1 March 2025

DESIGN OF CONCRETE FLOOR SLABS-ON-GROUND FOR DOD FACILITIES

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

1 March 2025

1 March 2025

DESIGN OF CONCRETE FLOOR SLABS-ON-GROUND FOR DOD FACILITIES

Indicate the Military Department Preparing Activity responsible for the document.

U.S. ARMY CORPS OF ENGINEERS

NAVAL FACILITIES ENGINEERING SYSTEMS COMMAND (Preparing Activity)

AIR FORCE CIVIL ENGINEER CENTER

TABLE OF CONTENTS

CHAPTER 1 INTRODUCTION 1

1-1 PURPOSE AND SCOPE. 1

1-2 REISSUES AND CANCELS. 2

1-3 BASIC CONSIDERATIONS. 2

1-4 SLAB SUPPORT SYSTEM. 3

1-5 SLAB TYPES. 3

1-5.1 Plain Concrete Slabs-on-Ground. 3

1-5.2 Lightly Reinforced Concrete Slabs-on-Ground. 3

1-5.3 Reinforced Concrete Slabs-on-Ground. 4

1-5.4 Steel-Fiber Reinforced Concrete Slabs-on-Ground. 4

1-5.5 Structural Slabs-On-Ground. 4

1-5.6 Prestressed Concrete Slabs-on-Ground. 4

1-5.7 Synthetic-Fiber Reinforced Concrete Slabs-on-Ground. 4

1-6 GLOSSARY 7

1-7 REFERENCES. 7

CHAPTER 2 SITE INVESTIGATION AND EVALUATION 9

2-1 GENERAL. 9

2-2 SOIL CLASSIFICATION. 10

2-2.1 Initial Investigation. 10

2-2.2 Exploration and Classification. 10

2-3 SUBGRADE. 13

2-3.1 Resilient Modulus, M_R. 14

2-3.2 Modulus of Subgrade Reaction. 14

2-4 SITE PREPARATION RECOMMENDATION. 18

2-4.1 Proof-Rolling and Compaction. 18

2-4.2 Cut Sections. 19

2-4.3 Fill Sections. 19

2-4.4 Cut-to-Fill Sections. 20

2-4.5 Non-uniformity. 20

2-4.6 Special Soils (Problematic Soils). 20

2-4.7 Backfilling. 20

2-4.8 Treatment of Unsuitable Materials. 20

2-4.9 Subbase course. 22

2-5 ENVIRONMENTAL CONDITIONS. 26

2-5.1 Freezing and Thawing. 26

2-5.2 Cold Storage Facilities. 27

2-5.3 Permafrost. 28

2-5.4 Applicable Technical Manuals. 28

2-6 SUMMARY. 28

CHAPTER 3 DETERMINATION OF SLAB-ON-GROUND LOADS 29

3-1 LOAD CATEGORIES. 29

3-2 STRESSES. 29

3-3 TRANSIENT/VEHICLE-IMPOSED LOADS. 29

3-3.1 Traffic Distribution. 30

3-3.2 Aircraft Loads. 31

3-3.3 Wheel Contact Area. 35

3-4 DISTRIBUTED LIVE LOADS. 36

3-4.1 Positive Bending Moments. 37

3-4.2 Negative Bending Moments. 37

3-5 WALL LOADS. 37

3-6 CONCENTRATED LOADS. 38

3-7 CONSTRUCTION LOADS. 38

3-8 ENVIRONMENTAL FACTORS 39

3-9 UNUSUAL LOADS. 39

3-10 FACTORS OF SAFETY. 39

3-11 SUMMARY. 41

CHAPTER 4 CONCRETE MIXTURE 43

4-1 INTRODUCTION. 43

4-2 CONCRETE STRENGTH. 43

4-3 CONCRETE QUALITY. 43

4-3.1 Water. 44

4-3.2 Cement. 44

4-3.3 Blended Hydraulic Cement. 44

4-3.4 Pozzolans. 44

