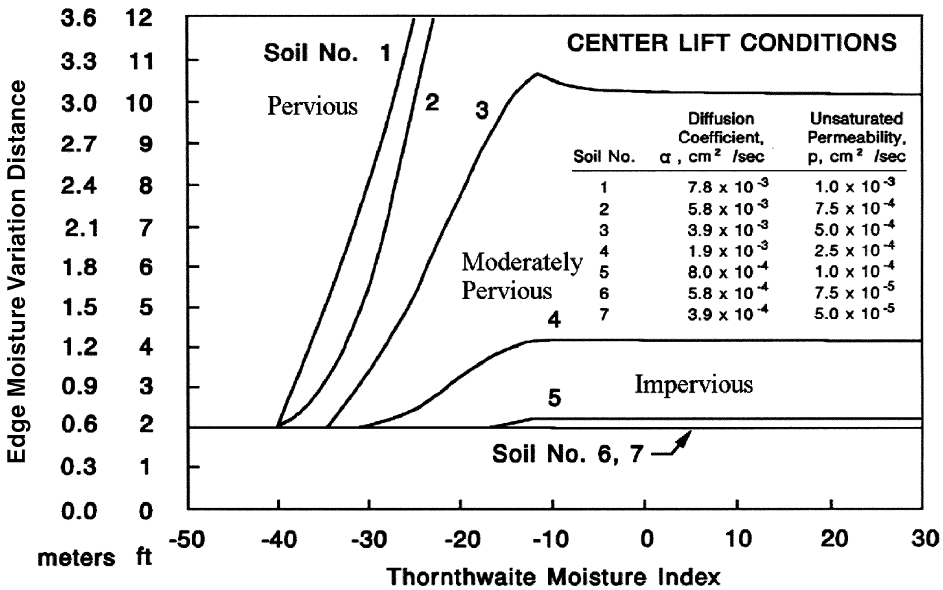

Fig. B.1—Width of area outside pavement edges as a function of TMI and soil type.[41]

Table B.2—Approximate relationship between soil plasticity and expansion

Degree of expansion	Approximate plasticity index
Nonexpansive	0 to 15
Expansive	More than 15

The truck axle loadings are distributed according to the type of roadway classification in the categories described in Table A.2. The relationship between the categories listed in Table A.2 and the street classifications shown in Chapter 3 is:

- Light Residential: Category LR;
- Residential: Category 1;
- Collector, Business and Minor Arterial: Category 2; and
- Industrial, Major Arterial: Category 3.

An alternative to this approach is the design method suggested by AASHTO. This was developed from pavement performance at the AASHTO Road Test, which was conducted during the period of 1958 to 1960. The *Guide for Design of Pavement Structures*[2] was published in May 1986 and updated in 1997. It follows three interim versions of the guide, and it constitutes a major revision of previous versions. The AASHTO guide contains design procedures and algorithms for construction and reconstruction of rigid and flexible pavements. The rigid pavement design procedure can be used to find the required pavement thickness to carry the design traffic with an acceptable loss in serviceability.

A computer program is also available to solve the AASHTO equations.[40] The program will solve for the required pavement thickness for design traffic, or it will analyze a selected thickness for traffic-carrying capacity. In the AASHTO procedures, all vehicle axle loads are expressed in terms of 80 kN equivalent axles. The guide and computer program include procedures for converting single-, tandem-, and triple-axle loads of various sizes into 80 kN equivalents.

APPENDIX B—SUBGRADE

B.1—Introduction

The designer should give careful consideration to the specific subgrade soils at the site. Troublesome subgrade conditions should be accommodated in the design. Normally construction budgets do not allow for extensive subgrade testing and evaluation. The engineer should, however, make the best use of the soil information available.

B.2—Soil classification

Soils differ from other engineering materials because they generally should be used as they occur in nature. Unlike manufactured products like concrete or steel, the properties of subgrade soils are highly variable from site to site, and even within a job site. Over time, geotechnical engineers have developed a number of standard classification systems to characterize the engineering properties of soils.

