

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

Reported by ACI Committee 325



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

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

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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.

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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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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 18 kip (80 kN) single-axle loads and 34 kip (150 kN) 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 8 in. (200 mm) 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

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)—in accordance with ASTM D1883, the ratio of the force per unit area required to penetrate a soil mass with a 3 in.² (1900 mm²) circular piston

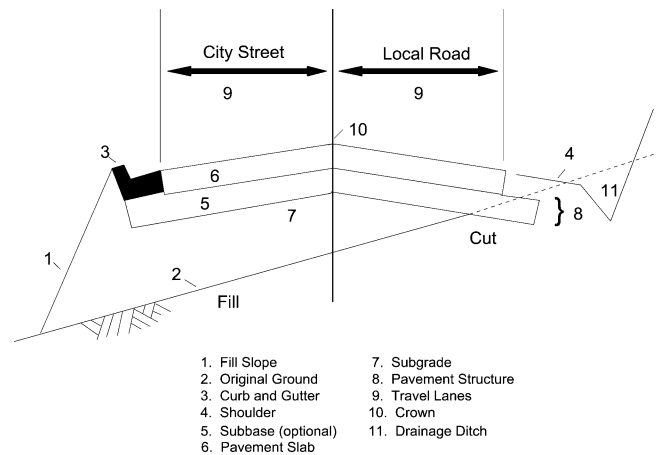


Fig. 1.1—Typical section for rigid pavement structure.

at the rate of 0.05 in. (1.27 mm) per min to the force required for corresponding penetration of a standard crushed-rock base material; the ratio is typically determined at 0.1 in. (2.5 mm) 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 18 kip (80 kN) 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 C78, 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 0.05 in. (1.27 mm) settlement, of a load-settlement curve obtained from a plate load test on a soil using a 30 in. (760 mm) 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 20 ft [6 m] for doweled pavements and 15 ft [4.5 m] 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 40 to 60 ft (13 to 19 m) 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 D4318.

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 D2844. 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 D698 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 1 to 2 ft (0.3 to 0.6 m) 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.

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 D1196 or AASHTO T-222. The procedure consists of incrementally loading a 300-mm (12 in.) (760 mm) diameter plate while measuring the deflection of the

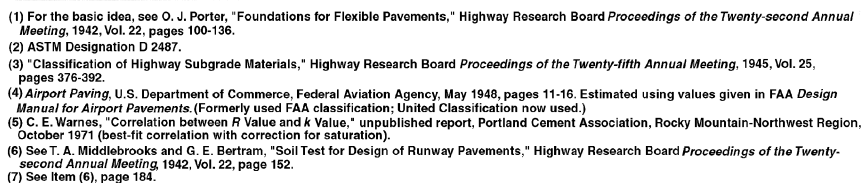


Fig. 2.1—Approximate interrelationships of soil classifications and bearing values.^{12,13}

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 (refer to 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 (18 kip [80 kN] single-axle or 34 kip [150 kN] 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 No. 200 (75 μ m) 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 4 in. (100 mm) 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

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

AASHTO climatic classification	CBR [†] classification		
	Low	Medium	High
Wet-freeze	4	4 [‡]	4 [‡]
Wet	4	4 [‡]	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 4 in. (100 mm) may be eliminated from the design if the subgrade soils met the AASHTO Soil Drainage classification of fair to excellent.

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.

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 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 3/4 in. (19 mm), which is practical, to minimize the mixture water demand and reduce

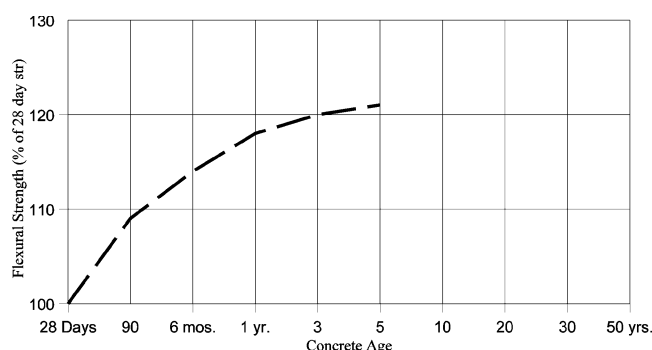


Fig. 2.2—Flexural strength gain versus age.¹²

Table 2.2—Design *k*-values for granular subbases (1 MPa/m = 7 psi/in.)

Subgrade <i>k</i> value, psi/in.	Subbase thickness, in.	
	4.0	6.0
50	60	70
100	110	120
200	220	230
300	320	330

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 C78, 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 C78. 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 C33. Cubical-shaped coarse aggregates have been shown to have a beneficial effect on workability¹⁷ 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 0.5 in. (13 mm) for a 70 psi (0.5 MPa) 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}

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

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 550 to 700 psi (3.8 to 4.8 MPa) 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

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

where γ_{conc} is the concrete unit weight, and a_1 varies between 0.6 to 1.0 for units of psi (0.012 and 0.20 for units of MPa). If desired, however, a specific flexural-to-compressive 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 1.5 in. (38 mm). 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 C94, 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 C94.

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 0.5 and 1.5 in. (15 and 40 mm). Concrete to be placed by hand or with a vibratory

Table 2.3—Recommended percentage air content for air-entrained concrete (ASTM C94)*

Nominal maximum size aggregate, in.	Typical air contents of non-air-entrained concretes	Recommended average air content for air-entrained concretes, %		
		Mild exposure	Moderate exposure	Severe exposure
3/8	3.0	4.5	6.0	7.5
1/2	2.5	4.0	5.5	7.0
3/4	2.0	3.5	5.0	6.0
1.0	1.5	3.0	4.5	6.0
1.5	1.0	2.5	4.5	5.5

Note: 1 in. = 25.4 mm.

*Tolerances: for average air content of 6% or greater, $\pm 2\%$; for average air content less than 6%, $\pm 1\text{--}1/2\%$.

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.

or roller screed should have a higher slump, no greater than 4 in. (100 mm). 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 studies that have been validated by road tests, pavement studies, and surveys of