4-4 COARSE AGGREGATE. 46

4-5 FINE AGGREGATE **47**

4-6 CHEMICAL ADMIXTURES. **47**

4-7 SURFACE TREATMENTS. **48**

4-8 SUMMARY. **48**

CHAPTER 5 DESIGN PROCEDURE **51**

5-1 GENERAL. **51**

5-2 **COMPARISON BETWEEN THE THREE CLASSICAL DESIGN METHODS—COE, PCA, AND WRI.** **52**

5-2.1 United States Army Corps of Engineers (COE). 53

5-2.2 Portland Cement Association (PCA). 53

5-2.3 Wire Reinforcement Institute (WRI). 53

5-3 **DESIGN METHODS.** **53**

5-4 MOVING/VEHICLE LOADS. **54**

5-4.1 Corps of Engineering (COE) Design Method. 55

5-4.2 Portland Cement Association (PCA) Design Method. 58

5-4.3 Wire Reinforcement Institute (WRI) Design Method 62

5-5 DISTRIBUTED LIVE LOADS. **66**

5-5.1 COE Method. 67

5-5.2 PCA Method. 69

5-5.3 WRI Method. 72

5-6 LINE/WALL LOADING. **73**

5-6.1 COE Method. 73

5-6.2 PCA and WRI Methods. 77

5-7 CONCENTRATED LOADS. **77**

5-8 DESIGN PROCEDURES FOR STABILIZED FOUNDATIONS. **78**

5-9 STEEL REINFORCEMENT. **79**

5-9.1 Subgrade Conditions. 80

5-9.2 Economic Considerations. 80

5-9.3 Other Uses. 80

5-9.4 Slab-on-Ground Reinforcement Design per the COE Method. 80

5-9.5 Steel Specifications. 83

5-10 STEEL FIBER REINFORCEMENT DESIGN. **84**

5-10.1 Basis of Steel Fiber-Reinforced Concrete (SFRC) Slab-on-Ground Design. 85

5-10.2 Uses. 86
5-10.3 Mixture Proportioning Considerations. 86
5-10.4 Thickness Determination. 88
5-10.5 Allowable Deflection for SFRC Slab-on-Ground. 90
5-11 CONCRETE SLAB-ON-GROUND REINFORCED WITH FIBER-REINFORCED POLYMER (FRP) BARS. 91
5-12 FINITE ELEMENT ANALYSIS METHOD. 92
5-13 DESIGN MODEL FOR PILE-SUPPORTED FLOOR. 94
5-14 ACI 318 DESIGN LIMITATIONS. 98
5-15 SUMMARY. 101
CHAPTER 6 JOINTS AND DOWELS. 103
6-1 JOINT TYPES AND USAGE. **103**
6-2 SAWCUT CONTRACTION JOINTS. 104
6-2.1 Width and Depth of Weakened Plane Groove. 105
6-2.2 Width and Depth of Contraction Joint. 107
6-2.3 Spacing of Contraction Joints. 108
6-3 CONSTRUCTION JOINTS. 115
6-3.1 Doweled Butt Joint. 117
6-3.2 Keyed Joint. 118
6-3.3 Thickened-Edge Joint. 118
6-4 ISOLATION JOINTS. 119
6-5 SPECIAL JOINTS AND JUNCTURES. 120
6-5.1 Slip-Type Joints. 120
6-5.2 Special joint between new and existing floors. 121
6-6 LOAD TRANSVERSE MECHANISMS. 122
6-6.1 Aggregate Interlock. 123
6-6.2 Steel Dowels. 123
6-6.3 Dowels Other Than Circular In Shape. 130
6-6.4 GFRP Dowels. 133
6-7 SUMMARY. 134
CHAPTER 7 CONSTRUCTION CONSIDERATION 135
7-1 CONSTRUCTION DOCUMENT INFORMATION. 135
7-2 PRECONSTRUCTION MEETING AGENDA. 136