In the AASHTO system (M-145), soils are divided into two major groups: granular materials containing 35% or less passing the 75 µm sieve, and clay and clay-silt materials containing more than 35% passing the 75 µm sieve. The soil components are further classified as gravel, coarse sand, fine sand, silt, or clay. The final classification parameter is the group index (GI) computed from sieve analysis data, the liquid limit (LL), and the plasticity index (PI).

The Unified system, originally developed by Casagrande and standardized by ASTM D 2487, designates letter symbols for classification as follows:

G = gravel;
S = sand;
M = silt;
C = clay;
W = well graded;
P = poorly graded;
U = uniformly graded;
L = low-liquid limit;
H = high-liquid limit; and
O = organic.

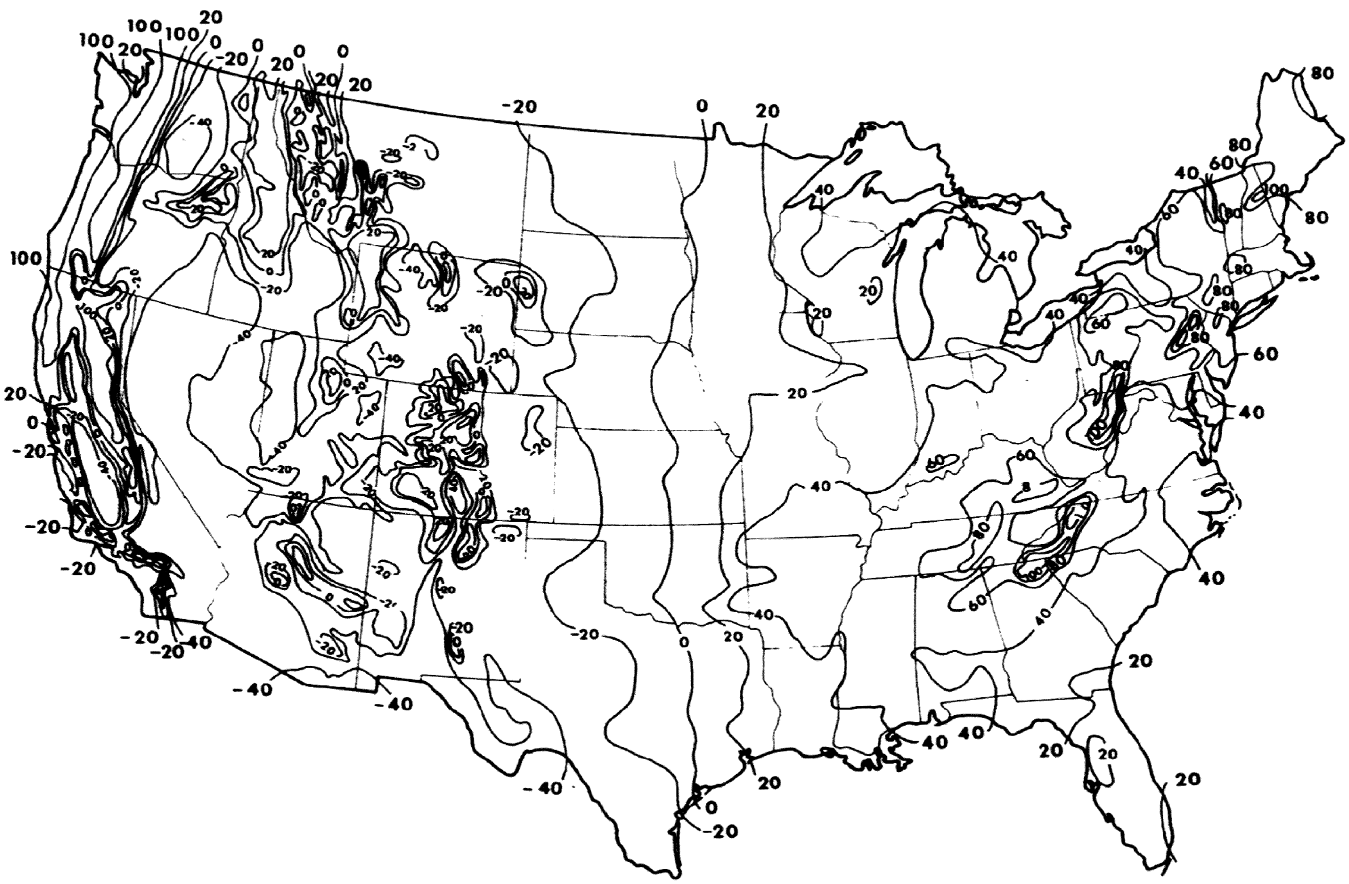

Fig. B.2—Distribution of Thornthwaite Moisture Index in the U.S.[41]

