

Guide to Design of Slabs-on-Ground

Reported by ACI Committee 360



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Guide to Design of Slabs-on-Ground

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Guide to Design of Slabs-on-Ground

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This guide presents information on the design of slabs-on-ground, primarily industrial floors. It addresses the planning, design, and detailing of slabs. Background information on design theories is followed by discussion of the types of slabs, soil-support systems, loadings, and jointing. Design methods are given for unreinforced concrete, reinforced concrete, shrinkage-compensating concrete, post-tensioned concrete, fiber-reinforced concrete slabs-on-ground, and slabs-on-ground in refrigerated buildings, followed by information on shrinkage and curling. Advantages and disadvantages of these slab design methods are provided, including the ability of some slab designs to minimize cracking and curling more than others. Even with the best slab designs and proper construction, it is unrealistic to expect crack-free and curl-free floors. Every owner should be advised by the designer and contractor that it is normal to expect some cracking and curling on every project. This does not necessarily reflect adversely on the adequacy of the floor's design or quality of construction. Design examples are given.

Keywords: curling; design; floors-on-ground; grade floors; industrial floors; joints; load types; post-tensioned concrete; reinforcement (steel, fibers); shrinkage; shrinkage-compensating; slabs; slabs-on-ground; soil mechanics; warping.

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CHAPTER 1—INTRODUCTION

1.1—Purpose and scope

This guide presents information on the design of slabs-on-ground. Design is the decision-making process of planning, sizing, detailing, and developing specifications preceding construction of slabs-on-ground. Information on other aspects, such as materials, construction methods, placement of concrete, and finishing techniques is included only where needed in making design decisions.

In the context of this guide, slab-on-ground is defined as: a slab, supported by ground, whose main purpose is to support the applied loads by bearing on the ground. The slab is of uniform or variable thickness and it may include stiffening elements such as ribs or beams. The slab may be unreinforced or reinforced with nonprestressed reinforcement, fibers, or post-tensioned tendons. The reinforcement may be provided to limit crack widths resulting from shrinkage and temperature restraint and the applied loads. Post-tensioning tendons may be provided to minimize cracking due to shrinkage and temperature restraint, resist the applied loads, and accommodate movements due to expansive soil volume changes.

This guide covers the design of slabs-on-ground for loads from material stored directly on the slab, storage rack loads, and static and dynamic loads associated with equipment and vehicles. Other loads, such as roof loads transferred through dual-purpose rack systems, are also mentioned.

This guide discusses soil-support systems, shrinkage and temperature effects; cracking, curling or warping; and other concerns affecting slab design. Although the same general principles are applicable, this guide does not specifically address the design of roadway pavements, airport pavements, parking lots, or mat foundations.

1.2—Work of ACI Committee 360 and other relevant committees

There are several ACI committees listed below that provide relevant information concerning slabs-on-ground design and construction or similar slab types that are not addressed in this guide such as pavements, parking lots, or mat foundations. These committees provide documents where more detailed information for topics discussed in this guide can be found.

1.2.1 ACI Committee 117 develops and reports information on tolerances for concrete construction through liaison with other ACI committees.

1.2.2 ACI Committee 223 develops recommendations on the use of shrinkage-compensating concrete.

1.2.3 ACI Committee 301 develops and maintains specifications for concrete construction.

1.2.4 ACI Committee 302 develops and reports information on materials and procedures for the construction of concrete floors. ACI 302.1R provides guidelines and recommendations on materials and slab construction. ACI 302.2R provides guidelines for concrete slabs that receive moisture-sensitive flooring materials.

1.2.5 ACI Committee 318 develops and maintains building code requirements for structural concrete.

1.2.6 ACI Committee 325 develops and reports information on concrete pavements.

1.2.7 ACI Committee 330 develops and reports information on concrete parking lots and paving sites. Parking lots and paving sites have unique considerations that are covered in ACI 330R.

1.2.8 ACI Committee 332 develops and reports information on concrete in residential construction.

1.2.9 ACI Committee 336 develops and reports information on footings, mats, and drilled piers. The design procedures for combined footings and mat foundations are given in ACI 336.2R. Mat foundations are typically more rigid and more heavily reinforced than common slabs-on-ground.

1.2.10 ACI Committee 360 develops and reports information on the design of slabs-on-ground, with the exception of highways, parking lots, airport pavements, and mat foundations.

1.2.11 ACI Committee 544 develops and reports information on concrete reinforced with short, discontinuous, randomly-dispersed fibers. ACI 544.3R is a guide for specifying, proportioning, and production of fiber-reinforced concrete (FRC).

1.3—Work of non-ACI organizations

Numerous contributions of slabs-on-ground design and construction information used in this guide come from organizations and individuals outside the American Concrete Institute. The U.S. Army Corps of Engineers (USACE), the National Academy of Science, and the Department of Housing and Urban Development (HUD) have developed guidelines for floor slab design and construction. The Portland Cement Association (PCA), Wire Reinforcement Institute (WRI), Concrete Reinforcing Steel Institute (CRSI), Post-Tensioning Institute (PTI), as well as several universities and consulting engineers have studied slabs-on-ground and developed recommendations for their design and construction. In addition, periodicals such as *Concrete International* and *Concrete Construction* have continuously disseminated information about slabs-on-ground.

1.4—Design theories for slabs-on-ground

1.4.1 Introduction—Stresses in slabs-on-ground result from applied loads and volume changes of the soil and concrete. The magnitude of these stresses depends on factors such as the degree of slab continuity, subgrade strength and

uniformity, construction method, construction quality, and magnitude and position of the loads. In most cases, the effects of these factors are evaluated by making simplified analysis assumptions with respect to material properties and soil-structure interaction. The following sections briefly review some of the design theories of soil-supported concrete slabs.

1.4.2 Review of classical design theories—Design methods for slabs-on-ground are based on theories originally developed for airport and highway pavements. Westergaard developed one of the first rigorous theories of structural behavior of rigid pavement (Westergaard 1923, 1925, 1926). This theory considers a homogeneous, isotropic, and elastic slab resting on an ideal subgrade that exerts, at all points, a vertical reactive pressure proportional to slab deflection; known as a Winkler subgrade (Winkler 1867). The subgrade acts as a linear spring with a proportionality constant k with units of pressure (lb/in.² [kPa]) per unit deformation (in. [mm]). The units are commonly abbreviated as lb/in.³ (kN/m³). This constant is defined as the modulus of subgrade reaction.

In the 1930s, the structural behaviors of concrete pavement slabs were investigated at the Arlington Virginia Experimental Farm and at the Iowa State Engineering Experiment Station. Good agreement occurred between experiential stresses and those computed by the Westergaard's theory, as long as the slab remained continuously supported by the subgrade. Corrections were required only for the Westergaard corner formula to account for the effects of slab curling and loss of contact with the subgrade. Although choosing the modulus of subgrade reaction was essential for good agreement with respect to stresses, there remained ambiguity in the methods used to determine the correction coefficient.

In the 1930s, experimental information showed that the behavior of many subgrades may be close to that of an elastic and isotropic solid. Two characteristic constants—the modulus of soil deformation and Poisson's ratio—are typically used to evaluate the deformation response of such solids.

Based on the concept of the subgrade as an elastic and isotropic solid, and assuming that the slab is of infinite extent but of finite thickness, Burmister proposed the layered-solid theory of structural behavior for rigid pavements (Burmister 1943). He suggested basing the design on a criterion of limited deformation under load. Design procedures for rigid pavements based on this theory are not sufficiently developed for use in engineering practice. The lack of analogous solutions for slabs of finite extent, for example, edge and corner cases, is a particular deficiency. Other approaches based on the assumption of a thin elastic slab of infinite extent resting on an elastic, isotropic solid have been developed. The preceding theories are limited to behavior in the linear range where deflections are proportional to applied loads. Lösberg (Lösberg 1978; Pichumani 1973) later proposed a strength theory based on the yield-line concept for ground-supported slabs, but the use of ultimate strength for slab-on-ground design is not common.

All existing design theories are grouped according to models that simulate slab and the subgrade behavior. Three models used for slab analysis are:

1. Elastic-isotropic solid;
2. Thin elastic slab; and
3. Thin elastic-plastic slab.

Two models used for subgrade are:

1. Elastic-isotropic solid; and
2. Winkler (1867).

The Winkler subgrade models the soil as linear springs so that the reaction is proportional to the slab deflection. Existing design theories are based on various combinations of these models. The methods in this guide are generally graphical, plotted from computer-generated solutions of selected models. Design theories need not be limited to these combinations. The elastic-isotropic model provides close prediction for the response of real soils, but the Winkler model is widely used for design and a number of investigators have reported good agreement between observed responses to the Winkler-based predictions.

1.4.3 Finite-element method—The classical differential equation of a thin elastic plate resting on an elastic subgrade is often used to represent the slab-on-ground. Solving the governing equations by conventional methods is feasible for simplified models where slab and subgrade are assumed to be continuous and homogeneous. In reality, a slab-on-ground usually contains discontinuities, such as joints and cracks, and the subgrade support may not be uniform. Thus, the use of this approach is limited.

The finite-element method can be used to analyze slabs-on-ground, particularly those with discontinuities. Various models have been proposed to represent the slab (Spears and Panarese 1983; Pichumani 1973). Typically, these models use combinations of elements, such as elastic blocks, rigid blocks, and torsion bars, to represent the slab. The subgrade is typically modeled by linear springs (Winkler subgrade) placed under the nodal joints. Whereas the finite-element method offers good potential for complex problems, graphical solutions and simplified design equations have been traditionally used for design. The evolution of modern computer software has made modeling with finite elements more feasible in the design office setting.

1.5—Construction document information

Listed below is the minimum information that should be addressed in the construction documents prepared by the designer. Refer to ACI 302.1R for information related to the installation and construction for some of these items.

- Slab-on-ground design criteria;
- Base and subbase materials, preparation requirements, and vapor retarder/barrier, when required;
- Concrete thickness;
- Concrete compressive strength, or flexural strength, or both;
- Concrete mixture proportion requirements, ultimate dry shrinkage strain, or both;
- Joint locations and details;
- Reinforcement (type, size, and location), when required;
- Surface treatment, when required;
- Surface finish;

- Tolerances (base, subbase, slab thickness, and floor flatness and levelness);
- Concrete curing;
- Joint filling material and installation;
- Special embedments;
- Testing requirements; and
- Preconstruction meeting, quality assurance, and quality control.

1.5.1 Slab-on-ground design criteria—It is helpful that when the slab-on-ground design criteria are well established, that it be shown on the drawings. This information is especially useful when future modifications are made to the slab or its use. Design issues, such as the slab contributing to wind or seismic resistance or building foundation uplift forces, would not be readily apparent unless noted on the drawings. Because it is not readily apparent when a slab is used as a horizontal diaphragm, it should be noted on the drawings. Removing or cutting a slab that is designed to resist uplift or horizontal forces could seriously impair the building's stability.

The design criteria should include some of the following:

- Geotechnical soil properties used for the different loading types;
- Uniform storage loading;
- Lift-truck and vehicle loadings;
- Rack loadings;
- Line loads;
- Equipment loads;
- When the slab is used to resist wind or seismic foundation uplift forces; and
- When the slab is used as a horizontal diaphragm and to resist horizontal forces or both due to tilt-walls, masonry walls, tops of retaining walls, and metal building system columns.

Refer to Appendix 7 for an example of design criteria.

1.5.2 Floor flatness and levelness tolerances—Tolerances for floor uses should conform to ACI 117. For additional information, including how to specify floor flatness and levelness requirements, refer to ACI 117 commentary and ACI 302.1R.

When using slabs in offices, areas of pedestrian traffic, wide aisle warehousing, and manufacturing, where the movement is intended to be random in any direction, then a random traffic tolerance system, such as F_F/F_L , should be designated. The subject areas should be shown on the construction documents and tolerances specified.