7-3 PLACING SEQUENCE. 139
7-4 VAPOR RETARDER 139
7-4.1 Vapor Retarder In Direct Contact with Slab-on-Ground. 141
7-4.2 Vapor Retarder Not In Direct Contact with Slab-on-Ground. 142
7-4.3 Polyethylene Sheets as Slip Sheets. 142
7-5 JOINT CONSTRUCTION AND DOWEL PLACEMENT. 142
7-5.1 Sawcut Contraction Joints. 142
7-5.2 Joint Sealing. 143
7-5.3 Special Provisions for Slipform Slab-on-Ground. 145
7-5.4 Dowel Placements. 145
7-6 CONCRETE OVERLAY. 148
7-7 SLAB TOLERANCES. 149
7-8 SPECIAL CONSIDERATIONS. 153
7-9 SUMMARY. 153
APPENDIX A EQUATIONS FOR COMPUTING THE ALLOWABLE WALL LOADS NEAR CENTER OF SLAB OR NEAR KEYED OR DOWELED JOINTS 155
A-1 LINE LOAD LOCATED NEAR CENTER OF SLAB FAR FROM JOINT. 155
A-2 LINE LOAD LOCATED NEAR KEYED OR DOWELED JOINT. 156
APPENDIX B DESIGN EXAMPLES 159
B-1 DESIGN EXAMPLES PER CORPS OF ENGINEERS (COE) METHOD. 159
B-1.1 Example 1: Concrete Slab-on-Ground Thickness for Moving and Stationary Loads 159
B-1.2 Example 2: Thickened Slab-on-Ground Design for Exterior Wall. 164
B-1.3 Example 3: Reinforced Concrete Slab-on-Ground 166
B-1.4 Example 4: Concrete Slab-on-Ground Thickness For Tracked Vehicle. 168
B-1.5 Example 5: Slab-on-Ground Thickness For 4.5-Ton Forklift Truck. 170
B-2 DESIGN EXAMPLES PER PORTLAND CEMENT ASSOCIATION (PCA) METHOD. 172
B-2.1 Example 1: Concrete Slab-on-Ground Thickness for Forklift Truck. 172
B-2.2 Example 2: Concrete Slab-on-Ground Thickness For Forklift. 175
B-2.3 Example 3: Concrete Slab-on-Ground Thickness for Forklift with Factor Of Safety; SF = 1.5 and 2.5 177

B-2.4 Example 4: Concrete Slab-on-Ground Thickness for Dual Tire 5-Ton Forklift. 180

B-3 DESIGN EXAMPLES PER WIRE REINFORCEMENT INSTITUTE (WRI) 184

B-3.1 Slab-on-Ground Thickness for 4.5-Ton Forklift Truck. 184

APPENDIX C Slab-on-Ground Quick References 189

APPENDIX D Slab-on-Ground Construction Defects Mitigation 193

APPENDIX E GLOSSARY 206

E-1 NOTATIONS........................ 206

E-2 DEFINITIONS. 207

APPENDIX F REFERENCES 212

F-1 GOVERNMENT PUBLICATIONS 212

F-2 NON-GOVERNMENT PUBLICATIONS 213

F-3 ADDITIONAL REFERENCES 217

FIGURES

Figure 1-1 Slab Support System Terminology 3

Figure 2-1 Plasticity Chart (adopted from ASTM D2487 Figure 4)........................ 12

Figure 2-2 Cumulative Particle-Size Plot (adopted from ASTM D2487 Figure 5) 13

Figure 2-3 Approximate Interrelationships of Soil Classifications and Bearing Values (PCA 1988). (Note: 1 psi/in. = 0.271 kPa/mm; 1 psi = 6.90 kPa.)....... 17

Figure 2-4 Effect of Subbase Thickness on Design Modulus of Subgrade Reaction 24

Figure 2-5 Typical Slab-on-Ground Construction for Refrigerated Building...... 27