Combinations of these symbols are used to describe soils. Soils described by a unique description of a classification system generally exhibit similar engineering properties, regardless of location. Table B.1 shows general properties for soils classified in the ASTM system.

B.3—Subgrade soils

Unfortunately, concrete roadways cannot always be built on coarse grained soils, which generally provide excellent subgrades. The designer may need to use less desirable soils that are subject to frost action[22,29] and soil expansion; therefore, the designer should understand how to minimize problems these soils may cause.

B.4—Expansive soils

Expansive soil types and the mechanisms that cause soil volume change are well-known by geotechnical and highway engineers. Test procedures for identifying expansive soils are also well-known and commonly used. Table B.2 shows the approximate relationships between soil plasticity and expansion.

Most soils sufficiently expansive to cause distortion of pavements are in the AASHTO A-5, A-6, or A-7 groups. In the Unified Soil Classifications system, these soils are classified as CH, MH, or OH. Soil survey maps prepared by the USDA Soil Conservation Service may be helpful in determining soil classifications.

Expansive soils can be controlled effectively and economically by the following:

1. *Subgrade grading operations*—Swelling can be controlled by placing the more expansive soils in the lower parts of embankments and by cross-hauling or importing less-expansive soils to form the upper part of the subgrade. Selective grading can create reasonably uniform soil condition in the upper subgrade and will help ensure gradual transition between soils with varying volume change properties.

In deep cuts into highly expansive soils, a great deal of expansion may occur because of the removal of the natural surcharge load and absorption of additional moisture. Because this expansion usually takes place slowly, the design should consider the effects of long- and short-term heave.

2. *Use of sacrificial shoulder*—Soil volume changes below the pavement may also be reduced by use of a sacrificial shoulder along the longitudinal edges of the pavement. The placement of a compacted 100 mm (4 in.) dense-graded aggregate sprayed with a seal coat to reduce evaporation will serve to provide a sacrificial shoulder. The sacrificial shoulder is intended to be subjected to expansive movement but minimize changes in moisture (and consequently expansive movement) of the soil immediately below the concrete pavement. The width of the sacrificial shoulder depends on the Thornthwaite moisture index of the subgrade soils as indicated in Fig. B.1.[42] The distribution of Thornthwaite moisture index across the U.S. is shown in

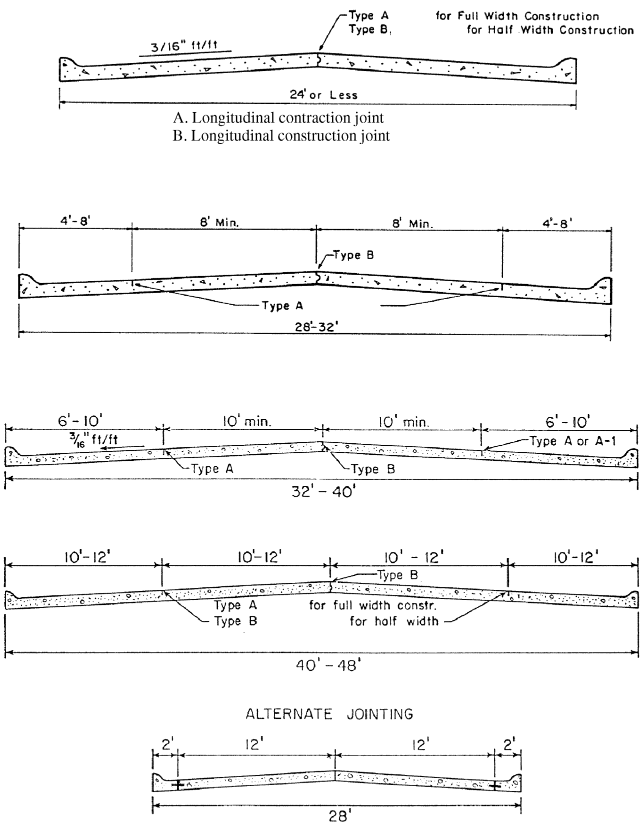

Fig. C.1—Pavement cross sections and longitudinal joint locations[43] (1 ft = 0.3048 m; 1 in. = 25.4 mm).