In defined traffic areas such as narrow aisle or very narrow aisle warehousing and manufacturing, where vehicle paths are restrained by rail, wire, laser, or telemetry guidance systems, a tolerance system such as F-min should be implemented (Fudala 2008), with subject areas shown on the construction documents, and tolerances specified. Table 1.1 provides typical defined traffic values for different rack heights that have been used successfully. Narrow aisle and very narrow aisle systems, however, use specialized equipment and the manufacturers should be consulted for F-min recommendations.

Table 1.1—Defined traffic values

Rack height, ft (m)	Longitudinal* F-min	Transverse† F-min
0 to 25 (0 to 7.6)	50	60
26 to 30 (7.9 to 9.1)	55	65
31 to 35 (9.4 to 10.7)	60	70
36 to 40 (11 to 12.2)	65	75
41 to 45 (12.5 to 13.7)	70	80
46 to 50 (14 to 15.2)	75	85
51 to 65 (15.5 to 19.8)	90	100
66 to 90 (20.1 to 27.4)	100	125

*Longitudinal value between the front and rear axle.

†Transverse value between loaded wheel tracks.

1.6—Further research

There are many areas that need additional research. Some of these areas are:

- Developing concrete mixture proportions that have low shrinkage characteristics and are workable, finishable, and provide a serviceable surface;
- Flexural stress in slabs with curl and applied loads and how curling stresses change over time due to creep;
- Base restraint due to shrinkage and other volume changes and how this restraint changes over time;
- Crack widths for different amounts of reinforcement for slabs-on-ground;
- Provide guidance on acceptable joint and crack widths for different slab usages;
- Provide dowel recommendations based on loadings (lift truck, rack post, and uniform storage) rather than slab thickness;
- Provide plate dowel spacing recommendations for plate dowel geometries;
- Provide design guidance for slabs with macrosynthetic fibers;
- Provide design aids for slabs with rack uplift loads due to seismic and other uplift loadings;
- Provide design aids for slabs with non-uniform rack post loads;
- Develop a standardized method for testing and specifying slab surface abrasion resistance;
- Soil properties and how they may change over time under load repetitions, wide area long-term loadings, or both; and
- Recommended joint spacing for fiber-reinforced concrete.

CHAPTER 2—DEFINITIONS

2.1—Definitions

ACI provides a comprehensive list of definitions through an online resource. “ACI Concrete Terminology,” <http://terminology.concrete.org>. Definitions provided herein complement that resource.

curling or warping—out-of-plane deformation of the corners, edges, and surface of a pavement, slab, or wall panel from its original shape.

slab-on-ground—slab, supported by ground, whose main purpose is to support the applied loads by bearing on the ground.

CHAPTER 3—SLAB TYPES

3.1—Introduction

Chapter 3 identifies and briefly discusses the common types of slab-on-ground construction. The term “slab-on-ground” is preferred but “slab-on-grade” is often used. Slab-on-ground includes interior slabs subject to loadings as described in Chapter 5. These include industrial, commercial, residential, and related applications. Although the term might include parking lot and roadway pavements, this guide does not specifically address them.

An important responsibility of the slab designer is to discuss the requirements of the floor slab with the owner. Discussions should include the advantages and disadvantages of the different slab types and how they relate to the owner’s requirements. It is important for this discussion to occur so the owner has reasonable expectations of the slab performance and required future maintenance for the slab type selected. Some of the more important expectations that should be discussed for the prospective slab type are:

- Cracking potential;
- Crack widths for slabs designed with reinforcement to limit crack widths;
- Use of doweled joints versus aggregate interlock;
- Possible future repairs including joint deterioration;
- Joint maintenance requirements and the owner’s responsibility for this maintenance;
- Floor flatness and levelness requirements to meet the owner’s needs;
- Changes to the flatness and levelness over time, especially in low-humidity environments;
- Advantages and disadvantages of slab placement with the watertight roofing system in place versus placing the slab in the open;
- Level of moisture vapor resistance required; and
- Advantages and disadvantages of using the building floor slab for tilt-wall construction form and temporary bracing.

3.2—Slab types

There are four basic design choices for slab-on-ground construction:

1. Unreinforced concrete slab.
2. Slabs reinforced to limit crack widths due to shrinkage and temperature restraint and applied loads. These slabs consist of:
 - a. Nonprestressed steel bar, wire reinforcement, or fiber reinforcement, all with closely spaced joints; and
 - b. Continuously reinforced, free-of-sawcut, contraction joints.
3. Slabs reinforced to prevent cracking due to shrinkage and temperature restraint and applied loads. These slabs consist of:
 - a. Shrinkage-compensating concrete; and
 - b. Post-tensioned.
4. Structural slabs designed in accordance with ACI 318:
 - a. Plain concrete; and
 - b. Reinforced concrete.

3.2.1 Unreinforced concrete slab—The thickness is determined as a concrete slab without reinforcement; however, it may have joints strengthened with steel dowels. It is designed to remain uncracked between joints when loaded and restraint to concrete volumetric changes. Unreinforced concrete slabs do not contain macrosynthetic fibers, wire reinforcement, steel fibers, plain or deformed bars, post-tensioning, or any other type of steel reinforcement. Type I or II portland cement (ASTM C150/C150M) is normally used. Drying shrinkage effects and uniform subgrade support on slab cracking are critical to the performance of unreinforced concrete slabs. Refer to Chapter 7 for unreinforced slab design methods.

3.2.2 Slabs reinforced for crack-width control—Thickness design can be the same as for unreinforced concrete slabs, and they are designed to remain uncracked when loaded. For slabs constructed with portland cement, shrinkage crack widths (when cracking occurs) between joints are controlled by a nominal quantity of distributed reinforcement. Slabs reinforcement can consist of bars, welded wire reinforcement sheets, steel fibers, or macrosynthetic fibers. Bar and wire reinforcement should be stiff enough to be accurately located in the upper 1/3 of the slab.

Bars or welded wire reinforcement are used to provide flexural strength at a cracked section. In this case, and for slabs of insufficient thickness to carry the applied loads as an unreinforced slab, the reinforcement required for flexural strength should be sized by reinforced concrete theory as described in ACI 318. Using the methods in ACI 318 with high steel reinforcement stresses, however, may lead to unacceptable crack widths. Building codes do not support the use of fiber reinforcement to provide flexural strength in cracked sections for vertical or lateral forces from other portions of a structure.

Other than post-tensioning or the reinforcement in a shrinkage-compensating slab, reinforcement does not prevent concrete cracking. Typically, the most economical way to increase flexural strength is to increase the slab thickness. Chapters 7, 8, and 11 contain design methods for slabs reinforced for crack-width control.

3.2.3 Slabs reinforced to prevent cracking—Post-tensioned slabs and shrinkage-compensating slabs are typically designed not to crack, but some incidental minor cracking may occur. For shrinkage-compensating slabs, the slab is designed unreinforced, and the reinforcement is designed to prestress the expanding slab to offset the stresses caused by the shrinkage and temperature restraint. For post-tensioned slabs, the reinforcement is typically designed to compensate for shrinkage and temperature restraint stress and applied loads.

Shrinkage-compensating concrete slabs are produced either with a separate component admixture or with ASTM C845 Type K expansive cement. This concrete does shrink, but first expands to an amount intended to be slightly greater than its drying shrinkage. To limit the initial slab expansion and to prestress the concrete, reinforcement is distributed in the upper 1/3 of the slab. Such reinforcement should be rigid and positively positioned. The slab should be located near fixed portions of the structure, such as columns and perimeter

Table 3.1—General comparison of slab types

Slab type	Advantages	Disadvantages
Unreinforced concrete	- Simple to construct. - Generally is less expensive to install than slabs designed by other methods.	- Requires relatively closely spaced sawcut contraction joints. - More opportunity for slab curl and joint deterioration. - Large number of joints to maintain. - Positive load transfer may be required at joints. - Flatness and levelness may decrease over time.
Reinforced with deformed bars or welded-wire reinforcement sheets for crack-width control	Reinforcement is used to limit crack width.	- May be more expensive than an unreinforced slab. - Reinforcement can actually increase the number of random cracks, particularly at wider joint spacings. - More opportunity for slab curl and joint deterioration. - Positive load transfer may be required at joints.
Continuously reinforced with deformed bars or welded-wire reinforcement mats	- Sawcut contraction joints can be eliminated where sufficient reinforcement is used. - Eliminates sawcut contraction joint maintenance. - Curling is reduced when high amounts of reinforcement are used. - Less changes in flatness and levelness with time.	- Requires relatively high amounts (at least 0.5%) of continuous reinforcement placed near the top of the slab to eliminate joints. - Typically produces numerous, closely spaced, fine cracks (approximately 3 to 6 ft [0.9 to 1.8 m]) throughout slab.
Shrinkage-compensating concrete	- Allows construction joint spacings of 40 to 150 ft (12 to 46 m). - Sawcut contraction joints are normally not required. - Reduces joint maintenance cost due to increased spacing of the joints reducing the total amount of joints. - Negligible curl at the joints. - Increases surface durability and abrasion resistance (ACI 223, Section 2.5.7—Durability).	- Requires reinforcement to develop shrinkage compensation. - Window of finishability is reduced. - Allowance should be made for concrete to expand before drying shrinkage begins. - Construction sequencing of adjacent slab panels should be considered, or joints should be detailed for expansion. - Contractor should have experience with this type of concrete.
Post-tensioned	- Construction spacings 100 to 500 ft (30 to 150 m). - Most shrinkage and flexural cracks can be avoided. - Eliminates sawcut contraction joints and their maintenance. - Negligible slab curl when tendons are draped near joint ends. - Improved long-term flatness and levelness. - Decreased slab thickness or increased flexural strength. - Resilient when overloaded. - Advantages in poor soil conditions	- More demanding installation. - Contractor should have experience with post-tensioning or employ a consultant with post-tensioning experience. - Inspection essential to ensure proper placement and stressing of tendons. - Uneconomical for small areas. - Need to detail floor penetrations and perimeter for slab movement. - Impact of cutting tendons should be evaluated for post-construction slab penetrations.
Steel fiber-reinforced concrete	- Increased resistance to impact and fatigue loadings when compared to slabs reinforced with bars or mesh. - Simple to construct.	- May require adjustments to standard concrete mixing, placement, and finishing procedures. - Fibers may be exposed on the surface of slab. - Floors subjected to wet conditions may not be suitable for steel fiber because fibers close to the surface and in water-permeable cracks will rust.
Synthetic fiber-reinforced concrete	- Helps reduce plastic shrinkage cracking. - Simple to construct. - Macrosynthetic fibers provide increased resistance to impact and fatigue loadings, similar to steel fibers. - Synthetic fibers do not corrode.	- Microsynthetic fibers do not help in controlling drying shrinkage cracks. - Joint spacing for microsynthetic fiber-reinforced slabs are the same as unreinforced slabs.
Structural slabs reinforced for building code requirements	- Slabs can carry structural loads such as mezzanines. - Reduces or eliminates sawcut contraction joints where sufficient reinforcement is used.	Slab may have numerous fine or hairline cracks if reinforcement stresses are sufficiently low.

foundations, with a compressible material that allows the initial slab expansion.

Refer to Chapters 9 and 10 for design methods for slabs reinforced to prevent cracking.

3.2.4 Structural slabs—Structural plain and reinforced slabs that transmit vertical loads or lateral forces from other portions of the structure to the soil should be designed in accordance with ACI 318. Using the methods in ACI 318 with high steel reinforcement stresses, however, may lead to unacceptable crack widths.

3.3—General comparison of slab types

To assist with selecting the most appropriate slab type for the particular project, Table 3.1 provides general advantages and disadvantages for the slab types discussed in Section 3.2.

