

ACI 330.2R-17

Guide for the Design and Construction of Concrete Site Paving for Industrial and Trucking Facilities

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Guide for the Design and Construction of Concrete Site Paving for Industrial and Trucking Facilities

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Guide for the Design and Construction of Concrete Site Paving for Industrial and Trucking Facilities

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This guide provides information useful in the design and construction of a successful site-paving project for heavy-duty industrial and trucking facilities. This information assists architects/engineers, contractors, and testing agencies with designing, detailing, constructing, repairing, and inspecting site paving. Engineers use this guide to make recommendations for the pavement support system, concrete mixture, pavement thickness, joint spacing, and load transfer devices. Thickness design tables are including for common over-the-road trucks and industrial lift trucks. Tables are also provided to check the pavement thickness for punching shear and concrete strength for bearing stress applied by loaded trailers that have been disconnected from the tractor. Contractors use this guide to understand proper ways to construct site paving with block or strip placements and avoid common mistakes made during construction. Proper placing, consolidating, and finishing techniques are described to construct a durable pavement that complies with the project documents. Inspectors and testing agencies use this guide to understand the design and be better equipped to monitor the project from stripping and grubbing of the site to concrete pavement curing. Testing and inspection included in this guide should only be done by individuals holding the appropriate certifications.

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Keywords: industrial pavement; joint stability; lift truck; lug anchor; over-the-road truck; pavement support system; sustainable industrial pavement system; unreinforced concrete pavement.

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CHAPTER 1—GENERAL

1.1—Introduction

Concrete provides a strong and durable surface for vehicle maneuvering and storage areas, making it especially suited for site paving at industrial and trucking facilities. Concrete site paving for industrial and trucking facilities has many similarities to other types of concrete pavements, such as typical concrete parking lots, streets, and highways. Service distinctions may include traffic speed and zones dedicated specifically to multi-directional or channelized traffic flow. These facilities are often constructed to serve not only over-the-road trucks, but industrial lift trucks, such as those imposed by dolly wheels and trailer pads, tracked vehicles, other nontraditional vehicles, and other vehicular-related static loads such as trailers dropped on-site between loading and off-loading. Industrial and trucking facilities have paved areas that are generally larger in size than most parking lots. The scale of these projects and the comparatively high traffic count and special loads generally justify more attention to design than typical parking lots. These distinctions along with changing technologies initiated the development of this guide.

Note that **ACI 330R** can be used as a resource for some similarly-described facilities. Each document has been developed as a stand-alone guide that provides critical design information and recommended construction practices for successful paving projects. Guide selection to a specific project should consider the specific traffic loads to be accommodated as well as the design load types, espe-

cially if they include industrial lift trucks and other special loads, the percentage of accommodated vehicles (which are very heavy), site geotechnical considerations such as in-place subgrade character and drainage, joint spacing, and potential future uses of the facility. In general, this guide is intended for facilities with heavier design loads, nonstandard vehicles, higher volumes of heavy trucks, or both. Examples of such facilities include warehouses, factories, truck terminals, heavy equipment sales and service distribution centers, and ports. **ACI 330R** is intended for use when truck loads are generally lighter, traffic volumes lower, or both, though many successful projects accommodating higher average daily truck traffic of mixed vehicle loads have been designed using ACI 330R. Examples of typical parking lots most consistent with the intended scope of ACI 330R would include concrete pavements for apartment complexes, shopping malls, convenience stores, gas stations, banks, and office buildings.

Concrete offers many advantages over asphalt for pavements at industrial or trucking facilities. Concrete provides greater surface and pavement system durability and favorable economics with respect to life-cycle costs, and sometimes even with initial construction costs. Facility night-time illumination can be provided at a lower cost with concrete due to concrete surface reflectance. Concrete also reduces traffic load stresses imposed on subbase and subgrade soils and can be constructed with a wide variety of construction equipment, ranging from hand tools and vibratory screeds, to laser-guided screeds and large highway paving equipment. The sustainable construction benefits of concrete are also an important consideration in pavement type selection (**Chapter 9**).

The paired values stated in inch-pound and SI units are usually not exact equivalents. Therefore, each system is to be used independently of the other. Combining values from the two systems could result in nonconformance with this guide.

1.2—Scope

This guide is based on the current knowledge and practices for the design, construction, and maintenance of concrete site pavements for industrial and trucking facilities, emphasizing the aspects of concrete pavement technology that are different from procedures used to design and construct floor slabs, parking lots, streets, and highways. This guide is neither a standard nor a specification, and it is not intended to be included by reference in construction contract documents.

Pavements for industrial and trucking facilities are designed similarly to parking lots, streets, and highways, but with a few key technical differences. Site pavements have most loads imposed on interior panels surrounded by other pavement, which provide varying degrees of panel edge support or load transfer on all sides. Other pavement applications may carry loads along and across relatively unsupported edges, where greater deflections and stresses are not a significant concern due to lighter design traffic. Streets and highways are commonly designed to drain toward an edge where storm water can be carried away from the pave-

ment. Site pavements are commonly designed so a portion of the storm water is collected internally and conveyed away through underground systems. Site pavements often accommodate appurtenances, such as drainage structures, lighting standards, bollards, and fuel islands. Provisions for these appurtenances should be considered in the design, layout, and construction of the crack-control (jointing) system.

1.3—Background

Design practices for concrete site pavements have often varied by local experiences and are based on guidance derived from a combination of design references covering heavy pavements and floor slabs. The unique demands of these types of facilities have made it challenging for project designers to integrate all appropriate design protocols and consider all performance influences. This document is intended to respond to the need for a single, source guide on concrete site paving for industrial and trucking facilities.

Concrete pavement thickness is one of the critical design elements for industrial and trucking facility site paving applications, just as it is for parking lots and other mixed-vehicle pavements. This is true not only for engineering economy but also for the pavement structure to reliably carry loads from nontraditional vehicles and certain static loads. For concrete site paving, proper thickness design should minimize pavement stresses and deflections along joints and pavement edges. Many types of geotechnical site conditions that can successfully accommodate light traffic pavements are not appropriate for industrial and trucking facility site pavements without enhancement of the subgrade system, inclusion of one or more subbases, or both. This type of distinction also extends to load transfer considerations.

Subgrade improvement, joint spacing and layout, and load transfer strategies are important elements of industrial and trucking site pavement design. Thickness should reflect these considerations along with pavement stress levels for all envisioned loadings. Construction planning should consider surface durability needs and appropriate tolerances.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

B_n	=	nominal bearing strength
B_u	=	factored bearing load
E_C	=	modulus of elasticity
k -value	=	modulus of subgrade reaction
M_R	=	resilient modulus
M_R	=	resilient modulus
V_n	=	nominal shear strength
V_u	=	factored shear force

2.2—Definitions

ACI provides a comprehensive list of definitions through an online resource, “ACI Concrete Terminology,” <https://www.concrete.org/store/productdetail.aspx?ItemID=CT13>. Definitions provided herein complement that source.

distributed steel reinforcement—steel reinforcement bar mats used in pavement to hold concrete together across

cracks that form; this type of reinforcement is assumed not to contribute to the structural capacity of pavement.

dowelled joint—joint that uses smooth parallel bars or plates for load transfer, allowing for in-plane movement.

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

expansive soils—soils that exhibit relatively significant shrinkage or expansion caused by loss or gain of moisture, often resulting in reduction of soil support; these soils are typically, but not always, classified as AASHTO A-6 and A-7 materials, or USCS type CH, MH or US soils with a plasticity index (PI) greater than 25.

frost-susceptible soil—material in which significant detrimental ice aggregation will occur because of capillaries that permit the movement of moisture to the freezing zone when requisite moisture and freezing conditions are present.

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

modulus of subgrade reaction, k —stress per 1 in. (25 mm) penetration of a circular plate into the subgrade and determined generally from the stress required to cause 0.05 in. (1.3 mm) penetration of a 30 in. (760 mm) diameter plate.

moisture-density curve—graphical representation of the relationship between the compacted density of a subgrade soil to its moisture content, which is determined as a function of the compacted dry density.

pavement structure—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 loads to the subgrade.

reinforced pavement—pavement containing distributed steel reinforcing to control cracking due to shrinkage and temperature gradients.

resistance value R —stability of a soil, as determined by the Hveem Stabilometer using [ASTM D1560](#) and [ASTM D2844](#) or [AASHTO T90](#) and [T246](#), measures the horizontal pressure resulting from a vertical load.

sawing window—the period of time between which sawing of the concrete should be begun and completed.

soil support—index number that expresses the relative ability of a soil or aggregate mixture to support traffic loads through a flexible pavement structure; also, a term found in the basic design equation developed from the results of the AASHTO Road Test ([National Research Council 1962](#)).

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

standard Proctor density—maximum soil density at optimum moisture content as defined in [ASTM D698](#).

swelling soil—see **expansive soil**.

tied joint—joint that uses deformed reinforcing bars to inhibit the joint from opening.

window of finishability—the time available to complete all concrete placing and finishing operations required to achieve the desired surface tolerance and texture

CHAPTER 3—SUBGRADES AND SUBBASES

3.1—Pavement support system

The foundation layers on which a pavement is supported are important to the proper design of the pavement and are critical to its long-term performance under traffic. The foundation support system consists of a subgrade and, as needed, a subbase layer. Figure 3.1 presents a typical section through a concrete pavement showing subgrade and subbase layers. When the existing soil has adequate strength, volumetric stability, and nonpumping material properties, the pavement can be placed directly on the existing prepared, graded, and compacted subgrade. Subgrade soils alone, however, might not be an adequate foundation for concrete pavements that support heavy industrial or truck load applications. If the subgrade soils are not adequate, a subbase layer can be added to improve the strength and uniformity of the material directly under the pavement and improve its long-term performance. Subbases can also facilitate construction operations and schedules, as they can provide a stable working platform for paving operations.

The pavement foundation system provides support for the pavement and is included in the structural analysis of the pavement thickness using a support reaction. This is typically modeled as a subgrade reaction k -value, which is essentially a spring constant. Note that some methods of pavement analysis can structurally analyze a multi-layer rigid pavement system that includes the surface, subbase, and subgrade layers. These methods are beyond the scope of this guide. Finite element modeling or layer-elastic analysis can be employed for this type of multi-layer design, and can often result in optimized pavement sections. However, appropriate analysis and design computer programs and advanced expertise of the designer are necessary.

The foundation support system for a concrete pavement should provide the following characteristics:

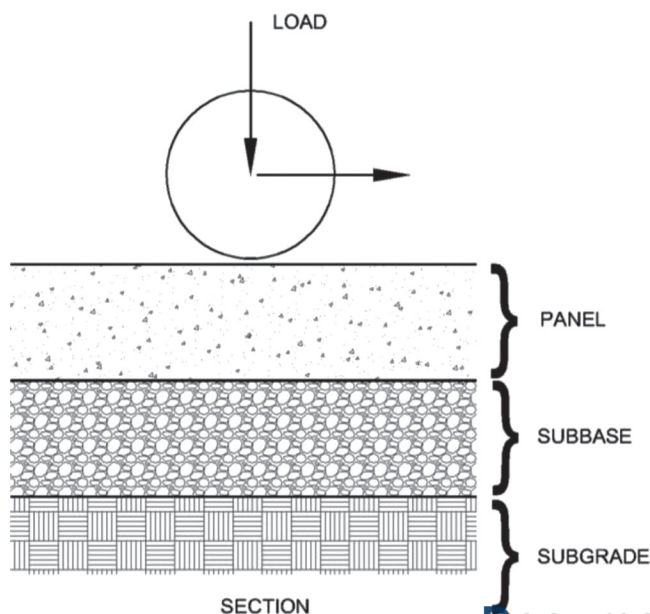


Fig. 3.1—Panel support system

- (a) Adequate and uniform support
- (b) Control of volumetric stability if subgrade materials are expansive
- (c) Frost-heave resistance
- (d) Resistance to erosion (pumping) under heavy loads
- (e) Support of construction operations
- (f) Appropriate drainage for the subbase/subgrade system used

Rigid concrete pavements require foundation systems that accomplish the tasks noted previously. The stiffness of concrete spreads surface loads over wide areas. Therefore, subgrade/subbase strength is not an overriding criterion for the system, as is the case for flexible pavement systems. Concrete pavement thickness is somewhat insensitive to foundation strength and stiffness; designing a stronger or thicker foundation system to achieve a thinner concrete pavement is not a cost-effective strategy. The other considerations noted previously, however, will often require subgrade modification, a subbase layer to achieve foundation support objectives, or both, as well as ensuring long-term performance of the concrete pavement.