Fig. B.2.[42] A positive Thornwaite moisture index indicates a net surplus of moisture in the soil while a negative value indicates a net deficit of soil moisture.

3. *Nonexpansive cover*—In areas with prolonged periods of dry weather, highly expansive subgrades may require a cover layer of low-volume-change soil. This layer will help minimize changes in moisture content of the underlying expansive soil. A low-volume-change layer with low-to-moderate permeability is usually more effective and less costly than permeable, granular soil. Highly permeable, open-graded subbase materials are not recommended as cover for expansive soils because they allow more moisture to reach the subgrade. Local experience with expansive soils is always an important consideration in pavement design.

B.5—Frost action

Field experience with concrete pavements has shown that frost action damage is usually caused by abrupt differential heave rather than subgrade softening during thawing. Design of concrete pavement projects should be concerned with reducing nonuniformity of subgrade soil and moisture conditions that could lead to differential heaving.[18,29]

For frost heave to occur, three conditions must be present: a frost-susceptible soil, freezing temperatures penetrating the subgrade, and attraction of moisture into the frozen zone. If the soil has a high capillary suction, the water moves to ice crystals initially formed, freezes on contact, and expands. If a supply of water is available, the ice crystals continue to grow, forming ice lenses that will eventually lift or heave the

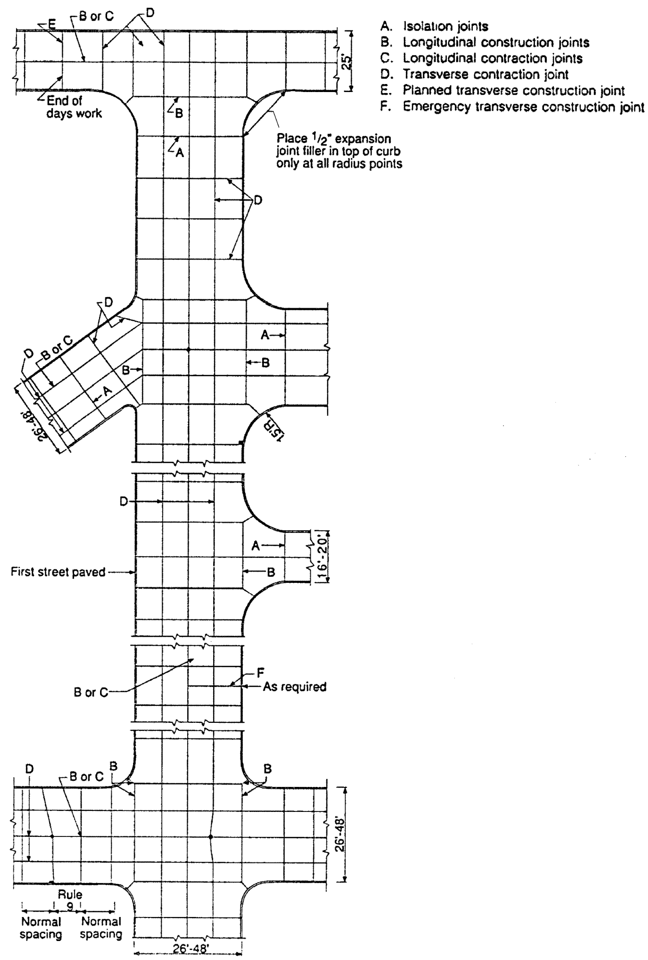

Fig. C.2—Pavement joints and pattern details[33] (1 ft = 0.3048 m).

overlying pavement. The worst heaving usually occurs in fine-grained soils subject to capillary action. Low-plasticity soils with a high percentage of silt-size particles (50 to 5 μm) are particularly susceptible to frost heave. These soils have pore sizes that are small enough to develop capillary suction but are large enough for rapid travel of water to the freezing zone.