3.4—Design and construction variables

Design and construction of slabs-on-ground involves both technical and human factors. Technical factors include loadings, soil-support systems, joint types and spacings, design method, slab type, concrete mixture, development of maintenance procedures, and the construction process. Human factors include the workers' abilities, feedback to evaluate the construction process, and conformance with proper maintenance procedures for cracking, curling, and shrinkage. These and other factors should be considered when designing a slab (Westergaard 1926).

3.5—Conclusion

No single slab design method is recommended for all applications. Rather, from the number of identifiable construction concepts and design methods, a contractor should be selected based on the requirements of the specific application.

CHAPTER 4—SOIL SUPPORT SYSTEMS FOR SLABS-ON-GROUND

4.1—Introduction

The design of slabs-on-ground to resist moments and shears caused by applied loads depends on the interaction between the concrete slab and the supporting materials. Properties and dimensions of the slab and the supporting materials are important in the design of a slab-on-ground. The support system should be of acceptable uniform strength and not easily susceptible to the effects of climatic changes. Slab-on-ground failures can occur because of an improper support system. Issues related to the support system of the slab-on-ground include:

- Geotechnical engineering reports providing soil properties;
- Subgrade classification;
- Modulus of subgrade reaction;
- Design of the slab support system;
- Site preparation; and
- Inspection and testing of the slab support system.

This chapter is limited to aspects of the support system necessary for proper slab-on-ground performance.

The slab support system consists of a subgrade, usually a base, and sometimes a subbase, as illustrated in Fig. 4.1. Crushed rock, gravels, or coarse sands have high strength, low compressibility, and high permeability, are commonly used as base courses. Crushed rock, gravels, sands, select soils, and stabilized soils are commonly used as subbases and may be used as base materials. Soils in the subgrade are generally the ultimate supporting materials, but bedrock, competent or weathered, may also be encountered. When the existing soil has uniform strength and other necessary properties to support the slab, the slab may be placed directly on the existing subgrade. The existing grade, however, is frequently not at the desired elevation or slope and some cut and fill is required. To improve surface drainage or to elevate the floor level, controlled fill using on-site or imported soils is required on some sites.

4.2—Geotechnical engineering reports

4.2.1 Introduction—Geotechnical engineering investigations supply subsurface site information primarily for design and construction of the building foundation elements and to meet building code requirements. Within the geotechnical engineering report, slab-on-ground support is frequently discussed, and subgrade drainage and preparation recommendations are given. Even when slab support is not discussed in detail, information given within these reports, such as boring or test pit logs, field and laboratory test results, and discussions of subsurface conditions, are useful in evaluating subgrade conditions relative to slab-on-ground design and construction.

4.2.2 Boring or test pit logs—Descriptions given on boring or test pit logs provide information on the texture of the soils and their moisture condition and relative density, when noncohesive; or consistency, when cohesive. These logs present field test results, such as the standard penetration test (ASTM D1586) in blows per 6 in. (150 mm) interval values. The log notes the location of the water table at the time of boring and depths to shallow bedrock. The Atterberg limits,

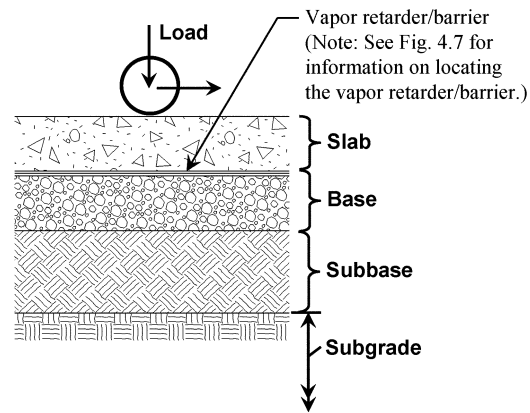


Fig. 4.1—Slab support system terminology.

and laboratory test results, such as the moisture content and dry density of cohesive soils, are often included on the boring logs or in the geotechnical report. Also, the soil is classified as discussed in Section 4.3.

4.2.3 Report evaluations and recommendations—Evaluations and recommendations relative to the existing subgrade material, its compaction, and supporting capability can be included in the report and should be evaluated against the design requirements. The geotechnical engineer may provide suggestions for subbase and base course materials. In some cases, local materials that are peculiar to that area, such as crushed sea shells, mine tailings, bottom ash, and other waste products, can be economically used. The local geotechnical engineer is generally knowledgeable about using these materials in the project area. The expected performance characteristics of the slab-on-ground should be made known to the geotechnical engineer before the subsurface investigation to obtain the best evaluation and recommendations. For example, some of the information that should be provided to the geotechnical engineer includes:

- Facility use and proposed floor elevation;
- Type and magnitude of anticipated loads;
- Environmental conditions of the building space;
- Floor levelness and flatness criteria; and
- Floor-covering requirements.

It may be beneficial for the geotechnical engineer to visit local buildings or other facilities of the client that have similar use. Coordination between the geotechnical engineer and the slab-on-ground designer from the beginning of the project can lead to an adequate and economical slabs-on-ground.

4.3—Subgrade classification

Soil supporting the slab-on-ground may meet the criteria for a subbase or even a base material, but should be identified and classified to estimate its suitability as a subgrade. The Unified Soil Classification System is predominantly used in the U.S. and is referred to in this guide. Table 4.1 provides information on classification groups of this system and important criteria for each soil group. Visual procedures (ASTM D2488) can be used, but laboratory test results (ASTM D2487) provide classification that are more reliable.

Table 4.1—Unified soil classification system (Winterkorn and Fang 1975)

Field identification procedures (excluding particles larger than 3 in. [75 mm], and basing fractions on estimated weights)					Group symbol	Typical names
Coarse-grained soils (more than half of material is larger than No. 200 sieve* [75 μm])	Gravels (more than half of coarse fraction is larger than No. 4 sieve* [4.75 mm])	Clean gravels (little or no fines)	Wide range in grain size and substantial amounts of all intermediate particle sizes	GW	Well-graded gravel, gravel-sand mixtures, little or no fines	
			Predominantly one size or a range of sizes with some intermediate sizes missing	GP	Poorly graded gravels, gravel-sand mixtures, little or no fines	
		Gravels with fines (appreciable amount of fines)	Nonplastic fines (for identification procedures, refer to CL below)	GM	Silty gravels, poorly graded gravel-sand-silt mixtures	
			Plastic fines (for identification procedures, refer to ML below)	GC	Clayey gravels, poorly graded gravel-sand-clay mixtures	
	Sands (more than half of coarse fraction is smaller than No. 4 sieve* [4.75 mm])	Clean sands (little or no fines)	Wide range in grain sizes and substantial amounts of all intermediate particle sizes	SW	Well-grades sands, gravelly sands, little or no fines	
			Predominantly one size or range of sizes with some intermediate sizes missing	SP	Poorly graded sands, gravelly sands, little or no fines	
		Sands with fines (appreciable amount of fines)	Nonplastic fines (for identification procedures, refer to ML below)	SM	Silty sands, poorly graded sand-silt mixtures	
			Plastic fines (for identification procedures, refer to CL below)	SC	Clayey sands, poorly graded sand-clay mixtures	
Identification procedures on fraction smaller than No. 40 (4.25 μm) sieve						
		Dry strength (crushing characteristics)	Dilatancy (reaction to shaking)	Toughness (consistency near plastic limit)	Group symbol	Typical names
Fine-grained soils (more than half of material is smaller than No. 200 sieve* [75 μm])	Silts and clays (liquid limit less than 50)	None to slight	Quick to slow	None	ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands with slight plasticity
		Medium to high	None to very slow	Medium	CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays
		Slight to medium	Slow	Slight	OL	Organic silts and organic-silt clays of low plasticity
	Silts and clays (liquid limit greater than 50)	Slight to medium	Slow to none	Slight to medium	MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts
		High to very high	None	High	CH	Inorganic clays of high plasticity, fat clays
		Medium to high	None to very slow	Slight to medium	OH	Organic clays of medium to high plasticity
Highly organic soils		Readily identified by color, odor, spongy feel; frequently by fibrous texture			PT	Peat or other highly organic soils

* All sieve sizes herein are U.S. standard. The No. 200 sieve (75 µm) is approximately the smallest particle visible to the naked eye. For visual classifications, the 1/4 in. (6.3 mm) size may be used as equivalent for the No. 4 (4.75 mm) sieve size. Boundary classifications: soil possessing characteristics of two groups are designated by combinations of group symbols.

For example, use the plasticity chart of Table 4.2 to classify the fine-grained soils.

The following tests and test methods are useful for soil classification:

- Moisture content: ASTM D2216;
- Specific gravity: ASTM D854;
- Liquid and plastic limits: ASTM D4318; and
- Expansion Index: ASTM D4829.

The standard Proctor compaction test (ASTM D698) and modified Proctor compaction test (ASTM D1557) are not strictly classification tests. Their moisture-density relationships are useful in assessing a soil subgrade or subbase. A more detailed listing of the ASTM standards appears in Chapter 15.

4.4—Modulus of subgrade reaction

4.4.1 Introduction—Design methods listed in Chapter 3, including Westergaard's pioneering work on rigid pavement analysis (Westergaard 1923, 1926), employ the modulus of subgrade reaction as a single property to represent the design

support strength. This modulus, also called the modulus of soil reaction or Winkler foundation, is a spring constant that assumes a linear response between load and deformation from the subgrade.

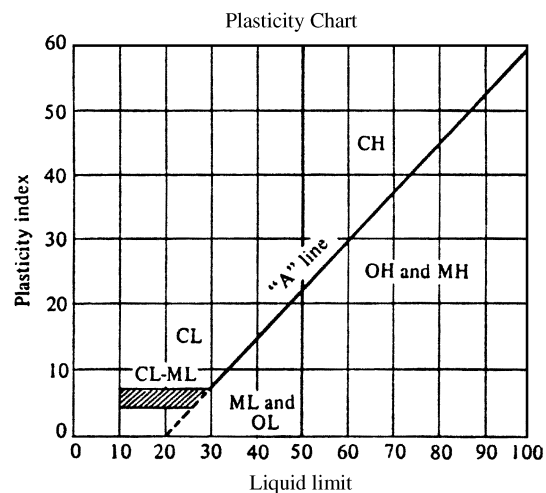
Actually, there is no single k value for a subgrade because the relationship between load and soil deformation is nonlinear and is not a fundamental soil property. Figure 4.2 depicts a typical nonlinear relationship between a normal compressive load and the resulting deformation for an area. The type of soil structure, density, moisture content, and prior loading determine the load-deformation relationship. The relationship also depends on the width and shape of the loaded area, depth of the subgrade, and position under the slab. In addition, time may be a significant factor because any deeper compressible soils may settle due to consolidation, and near-surface soils may settle due to shrinkage from alternate wetting and drying. Nevertheless, the procedures for static nonrepetitive plate load tests and the subgrade modulus D1196 have been used to estimate the subgrade modulus.