Concrete pavement designs incorporate a spring constant, called the modulus of subgrade reaction, or k -value, to account for the subgrade stiffness and its reaction with the concrete pavement. The k -value is determined by the plate load test (AASHTO T235; ASTM D1194), which is performed by placing a 30 in. (760 mm) diameter plate on the subgrade and loading it with a very heavy load. The k -value is found by dividing the plate pressure by plate deflection under the load. The plate load test is seldom conducted, however, and k -values are often calculated by a correlation from a more common soil test such as resilient modulus (M_R) (AASHTO T307) or California Bearing Ratio (CBR) (ASTM D1883; AASHTO T193). Guidance on k -values for various subgrade and subbase conditions is provided in 3.3 and 3.4. Information on using a dynamic cone penetrometer (DCP) (ASTM D6951/6951M) to correlate CBR values for subgrade soils is found in Appendix A.2.

It is highly recommended that a licensed professional architect/engineer with competence in geotechnical engineering be involved in soil evaluation and recommendations for subgrades and subbases for industrial pavements.

3.2—Subgrade/subbase failure modes

A well-designed concrete pavement can fail prematurely if the foundation system fails to maintain uniform support. This can happen in several ways. It is the function of the subgrade and subbase to prevent pavements from failing due to the effects that follow.

3.2.1 Weak and wet soils—Weak soils are generally wet and compressible, potentially resulting in an unstable construction platform and isolated weak spots that cause abrupt changes in pavement support.

3.2.2 Erosion at joints and cracks and pumping—For erosion of the subgrade or subbase to occur at joints, the following four conditions must exist: 1) poor load transfer (no dowel bars); 2) heavy and fast moving traffic; 3) a pumpable subgrade/subbase material; and 4) water presence. These

conditions can cause a loss of support at joints, resulting in faulting. Faulting is the differential, often vertical, displacement between panels at a joint. Faulting can also occur in a similar manner at random cracks within a panel, especially if it occurs outside of areas that require positive load transfer via a dowel.

3.2.3 Frost action—Frost-susceptible foundation material can cause frost heaving during the winter months, and subgrade softening in the spring, both of which can result in uneven support. This results in degradation of ride quality, as well as increased stresses in the concrete, causing cracking.

3.2.4 Expansive soils—Expansive soils can shrink or swell, depending on their moisture state. The effect on concrete pavement is similar to that from frost action: uneven support, degradation of ride quality, and cracking.

3.3—Subgrade considerations

Every pavement foundation begins with the subgrade—the natural soils that ultimately support all the pavement layers above. The uniformity and long-term stability of the foundation soils affect the performance and constructability of the concrete pavement. If a subgrade will be the only layer in the foundation system, it is vital that it is also can support the paving operations during construction.

The in-place subgrade soil conditions and properties should be determined by appropriate soils testing on the area to be paved. The extent of the geotechnical investigation should be determined by the magnitude of the project and by conditions discovered that may warrant a more detailed examination. Typical soil borings are spaced 100 to 300 ft (30.5 to 91.4 m) apart and should generally extend 5 to 10 ft (1.5 to 3.0 m) below the planned finished grade. A geotechnical investigation should include soil identification and classification for determining the properties of in-place soils and their suitability for use as foundation soils. The soil should be classified according to one of the standardized systems, such as the Unified Soil Classification System (USCS) (ASTM D2487) or the AASHTO M145 system. Laboratory testing on subgrade soils should include moisture content, Atterberg limits, sieve analysis, and moisture-density relationship. The modulus of subgrade reaction (k -value), CBR, resistance value (R -value), or soil support value (SSV) can also be determined for design purposes. The resilient modulus (M_R) can be measured through AASHTO T307. Figure 3.3 provides the approximate interrelationship among various soil classifications and bearing types (Packard 1984). Information on soil classification are found in Appendix A.1.

The modulus of subgrade reaction (k -value) is normally used as the design parameter for concrete pavements. Table 3.3 shows typical k -values for three broad classifications of subgrade soils (American Concrete Pavement Association [ACPA] 2012).

Corrective action should be taken if problem subgrade soils are encountered. Problem subgrade soils that may potentially cause a negative effect on the performance of the concrete pavements are this soil type:

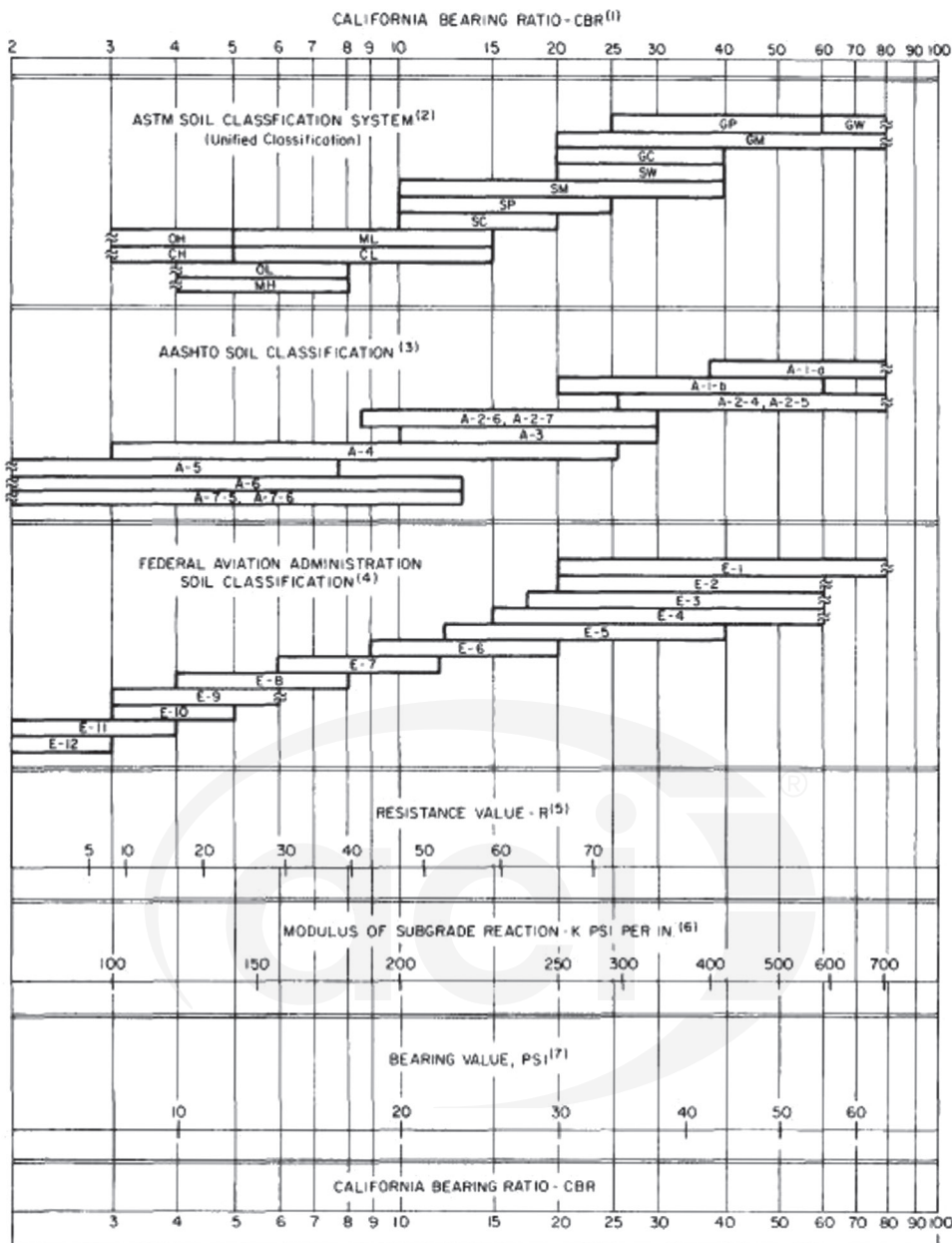
- (a) Pumping
- (b) Frost-susceptible



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- (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 D2487.
 (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, Unified Classification now used).
 (5) C. E. Warrens, "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 Tests 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. 3.3—Approximate relationships of soil classifications and bearing index values (ACPA 2012).

(c) Expansive

(d) Inadequate for a construction platform

3.3.1 Pumping—Pumping is the forceful displacement of subgrade soils that have been mixed with water through concrete panel joints, cracks, or edges. Continued pumping along pavement joints, cracks, and edges produces loss of subgrade strength, loss of support, and erosion. This subgrade distress is generally caused by the movement of fine-grained subgrade soils in the presence of water. These

fine-grained soils are pumped upward out of the joint or laterally as a result of deflection of adjacent panels caused by heavy traffic loads and poor load transfer at the joints. When sufficient fines are removed from under the slab, faulting of the joint can occur. Pumping can be reduced by installing a quality granular subbase layer, the cementitious stabilization of the subgrade foundation soils (although stabilized fine grained soils are still susceptible to pumping), or installing a geotextile that can prohibit the passing of the soils through

Table 3.3—Modulus of subgrade reaction, k , for typical subgrade soils (ACPA 2006)

Soil type	Support	Typical k -values, pci (MN/m ³)
A. Fine grained with high amounts of silt/clay	Low	75 to 120 (20 to 34)
B. Sand and sand-gravel with moderate silt/clay	Medium	130 to 170 (35 to 49)
C. Sand and sand-gravel with little or no silt/clay	High	180 to 220 (50 to 60)

the fabric. Improved joint stability using a dowel system will also reduce or eliminate pumping and faulting.

3.3.2 Frost susceptible soils—Where frost penetration is deeper than the thickness of the pavement plus any granular subbase thickness, frost action should be considered. For frost heave to occur, three conditions are required, including: 1) frost susceptible soil; 2) freezing temperatures penetrating the subgrade; and 3) supply of water. Frost action damage is caused by abrupt differential heave rather than subgrade softening during thawing. Low-plasticity soils with a high percentage of silt-size particles at least 15 percent finer than 0.02 mm (No. 10 sieve), such as very fine silty sands (SP), silts (ML, MH), and clays with a plasticity index (PI) less than 12 (CL, CL-ML), are particularly susceptible to frost heave. If possible, grade lines should be set high enough 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 similar to those surrounding the pocket. Where high grade lines are impractical, subgrade drainage or non-frost-susceptible cover should be considered. Soil modification with cement, Class C fly ash, or lime/Class F fly ash, is another option. Alternatively, the entire full-depth pavement cross section may be designed to be non-frost-susceptible.

3.3.3 Expansive soils—Expansive soils shrink and swell with changes in moisture content. Typical soil types that are susceptible to problematic differential movement, also known as volume change, include AASHTO A-6 and A-7 materials, or Unified Classification System CH, MH, or OH soils, with a PI greater than 25. Clays with PIs less than 25 are typically not problematic for concrete pavements. Cross-hauling, selective grading, and blending of these lower-plasticity clays can even out changes in soil characteristics.

The amount of volume change in clay soils depends on the degree of moisture change and the moisture and density conditions at the time of construction. To minimize the impact of volume change, these clay soils should be compacted at 1 to 3 percent above optimum moisture content as determined by the Standard Proctor test (ASTM D698). The modified Proctor test (ASTM D1557) is not recommended for clay soils.