To a larger degree, frost heave can be managed by appropriate grading operations and control of subgrade compaction and moisture. If possible, grade lines should be set high enough so that frost-susceptible soils are above the capillary range of the groundwater table. Pockets of highly frost-susceptible soil should be removed and backfilled with soils like those surrounding the pocket. Fine-grained soils should be compacted slightly wet of ASTM D 698 optimum moisture content. Where high grades are impractical, subgrade drainage or non-frost-susceptible cover should be considered.

B.6—Pumping

Pumping is the forced displacement of fine-subgrade soil and water from slab joints, cracks, and pavement edges. It is caused by frequent deflection of slab edges by heavy wheel loads. Highway studies have shown that the following three factors are necessary for pumping to occur: a subgrade soil that will go into suspension; free water between the pavement

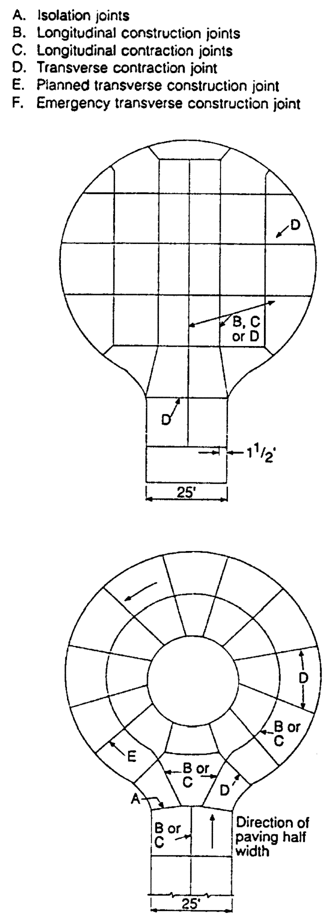

Fig. C.3—Joint layout for cul-de-sac[33] (1 ft = 0.3048 m).

and subgrade or subgrade saturation; and frequent passage of heavy loads.

Normally, pavements that carry less than 100 heavily loaded trucks (80 kN [18,000 lbs] axle loads) per day will not be damaged by pumping, especially if speeds are low; therefore, they do not require subbases. Most parking lots do not have this traffic volume and therefore are not susceptible to pumping.

If a subbase is required, 100 mm of well-compacted granular material with a minimum percentage passing the 75 μm sieve is normally adequate. Cement, lime, or other stabilization agents may also be used. Unstabilized subbases have little influence on pavement thickness design. They cannot be economically justified on the basis of reduced pavement thickness in most cases. On the other hand, stabilized subbases significantly improve pavement support and influence pavement thickness.

APPENDIX C—JOINTING DETAILS FOR PAVEMENTS AND APPURTENANCES

The following are ten rules of practice with respect to joint layout:

1. Joints are used in concrete pavements to aid construction and to minimize random cracking. Odd-shaped areas of pavement should be avoided;

2. Longitudinal joint spacing should not exceed 4.5 m and should conform to the limits suggested by Fig. 4.1. In

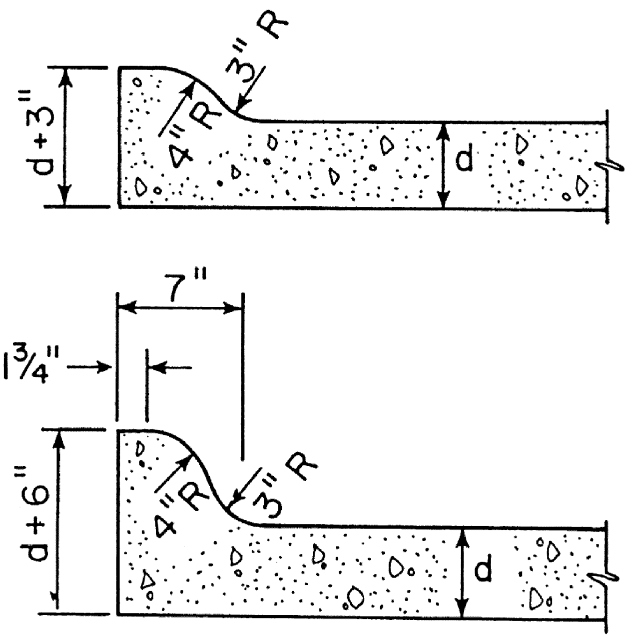

Fig. C.4—Integral curb details[43] (1 in. = 25.4 mm).