Table 4.2—Laboratory classification criteria for soils (Winterkorn and Fang 1975)

Major Divisions		Group Symbols	Typical Names		Laboratory Classification Criteria											
Coarse-grained soils (More than half of material is larger than No. 200 [75 μm] sieve size)					Determine percentages of sand and gravel from grain-size curve. Depending on percentage of fines (fraction smaller than No. 200 [75 μm], coarse-grained soils are classified as follows: Less than 5 per cent More than 12 per cent 5 to 12 per cent GW, GP, SW, SP GM, GC, SM, SC <i>Borderline</i> cases requiring dual symbols†											
									Gravels (More than half of coarse fraction is larger than No. 4 [4.75 mm] sieve size)		Clean gravels (Little or no fines)		$C_u = \frac{D_{60}}{D_{10}}$ greater than 4; $C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ between 1 and 3			
											GP		Poorly graded gravels, gravel-sand mixtures, little or no fines			
									Gravels with fines (Appreciable amount of fines)		GM*		d	Silty gravels, gravel-sand-silt mixtures	Atterberg limits below "A" line or P.I. less than 4	
											u					
									GC		Clayey gravels, gravel-sand-clay mixtures		Atterberg limits below "A" line with P.I. greater than 7			
											SW				Well-graded sands, gravelly sands, little or no fines	
									SP		Poorly graded sands, gravelly sands, little or no fines		$C_u = \frac{D_{60}}{D_{10}}$ greater than 6; $C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ between 1 and 3			
											SM*				d	Silty sands, sand-silt mixtures
									SC		Clayey sands, sand-clay mixtures		Atterberg limits above "A" line with P.I. greater than 7			
u																
Fine-grained soils (More than half of material is smaller than No. 200 [75 μm] sieve)					Plasticity Chart 											
									Silt and clays (Liquid limit less than 50)		ML		Inorganic silts and very fine sands, rock flour, silty or clayey fine sands, or clayey silts with slight plasticity			
											CL		Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays			
											OL		Organic silts and organic silty clays of low plasticity			
									Silt and clays (Liquid limit greater than 50)		MH		Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts			
											CH		Inorganic clays of high plasticity, fat clays			
											OH		Organic clays of medium to high plasticity, organic silts			
									Highly organic soils		Pt		Peat and other highly organic soils			

*Division of GM and SM groups into subdivisions of d and u are for roads and airfields only. Subdivision is based on Atterberg limits; suffix d used when L.L. is 28 or less and the P.I. is 6 or less; the suffix u used when L.L. is greater than 28.

[†] Borderline classifications, used for soils possessing characteristics of two groups, are designated by combinations of group symbols. For example, GW-GC, well-graded gravel-sand mixture with clay binder.



4.4.2 Plate load field tests—Determining the modulus of subgrade reaction on representative subgrade in place with a 30 in. (760 mm) diameter bearing plate, which is recommended by ASTM D1196, is time-consuming and expensive. It takes several days to plan and execute a load-testing program. Large loads may be needed to obtain significant settlement of the plates. Adjustments should be made for nonrecoverable

deformation and any plate deflections. Because the load-deformation results are nonlinear, either an arbitrary load or deformation should be assumed to calculate k (Fig. 4.2).

Several tests over the project area are required to obtain representative k values, which generally result in a range of k values. A correction is generally necessary to account for future saturation of cohesive soil lab. ads, and this requires

sampling and laboratory tests. It is usually impractical to conduct field tests on subgrade soils at their expected range of densities and moisture contents. It is also impractical to test the various possible types and thicknesses of base courses and subbases on a representative subgrade. It is difficult to test during adverse climatic conditions. Smaller plates, such as 12 in. (300 mm) diameter, have been used, but the diameter of the plate influences the results, and this is difficult to take into account when reporting a k value.

Typically, these tests are made directly on an unconfined natural or compacted subgrade or on a layer of compacted subbase or base course over a subgrade. The physical characteristics of the base course and subgrade material are necessary to properly interpret the plate bearing test results. At a minimum, data should include gradations, moisture contents, densities, and Atterberg limit of the materials in the supporting system. Before initiating a plate load field test, it is advisable to consult a geotechnical engineer familiar with site conditions to estimate price and time required and the probable results.

4.4.3 American Association of State Highway Transportation Officials (AASHTO) approach—For rigid pavements, AASHTO developed a design procedure using the following theoretical relationship between k values from plate bearing tests and M_R , the resilient modulus of the subgrade

$$k \text{ (lb/in.}^3\text{)} = M_R \text{ (psi)}/19.4 \text{ (in.-lb units)}$$

$$k \text{ (kN/m}^3\text{)} = M_R \text{ (kPa)} \times 2.03 \text{ (SI units)}$$

The resilient modulus is a measure of the assumed elastic property of soil considering its nonlinear characteristics. It is defined as the ratio of the repeated axial deviator stress to the recoverable axial strain and is widely recognized as a method for characterizing pavement materials. The AASHTO Test Method T 307 describes the methods for determining M_R . The value of M_R can be evaluated using a correlation with the older and more common California bearing ratio (CBR) test value (ASTM D1883) by the following empirical relationship (Heukelom and Klomp 1962)

$$M_R \text{ (psi)} = 1500 \times \text{CBR (in.-lb units)}$$

$$M_R \text{ (kPa)} = 10,342 \times \text{CBR (SI units)}$$

This approximate relationship has been used extensively for fine-grained soils having a soaked, saturated 96-hour CBR value of 10 or less (Heukelom and Klomp 1962). Correlations of M_R with clay content, Atterberg limits, and moisture content have also been developed.

The effective k value used for design, as recommended by AASHTO for rigid pavements, depends on several different factors besides the soil resilient modulus, including subbase types and thicknesses, loss of support due to voids, and depth to a rigid foundation. Tables and graphs in the "Guide for the Design of Pavement Structures" (AASHTO 1993) may be used to obtain an effective k for design of slabs-on-ground. The k values obtained from measured CBR and M_R data using the AASHTO relationships can yield unrealistically

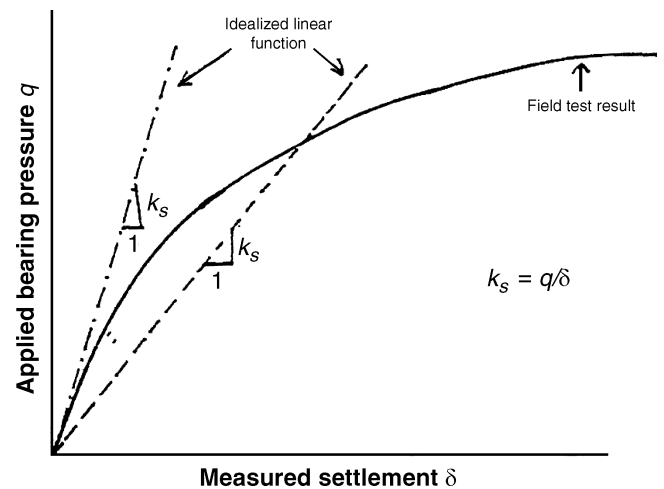


Fig. 4.2—Plate load-deformation diagram.

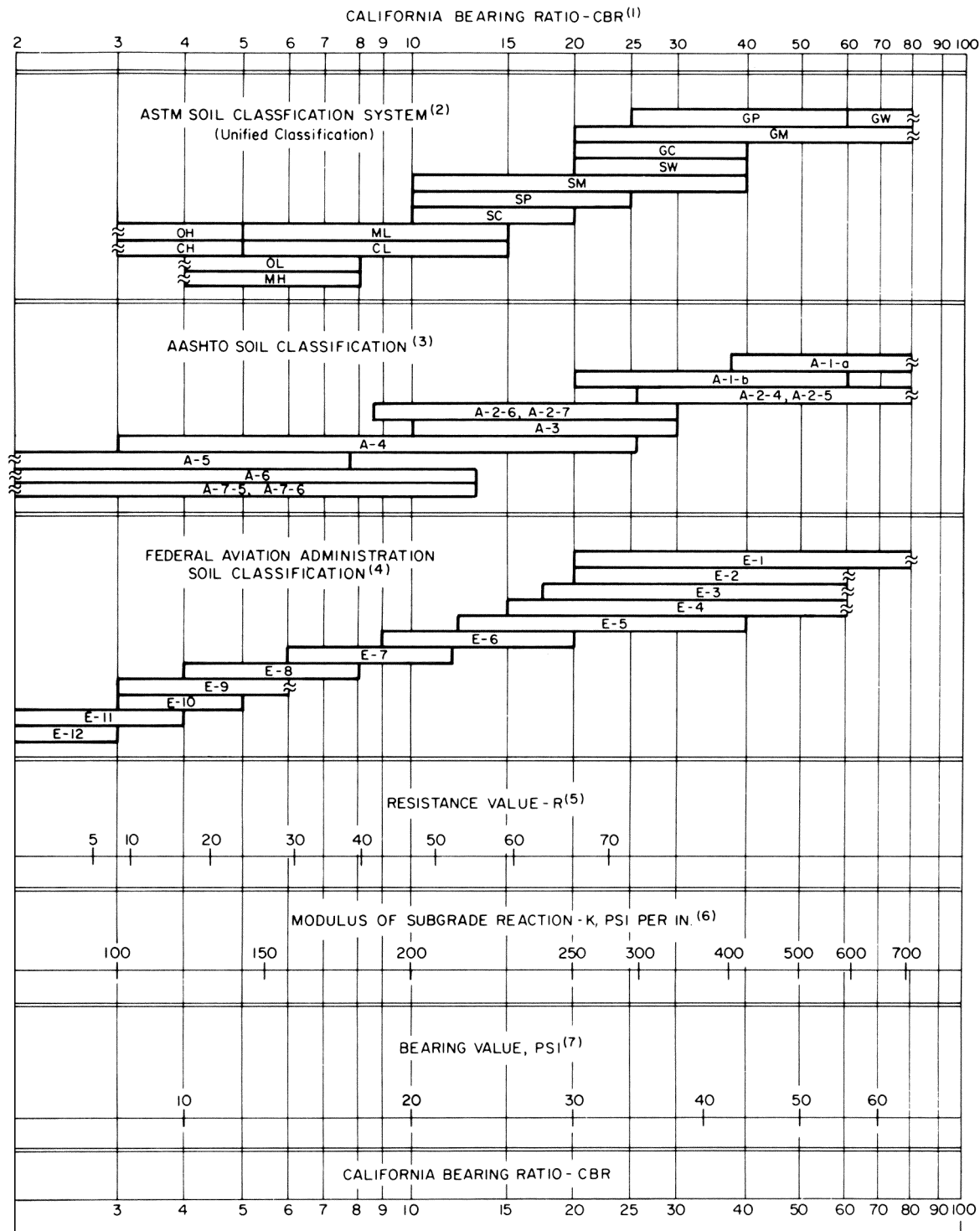
high values. It is recommended that the nomograph relationships contained in Fig. 4.3 be used to validate the results of correlated k values derived from AASHTO correlations.

4.4.4 Other approaches—The Corps of Engineers (COE) developed empirical relations between soil classification type, CBR, and k values, as illustrated by Fig. 4.3. These relationships are usually quite conservative. All of these test methods and procedures have been developed for pavements, not for slab-on-ground floors for buildings. Nevertheless, correlations such as these are widely used to approximate the subgrade support values for slab-on-ground design and construction.

4.4.5 Influence of moisture content—The moisture content of a fine-grained soil affects the modulus of subgrade reaction k at the time of testing and throughout the slab service life. Nearly all soils exhibit a decrease in k with an increase in saturation, but the amount of reduction depends chiefly on the texture of the soil, its density, and the activity of clay minerals present. In general, the higher the moisture content, the lower the supporting strength, but the relationship is unique for each type of soil. The more uniform the moisture content and dry density, the more uniform the support. Therefore, good site surface drainage and drainage of the subgrade is very important. Experience demonstrates that high water tables and broken water or drain lines cause slab-on-ground failures.

To evaluate the influence of moisture, test procedures (such as CBR), unconfined compression, and triaxial shear can be followed. Moisture and dry density ranges chosen for testing should match those anticipated in the field. Laboratory tests are more practical than field tests.

4.4.6 Influence of soil material on modulus of subgrade reaction—Soils found at a building site are capable of providing a range of subgrade support, as illustrated in Fig. 4.3. Clay soils, such as CL and CH materials, provide the lowest subgrade support. Well-graded, noncohesive soils, such as SW and GW material, provide the greatest support. An increase in density by compaction can improve a soil's strength, but to a limited extent. Using stabilization methods will also have a limited range of effectiveness. Drainage conditions can change the support strength of most soils, but



(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. Warnes, "Correlation Between R Value and k Value," unpublished report, Portland Cement Association, Rocky Mountain-Northwest Region, October 1971 (best-fit correlation with correction for saturation).