Figure 3-1 Loading Gear Assemblies........................ 32

Figure 3-2 Equivalent Contact Area of Single- and Dual-Tire Vehicles............... 36

Figure 5-1 Controlling Design Consideration depends on Size of Load Contact Area (Packard 1996). 52

Figure 5-2 Possible Loading Locations 55

Figure 5-3 Design Curves for Concrete Slabs-on-Ground by Design Index....... 56

Figure 5-4 Design Curves for Concrete Slabs-on-Ground for Heavy Forklifts. .. 57

Figure 5-5 Design Chart for Axles with Single Wheels—Complete Load Transfer at Joint 59

Figure 5-6 Design Chart for Axles with Dual Wheels........................ 60

Figure 5-7 Effective Load Contact Area Depends on Slab-on-Ground Thickness (adopted from PCA). 61
Figure 5-8 Subgrade and Slab Stiffness Relationship 63
Figure 5-9 Wheel Loading Design Chart 64
Figure 5-10 Slab Tensile Stress Charts 65
Figure 5-11 Uniform Load Design and Slab Tensile Stress Charts Used with WRI Design Procedure 73
Figure 5-12 Widths of Thickened Slabs and Slab Edge Conditions under Wall Loads 77
Figure 5-13 The PCA Design Chart for Post Loads when Subgrade Modulus is 100 psi/in. (27.1 MPa/m) 78
Figure 5-14 Design Thickness for Reinforced Slabs-on-Ground 82
Figure 5-15 Shapes of Steel Fibers 85
Figure 5-16 Design Curves for Fiber-Reinforced Concrete Slab-on-Ground by Design Index 88
Figure 5-17 Design Curves for Steel Fiber-reinforced Concrete Slabs-on-Ground for Heavy Forklifts. 89
Figure 5-18 Deflection Curves for Steel Fiber-Reinforced Concrete Slabs-on-Ground 90
Figure 5-19 Allowable Deflections for Steel Fiber-Reinforced Concrete Floor Slabs 91
Figure 5-20 Tributary Area to a Node 93
Figure 5-21 Subgrade Modulus Proposed Zones under a Slab-on-Ground Panel 94
Figure 5-22 Pile and Pile Head Supporting Slab-on-Ground 96
Figure 5-23 Pile Head Construction 97
Figure 5-24 Joint Located at Centerline of Pile 97
Figure 5-25 Joint Offset from Centerline of Pile within 1/6-1/3 Slab Span 98
Figure 6-1 Typical Joints in Slabs-on-Ground 103
Figure 6-2 Slab Curled Shape (Walker and Holland 1999) 105
Figure 6-3 Joint Sealant Details 106
Figure 6-4 Contraction Joints for Unreinforced and Reinforced Concrete Slabs-on-Ground 107
Figure 6-5 Avoid Discontinuous Joints and Reentrant Corners 109
Figure 6-6 Recommended Joint Spacing for Unreinforced Slabs (ACI 360R Figure 6.6) 110
Figure 6-7 Crack-Inducer Grid Installed Prior to Concrete Placement. 111

