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Guide to Design of Slabs-on-Ground

Reported by ACI Committee 360

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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. [m]). The units are commonly abbreviated as lb/in.^{3} (kN/m^3). 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 isolated from fixed portions of the structure, such as columns and perimeter