(6) See T. A. Middlebrooks and G. E. Bertram, "Soil 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. 4.3—Approximate interrelationships of soil classifications and bearing values (PCA 1988). (Note: 1 psi/in. = 0.271 kPa/mm, 1 psi = 6.90 kPa.)

this can be most significant for clays and silts. Frost action can also reduce the support strength of soils containing silt. Thus, the correlation between soil classification and supporting strength is useful for estimating the range of capability, but should be adjusted for expected site conditions.

4.4.7 Uniformity of support—The design charts of PCA, WRI, and COE indicate the influence that the modulus of subgrade reaction has on the required slab thickness. These design aids assume continuous slab contact with the base and a uniform subgrade modulus. Continuous intimate contact is not achieved in practice because of differences in composition, thickness, moisture content, slab curling, and subgrade density. By following the joint recommendations in Fig. 6.6, the curling stresses will be sufficiently low that the PCA, WRI, and COE methods will provide reasonable solutions. Cycles of load and climatic fluctuations of moisture may increase or decrease k , but such change is usually not uniform. Differences in subgrade support due to cuts and fills or irregular depths to shallow bedrock are common. Poor compaction control or variations in borrow material can cause fills to provide nonuniform support. Attempts to produce high subgrade moduli by compaction or stabilization may yield nonuniform support unless strict quality-control standards are implemented. Uniform high k values are difficult to achieve. After slab installation, densification of noncohesive soils, sand, and silts by vibration may yield nonuniform support. The shrinking and swelling action of cohesive soils (GC, SC, CL, and CH) causes cracks in concrete slabs, even when design and construction precautions are taken. Lack of uniform support can cause slab cracks. On some projects, a well-constructed subgrade has been compromised by utility trenches that were poorly backfilled. The importance of providing uniform support cannot be overemphasized. Inspection and testing of controlled fills should be mandatory.

4.4.8 Influence of size of loaded area—The k value, when derived from the plate load test, only provides information relative to the upper 30 to 60 in. (760 to 1520 mm) of the subsurface profile. This may be sufficient for the analyses of floor slabs subjected to relatively small concentrated loads, but it is not sufficient for floor slabs subjected to large, heavy loads. For example, a fully loaded warehouse bay measuring 25 x 25 ft (7.6 x 7.6 m) can load and consolidate soils 30 ft (9.1 m) or more when fills were used to develop the site. Slab settlement is not uncommon where fills were used to produce dock height floors or promote area drainage. The degree of settlement under such loading conditions typically indicates an equivalent k value of only 20 to 30% of that measured by a plate load test.

To properly consider the effect of heavy distributed loads on slab performance, a more comprehensive evaluation of subsurface conditions should be conducted. Such an evaluation may include the performance of soil test borings, laboratory tests of subgrade materials, or one of a variety of in-place testing techniques. Such information can be used to develop soil-support values that account for long-term consolidation settlements under sustained heavy distributed loads.

4.4.9 Influence of time—Time of load application and elapsed time are important. Short, transient loads such as lift

trucks, produce smaller deformations than sustained loads; therefore, a higher k value can be used for rolling loads. With the passage of time, the subgrade and subbase is subject to load cycling. Applications of surface loads may increase the stiffness of the subgrade and subbase, and a higher k value will result. Unfortunately, this may also produce nonuniform support because the areas of load application will not usually be uniform.

Subgrade moisture change over time may also affect the soil-support system. Stability through changes of climate, such as protracted dry or wet weather conditions or cycles of freezing and thawing, should be considered.

4.5—Design of slab-support system

4.5.1 General—After the subgrade soils have been classified, the general range of their k values can be approximated from Fig. 4.3. Adjustments may be made on the basis of local experience, expected seasonal changes, and expected construction conditions.

With this information, a decision can be made whether to use the existing subgrade, improve it by compaction or stabilization, use a subbase and a base course, or vary the thickness of these layers. Initially, a wide range of subgrade conditions may exist across the site. The soil-support system is rarely uniform and some soil work is generally required to produce a more uniform surface to support the slab. The extent of this work, such as the degree of compaction or the addition of a base course, is generally limited by economics. Selection of crushed rock or soils in the well-graded gravel (GW) and poorly-graded gravel (GP) groups may appear costly as a base material, but the selection of these materials has distinct advantages. They improve the modulus of subgrade reaction, produce more uniform support, and provide an all-weather working surface to speed construction during inclement weather.

4.5.2 Economics and simplified design—Designing a slab-support system requires identification of the subgrade material and the conditions to which it will be exposed. This knowledge is essential to estimate the modulus of subgrade and the potential volume change. With knowledge of soil classification and some local experience, the engineer can select an appropriate k value and design for the specific soil conditions. The slab thickness calculation is insensitive to small changes in k , therefore the exact k value need not be known. Significant variations do not significantly change the design thickness.

For small projects, it may be advantageous to assume a relatively low k factor and add an appropriate thickness of subbase and base course material to enhance performance of the slab rather than performing an expensive plate load test. Basing design on assumed conditions increases the risk of slab failure, but there are occasions when a simplified design approach is justified. These decisions are a matter of engineering judgment and economics.

4.5.3 Bearing support—Calculated bearing pressures under loaded slabs-on-ground are typically significantly lower and are not critical to typical designs as compared with the allowable foundation contact pressures for building elements controlled by ACI 318. Providing uniform support conditions is already important for serviceable slab performance.

4.6—Site preparation

4.6.1 Introduction—Initially, the top layer of soil should be stripped of all organic material, debris, and frozen material. Normally, to produce a uniform support, strip and till the surface, and recompact it before placing the subbase. Hard and soft pockets of soil should be located by proof-rolling or other means. Remove them and replace with compacted soil to provide a uniform subgrade for the base, subbase, or concrete slab. Refer to ACI 302.1R for additional information.

The site should be graded to provide good surface drainage throughout the construction period and for the lifetime of the structure. Groundwater may have to be intercepted and routed around the site.

Combinations of base and subbase materials and thicknesses can be used to increase the subgrade strength. Carefully examine sinkholes, expansive soils, highly compressible materials, or other subgrade problems, as they can influence slab performance.

4.6.2 Proof-rolling—As discussed in ACI 302.1R, proof-rolling usually refers to driving a loaded vehicle in a grid pattern over the subgrade in an effort to locate soft and compressible areas at or near the surface. This should be a part of the quality assurance process for the soil-support system and should be documented in the project specifications. The wheel load should be sized to avoid bearing failure, but be large enough to stress at least the upper foot of subgrade. Three cycles of the wheel load over the same track are usually specified. These repeated applications may expose weak areas by rutting or pumping behavior of the surface soils. Rutting normally indicates excess moisture at the surface. Pumping of the soils under the wheels of the loaded vehicle indicates the subgrade soils are likely wet of the optimum moisture and unable to achieve and maintain compaction. Areas of poor support should be removed and replaced with compacted material to provide a more uniform subgrade. After repairs, proof-rolling can be repeated. There are no standards for proof-rolling, and quantitative assessment cannot be made from its use. Guidelines for proof-rolling are given in ACI 302.1R. When a thick layer of dry and dense material, such as a base or subbase course, exists over the surface, or the subgrade surface has become hard due to drying and construction traffic, proof-rolling may not detect any soft or compressible areas under the surface. Some projects employ proof-rolling three times after:

- Stripping (before any fill is placed);
- Installing the fill; and
- Placing the base course.

Locating suspected deeper soft areas or buried debris may require borings, test pits, resistivity, or other procedures. Proof-rolling should be scheduled so remedial work does not interfere with the construction schedule.

4.6.3 Subgrade stabilization—A number of methods can improve the performance of a soil subgrade. Generally, for slabs-on-ground, the soil is densified by using compaction equipment such as a sheepsfoot, rubber tire, or vibratory rollers. Chemical stabilization may also be appropriate.

Weak subgrade material can be stabilized by adding chemicals that combine with the soil, as shown in Table 4.3.

Generally, portland cement, lime, or fly ash is mixed into the soil substrata with water and the mixture is recompact. Lime and fly ash are also used to lower the plasticity index of subgrade and subbase materials. For silty soils, portland cement may be effective. A geotechnical engineer should plan, supervise, and analyze the soil conditions before chemical stabilization is used.

Depending on the situation and soil conditions, certain compactors are more effective than others. Generally, granular soils are most responsive to vibratory equipment, and cohesive soils respond best to sheepsfoot and rubber-tired rollers, but there are exceptions. The depth of compacted lifts varies with soil type and compaction equipment, but in most cases, the depth of compacted lifts should be 6 to 9 in. (150 to 230 mm). The dry density achieved after compaction is normally measured and compared with maximum dry density values obtained from laboratory compaction tests. Maximum dry density and optimum moisture content values vary with texture and plasticity. Refer to Fig. 4.4, which illustrates standard Proctor tests (ASTM D698) on eight different soils.

Because the modified Proctor test (ASTM D1557) uses a higher level of energy, the maximum dry density will be higher and the optimum moisture content will be lower than the standard Proctor test values. Furthermore, the difference will vary with the texture and plasticity of the soil (Fig. 4.5).

Specifications frequently limit only the minimum field density, such as 95% of the standard Proctor maximum density or 90% of the modified Proctor maximum dry density. To achieve a more uniform subgrade modulus, a range of density should be specified. For example, $100 \pm 5\%$ of the standard Proctor maximum density, or $95 \pm 5\%$ of the modified Proctor maximum dry density. The range specified, however, should be compatible with the soil type, soil uniformity, contractor's operation, and project needs. Specifying a lower density range for clay soils having a plasticity index of 20 or higher, for example, $92 \pm 4\%$ of the standard Proctor maximum dry density is often used to control volume changes. Frequently, moisture content within $\pm 3\%$ of the optimum moisture content of the appropriate test is also specified. Higher moisture contents, from optimum moisture content to 4% above it, are frequently used to minimize volume changes.

4.6.4 Subbase and base materials—For many slabs-on-ground, the existing subgrade provides adequate support. Generally, the materials listed in Fig. 4.3 that yield a standard modulus of subgrade reaction above 100 lb/in.³ (3000 kN/m³) can be used (Fig. 4.3). Highly compressible organic materials (OL) should be avoided, as well as high-plasticity clays (CH), as they may cause heave or swell problems. Much of the variation in support strength is the result of compaction and moisture content; for example, the k value for lean clay (CL) ranged from 70 to 250 lb/in.³ (2000 to 7000 kN/m³).

The subbase material has better qualities than the subgrade, and may serve as a construction working surface and part of the floor support system. The subbase is generally omitted where the subgrades are of high quality. The use of a subbase with a base course usually represents an economical alternative for construction on a poor subgrade with an

Table 4.3—Soil stabilization with chemical admixtures

Admixture	Quantity, percent by weight of stabilized soil	Process	Applicability	Effect on soil properties
Portland cement	Varies from approximately 2-1/2 to 4% for cement treatment to 6 to 12% for soil cements.	Pulverize cohesive soil so that at least 80% will pass No. 4 (4.75 mm) sieve, mix with cement, moisten to between optimum and 2% wet, compact to at least 95% maximum density and cure for 7 or 8 days while moistening with light sprinkling or protecting by surface cover.	Forms stabilized subgrade or base course. Wearing surfaces should be added to provide abrasion resistance. Not applicable to plastic clays.	Unconfined compressive strength increased up to approximately 1000 psi (6.9 MPa). Decreases soil plasticity. Increases resistance to freezing and thawing, but remains vulnerable to frost.
Bitumen	Three to 5% bitumen in the form of cutback asphalt emulsion, or liquid tars for sandy soils. Six to 8% asphalt emulsions and light tars for fine-grained materials. For coarse-grained soils, anti-strip compounds are added to promote particle coating by bitumen.	Pulverize soil, mix with bitumen, aerate solvent, and compact mixture. Before mixing, coarse-grained soils should have moisture content as low as 2 to 4%. Water content of fine-grained soils should be several percent below optimum.	Forms wearing surface or construction stage, for emergency conditions, or for low-cost roads. Used to form working base in cohesionless sand subgrades, or for improving quality of base course. Not applicable to plastic clays.	Provides a binder to improve strength and to waterproof stabilized mixture.
Lime	Four to 8%. Fly ash, between 10 and 20%, may be added to increase pozzolanic reaction.	Spread dry lime, mix with soil by pulvimixers or discs, compact at optimum moisture to ordinary compaction densities.	Used for base course and subbase stabilization. Generally restricted to warm or moderate climates because the mixture is susceptible to breakup under freezing and thawing.	Decreases plasticity of soil, producing a grainy structure. Greatest effect in sodium clays with capacity for base exchange. Increases compressive strength up to a maximum of approximately 500 psi (3.4 MPa).