Cementitious modification is often the most economical method of dealing with expansive clay soils. Modification with portland cement, slag cement, hydrated lime, Class C fly ash or lime/Class F fly ash, or combinations of these materials, can reduce the shrink-swell potential and improve soil

strength. Stabilization also allows a higher-PI clay subgrade to act as an all-weather work platform. Each of these cementitious stabilizers acts in different ways with different soils. Additionally, the ultimate stabilized strength of the soil can vary widely depending on the stabilizer. Finally, the durability and permanence of the stabilizer should be considered during the service life and service conditions of the pavement. Recommended guidelines are provided by ACI and other associations for portland cement stabilization (ACI 230.1R; PCA 2004), fly ash stabilization (American Coal Ash Association 2008), and lime stabilization (National Lime Association 2004). Leach resistance of the stabilizer should also be considered. For lime, enough should be added to achieve long-term stabilization, as opposed to temporary modification. Lime (calcium hydroxide) principally can leach prior to the slow development of pozzolanic lime-clay reaction products that arrest leaching (National Lime Association 2004). Portland cement hydrates quickly, and early hydration keeps soluble calcium hydroxide within the soil matrix. One other caution exists with cementitious stabilization of soils with lime, cement, or Class C fly ash. If natural sulfate levels in the soil exceed 0.3 percent, sulfates could react with the calcium hydroxide from the cementitious materials, aluminates from the soil, and available water to form ettringite, a highly expansive calcium sulfoaluminate product, resulting in severe heaving. A geotechnical engineer should be consulted regarding alternatives if sulfates are present near the paving. Slag cement has been found to be a useful stabilization binder for preventing the expansive sulfate reactions when used as a prevalent component of the cementitious blend. (Harris et al. 2006).

The depth of stabilization should be determined by a geotechnical engineer, and can vary from 6 in. (150 mm) to several feet (meters). Soils can be stabilized in place up to approximately 12 in. (300 mm); if thicker stabilization is required, the soil will need to be stripped to an appropriate depth and then stabilized and compacted in layers.

Another method of reducing the influence of expansive soils is to construct a non-expansive buffer zone to reduce moisture changes that impact the extent of volume change in expansive soils. This buffer layer should be at least 3 ft (0.9 m) thick and should consist of low-permeability materials such as silty and sandy clays (CL) with a PI ranging from 10 to 24. Sands and other granular materials are not recommended for this buffer zone, as they can allow moisture intrusion into the underlying expansive subgrade. Buffer zone soils should be compacted to a minimum of 98 percent of maximum dry density as determined by ASTM D698, or 95 percent of maximum dry density as determined by ASTM D1557.

One important note is that the inclusion of steel reinforcement in the concrete pavement does not negate the need for stabilization or a buffer zone to compensate for poor subgrade materials and preparation (ACPA 2007).

3.3.4 Weak and wet soils—Weak soils are generally wet and compressible, potentially resulting in an unstable construction platform. Isolated weak spots also cause abrupt changes in pavement support and should be avoided. Weak soils are generally excavated and replaced with firm soils and then

backfilled with select borrow material of a similar strength. When the depth of weak soils is excessive, a bridging layer can be constructed using a geotextile fabric or membrane. Cementitious stabilization is also an alternative to the removal of an excessive amount of weak subgrade soils.

For excess moisture in the soils, drains can be built before construction to allow the soil to dry. This may take longer than expected, so other methods may need to be employed. Excavation of wet soils and replacement with soils of the proper moisture content is also an alternative, but often too expensive if needed for more than isolated areas. Selective grading and mixing of soils can also be helpful. Cementitious stabilization can be an effective alternative for large areas, as the stabilizer, when applied as a dry powder, both consumes moisture through hydration and strengthens the soil as it cures. Finally, geosynthetics can be used to remove excess moisture. The proper use of geosynthetics is a specialized process that requires knowledge of the normally proprietary geosynthetic materials, the soils, and the functional objectives.

3.3.5 Working platform—Concrete pavements spread loads over wide areas; therefore, often the highest subgrade stresses encountered are during construction operations, and not under service traffic conditions. A minimum CBR of 6 in the top 24 in. (600 mm) has been found by researchers for the Wisconsin Department of Transportation to provide an adequate working platform for construction loads (Crovetti and Schabelski 2001). Compacting the subgrade to a uniform density that provides this working platform is important. The most commonly specified minimum compaction density at optimum moisture is 95 percent, although lower target densities are acceptable if the compaction is uniform and soil strength at the target density is adequate for both construction and service conditions. Although many native soils provide adequate support to allow for construction directly on the subgrade, many designs may include subgrade stabilization, even when the subgrade soils are adequate for construction and service conditions. This provides an all-weather work platform that does not need to be dried, regraded, and/or recompacted during wet weather or heavier-than-expected loads. Alternatively, a granular, stabilized or unstabilized, subbase layer could be added to provide this platform. A granular unstabilized subbase may still require drying or reworking after rain events.

3.4—Subbase considerations

Subbases are included as a design element in many heavy-duty pavements. A subbase layer, or layers, is located directly below the concrete pavement. The goals of a subbase are to provide a non-eroding, nonpumping layer that gives uniform support to the concrete pavement under all loading and environmental conditions, and to provide a stable working platform for paving operations. If the subgrade soils are adequate to accomplish these goals, a subbase is probably an unwarranted expense. Many of the problem soil issues noted in 3.3, however, can be partially or completely mitigated by using a subbase layer.

3.4.1 Mitigating subbase problems

3.4.1.1 Pumping—Improving load transfer at the joints and preventing the presence of water between the surface and support layers are good methods for mitigating pumping. Pumping can be mitigated using an adequate subbase, however, and is often the principal reason for considering a subbase. In concrete site paving for industrial and trucking facilities subjected to heavy axle loads, dowels are typically used at the joints, and often the vehicle speeds are relatively low. These factors can eliminate pumping as a criterion for choosing a subbase, though a designer may select a subbase based on other considerations. Materials most susceptible to pumping are high-plasticity silts and clay soils, and granular subbase materials with more than 15 percent fines passing the No. 200 (75 μ m) sieve. Unstabilized, pump-resistant subbase materials are discussed in 3.4.1.1. If a subbase is required to prevent pumping, even though only 2 or 3 in. (50 to 75 mm) are needed to prevent pumping, 4 in. (100 mm) is a practical minimum thickness because of the difficulty of compacting thin layers.

3.4.1.2 Frost action—A subbase can help protect a frost-susceptible subgrade. If the thickness of the concrete surface layer plus the frost-resistant subbase layer is deeper than the expected frost penetration level, the subgrade soils will not exhibit frost heave, even if they are frost-susceptible. A frost-resistant unstabilized subbase material generally contains less than 15 percent fines passing the No. 200 (75 μ m) sieve, and preferably the fines should be near the minimum fines content noted in the gradation specification. Also, cement-stabilized or asphalt-stabilized subbase layer can mitigate frost susceptibility. Lime-stabilized subbases, which should contain enough plastic clayey material to react with the lime, are not suitable for frost-resistant subgrades. Lime/fly ash-stabilized subbase materials should be used with caution and adequate strength should be achieved prior to the first frost penetration.

3.4.1.3 Expansive subgrades—A subbase helps reduce the problems associated with expansive soils by providing a buffer zone for reduced moisture intrusion into the expansive soils, as recommended in 3.3.3. Cement or asphalt-stabilized subbase layers also can reduce moisture intrusion below, but lime-stabilized subbase layers should not be used for this purpose. Sometimes, a combination of subgrade stabilization and the use of treated subbases are needed to mitigate expansive subgrade soils.

3.4.1.4 Weak and wet subgrade soils—The subbase should never be placed prior to the subgrade being compacted at proper moisture and density. A subbase, even the stiffest stabilized or lean concrete subbase, will not compensate for the problems caused by a wet or soft subgrade.

3.4.2 Working platform—A common reason for use of a subbase is to provide a stable working platform. This is particularly important for slipform paving, as the subbase provides a smooth track line. Also, if the subgrade soils are relatively weak, with a CBR of less than 6, the subbase can provide adequate strength to support construction operations, even if the lower-strength subgrade is adequate for nonconstruction service conditions. If the subgrade is to be placed using a slipform paver, the working platform

should be extended approximately 3 ft (0.9 m) from each edge of the pavement to provide a stable platform for the slipform paver tracks.

3.4.3 Subbase design—A subbase layer can range in thickness from 4 to 12 in. (100 to 300 mm) or more, depending of the characteristics of the subbase and subgrade materials. Subbases can be made from either unbound granular materials or stabilized materials.

3.4.3.1 Unstabilized subbases—In selecting unstabilized subbase materials, a wide variety of soils or aggregates can be chosen. This variety allows the designer to consider lower-cost local materials, including, but not limited to, crushed stone, sands, sand-gravels, crushed recycled concrete, or sand-shell mixtures. The ideal materials will have:

- (a) Maximum-sized aggregate less than one-third the subbase thickness
- (b) Less than 15 percent passing the No. 200 (75 μ m) sieve
- (c) PI of 6 or less
- (d) Liquid limit (LL) of 25 or less
- (e) Percentage of wear when tested in accordance with **AASHTO T96** or **ASTM C131/C131M** of 45 percent or less
- (f) Permeability of approximately 150 ft/day (45 m/day), but no more than 350 ft/day (107 m/day), using **AASHTO T215**

Specifications for unstabilized base course material include **AASHTO M147**, **AASHTO M155**, **ASTM D1241**, and **ASTM D2940/D2940M**. Most state departments of transportation also have base course specifications suitable for a concrete subbase for heavy-duty pavements.

Unstabilized subbases should be free-draining, which is defined in 3.4.3.1(f), but not permeable. Permeable unstabilized subbases, where gradation excludes a fines component making them essentially porous, are not recommended because of problems with stability and long-term consolidation.

Thorough compaction of the subbase is essential. Soft, spongy, or wet subgrades will preclude proper subbase compaction; therefore, adequate subgrade preparation is important prior to subbase construction.

Typical resilient moduli (M_R) for dense-graded, free-draining unbound aggregate subbases range from 15,000 to 45,000 psi (100 to 300 MPa), and are compared in Table 3.4.3.1a to different types of subgrade stabilization and subbase stabilization alternatives. When subbases are used, a composite k -value, representing the combined effects of a subbase on a subgrade is typically employed as the reaction constant in concrete pavement design. Table 3.4.3.1b shows typical composite k -values for various thicknesses of unbound granular subbase on different soil types. This table is also applicable for different thicknesses of lime-stabilized subgrade on unstabilized subgrade.

k -values can also be estimated from the resilient modulus for an unbound soil, through the equation

$$k \text{ (pci)} = M_R \text{ (psi)} / 19.4 \text{ (AASHTO 1993)} \quad (3.4.3.1a)$$

If the soil resilient modulus is not known, M_R can be estimated from CBR through the equation

Table 3.4.3.1a—Resilient modulus values for different subbase and stabilized subgrade types (ACPA 2012)

Type	Subbase resilient modulus M_R , psi	Subbase resilient modulus M_R , MPa
Dense/free draining unbound compacted granular materials	15,000 to 45,000	100 to 300
Lime modified subgrade	20,000 to 70,000	140 to 480
Bituminous stabilized subbase	40,000 to 300,000	280 to 2000
Cement stabilized subgrade	50,000 to 1,000,000	340 to 7000
Hot-mix asphalt subbase	350,000 to 1,000,000	2400 to 7000
Cement treated subbase	500,000 to 1,000,000	3500 to 7000
Lean concrete/economy concrete subbase	1,000,000 to 2,000,000	7000 to 14,000

Table 3.4.3.1b—Composite k -values for unbound granular subbase on unstabilized subgrade (ACPA 2006)

Soil type*	Soil layer k -value, pci (MN/m ³)	Thickness of unbound granular subbase			
		4 in. (100 mm)	6 in. (150 mm)	9 in. (225 mm)	12 in. (300 mm)
A	100 (27)	130 (35)	140 (38)	160 (43)	190 (52)
B	150 (41)	176 (48)	185 (50)	215 (58)	255 (69)
C	200 (54)	220 (60)	230 (62)	270 (73)	320 (87)

*Refer to Table 3.3.

$$M_R \text{ (psi)} = 1500 \times \text{CBR (AASHTO 1993)} \quad (3.4.3.1b)$$

3.4.3.2 Stabilized subbases—Stabilized subbases are normally bound by either portland cement, combinations of cementitious materials, or asphalt. Lime is typically not an appropriate material for subbase stabilization, as it will not provide adequate binding capability. However, lime modification, as well as cement modification, can be considered if the objective is to reduce PI of a marginal aggregate. This aggregate, however, is still considered an unstabilized material. Blends of portland cement, slag cement, and fly ash can also be considered as stabilizers. Class C self-cementing fly ash or a lime/Class F fly ash mixture are other alternatives if adequate strength and durability can be achieved with the specific fly ash. Lean concrete is another subbase type that is considered a stabilized material.