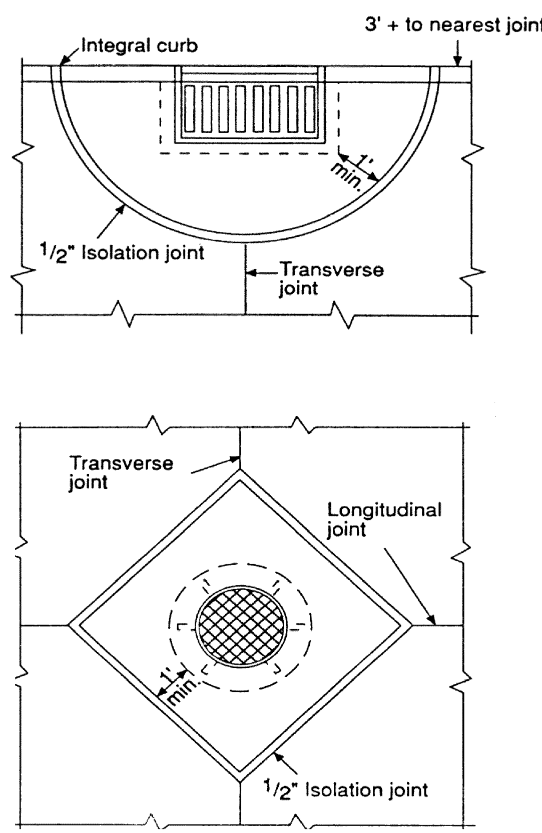

Fig. C.5—Isolation joint for drainage structures and manhole covers[38] (1 ft = 0.3048 m; 1 in. = 25.4 mm).

other words, the layouts shown in Fig. C.2 and C.3 pertain to certain pavement thickness and subgrade modulus combinations;

3. Transverse joint spacing should be at regular intervals as suggested by Fig. C.1 and 4.1, or less, unless local experience indicates that longer spacing can be used without excessive

intermediate cracking. Undoweled slabs may have joints skewed no more than 1 in 10 (counterclockwise);

4. Typically, thinner slabs tend to crack at closer intervals than thicker slabs, and long narrow slabs tend to crack more than square ones. Refer to Fig. 4.1 for specific guidance for joint spacing. Slab panels should be as nearly square as is practical;

5. All contraction joint sawcuts should be continuous through the curb and made at a depth in accordance with the method of sawcutting. Sawcuts made by conventional sawcutting methods should be equal to 1/4 to 1/3 of the pavement thickness. Isolation joint filler should be full depth and extend through the curb. Reinforcement, if used in the curb, should be discontinued at the joint;

6. Longitudinal construction joints can be keyed (tongue and groove or butt-type with tie bars) to hold adjacent slabs in vertical alignment. Keyed joints may be difficult to construct properly in thin pavements. They should not be used in slabs thinner than 150 mm (6 in.) and that particular care be exercised in their construction of pavement thickness of 150 mm (6 in.) or more. The normal backfill behind the curb constrains the slabs and holds them together. With separate curb and gutter built on fill, use tie bars per Fig. 4.3;

7. Offsets at radius points should be at least 0.5 m wide. Angles of less than 60 degrees should be avoided;

8. Minor adjustments in joint location made by skewing or shifting to meet inlets and manholes will improve pavement performance;

9. When pavement areas have many drainage structures, particularly at intersections, place joints to align with the structure configuration; and

10. Depending on the type of castings:

- Manhole and inlet frames may be boxed out and isolated using isolation joint filler;
- The frames may be wrapped with isolation joint filler; or
- The frames may be cast rigidly into the concrete.