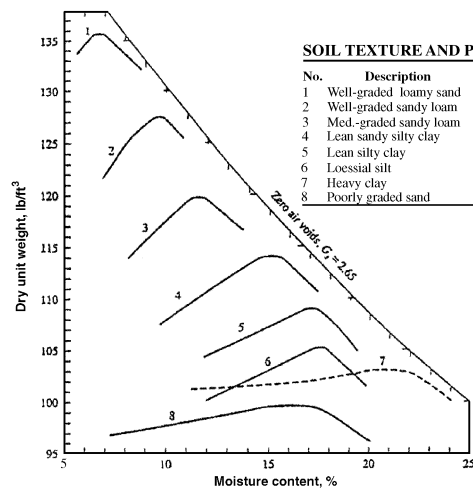


Fig. 4.4—Standard Proctor curves for various soils.
(Note: 1 lb/ft³ = 0.1571 kN/m³.)

expensive base course material. The subbase may be composed of:

- Stabilized subgrade soil;
- A fill of higher quality soil;
- Sand;
- Crushed rock;
- Reclaimed crushed concrete or asphalt pavement; or
- Local material with properties that satisfy project requirements.

Base material should be a clean, densely-graded, granular material with a balanced fine content. It should produce an easily constructed, low-friction surface while minimizing wicking of moisture from below. These densely-graded crushed products are commonly referred to as “crusher-run” materials. The following material sources have proven to be adequate:

1. The local Department of Transportation (DOT) approved road base material with 100% passing the 1-1/2 in.

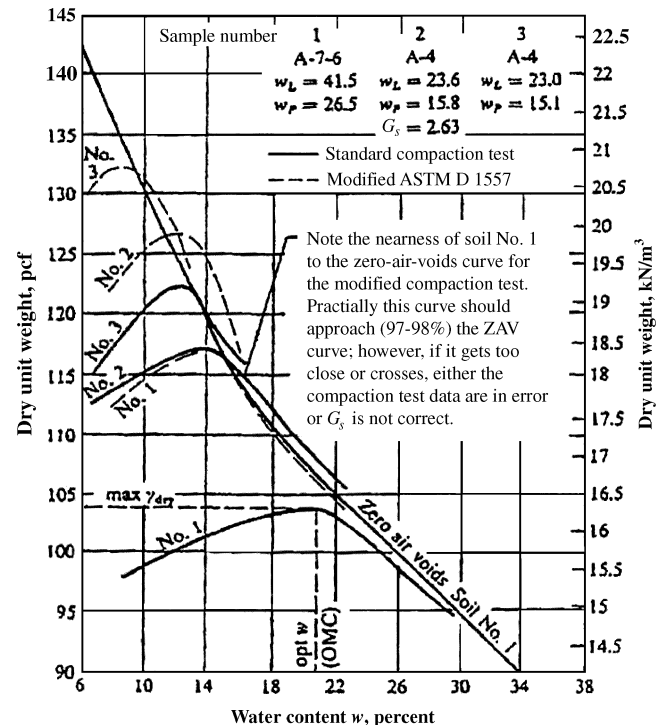


Fig. 4.5—Standard and modified Proctor curves.

(37.5 mm) sieve, 15% to 55% passing the No. 4 (4.75 mm) sieve, and less than 12% passing the No. 200 sieve (75 μm).

2. Material satisfying the requirements of ASTM D1241, Gradation “A,” “C,” or “D” (with the modified allowance of less than 12% passing the No. 200 sieve [75 μm]).

Material passing the No. 200 sieve (75 μm) should be clean, granular fill with less than 3% clay or friable particles.

These materials are easily compacted and have high strengths and low compressibilities. When they have little or no fines (material passing a 200 mesh [75 μm] sieve), they are easily drained and act as a capillary break. Their effect on

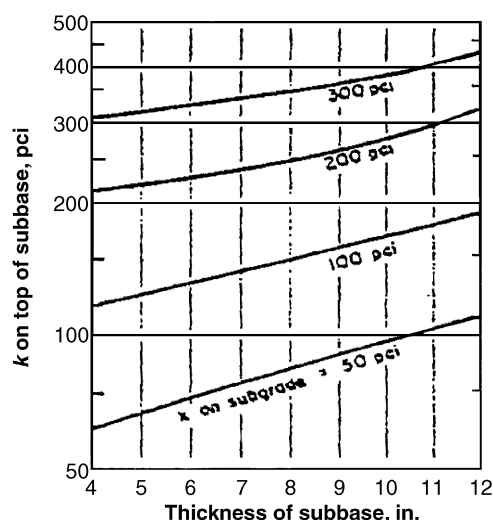


Fig. 4.6—Effect of subbase thickness on design modulus of subgrade reaction. (Note: 1 pci = 0.2714 MN/m³; 1 in. = 25.4 mm.)

the slab support and the overall k value depends on the type and thickness of the base material (Fig. 4.6). Data for specific designs should be based on laboratory analysis and site-testing results. When using an open-graded, crushed rock, the surface may have to be filled in, “choked off” with sand or fine gravels, and compacted to provide a smooth, planar surface to reduce the restraint due to linear concrete shrinkage.

4.6.5 Stabilization of base and subbase—Base and subbase materials are often densified by mechanical compaction to improve the k value. Consider the relative price of alternatives such as chemical stabilization of the subgrade, use of high-quality base courses, or using a thicker slab.

Measure the mechanical compaction of clay and silt as a percent of standard Proctor density (ASTM D698) or modified Proctor density (ASTM D1557). Minimum dry densities typically specified for these materials range from 90 to 95% of the maximum dry densities of the standard and modified tests, respectively.

4.6.6 Grading tolerance—Usually, compliance with the initial rough and fine grading tolerance is based on a rod and level survey using a grid pattern of no more than 20 ft (6.1 m). Grading tolerances specified for a project should be consistent with the recommendations of ACI 117. When a minimum slab thickness has been specified, however, then the slab designer will need to take exception to ACI 117 slab and base tolerances requirements in the construction documents. Specifying a minimum acceptable slab thickness significantly increases the effort to minimize the base and slab tolerances. It may also increase the concrete thickness overages needed to ensure a slab minimum thickness.

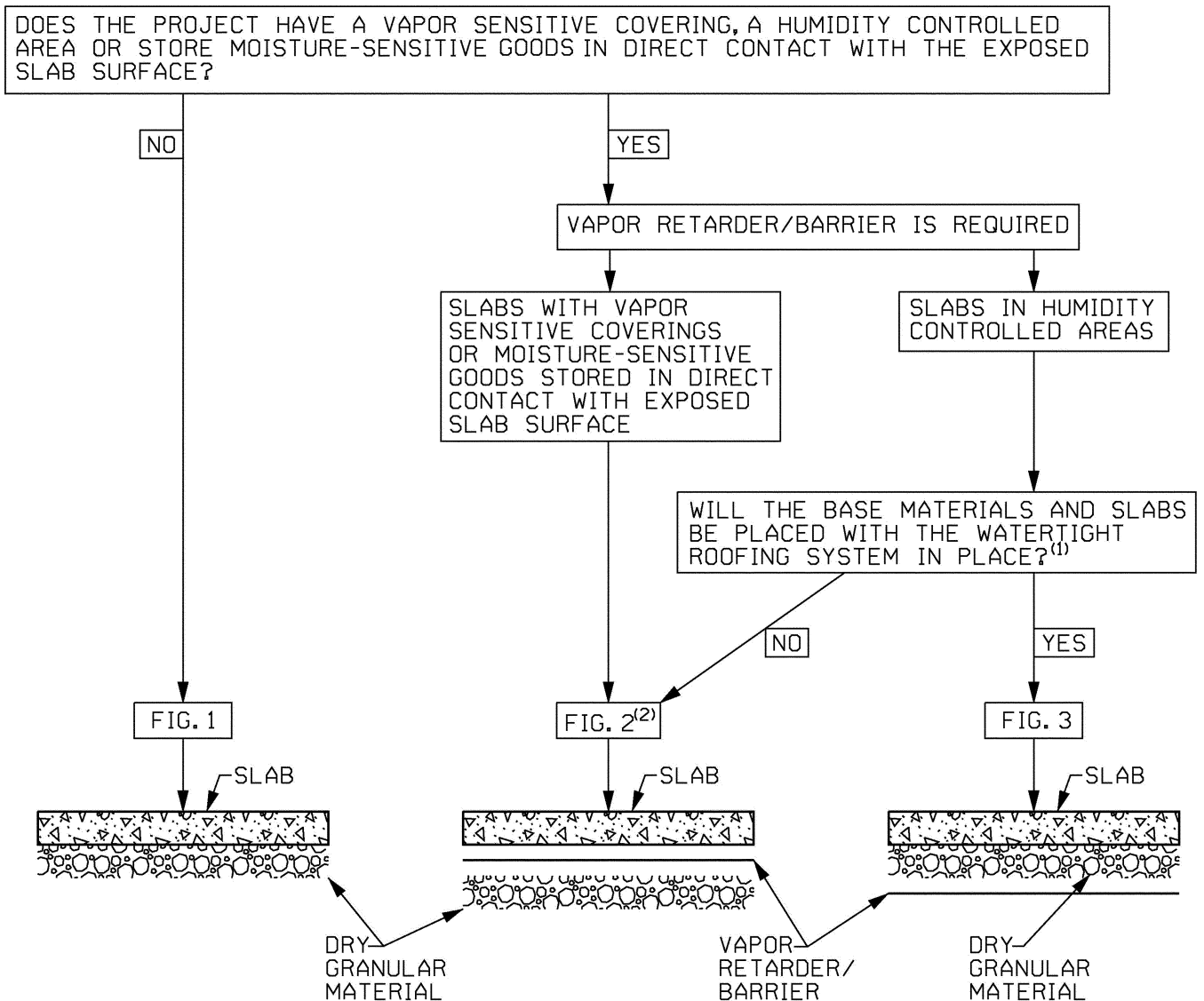
4.6.7 Vapor retarder/barrier—All concrete is permeable to some degree. Water and water vapor can move through slabs-on-ground (Brewer 1965; Neville 1996). This can adversely affect the storage of moisture-sensitive products on the slab, humidity control within the building, and a variety of flooring materials from coatings to carpets. For storage facilities, anticipated stored goods, and methods of

storage should be discussed with the owner. Emitting vapor can become trapped and condensed beneath products such as cardboard stored in direct contact with the slab. Because this moisture can damage stored products, the slab designer should consider positive moisture protection such as a vapor retarder. Products that are not stored in direct contact with the slab, but are sensitive to moisture, may require humidity control. For slabs to receive moisture-sensitive floor coverings, product manufacturers specify a maximum moisture emission rate from the slab surface, generally in the range of 3 to 5 lb/1000 ft² (12 to 21 N/100 m²)/24 hours or a maximum relative humidity, generally 75 to 80% at a depth of 40% of the slab thickness. The use and the location of vapor retarders/barriers require careful consideration. Figure 4.7 provides guidance.