A stabilized subbase provides several benefits:

- (a) Provides strong, uniform support, even with somewhat varying materials
- (b) Provides high degree of support (very high modulus of subgrade reaction or k -values)
- (c) Maintains excellent all-weather construction work platform
- (d) Minimizes subbase consolidation
- (e) Minimizes intrusion of subgrade materials into the subbase over time

(f) Maintains strength, stability, and uniform support during saturated conditions

From a cost and sustainability perspective, one key reason to consider stabilization is to enhance marginal or inferior local materials to a point where they can be effectively used as a subbase. In particular, stabilization can make use of recycled crushed concrete that otherwise could perform poorly in wet conditions or could be of poor gradation. Examples of poor gradation include recycled asphalt pavement, or inferior local aggregates such as poorly graded materials, soft aggregates, and aggregates with high-plasticity fines that will not pass traditional unbound aggregate specifications.

Stabilized subbase layers are generally 4 to 12 in. (100 to 300 mm) thick and develop strength as a result of the bond that develops between the aggregates and cementing materials. Stabilized subbases are commonly compacted to at least 100 percent of maximum dry density using standard effort as determined by [ASTM D698](#), or 95 percent of maximum dry density using modified effort as determined by [ASTM D1557](#), although lean concrete subbases are better regulated by concrete cylinder strength testing as defined by [ASTM C39/C39M](#). If a stabilized subbase or treated subgrade is used, the increased support it provides should be considered in the thickness design. Table 3.4.3.2a for asphalt/bituminous treated subbases and Table 3.4.3.2b for cement treated and lean concrete subbases show ranges of *k*-values for different thicknesses of subbase on various soil types ([ACPA 2006](#)).

One concern from the use of stabilized subbases of any type is the potential for uncontrolled cracking in concrete pavement. Uncontrolled cracking can occur in concrete pavement on very stiff, stabilized subbases due to two principal factors: 1) high friction between the concrete and the subbase, which restrains concrete panel movement and induces higher tensile stresses; and 2) greater curling stresses due to stiff subbases that are less able to spread out the loads caused by concrete slab curling. This cracking potential can be minimized three ways:

- 1) Minimize bonding of the concrete pavement to the subbase
- 2) Keep strength of stabilized subbase materials as low as possible while still maintaining adequate strength and durability
- 3) Use shorter joint spacing and deeper saw-cut joints

Bonding can be minimized in several ways: for example, using two coats of white pigmented, waxed-based curing compound, a thin sand dusting layer, asphalt emulsion, or nonwoven geotextile.

Strength of stabilized subbases should be kept at 300 psi (2 MPa) for less at 14 days as long as this achieves appropriate durability for the moisture, frost, and service conditions. When stabilized subbases are used, joint spacing should be kept less than the maximum for the given pavement thickness. Additionally, joints should be cut a minimum of one-third the pavement thickness depth for traditional saw-cutting. Early-entry saw-cutting depths on stabilized subbases should be based on the saw manufacturer's recommendations.

Table 3.4.3.2a—Composite *k*-values for asphalt/bituminous treated subbase (ACPA 2006)

Soil type*	Soil layer <i>k</i> -value, pci (MN/m ³)	Thickness of bituminous/asphalt treated subbase			
		4 in. (100 mm)	6 in. (150 mm)	9 in. (225 mm)	12 in. (300 mm)
A	100 (27)	152 (41)	194 (53)	259 (70)	325 (88)
B	150 (41)	217 (59)	271 (74)	353 (96)	437 (119)
C	200 (54)	280 (76)	345 (94)	442 (120)	541 (147)

*Refer to Table 3.3.

Table 3.4.3.2b—Composite *k*-values for cement treated subbase and lean concrete/econcrete subbase (ACPA 2006)

Soil type*	Soil layer <i>k</i> -value, pci (MN/m ³)	Thickness of cement treated/lean concrete subbase			
		4 in. (100 mm)	6 in. (150 mm)	9 in. (225 mm)	12 in. (300 mm)
A	100 (27)	185 (50)	257 (70)	372 (101)	496 (135)
B	150 (41)	263 (71)	357 (97)	506 (137)	664 (180)
C	200 (54)	348 (95)	454 (123)	634 (172)	823 (223)

*Refer to Table 3.3.

Deciding on the proper stabilizer dosage rate for a material should be based on laboratory testing and good industry practice. The following references provide recommendations for stabilized subbase design and construction:

- (a) Cement-treated base ([ACI 230.1R](#); [Halsted et al. 2006](#))
- (b) Asphalt-treated base ([Asphalt Emulsion Manufacturers Association 2009](#))
- (c) Fly ash ([ACAA 2008](#))

For more information about all aspects of stabilized and unstabilized subgrade/subbase design and construction, refer to [ACPA \(2007\)](#).

CHAPTER 4—PAVEMENT DESIGN

4.1—Introduction

Design of an industrial or trucking facility pavement entails selecting dimensions and other details to provide a system of concrete panels that will carry the anticipated loads to the subgrade, provide proper joint stability and performance, channelize and segregate traffic where needed, incorporate required drainage features and lighting, and allow for efficient and economical construction.

For industrial and trucking facilities, it is imperative that the designer consider all factors that influence the performance of a concrete pavement. Such factors include truck traffic or other vehicular loads, patterns and frequencies, subgrade/subbase support, concrete strength, pavement panel thickness, joint spacing, joint stability (load transfer), the use of curbs and widened lanes, humidity and ambient effects (humidity and temperature).

Ambient effects on pavement during construction and throughout its design life have a significant effect on the magnitude of warping and curling in the pavement, and, therefore, the stresses in the concrete under load. The

analysis of ambient effects on the pavement design adds a level of complexity that this guide does not consider, but there are proprietary design systems available that do if the designer should wish to optimize the design to this level. Four of these design approaches are discussed in [Appendix B \(B.1\)](#) under proprietary design software.

After the estimation of traffic levels, the most influential factors in the design of concrete pavements are thickness; joint spacing, which also affects the magnitude of warping and curling; and joint detailing. Compared to concrete material strength and subgrade/subbase support, the pavement thickness, joint spacing, and joint detailing have a far greater impact on the load-carrying capability of the pavement. There is a significant interaction between joint spacing, thickness, and joint stability, which is the load transfer between adjacent panels, so all three requirements should be considered together as part of the design system.

While pavement thickness more than that required by proper design can result in a higher construction cost, thicker slabs have lower load-induced deflections and flexural stresses. A decreased joint spacing will result in reduced magnitudes of warping and curling, and joint detailing with appropriate load transfer will provide joint stability and reduce edge and corner stresses. Inadequate thickness or joint detailing could result in unsatisfactory performance, an increase in maintenance expenses, or even require early replacement. Selection of the appropriate thickness, joint spacing, and details requires an evaluation of traffic levels, soil conditions, selection of concrete properties, and design life.

Selecting the proper pavement subgrade/subbase, thickness, materials, and details will result in a pavement system that supports the most critical loads without inducing excessive stress in the pavement panels. The most critical loads are determined by magnitude, contact area, and frequency. Joints, or cracks between joints, produce discontinuities in the pavement system. Loads crossing these discontinuities can cause increased deflections and stresses in the pavement panels and the supporting subgrade/subbase. Repeated deflections of a panel edge or undoweled joint, and the resulting displacement or pumping of the subgrade/subbase, can eventually cause cracking in the central portion of the panel and faulting at the joint. Providing the proper joint stability using load-transfer devices helps minimize joint faulting during pavement life.

Proper joint detailing has a significant influence on the load-induced stresses in pavement. Sufficient joint stability should be achieved to reduce the stress on the subgrade/subbase and in the concrete pavement. Some pavement designs rely upon aggregate interlock as the load-transfer mechanism. Warping, curling, and shrinkage, however, can reduce joint stability by disengaging aggregate interlock, allowing the free edges to deflect independently under wheeled traffic. Positive load-transfer devices, such as dowels, are commonly used whenever the designer cannot be assured of positive long-term load transfer at the joints through aggregate interlock. Dowels, either round or square steel bars, or plates should be used in joints intended to open, such as the transverse joints in lengths of access road or joints

extending in both transverse and longitudinal directions to large paving areas common in industrial and trucking facilities. Careful evaluation of the size, shape, spacing, alignment, and method of installation for the dowels is required to ensure the required performance. Dowels should provide positive load transfer for joint stability, allow joints to activate freely, and accommodate the differential shrinkage of adjacent panels. If dowels restrain the joints from opening or induce restraint to the normal shrinkage of panels, then random cracking or dominant joint activation may occur. Dominant joints are the joints that open wider than other joints to compensate for adjacent joints that are locked or remain tight due to some form of restraint. Properly-designed dowels minimize lateral restraint, provide improved joint stability, and reduce load-induced deflections and stresses. Tie-bars can also be used, but their use should be limited to joints intended to remain tight, such as the longitudinal joints between pavement lanes in stretches of access road or the joints between the two outermost panels of a pavement, without curbs to prevent panel shifting. Joint stability can be provided in saw-cut contraction joints by enhanced aggregate interlock. Enhanced aggregate interlock depends on a combination of the effect of the tie-bar (short length of deformed reinforcement) through the joint and the irregular face of the cracked concrete at the joints for load transfer.

Methods used to determine concrete pavement design are based on theoretical (mechanistic) and field (empirical) studies that relate:

- (a) Applied loads (truck traffic)
- (b) Material properties, which is the subgrade/subbase support and concrete strength
- (c) Pavement panel geometry, including thickness, panel length, and panel width
- (d) Edge support, such as joint stability and curb and shoulder details, to the required performance of concrete stresses, fatigue characteristics, and required design life

Experimental pavement performance studies have been supplemented by studies of the performance of pavements built to commercial standards that carry random combinations of traffic and are exposed to environmental changes. These studies have enabled paving engineers to gain knowledge about the performance of concrete pavements under controlled and normal conditions. Though the intent of these studies was to provide data for the design of pavements intended to carry street and highway traffic, the data and analysis also provide useful information for those responsible for designing concrete pavements for industrial and trucking facilities, as the traffic and loads are often very similar.

This chapter addresses design from the point of view of accommodating loads, shrinkage, and thermal effects, but does not address concrete durability, which influences the long-term performance of concrete pavement. Those considerations are addressed in [Chapter 5](#).

4.2—Loads

4.2.1 Introduction—An industrial or trucking facility pavement will be subjected to varying, but repeatable, vehicular and storage loads throughout its lifetime. To deter-

mine the required concrete pavement thickness, the designer should know the types of loads that will be applied to the pavement, such as static, point, and wheeled vehicle loads of various types; the magnitude, contact area, and configuration of the loads; and the repetition or total volume anticipated for each type of wheeled vehicle load over the design life of the facility. Owner's projections of the type of loads expected in a facility, supplemented by traffic studies or counts for similar facilities, should provide adequate information for the design.

4.2.2 Traffic loads—Estimating the expected traffic load magnitude and frequency is an important factor in pavement design. The required traffic information includes the vehicle type and frequency of operations for each separate section of the facility.

4.2.3 Traffic pattern effects—Because pavement thickness and other design details influence project costs, one should consider planned facility traffic patterns early in the design process. Different areas of the facility can accommodate different vehicle loads or frequencies. Apron areas where unloaded trailers are parked for long periods, for example, may not require the same thickness as loading dock areas where loaded trucks operate frequently. Another example to consider is the variation in truck loads; trucks leaving a facility are often full, whereas trucks returning to a facility are often empty. Consideration of these factors can allow for significant economizing of the pavement where design loads will be less severe. Likewise, pavement areas with the heaviest traffic may require more costly designs to provide good service for the intended design life.