Figure 6-8 Crack-Inducer Tubes 112
Figure 6-9 Placing Sequence: Long-Strip Construction 116
Figure 6-10 Doweled Construction Butt Joints for Concrete Floor Slabs 116
Figure 6-11 Keyed Construction Joints for Concrete Floor Slabs 116
Figure 6-12 Doorway Slab Design for Vehicular Traffic 119
Figure 6-13 Isolation Joints 120
Figure 6-14 Thickened Edge Longitudinal 121
Figure 6-15 Special Joint between New and Existing Slab-on-Ground 122
Figure 6-16 Transfer Mechanism Dowel between Two Adjacent Concrete Panels 124
Figure 6-17 Load Transfer versus Dowel Embedment (Observed and Computed), after Teller and Cashell (1958) 125
Figure 6-18 Effects of Dowel Embedment and Diameter on Dowel Looseness after 600,000 Repetitions of a 10,000 lb Load (after Teller and Cashell [1958]) 127
Figure 6-19 Typical Doweled Joint 129
Figure 6-20 Joints in Concrete Slabs-on-Ground. 130
Figure 6-21 Plan View Indicating Provisions for Longitudinal Movement at Doweled Construction Joints 132
Figure 6-22 Isometric View Indicating Provisions for Longitudinal Movement at Doweled Construction Joints 133
Figure 6-23 Glass Fiber-Reinforced Polymer Dowels 134
Figure 7-1 Preconstruction Meeting Agenda Example 138
Figure 7-2 Placing Sequence Long-Strip Construction (left) is Recommended; Checkerboard Construction (right) is Not Recommended 139
Figure 7-3 Flowchart to Determine When and Where a Vapor Retarder Should be Used 140
Figure 7-4 Vapor Retarder Placed before Slab-on-Ground Concrete Placement (Source: CTI) 141
Figure 7-5 Typical Armored Construction Joint Detail 144
Figure 7-6 Installation of (a) Diamond Plate Form and (b) Rectangular Plate Form 145
Figure 7-7 Dowel Bar Tolerances 147
Figure 7-8 Round Dowel Basket Assembly 148
Figure 7-9 Different Plate Dowel Basket Assemblies 148
Figure 7-10 Floor Flatness and Levelness Measurements 149

Figure 7-11 Improper Slab-on-Ground Tolerances may Result in Obstruction to Operations 151

TABLES

Table 1-1 Minimum Recommended Slab-on-Ground Thickness 2
Table 1-2 General Comparison of Slab Types (adapted from ACI 360R Table 3.1) 5
Table 2-1 Soil Classification Chart (adopted from ASTM D2487 Table 1) 11
Table 2-2 Typical Values of Modulus of Subgrade Reaction 16
Table 2-3 Soil Stabilization with Chemical Admixtures (ACI 360R) 21
Table 3-1 Forklift category based on axle load 30
Table 3-2 Tracked vehicles categories based on gross weight 31
Table 3-3 Aircraft Characteristics and Design Loadings 33
Table 3-4 Standard Design Aircraft Types 35
Table 3-5 Range of pressure per tire type 36
Table 3-6 Stress Ratio versus Allowable Load Repetitions (CPA Fatigue Curve)* 40
Table 3-7 Factors of Safety Used in Design of Various Types of Loading 40
Table 4-1 Recommended cementitious material contents for concrete floors . 44
Table 4-2 Summary of side effects and interactions of SCMs 46
Table 4-3 Preferred Grading of Fine Aggregates for Slabs-on-Ground (ACI 302.1R Table 8.5.1) 47
Table 5-1 Applicable Design Methods for Different Types of Loadings. 53
Table 5-2 Traffic Categories for Design Index 56
Table 5-3 Maximum Allowable Stationary/Distributed Live Load 68
Table 5-4 Allowable Distributed Loads for Unjointed Aisle with Nonuniform Loading Variable Layout (Packard 1996) 70
Table 5-5 Allowable Distributed Loads, Unjointed Aisles, Uniform Loading, and Variable Layout (Packard 1996) 71
Table 5-6 Minimum Thickness of Thickened Floor slab for Wall Load Near Center of Slab or near Keyed or Doweled Joint 75
Table 5-7 Maximum Allowable Wall Load near free Edge 76
Table 5-8 Range of proportions for normalweight steel fiber-reinforced concrete (ACI 544.1R) 87
Table 5-9 Recommended Maximum Bar Diameter per Slab-on-Ground Thickness 98
Table 6-1 Joint Filler Types Based on Different Categories of Traffic 108

Table 6-2	Dowels for military facilities slabs-on-ground	125
Table 6-3	Smooth Dowel Size and Spacing	129
Table 6-4	Square Dowel Sizes and Plate Dowel Spacing	131
Table 7-1	Slab-on-Ground Sawcut Methods	143
Table 7-2	Slab-on-Ground And Bar Dowel Tolerances	146
Table 7-3	ASTM E1155 Method	150
Table 7-4	Defined Traffic Values	150
Table 7-5	Slab-on-Ground Flatness/Levelness Construction Guide (ACI 360R)	152

CHAPTER 1 INTRODUCTION

1-1 PURPOSE AND SCOPE.