Excess water in the slab not taken up by chemical action evaporates through the slab top until reaching equilibrium with ambient humidity. Additionally, moisture can transpire from the subgrade and through the slab. When the base material under the slab is saturated and subjected to a hydrostatic head, as for a basement slab below a water table, liquid water may flow through cracks or joints in the concrete. When hydrostatic forces can occur, include them in the slab design considerations. The amount of flow depends on the amount of head and width, length, and spacing of the joints and cracks in the concrete. When the base material is saturated or near saturation and there is no head, moisture may transmit into the slab by capillary action of the interconnected voids in the concrete. Positive subgrade drainage is necessary where water would otherwise reach the slab base. Further, an open-graded stone is frequently used as a base course to form a break against capillary rise of moisture in the subgrade. Vapor retarders/barriers can substantially reduce vapor transmission through slabs, but some water vapor will transpire through the slab when the vapor pressure above the slab is less than that below the slab.

Climate-control systems may lower the relative humidity above the slab and result in water vapor movement through the slab. The vapor pressure is a function of temperature and relative humidity. The vapor drive is from high to low vapor pressure. The temperature of the soil base is usually lower than that of the space above the slab. The relative humidity of the subgrade is typically 100%.

Water in the subgrade under slabs-on-ground can change due to seasonal fluctuations of shallow water tables, capillary rise in the subgrade soils, poor subsurface drainage, ponding of storm water adjacent to the slab-on-ground, overwatering plants and lawns adjacent to the slab-on-ground, or from broken pipes in the subgrade. Because there are a variety of moisture sources, there is likely a nonuniform distribution of moisture beneath the slab-on-ground. Tests can be made to try to ascertain the moisture problem before a covering is placed. ASTM D4263 may detect moisture coming from the slab but does not yield a rate of moisture movement. A quantitative test method, ASTM F1869, uses a desiccant calcium chloride beneath an impermeable dome over a small slab area to calculate the moisture emission rate. These test results may be misleading when the ambient air conditions do not represent in-service conditions. ASTM F1869 requires

**NOTES:**

- (1) IF GRANULAR MATERIAL IS SUBJECT TO FUTURE MOISTURE INFILTRATION, USE FIG. 2.
- (2) IF FIGURE 2 IS USED, A REDUCED JOINT SPACING, A LOW SHRINKAGE MIX DESIGN, OR OTHER MEASURES TO MINIMIZE SLAB CURL WILL LIKELY BE REQUIRED.

Fig. 4.7—Decision flowchart to determine when a vapor retarder/bARRIER is required and where it is to be placed.

an ambient air temperature of $75^{\circ}\text{F} \pm 10^{\circ}\text{F}$ ($24^{\circ}\text{C} \pm 6^{\circ}\text{C}$) and a relative humidity of $50\% \pm 10\%$ for 48 hours before and during the test. This test measures moisture in the top 1/2 in. (13 mm) of the slab, and cannot detect moisture below 3/4 in. (19 mm). To better quantify moisture in slabs, ASTM F2170 was developed for the use of relative humidity probes.

Subgrade drainage and selecting subgrade materials have a great influence on vapor retarders/barriers performance. Protecting vapor retarders/barriers from damage during construction can significantly influence their effectiveness. Vapor retarders/barriers have been reported to affect the concrete behavior in the slab by increasing finishing time, promoting cracking, increasing slab curling, and reducing

strength. These problems, however, may be less costly than performance failures related to excessive moisture transmission through the slab.

4.7—Inspection and site testing of slab support

Inspection and testing are required to control the quality of the subgrade and subbase construction and determine conformance to project specifications. Before construction begins, the subgrade soils and subbase or base-course materials should be sampled, tested in the laboratory, and the results evaluated.

In general, perform the following tests for soils and soil-aggregate mixtures:

- Particle size (ASTM D 422);

- Plasticity (ASTM D4318); and
- Laboratory compaction tests (ASTM D698 or D1557).

For cohesionless and free-draining soils and aggregates gradation, perform the following:

- Maximum relative density (ASTM D4253);
- Minimum relative density (ASTM D4254); and
- Calculation of relative density.

After compaction, the in-place density can be determined in the field by:

- Drive cylinder (ASTM D2937);
- Sand cone (ASTM D1556);
- Water balloon (ASTM D2167); and
- Nuclear densometer (ASTM D2922 and D3017).

The sand cone test is the most accepted method, but the nondestructive nuclear density method is advantageous because it takes minutes to conduct, the results are available at the end of the field test, and it is widely used and accepted. This allows field density and moisture contents to be used to control construction. To check questionable results or to confirm calibrations, however, the sand cone method is generally specified. To check the nuclear gauge against the sand cone and provide an adjustment factor, conduct a series of calibration tests. Check the moisture readings against field moisture tests (ASTM D566). Testing frequency is relative to the uniformity of the materials used and the quality of compaction required. Work that does not conform to the project specifications should be corrected and retested. The subgrade should be tested in advance of installing the remainder of the slab-on-ground system. Minimum testing requirements should be established for each project. These should provide a reasonable test interval for each lift. These tests are relatively inexpensive and easy to perform.

4.8—Special slab-on-ground support problems

Because of their low shear strength and high compressibility, avoid placing slabs on topsoil. Project specifications generally require stripping topsoil from the building site.

Expansive soils are defined as fine-grained soils, as shown in Tables 4.1 and 4.2. Soils with a plasticity index of 15 or higher may have a potential for volume change that should be considered. A geotechnical engineer should examine the soil data and recommend appropriate options. Potential problems can be minimized by proper slab designs, stabilizing the soil, and preventing moisture migration through the slab. Failure to manage problems can, and often will, result in slab failure.

Frost action may be critical to silts, clays, and some fine sands. These soils can experience large volume changes and consequently heave due to the growth of ice lenses during freezing cycles and lose support due to saturation upon thawing. Three conditions are present when this problem occurs:

1. Freezing temperature in the soil;
2. Water table close to the frost level providing water for the formation of ice lenses; and
3. A soil that will transmit water from the water table into the frost zone by capillary action.

Possible remedies include lowering the water table, providing a barrier, or using a subbase or subgrade soil that

is not frost-susceptible. Properly designed insulation can be beneficial. Volume changes due to frost action occur at building perimeters, under freezer areas, and under ice-skating rink floors (NCHRP 1974).

CHAPTER 5—LOADS

5.1—Introduction

Chapter 5 describes loadings, the variables that control load effects, and provides guidance for factors of safety for concrete slabs-on-ground. Concrete slabs are typically subjected to some combinations of the following loads and effects:

- Vehicle wheel loads;
- Concentrated loads;
- Distributed loads;
- Line and strip loads;
- Unusual loads;
- Construction loads; and
- Environmental effects.

Slabs should be designed for the most critical combination of these loadings, considering variables that produce the maximum stress. Figure 5.1 presents the PCA guide for selecting the most critical or controlling design considerations for various loads (Packard 1976). Because a number of factors, such as slab thickness, concrete strength, subgrade stiffness, and loading are relevant, cases where several design considerations that may control should be investigated thoroughly.

Other potential load conditions, such as loadings that change during the life of the structure and those encountered during construction (Wray 1986), should also be considered. For example, material-handling systems today make improved use of the building's volume. Stacked pallets, once considered uniform loads, may now be stored in narrow-aisle pallet racks that produce concentrated loads. The environmental exposure of the slab-on-ground is also a concern. These effects include subgrade volume changes (shrink and swell soils), buildings with equipment to reduce humidity, and temperature changes. Thermal effects may be minimized by constructing the slab after the building is enclosed, but many slabs are placed before building enclosure. Therefore, construction sequence is important in determining whether transient environmental factors should be considered in the design. Finally, thermal effects due to in-service conditions should be considered.

5.2—Vehicular loads

Most vehicular traffic on industrial floors consists of lift trucks and distribution trucks with payload capacities as high as 70,000 lb (310 kN). The payload and much of a truck's weight are generally carried by the wheels of the loaded axle for the standard (counterbalanced) lift truck. The Industrial Truck Association (ITA) (1985) has compiled representative load and geometry data for lift truck capacities up to 20,000 lb (89 kN) (Table 5.1). Vehicle variables affecting the thickness selection and design of slabs-on-ground include:

- Maximum axle load;
- Distance between loaded wheels;
- Tire contact area; and
- Load repetitions during service life.



The axle load, wheel spacing, and contact area are functions of the lift truck or vehicle specifications. When vehicle details are unknown or when the lift truck strength is expected to change in the future, the values in Table 5.1 may be used for design. The number of load repetitions, which may be used to help establish a factor of safety, is a function of the facility's usage. Knowledge of load repetitions and traffic patterns helps the designer to quantify fatigue. Consider whether these values are predictable or constant during the slab's service life. Often, the slab is designed for an unlimited number of repetitions.

The contact area between tire and slab is used in the analysis for lift truck with pneumatic or composition tires (Wray 1986). The contact area of a single tire can be approximated by dividing the tire load by the tire pressure (Packard 1976). This calculation is somewhat conservative because the effect of tension in the tire wall is not included. Assumed pressures are variable; however, pneumatic non-steel-cord tire pressures range from 85 to 100 psi (0.6 to 0.7 MPa), whereas steel-cord tire pressures range from 90 to 120 psi (0.6 to 0.8 MPa). The ITA found that the standard solid and cushion solid rubber tires have floor contact areas based on internal pressures between 180 and 250 psi (1.2 to 1.7 MPa) (Goodyear Tire and Rubber Co. 1983). Polyurethane tire pressures exceeding 1000 psi (6.9 MPa) have been measured.

Dual tires have an effective contact area greater than the actual contact area of the two individual tires. Charts are available to determine this effective contact area (Packard 1976). A conservative estimate of this effective contact area can be made by using the contact area of the two tires and the areas between the contact area. When it is not known whether the vehicle has dual wheels or what the wheel spacings are, then a single equivalent wheel load and contact area can be used conservatively.

An important consideration for the serviceability of a slab subject to vehicular loads is the design of construction and sawcut contraction joints. Joints should be stiff enough and have sufficient shear transferability to limit differential movement such that the joint filler can perform properly and resists edge spalling as a vehicle travels across the joint. Refer to Chapter 6 for more information and joint details.

5.3—Concentrated loads

Warehousing improvements in efficiency and storage densities have trended toward increased rack post loads. These changes include narrower aisles, higher pallet or material stacking, and using automated stacking equipment. Pallet storage racks may be higher than 80 ft (24 m) and may produce concentrated post loads of 40,000 lb (180 kN) or more. For the higher rack loads, racks that cover a large plan area (which affects deeper soil layers), and racks with long-term loading, consider the effect of the long-term soil settlement in the design of the slab. Cracking can also be caused by early installation of rack systems that may restrain the slab's shrinkage and thermal movement and prevent joint activation. The racks may restrain the slab with the rack system bracing or by the increase in base friction from additional storage loads.

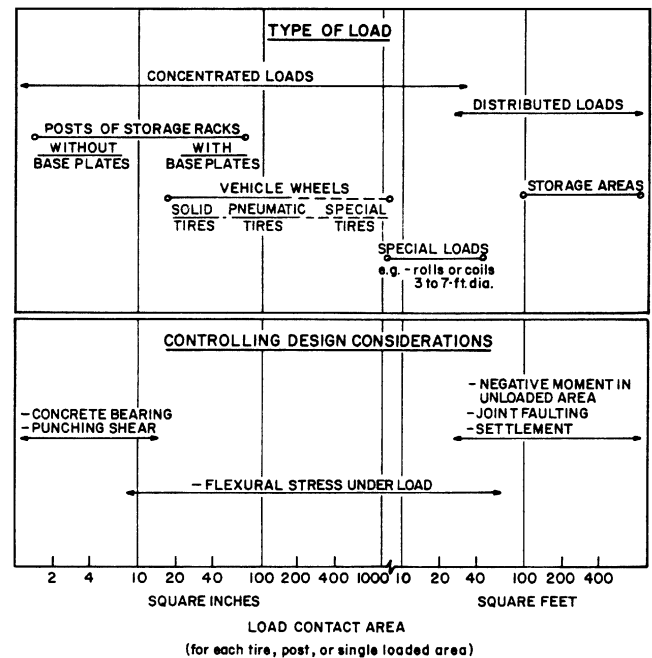


Fig. 5.1—Controlling design considerations for various types of slabs-on-ground loading (Packard 1976). (Note: $1 \text{ in.}^2 = 645.2 \text{ mm}^2$; $1 \text{ ft}^2 = 0.09290 \text{ m}^2$.)