The design process should be coordinated with the facility layout and traffic plan, in consideration of the specific vehicles to be accommodated. Vehicle turning radii typically control some of the design geometrics and dimensions, especially where maneuvering around loading docks or trailer parking spaces takes place. To the extent possible, channeling heavy traffic along specific corridors or patterns can allow larger portions of the facility paving to meet design requirements with less load, less repetition, or both.

Site slope and the direction, speed, or braking of vehicles can also affect the need for certain other design details, such as tie-bars across the outermost joints of pavements without curbs, to prevent panel shifting (4.6.3).

4.2.4 Truck traffic loadings and axle-load distributions—The design method of Tables 4.7.3b through 4.7.3m uses the number of trucks per day in the design lane to model the loads on the concrete pavement. This number includes only trucks with six tires or more and excludes panel and pickup trucks or other four-tire vehicles. The truck axle loadings are distributed according to Table 4.2.4a or 4.2.4b. Because the number of trucks presented in these tables represents the traffic over pavement life, the designer should adjust the present number of trucks to anticipate any future traffic growth. Table 4.2.4c can be used to multiply the present-day number of trucks by an appropriate projection factor to arrive at an estimated average daily truck count. Figure 4.2.4 provides an example of axle load configuration for over the road trucks.

Table 4.2.4a—Axle load distributions for Category D

Axle load		Number of axles per 1000 trucks
1000 lb	kN	
Single axles		
16	71	1000
Tandem axles		
32	142	2000

Table 4.2.4b—Axle load distributions for major arterial traffic

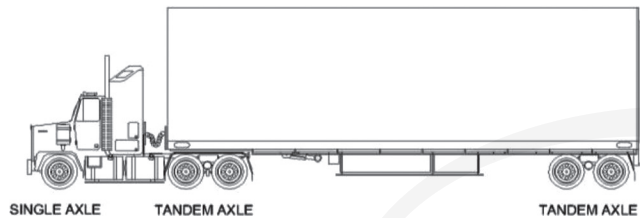
Axle load		Number of axles per 1000 trucks
1000 lb	kN	
Single axles		
16	71	57.07
18	80	68.27
20	89	41.82
22	98	9.69
24	107	4.16
26	116	3.52
28	125	1.78
30	133	0.63
32	142	0.54
34	151	0.19
Tandem axles		
24	107	71.16
28	125	95.79
32	142	109.54
36	160	78.19
40	178	20.31
44	196	3.52
48	214	3.03
52	231	1.79
56	249	1.07
60	267	0.57

4.2.5 Industrial lift-trucks and other industrial vehicles—Vehicles such as lift-trucks, mobile cranes, gantry cranes, log stackers, and other industrial equipment are commonly used at industrial facilities. These vehicles, which can carry huge payloads along with high tire pressure, can induce significant point loads to the concrete pavement. Section 4.7.4 provides thickness design tables for this type of equipment. Where pavement design is controlled by these vehicles, greater economy may be possible by confining these operations to specific, limited areas within the facility.

4.2.6 Static loads—Sometimes, loose or palletized materials, containers, and temporary structures are stored in industrial facility parking areas. If this is anticipated, the impact of the distributed load should also be considered. These loads are not included in design tables of this publication because of the site-specific nature of such loading.

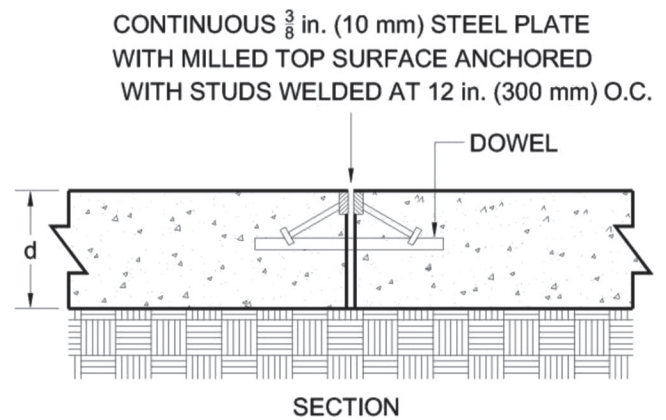
Table 4.2.4c—Yearly rates of traffic growth and corresponding projection factors

Yearly rate of traffic growth, %	Projection factor 20 years	Projection factor 30 years
1	1.1	1.2
1.5	1.2	1.3
2	1.2	1.4
2.5	1.3	1.5
3	1.3	1.6
3.5	1.4	1.7
4	1.5	1.9
4.5	1.6	2.0
5	1.6	2.2
5.5	1.7	2.4
6	1.8	2.6

**Fig. 4.2.4—Over-the-road truck.**

4.2.7 Concentrated loads—If semi-trailers are to be disconnected from the tractor, the design should consider the concentrated loads applied to the semi-trailer supports, which are commonly referred to as dolly jacks or sand shoes. The loads on these supports could exceed the axle loads of the semi-tractor trailer combination and are typically applied to smaller contact areas. Consequently, they can have a significant impact on the load-induced stresses of pavements, especially if they are applied near joint locations. Where pavement design is controlled by nonstandard loads, such as parked trailers supported by dolly jacks or sand shoes, greater economy is possible by confining these operations to specific, limited areas within the facility. Refer to 4.7.5 and 4.7.6 for the thickness design of pavements that will receive these loads.

4.2.8 Hard tires and track machine traffic—If the expected traffic has hard tires or wheels, such as solid rubber, polyurethane, or steel, consider designing joints to limit the differential deflection between joints to less than 0.010 in. (0.25 mm) (ACI 360R). Hard-wheeled vehicles apply higher contact stresses to the pavement joints than conventional pneumatic-tired vehicles. These higher stresses can result in severe joint deterioration if the joints are not designed and maintained properly. In some cases, a semi-rigid joint filler that restores surface continuity should be used as opposed to a flexible joint sealer to minimize the risk of joint spalling. In the most severe cases, such as for tracked vehicles, or where steel blades or buckets are used on industrial equipment to clean or move materials stored on the pavement, joints may need to be

**Fig. 4.2.8—Armored joint.**

armored with studded steel bars (Fig. 4.2.8) or other means such as angle iron with shear connectors or epoxy composites to reinforce concrete at joints (ACI 302.1R; ACI 360R). Another viable option is to design pavement with limited joints using continuous reinforcement—a design option that is outside the scope of this guide.

4.3—Concrete properties

4.3.1 Concrete mixtures—Concrete mixtures for paving should be designed to produce the required flexural strength, provide adequate durability, and have adequate workability for efficient placement, finishing, and texturing. Loads applied to concrete pavement produce both compressive and flexural stresses in the pavement panels. However, flexural stresses are more critical because heavy loads will induce flexural stresses that will approach the concrete flexural strength. Consequently, flexural strength or modulus of rupture (MOR) of the concrete is used in pavement design when selecting thickness.

4.3.2 Flexural strength—Flexural strength is determined by the modulus of rupture test in accordance with ASTM C78/C78M. The 28-day strength is normally selected as the design strength for pavements. This can be conservative because concrete continues to gain strength after 28 days, and the pavement may not be placed in service until after 28 days. Occasionally, because early-age construction loading can occur, it should be considered during design. Because the ASTM C78/C78M test requires relatively large and heavy test specimens, and is more subject to testing variability, it is more practical to use compressive strength testing for quality control and acceptance in the field. It is important that the correlation between compressive strength and flexural strength be documented with data. This is done by testing the concrete mixture in the laboratory or with performance records from a previous project or projects that used the same concrete mixture design and materials.

Flexural strengths can be estimated using the equations described below. It is highly recommended, however, that the correlation between compressive strength and flexural strength be defined by laboratory testing with the materials to be used on the project. As with all testing, careful handling and curing of specimens is important to avoid large variations

in test results. If the average flexural strength is not readily available, the correlations between flexural and compressive strength can be approximated using the following.

For concrete made with smooth-textured, round-shaped aggregates, an approximate relationship between specified compressive strength f'_c and MOR can be expressed using Eq. (4.3.2a) (Huang 1993).

$$\text{MOR (psi)} = 8\sqrt{f'_c} \text{ (in.-lb)} \quad (4.3.2a)$$

$$\text{MOR (MPa)} = 0.7\sqrt{f'_c} \text{ (SI)}$$

An approximate relationship between compressive strength f'_c and MOR for concrete made with rough-textured, angular-shaped and typically crushed aggregates can be expressed using Eq. (4.3.2b) (Huang 1993).

$$\text{MOR (psi)} = 10\sqrt{f'_c} \text{ (in.-lb)} \quad (4.3.2b)$$

$$\text{MOR (MPa)} = 0.8\sqrt{f'_c} \text{ (SI)}$$

4.3.3 Modulus of elasticity—Modulus of elasticity (E_c) is also used in the design of concrete pavements. E_c can be determined in accordance with **ASTM C469/C469M**. Modulus of elasticity is the ratio of stress to strain of a concrete specimen and expresses the stiffness of hardened concrete. This stiffness indicates how much the material will deflect under load and how the concrete panel will distribute loads. Typical values of E_c range from 2 to 6 million psi (14,000 to 41,000 MPa) based on correlations with compressive strength provided in **ACI 318**. Concrete pavement thickness design is relatively insensitive to E_c when compared to how sensitive thickness is to modulus of rupture. E_c may be correlated with compressive strength by using Eq. (4.3.3a) (ACI 318). The elastic modulus can be written in terms of MOR using Eq. (4.3.3b). Refer to Table 4.3.3 for values of E_c based on common values of modulus or rupture used for concrete pavements.

$$E_c \text{ (psi)} = 57,000\sqrt{f'_c} \text{ (in.-lb)} \quad (4.3.3a)$$

$$E_c \text{ (MPa)} = 4700\sqrt{f'_c} \text{ (SI)}$$

$$E_c = 6750 \text{ MOR} \quad (4.3.3b)$$

4.3.4 Shear and bearing strength—Shear and bearing strengths of concrete are important properties to consider in heavy trucking and industrial facilities. Heavy concentrated loads applied by semi-trailer support legs create high stresses capable of punching through or crushing thin concrete panels. Nominal shear and bearing strength of concrete can be found in ACI 318. Equation (4.3.4a) represents the nominal shear strength and Equation (4.3.4b) represents the nominal bearing strength of concrete.

$$V_n = 2.66\lambda\sqrt{f'_c}b_o d \quad (4.3.4a)$$

Table 4.3.3—Modulus of elasticity (E_c) values based on MOR

MOR, psi (MPa)	E_c , psi (MPa)
550 (3.8)	3,700,000 (25,511)
650 (4.5)	4,400,000 (30,337)
750 (5.2)	5,100,000 (35,163)

$$B_n = 0.85f'_c A_1 \quad (4.3.4b)$$

where $\lambda = 1.0$ for normalweight concrete; b_o is the periphery length (perimeter of vertical equivalent shear plane), in. (mm); d is the thickness, in. (mm); A_1 is the area, in.² (mm²); and f'_c is the specified compressive strength, psi (MPa).

4.4—Jointing

4.4.1 Introduction—Jointing is one of the most critical aspects of concrete pavement design and construction. Both joint spacing and joint stability affect the required pavement thickness, so the selection of joint spacing, joint type, and load transfer devices has a major impact on the pavements design and performance under traffic.

4.4.2 Joint types—Joints are placed in concrete pavement to minimize random cracking and facilitate construction. The three types of joints that are commonly used in concrete pavement are isolation (4.4.2.1), construction (4.4.2.2), and contraction (4.4.2.3).