Table 5.1—Representative axle loads and wheel spacings for various lift truck capacities

Truck rated capacity, lb	Total axle load static reaction, lb	Center-to-center of opposite wheel tire, in.
2000	5600 to 7200	24 to 32
3000	7800 to 9400	26 to 34
4000	9800 to 11,600	30 to 36
5000	11,600 to 13,800	30 to 36
6000	13,600 to 15,500	30 to 36
7000	15,300 to 18,100	34 to 37
8000	16,700 to 20,400	34 to 38
10,000	20,200 to 23,800	37 to 45
12,000	23,800 to 27,500	38 to 40
15,000	30,000 to 35,300	34 to 43
20,000	39,700 to 43,700	36 to 53

Notes: Calculate concentrated reaction per tire by dividing the total axle load reaction by the number of tires on that axle. Figures given are for standard trucks. The application of attachments and extended high lifts may increase these values. In such cases, consult the manufacturer. Weights given are for trucks handling the rated loads at 24 in. from load center to face of fork with mast vertical. 1 lb = 0.004448 kN; 1 in. = 25.4 mm.

The concentrated load variables that affect slab-on-ground design include:

- Maximum or representative post load;
- Duration of load;
- Spacings between posts and aisle width;
- Location of the concentrated load relative to slab joint location and the amount of shear transfer across the slab joint; and
- Area of contact between post base plate and slab.

Material-handling systems are major parts of the building layout and should be well defined early in the project. Rack data can be obtained from the manufacturer. It is uncommon to specify a larger base plate than is normally

supplied to reduce the flexural stress caused by the concentrated load. The base plate should be sized to distribute the load nearly uniformly over the plate area.

5.4—Distributed loads

In many warehouse and industrial buildings, materials are stored directly on the slab-on-ground. Flexural stresses in the slab are usually less than those produced by concentrated loads. The design should prevent negative moment cracks or limit crack widths for the reinforced slabs in the aisles and prevent excessive settlement. For higher load intensities, distributed loads that cover a large plan area (which affect deeper soil layers) and long-term uniform loads, consider the effect of the differential soil settlement in the slab design. The effect of a lift truck operating in aisles between uniformly loaded areas is not normally combined with the uniform load into one loading case, as the moments produced generally offset one another. The individual cases are always considered in the design.

For distributed loads, the variables affecting the design of slabs-on-ground are:

- Maximum load intensity;
- Load duration;
- Width and length of loaded area;
- Aisle width; and
- Presence of a joint located in and parallel to an aisle.

Load intensity and layout may not be constant during the service life of a slab. Therefore, the slab should be designed for the most critical case. For a given modulus of subgrade reaction and slab thickness, there is a critical aisle width that maximizes the center aisle moment (Packard 1976).

5.5—Line and strip loads

A line or strip load is a uniform load distributed over a relatively narrow area. Consider a load to be a line or strip load when its width is less than 1/3 of the radius of relative slab stiffness (Section 7.2). When the width approximates this limit, review the slab for stresses produced by line loading and uniform load. When the results are within 15% of one another, consider the load as uniform. Partition loads, bearing walls, and roll storage are examples of this load type. For higher load intensities and long-term loading, consider the effect of differential soil settlement in the design of the slab.

The variables for line and strip loads are similar to those for distributed loadings and include:

- Maximum load intensity;
- Load duration;
- Width, length of loaded area, and when the line or strip loads intersect;
- Aisle width;
- Presence of a joint in and parallel to an aisle;
- Presence of parallel joints on each side of an aisle; and
- The amount of shear transfer across the slab joint, which is especially important when the line load crosses perpendicular to a joint or is directly adjacent and parallel to a joint.

5.6—Unusual loads

Loading conditions that do not conform to the previously discussed load types may also occur. They may differ in the following manner:

- Configuration of loaded area;
- Load distributed to more than one axle; and
- More than two or four wheels per axle.

The load variables are similar to those for the load types previously discussed in Chapter 5.

5.7—Construction loads

During the building construction, various equipment types may be located on the newly placed slab-on-ground. The most common construction loads are:

- Pickup trucks;
- Scissor lifts;
- Concrete trucks;
- Dump trucks;
- Hoisting equipment and cranes used for steel erection;
- Tilt wall erection and bracing loads; and
- Setting equipment.

In addition, the slab may be subjected to loads such as scaffolding and material pallets. Because these loads can exceed design limits, anticipate the construction load case, particularly relative to early-age concrete strength. Also, consider limiting construction loads near the free edges or slab corners. The controlling load variables for construction loads are the same as for vehicle loads, concentrated loads, and uniform loads.

For construction trucks, the maximum axle load and other variables can usually be determined by referencing to local transportation laws or AASHTO standards. Off-road construction equipment may exceed these limits, but in most cases, construction equipment will not exceed the local DOT legal limits. For design, reference the values shown in Fig. 5.2.

Design codes are mostly silent on the subject of temporary construction loads during erection (Subrizi et al. 2004). In tilt-up construction, the slab-on-ground is often used as part of the temporary construction bracing. The Tilt-Up Concrete Association (TCA) has developed a temporary bracing guideline (TCA 2005) that provides some guidance for the slab's design. When the slab designer considers these tilt-up wall bracing loads during the initial design of the slab, then often a more economical bracing solution is achieved for the project (Kelly 2007). Kelly (2007) also provides some solutions when the bracing loads are considered after the slab has been constructed along with some design guidance for the slab's flexural strength.

5.8—Environmental factors

Overall slab design should consider flexural stresses produced by thermal changes, reduction in humidity, expansive soils, and moisture changes in the slab, which will affect curling due to the different shrinkage rates between the top and bottom of the slab. These effects are of particular importance for exterior slabs and for slabs constructed before the building is enclosed. Curling caused by these changes produces flexural stresses due to the slab lifting off the

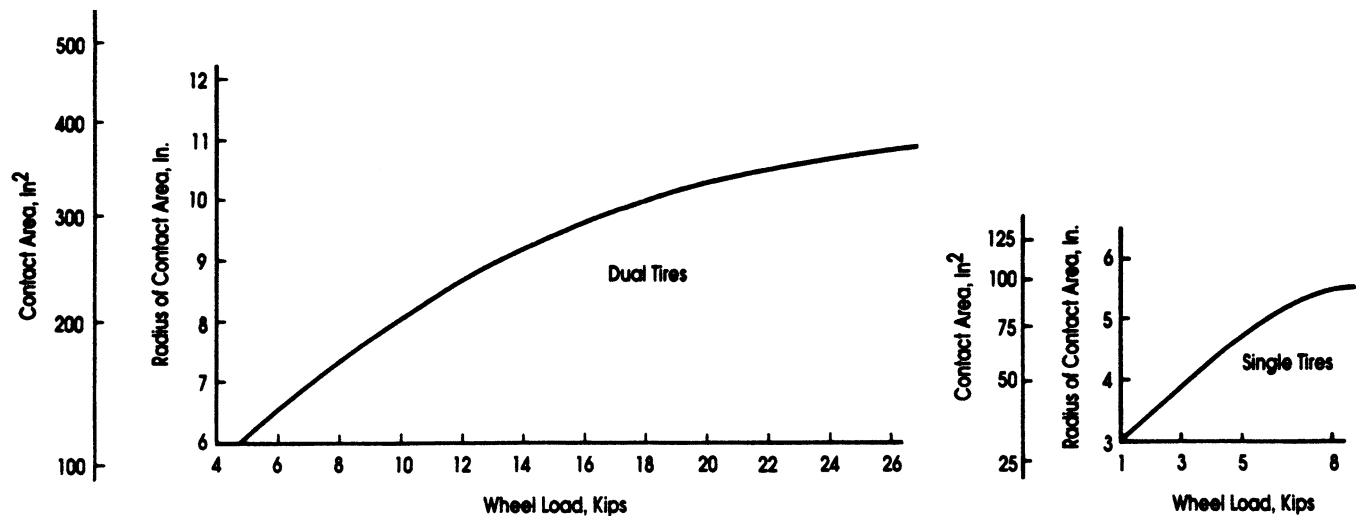


Fig. 5.2—Tire contact area for various wheel loads. (Note: 1 in. = 25.4 mm; 1 in.² = 645.2 mm²; 1 kip = 4.448 kN.)

subgrade. Generally, the restraint stresses can be ignored in short slabs because a smooth, planar subgrade does not significantly restrain the short slab movement due to uniform thermal expansion, contraction, or drying shrinkage. When the joint spacing recommendations given in Fig. 6.6 are followed, then these stresses will be sufficiently low. Built-in restraints such as foundation elements, edge walls, and pits should be avoided. Reinforcement should be provided at such restraints to limit slab crack widths. Chapter 14 discusses thermal and moisture effects. Chapter 10 discusses expansive soils.

5.9—Factors of safety

Unique serviceability requirements distinguish slabs-on-ground from other structural elements. Some of these serviceability requirements can:

- Minimize cracking and curling;
- Increase surface durability;
- Optimize joint locations and joint types for joint stability, which is the differential deflection of the adjacent slab panels edges as wheel loads cross the joint; and
- Maximize long-term flatness and levelness.

Because building codes primarily provide guidance to prevent catastrophic failures that affect public safety, the factors of safety for serviceability, inherent in building codes, are not directly addressed as are those for strength. When the slab-on-ground is part of the structural system used to transmit vertical loads or lateral forces from other portions of the structure to the soil, such as a rack-supported roof, then requirements of ACI 318 should be used for that load case.

The designer selects the factor of safety to minimize the likelihood of serviceability failure. Some items the designer should consider in selecting the factor of safety are:

- Consequences of serviceability failure, including lost productivity, lost beneficial use, and the costs for repairing areas in an active facility. For example, minimizing cracking and limiting crack widths for facilities such as pharmaceutical and food processing;

- Concrete mixture proportion and its shrinkage characteristics (test and minimize shrinkage to reduce linear drying shrinkage and curling);
- Humidity-controlled environment that increases linear drying shrinkage and slab curling;
- Subgrade smoothness and planeness to minimize restraint during linear drying shrinkage;
- Spacing and joint types;
- Geotechnical investigation to determine the shallow and deep properties of the soil;
- Number of load repetitions and traffic patterns to allow consideration of fatigue cracking;
- Impact effects;
- Storage racks installed at an early stage, which restrain linear drying shrinkage; and
- Compounding factors of safety that may produce an overly conservative design. Inclusion of cumulative factors of safety in the modulus of subgrade reaction, applied loads, compressive or flexural strength of the concrete, or number of load repetitions, may produce a very conservative and, consequently, expensive construction. The factor of safety is normally accounted for only in the allowable flexural stress in the concrete slab.

Table 5.2 shows some commonly used factors of safety for various types of slab loadings. Most range from 1.7 to 2.0, but some loading conditions use factors as low as 1.4.

A moving vehicle subjects the slab-on-ground to the effect of fatigue. Fatigue strength is expressed as the percentage of the static tensile strength that can be supported for a given number of load repetitions. As the ratio of the actual flexural stress to the modulus of rupture decreases, the slab can withstand more load repetitions before failure. For stress ratios less than 0.45, concrete can be subjected to unlimited load repetitions (PCA 2001). Table 5.3 shows various load repetitions for a range of stress ratios. The factor of safety is the inverse of the stress ratio.