4.4.2.1 Isolation joints—Concrete pavements should be separated from other structures or fixed objects within or abutting the paved area to offset the effects of expected differential horizontal and vertical movements. Isolation joints are used to separate pavement from structures, such as buildings, drains, manholes, light pole foundations, water valve covers, and drop inlets. Isolation joints are vertical joints that extend the full pavement thickness and are filled with a premolded material (Fig. 4.4.2.1a). Premolded material prevents the new concrete panel from bonding to other structures during and after concreting operations. The premolded material should extend through the full panel thickness or used with void caps so the joint can be properly sealed with closed-cell backer rod and joint-sealant material. The types of premolded materials include bituminous mastic, bituminous impregnated cellulose or cork, sponge rubber, recycled tire rubber, and resin-bound cork. These premolded materials should be installed in accordance with the manufacturer's recommendations.

Isolation joints should not be confused with expansion joints, which are not needed in jointed, unreinforced concrete pavement. Isolation joints are not recommended for routine use as regularly spaced joints because they are difficult to construct and maintain, and can often be a source of pavement distress, distortion, and premature failure. Avoid using isolation joints in areas that encounter wheeled traffic whenever possible. If on the rare occasion they are required to isolate an existing pavement from a new one with a different joint spacing or to avoid cracking at T-joint intersections, then they should be installed with a compressive material of 1/2 in. (13 mm) or less. Using the type of joint creates a

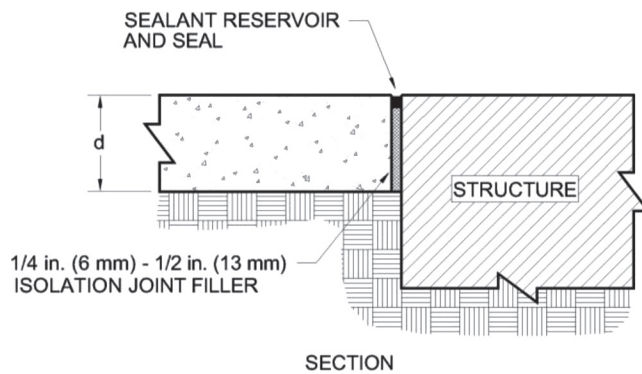


Fig. 4.4.2.1a—Isolation joint.

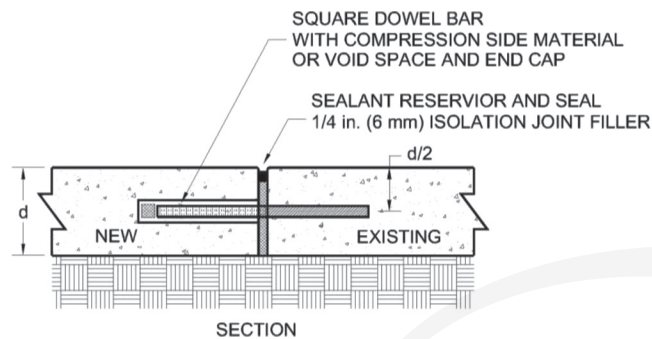


Fig. 4.4.2.1b—Transition between new and existing pavements with different joint spacing.

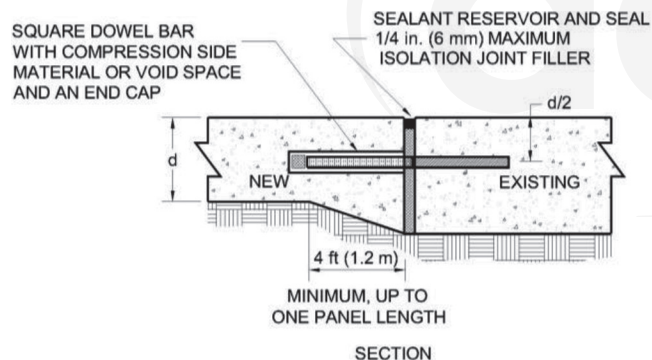


Fig. 4.4.2.1c—Transition between new and existing pavements with different joint spacing and thickness.

free edge condition requiring the use of dowels or a thickened edge to accommodate edge loading stresses. If dowels are required for positive load transfer, the designer should choose a dowel system that provides both room for expansion and allows for the differential shrinkage of the adjacent slab, such as a square dowel with compressible side material or void space and end cap (Fig. 4.4.2.1b). Where slabs of different thicknesses come together at isolation joints, the subgrades under the thinner pavement sections should be shaped to provide gradual thickness transition over a distance of 4 ft (1.2 m) or more (Fig. 4.4.2.1c). Isolation joints are not recommended along the face of curb and gutter abutting a pavement. Where isolation joints are used to isolate other objects, structures, or pavements that will receive traffic but cannot be doweled, such as manholes, drop inlet, or catch

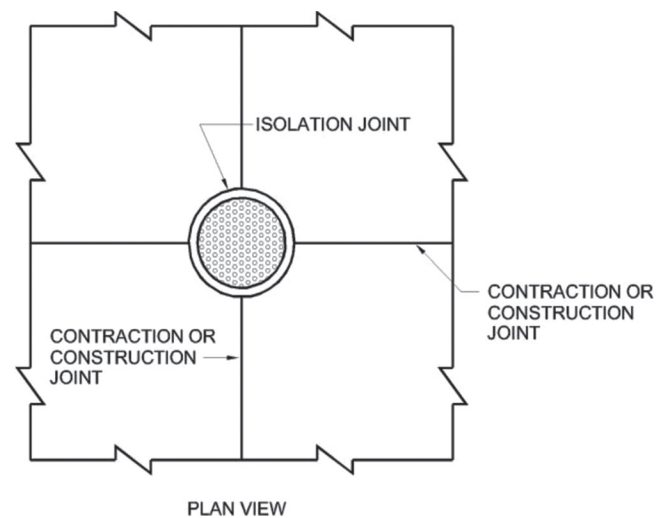


Fig. 4.4.2.1d—Manhole or drop inlet boxout.

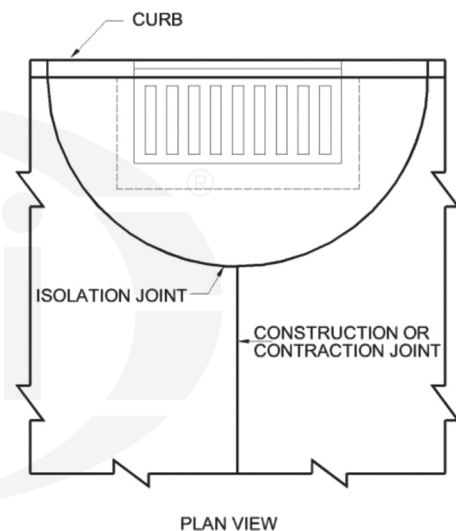


Fig. 4.4.2.1e—Catch basin boxout.

basin outlets (Fig. 4.4.2.1d through 4.4.2.1f), a thickened edge isolation joint (Fig. 4.4.2.1g) can be used to reduce the edge stresses in the pavement. In these areas, the subgrade/subbase should also be shaped to provide a gradual thickness transition, as described previously.

4.4.2.2 Construction joints—Construction joints separate areas of concrete placed at different times during construction stages. Construction joints are designed for both unplanned interruptions and planned work stoppages in paving operations, such as those that occur at the end of a day or construction shift. They are generally located in predetermined locations to conform to a specified joint layout and generally interchangeable with contraction joints.

Construction joints can be formed using bulkheads, slip-formed, or saw-cut full-depth. Forms typically are wood or metal and should be plumb, installed at the finished pavement elevation, and sufficiently rigid to support all placement and finishing operations. Keyways of half-round or trapezoidal shape are no longer recommended due to poor performance histories. When load-transfer devices (dowels)

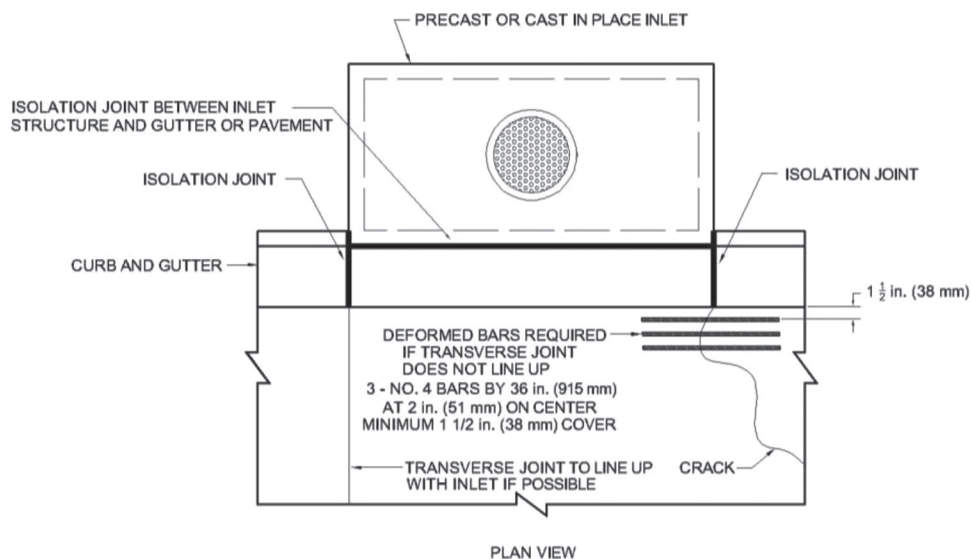


Fig. 4.4.2.1f—Precast or cast-in-place inlet.

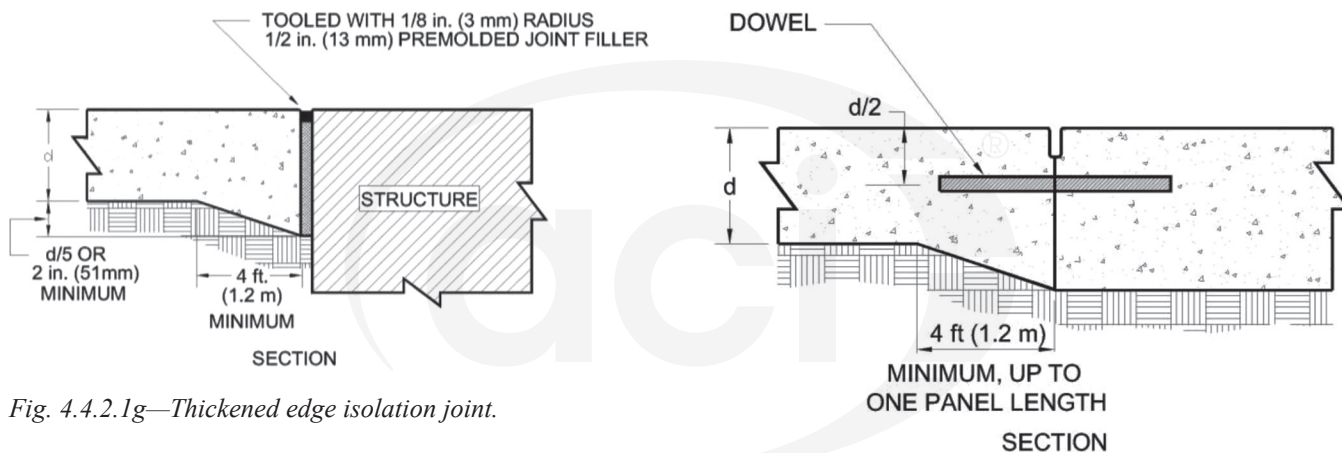


Fig. 4.4.2.1g—Thickened edge isolation joint.

are required, provisions should be made to ensure the proper alignment of the specified device. Refer to 4.6.2.5 for information on dowels in construction joints.

All construction joints should be internally vibrated at frequent intervals to properly consolidate the concrete at the joint and around load-transfer devices. In emergency situations, such as lack of materials, sudden changes in weather, or equipment breakdown, a construction joint should be installed in place of the nearest contraction joint location. Where slabs of different thicknesses come together at construction joints, the subgrade/subbase under the thinner pavement sections should be shaped to provide gradual thickness transition over a distance of 4 ft (1.2 m) or more (Fig. 4.4.2.2).

4.4.2.3 Contraction joints—Contraction joints are used to control the location of cracks caused by restrained shrinkage and thermal shortening of the concrete and the effects of warping and curling. As previously stated, there is a significant interaction between joint spacing, thickness, and joint stability; thus, the designer should consider the design and performance requirements of the pavement and specify an appropriate joint spacing as part of the design system (Section 4.4.4 and Table 4.4.4).

Fig. 4.4.2.2—Transition between sections of pavements with different thicknesses.

Contraction joints in industrial pavements should be created by sawing a continuous slot in the pavement to create planes of weakness that subsequently produce cracks at that location as the concrete shrinks and warps or curls. Plastic or metal inserts, or grooves tooled in the fresh concrete, are not recommended for constructing or forming contraction joints in industrial pavements exposed to wheeled traffic.

With conventional walk-behind concrete saws, the timing of the sawing generally begins 8 to 12 hours after placement, as soon as the concrete has hardened enough to support the saws, depending on weather conditions, mixture properties, and the effectiveness of curing procedures. If light, early-entry saws are used, sawing can begin much sooner—approximately when walking on the pavement is permitted. Regardless of sawing equipment, sawing cannot begin if doing so causes raveling. Therefore, rather than simply planning to start sawing operations at a specific time after placement, it is best to consider each mixture and each day of paving uniquely, and start sawing when the concrete does.

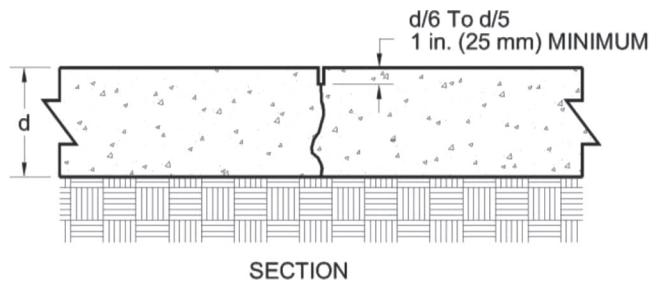


Fig. 4.4.2.3a—Contraction joint (early-entry saw).

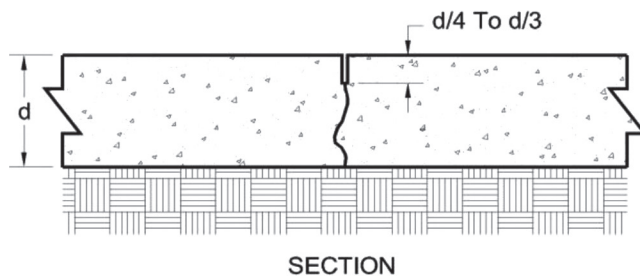


Fig. 4.4.2.3b—Contraction joint (conventional saw).

not ravel or crack prior to or during sawing. This is a judgment decision for the contractor.

The influence of saw-cut depth on early-age joint activation (controlled cracking beneath a sawed joint) depends primarily on the time of sawing. Early-entry sawing methods with sawing depths of $d/6$ to $d/5$ (where d is the panel thickness) but at least 1 in. (25 mm) deep (Fig. 4.4.2.3a) may provide better crack control than conventional methods with typical depths of $d/4$ to $d/3$ (Fig. 4.4.2.3b); such early-entry cuts should be made. Typically, early-entry sawing occurs within 3 hours of placement and 1 to 2 hours after finishing.

If the joints are to be sealed, a second cut typically is necessary to create a proper depth-to-width ratio for the sealant reservoir. If joints are to be unsealed or filled with either a rigid material to prevent joint spalling or a flexible material to minimize the ingress of sand, soil, or other incompressible materials, a second joint reservoir saw-cut is not necessary.

The depth of the cut should be at least one-fourth of the slab thickness when using a conventional saw or 1 in. (25 mm) when using early-entry saws on slabs 8 in. (200 mm) or less in thickness. Early-entry saws that can cut deeper (up to 3 in. [75 mm]) are now commonly available and should be used in thicker pavements to ensure the cut depth is at least one-sixth of the pavement thickness ($d/6$) when using early-entry saws.

Contraction joint patterns should divide pavements into panels as close to square as possible. The aspect ratio of a panel should not be more than 1.5 to 1. T- and L-shaped panels should be avoided and joint patterns across lanes should be continuous wherever possible (4.5.3). Where the exterior pavement edge curves or is not parallel with the pavement body, the intersecting joints should be offset a minimum of 18 in. (460 mm) to prevent acute angles or thin sections at their terminus. Refer to Fig. 4.4.2.3c for an illustration of how to avoid acute angles.

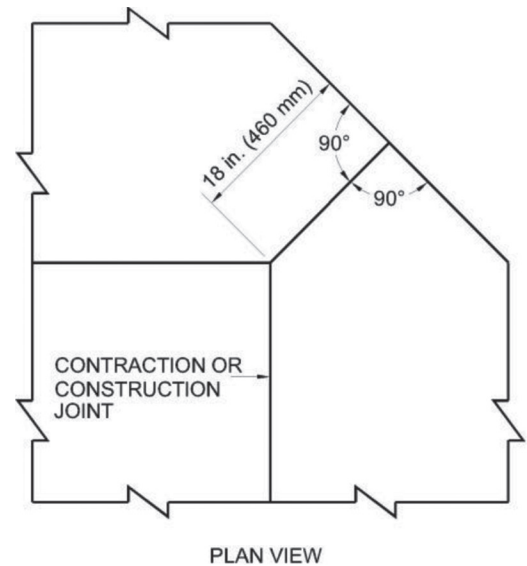


Fig. 4.4.2.3c—Illustration of avoiding acute angles.

Pavement joints of any type should extend through any curb and gutter. A scaled drawing of the jointing plan for the pavements and curbs should be part of the design package.

4.4.3 Joint sealing—Joints can be sealed for two reasons: 1) to keep water from saturating the subgrade/subbase; and 2) to prevent the introduction of incompressible materials into the joint. Joint sealant manufacturers' recommendations are designed to create a sufficient depth-to-width ratio and side wall adhesion to allow the joint sealant to stretch sufficiently to accommodate the joint's movement and maintain the seal. If the intent of the designer is to minimize the saturation of subgrades/subbases by reducing the ingress of water into the joint, then the saw-cuts should be at least 3/8 in. (10 mm) wide for sealed joints, although a 1/2 in. (13 mm) wide cut is commonly recommended (Fig. 4.4.3a). If the intent of the designer is to prevent the ingress of incompressibles into the joint, then joints can be left at their original width and filled (Fig. 4.4.3b). Full adhesion to both faces of the joint might not be maintained, but the compressible material will accommodate any necessary joint closure. If joint sealing is not specified, then the thinnest saw-cut available should be used. New saw-blade technology has made it possible to create saw-cuts as thin as 1/16 in. (1.6 mm) for both conventional saws and early-entry saws. Sealed joints are only recommended where the benefits justify the added expense to construct and maintain. For some projects, it might be determined that the cost of installation and maintenance of proper joint sealing outweighs the potential damage to the pavement and corrosion of the dowel system over time. Rather than spending money on sealing all joints, some designers recommend using granular subbases and geotextiles where silts and clays are present so that water passing through the open joints will not create significant subbase damage. There are four applications, however, where joint sealing is always recommended:

1. Where fuel or other chemical spills might contaminate the soil

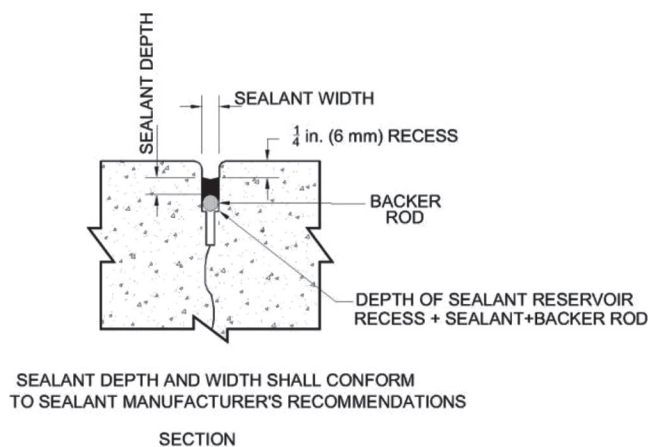


Fig. 4.4.3a—Joint sealant with backer rod.

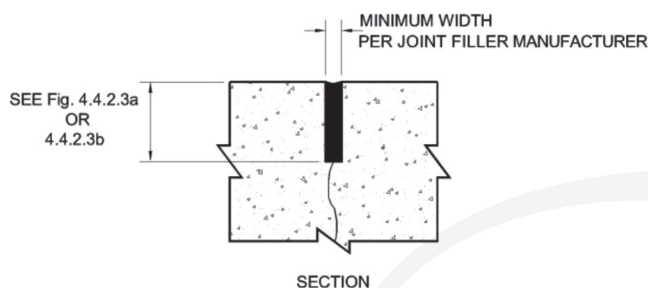


Fig. 4.4.3b—Joint filling.

2. At temporary ponding zones around stormwater drainage inlets
3. When needing to minimize the adverse effects of dowel corrosion
4. Where small-particle materials are spilled, mixed, or stored on the pavement.

4.4.4 Joint spacing—Joints are placed in concrete pavement to minimize random cracking and facilitate construction. To effectively control cracking due to tensile stresses created by restrained shrinkage and warping or curling caused by moisture or temperature differentials, respectively, it is important to have the joints properly spaced. Proper spacing of joints for conventional pavement designs depends on the pavement thickness and the concrete's shrinkage potential. Concrete mixtures with lower shrinkage potential result in pavements with reduced warping behavior, reducing the risk of random cracking between joints. In many areas, however, locally-available materials might not be favorable to the production of low-shrinkage concrete. As stated previously, there is a significant interaction between joint spacing, joint stability (load transfer), and thickness design. Therefore, the recommended joint spacings for pavements designed for over-the-road truck traffic are contained within the thickness designs presented in Tables 4.7.3b through 4.7.3m. For other designs, Table 4.4.4 provides recommendations for the spacing of joints for various pavement thicknesses up to a maximum spacing of 15 ft (4.5 m), regardless of thickness. Designers are cautioned that these recommended joint spacings are intended to minimize the potential for midpanel out-of-joint cracking and are independent of load transfer

Table 4.4.4—Joint spacing for unreinforced concrete pavements if spacing is not included in the thickness design table

Pavement thickness, in. (mm)	Maximum spacing, ft (m)
5, 5.5 (130, 140)	12.5 (3.8)
6 or greater (150 or greater)	15 (4.5)

Note: The recommended joint spacing for pavements designed for standard truck traffic are included in thickness Tables 4.7.3b through 4.7.3m.

requirements at joints. If aggregate interlock is being considered as the only load-transfer mechanism in contraction joints, the joint spacing and shrinkage potential of the concrete mixture design should be evaluated. Furthermore, not all joints activate uniformly. This results in some joint opening widths that are larger than might normally be anticipated (Walker and Holland 2007). When the designer cannot be sure of positive long-term load transfer at all joints by aggregate interlock, then dowels should be used at all joints subject to wheeled traffic.

4.5—Reinforcement

4.5.1 Steel reinforcement—When pavement is jointed to form short panel lengths that will reduce warping and curling as well as relieve internal stresses, midpanel reinforcement is not necessary. The practice of adding distributed steel to increase panel length, panel widths, or both leads to increased joint movement and intermediate panel shrinkage cracks that can deteriorate over time. Shorter unreinforced panels are generally more economical and provide better performance. In jointed pavement designs, the use of distributed steel reinforcement will not add to the load-carrying capacity of the pavement and should not be used in anticipation of poor construction practices or soil conditions. When fully loaded concrete trucks and screeding equipment must operate on the subgrade/subbase, the presence of reinforcement can prevent the contractor from recompacting and leveling the grade during construction, which is counterproductive to quality construction and the mitigation of out-of-joint cracking. In areas where deicing salts and similar materials are used, distributed steel and load-transfer devices also present a risk of corrosion.

4.5.2 Continuously reinforced concrete pavements (CRCPs)—In the rare condition where saw-cut contraction joints cannot be tolerated or are not wanted, they may be eliminated with the inclusion of a minimum steel ratio of 0.5 percent (Farny and Tarr 2008) of the pavement cross-sectional area in the direction where the contraction joints are eliminated. The significantly increased cost of materials and construction makes this design extremely rare in industrial and trucking facilities. This document does not cover the design and construction of CRCP. Refer to ACI 360R for more information on designing slabs reinforced for crack width control.

4.5.3 Odd-shaped panels—The designer should provide a layout of joints and joint details. Pavement panels should be as square as possible with a maximum aspect ratio of 1.5 to 1. Odd-shaped panels, such as L- and T-shaped panels, should be avoided to minimize restraint corner cracking.

Where odd-shaped panels cannot be avoided, or special circumstances require panels with an aspect ratio of greater than 1.5 to 1, designers should consider using reinforcement—macro-synthetic or steel fibers, or distributed steel—to minimize the width of random cracks. This reinforcement is normally furnished in the form of deformed steel bars, welded wire reinforcement, or macro-synthetic fibers. Steel reinforcing bars or welded wire reinforcement should be positioned in the upper one-third of the pavement thickness and should be supported during all placing and finishing operations. Light-gauge welded wire fabric should not be used because of the number of chairs necessary to hold it in the proper position and the safety hazards associated with its use. Using macro-synthetic fibers in dosages as high as 7.5 lb/yd³ (4.4 kg/m³) has proved successful in limiting crack widths in pavements with odd-shaped panels or in locations where the aspect ratio of panels exceeds 1.5 to 1.

4.6—Joint stability (load transfer)

4.6.1 Load-transfer devices—Positive load transfer between adjacent panels has a major effect on a pavement's service life, performance, and surface profile, which is the international roughness index (IRI); and minimizes pumping due to subgrade/subbase erosion that, in turn, minimizes erosion and faulting. Additionally, positive load-transfer devices increase joint sealant service life and enhance long-term joint stability. Load-transfer devices force concrete on both sides of a joint to deflect approximately equally when subjected to a load. This can help prevent damage to an exposed edge when subjecting the joint to wheel traffic. Load-transfer devices in direct contact with concrete will be the most effective load-transfer mechanism for controlling vertical joint deflection. The choice and specification of load-transfer devices should be related to the pavement's design and construction methodology such that joints perform in the way the designer intends.

4.6.2 Dowels—Dowels transfer loads between adjacent panels, reduce the edge and corner stresses in the concrete, and force concrete on both sides of a joint to deflect approximately equally when subjected to a load, helping to prevent pumping, subgrade/subbase material erosion, faulting, increased joint sealant service life, and damage to slab edges as the joint is traversed. Using positive load transfer has a direct impact on the thickness design of the pavement. Dowels should also allow the joints to activate with minimum restraint. For dowels to be effective, they should be smooth, aligned, and supported so they will remain parallel in both the horizontal and the vertical planes during the placing and finishing operation. All dowels should have flat, square, and deburred edges that will not restrain concrete shrinkage. Properly aligned dowels should allow the joint to open freely as concrete shrinks. Dowels can be either steel bars that are round or square, or plates of various shapes. In any case, dowels should be designed to suit the application and properly constructed to function and reduce occurrences of spalling over the dowel. Construction methods should include proper positioning and alignment of the dowel and proper consolidation of the concrete around the dowel. A

corrosion-resistant coating on the dowel is recommended where deicing chemicals are used on pavements where steel corrosion may be an issue. The designer should discuss corrosion resistance costs and advantages with the owner to determine if the additional cost is of value. The benefit of using dowels in concrete pavements has been recognized for nearly 100 years with the first reported U.S. installation in 1917. These earlier dowels were generally much longer, up to 48 in. (1219 mm), with smaller diameters as little as 1/2 in. (13 mm), and greater spacing as few as two bars per travel lane. Numerous dowel bar studies and tests conducted by Bradbury (1932), and Teller and Sutherland (1935, 1936, 1943) resulted in the use of dowels that were stiffer and larger in diameter, more closely spaced, and shorter in length (Snyder 2011). Repeated load testing of dowels in slabs performed at Bureau of Public Roads labs in the 1950s (National Research Council (U.S.) 1952) led to the development of design recommendations that eventually became the standard in the United States in the 1960s and 1970s: dowel diameter equal to one-eighth the slab thickness and spaced at 12 in. (300 mm) on center (Snyder 2011). This remained the de facto standard for the dowel industry for many years. The first broad-based concrete pavement performance and distress models were developed in the 1980s, and the effects of dowel diameter were more accurately quantified, leading some agencies to move toward increased round dowel diameters to compensate for the problems associated with very high bearing pressures between the dowels and the concrete.

4.6.2.1 Round dowels—Round dowels should be placed no closer than 12 in. (300 mm) from the intersection of any joints, as shown in Fig. 4.6.2.1, because the maximum movement caused by drying shrinkage occurs at this point, and the corner of the pavement may consequently crack (ACI 302.1R). Using conventional round dowels in pavements with two-directional doweling or adjacent panels or lanes constructed at different times can also create restraint, stresses, and cracking (Schrader 1987, 1991). Table 4.6.2.1 provides recommendations for round and square dowels in construction and contraction joints.

4.6.2.2 Square dowels—Square dowels cushioned on the vertical sides by a compressible material or void space permit horizontal movement parallel and perpendicular to the joint, such as might be necessary in pavements with two-directional doweling (Schrader 1987, 1991; Ringo and Anderson 1992; Metzger 1996; ACPA 1992; ACI 302.1R; ACI 360R). Table 4.6.2.1 also provides recommendations for square dowels in construction and contraction joints.

4.6.2.3 Plate dowels—Plate dowels are now commonly used in construction and contraction joints for industrial and trucking facility pavements. Manufacturers offer various plate dowel geometries and associated installation devices. Plate dowels can minimize shrinkage restraint by using a tapered shape, formed void, or by having compressible material on the vertical faces with a thin bond breaker on the top and bottom dowel surfaces (Fig. 4.6.2.3a and 4.6.2.3b) (Schrader 1987, 1991; Ringo and Anderson 1992; Metzger 1996; Walker and Holland 1998; ACPA 1992). When a formed void on the vertical sides is constructed using an in-place device, that device should be of a rigid material and

Table 4.6.2.1—Dowel size and spacing for round and square dowels at construction and contraction joints*

Pavement depth, in. (mm)	Dowel dimensions, in. (mm)		Dowel dimensions, in. (mm)			Dowel spacing center to center [†] , in. (mm)		
	Construction joint		Contraction joint		Plate dowel	Round [‡] , in. (mm)	Square [§] , in. (mm)	Plate dowel
	Round [‡]	Square [§]	Round [‡]	Square [§]				
5 to <6 (130 to <150)	3/4 x 10 (19 x 250)	3/4 x 10 (19 x 250)	NR	NR	M/R [#]	12 (300)	14 (360)	18 (460)
6 to <8 (150 to <300)	1 x 13 (25 x 330)	1 x 13 (25 x 330)	1 x 16 (25 x 410)	1 x 16 (25 x 410)	M/R [#]	12 (300)	14 (360)	18 (460)
8 to <10 (200 to <250)	1-1/4 x 15 (32 x 380)	1-1/4 x 15 (32 x 380)	1-1/4 x 19 (32 x 480)	1-1/4 x 19 (32 x 480)	M/R [#]	12 (300)	12 (300)	18 (460)
10 to 12 (250 to 300)	1-1/2 x 18 (38 x 460)	1-1/2 x 18 (38 x 460)	1-1/2 x 22 (38 x 560)	1-1/2 x 22 (38 x 560)	M/R [#]	12 (300)	12 (300)	18 (460)

*Table values based on a maximum joint opening of 0.20 in. (5 mm). Carefully align and support dowels during concrete operations. Misaligned dowels can lead to cracking. Spacings are based on dowels in direct contact with a thin bond breaker. Total dowel length includes allowance made for joint opening and minor errors in positioning dowels.

[†]Dowel spacing up to 24 in. (600 mm) for round, square, and plate dowels have been used successfully.

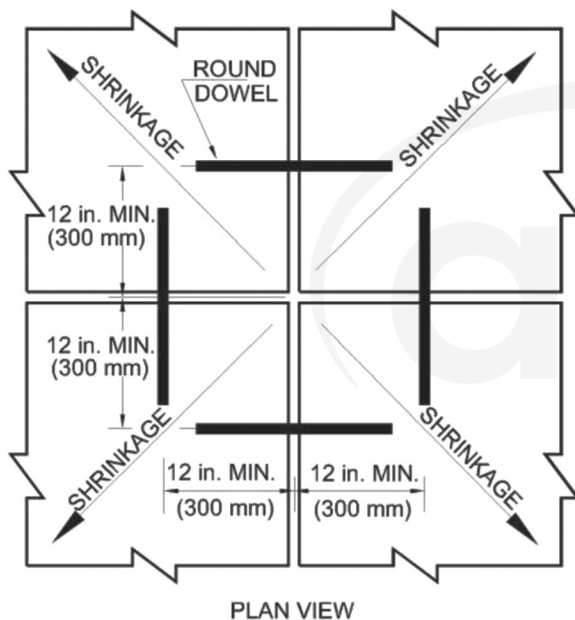
[‡]ACI Committee 325 (1956).

[§]Walker and Holland (1998).

^{||}Square dowels should have compressible material securely attached on both vertical faces.

[#]M/R = manufacturers' recommendations. Because of various plate dowel geometries and installation devices available from different manufacturers, manufacturers should be consulted for their recommended plate dowel size.

Note: (NR) denotes that dowels are not recommended in contraction joints of pavements less than 6 in. (150 mm) thick.

**Fig. 4.6.2.1—Joint intersection with round dowel.**

fit tightly with the dowel surface to minimize vertical deflection of the joint. The tapered shape along with a thin bond breaker on all sides allows a void space to develop along the vertical sides of the dowel to reduce restraint as the slab shrinks from the joint. Similarly, a formed void or the compressible material will also reduce restraint as the slab shrinks from the joint. These types of load-transfer devices are useful in pavements where the joint should have load-transfer capability while allowing some differential movement in the direction of the joint, such as might be necessary in pavements with two-directional doweling (Walker and Holland 1998; Fricks and Parkes 2002; Parkes 2007; ACI 302.1R; ACI 360R; ACPA 2008, 2010).

4.6.2.4 Dowel installation—Different construction practices, installation procedures, and joint types require different installation tolerances and possibly even different dowel and

plate geometries. Alignment or installation devices should be incorporated into the bulkhead (forms) of all formed construction joints to ensure that dowels are horizontal with the pavement surface and perpendicular to the joint. When incorporating alignment or installation devices into the bulkhead, which remain in the slab, the device should be manufactured with a thin rigid material that is tight fitted with the load-transfer device to minimize vertical deflection due to load (ACI 360R). Excessive greasing of bars or plates can impact consolidation of the concrete and can lead to pockets on the top or underside of the dowel (Schradler 1991; Walker and Holland 2007).

4.6.2.5 Dowel installation for construction joints—In formed construction joints, using stay-in-place devices rigidly attached to bulkheads or specially designed forms can also ensure that the dowel is centered in the joint. In slipformed or full-depth saw-cut construction joints, as would be encountered in a remove-and-replace repair situation, designers should recognize that when new concrete, with an inherent tendency to shrink, is tied to previously placed concrete that has already gone through the shrinkage process, stresses will develop that can cause cracking. Load transfer between previously placed pavement sections and newly placed concrete can be obtained using square or rectangular dowels with compressible foam material or formed voids on their vertical faces or plate dowels. In this application, holes or slots can be drilled or cut into the existing slab to receive square dowels or plate dowels, respectively. An epoxy grout or similar material should be used in the hole or slot to ensure a tight fit so that the dowel provides the required joint stability. Joints and cracks intersecting the joint in the older pavement should be matched by joints in the new pavement to avoid T-joint intersections whenever possible. Refer to Fig. 4.4.2.1b and 4.4.2.1c for a recommendation of when T-joints cannot be avoided. Manufacturers offer various plate dowel geometries and associated installation devices or systems to help contractors locate the plate centrally in the joint. With available plate dowel products,