This manual prescribes the criteria for the design of concrete slabs-on-ground in military facilities such as office, warehouse, and maintenance hangar structures. The design and construction of sound and durable slabs-on-ground is essential for the longevity of the facility and uninterrupted operations.

The chapters in this manual are presented in the order that a structural engineer of record (SER) will normally follow when designing a slab-on-ground. This manual starts with a brief introduction, basic considerations, and the design choices for slab-on-ground construction in Chapter 1. Importance of communication and information the SER should request from the geotechnical engineer is addressed in Chapter 2. In addition, the chapter lays out what information the geotechnical report should include to aid the SER in the design process.

The slab-on-ground is subjected to various loading conditions during its service life. Those loads vary from moving loads for vehicle and aircraft; stationary distributed, line, and concentrated loads; construction loads; and environmental loads. Those different load conditions are presented in Chapter 3. Type of cement, properties of supplementary cementitious material, coarse and fine aggregate, and chemical admixtures to produce quality concrete are briefly reviewed in Chapter 4. A comparison of the available design methods in the industry are presented, compared, and the differences between them is outlined in Chapter 5. The slab-on-ground thickness is determined in this chapter and design examples of each of the classical methods is presented in Appendix B. Type of joints, recommended joint spacings to control cracking and curling, and the different transfer mechanisms available, dowels, are presented and discussed in Chapter 6. The importance of a preconstruction meeting and facilitating proper communication among key participants key to the success of slab-on-ground construction is addressed in Chapter 7.

Summary of relevant information and a quick reference to the designer is provided in Appendix C. Causes for slab-on-ground deterioration and shortcomings are discussed and mitigation suggestions of those shortcomings are presented in Appendix D.

Various design procedures for slabs-on-ground are discussed in this manual. The design of plain, lightly reinforced, and reinforced concrete slabs-on-ground is based on the working stress method. The finite element analysis and the strength design method is provided for conditions not covered by the working stress methods.

This manual covers the following working stress methods; Corps of Engineers (COE), Portland Cement Association (PCA), and Wire Reinforcement Institute (WRI). The manual discusses the appropriate slab-on-ground design for defined loading conditions for each working stress method. The finite element method for analyses and ACI 318 strength design approach may be used for all types of loading and soil conditions.

A minimum slab-on-ground thickness is suggested for each facility slab type based on experience; refer to Table 1-1. A clear understanding of the soil properties, familiar with the different available design methods and their limitations, proper detailing of joints and dowels, and implementing sound construction methods is essential to the success and durability of a slab-on-ground.

Table 1-1 Minimum Recommended Slab-on-Ground Thickness

Structure type	Minimum recommended slab-on-ground thickness, inch (millimeter)
Office type facilities	4 (100)
Warehouse and light industrial (forklift and light traffic)	6 (150)
Maintenance hangars (airplanes)	8 (200)

1-2 REISSUES AND CANCELS.

None

1-3 BASIC CONSIDERATIONS.

Slabs-on-ground are nonstructural members in general but are a necessary element in building structures. The failure of a slab-on-ground does not result in life-threatening conditions, but they are an expensive repair type and may result in the disruption of the operations within the structure. Therefore, the performance of a slab-on-ground depends on sound engineering, complete specification, proper construction practices, and comprehensive quality control (QC) and quality assurance (QA) programs.

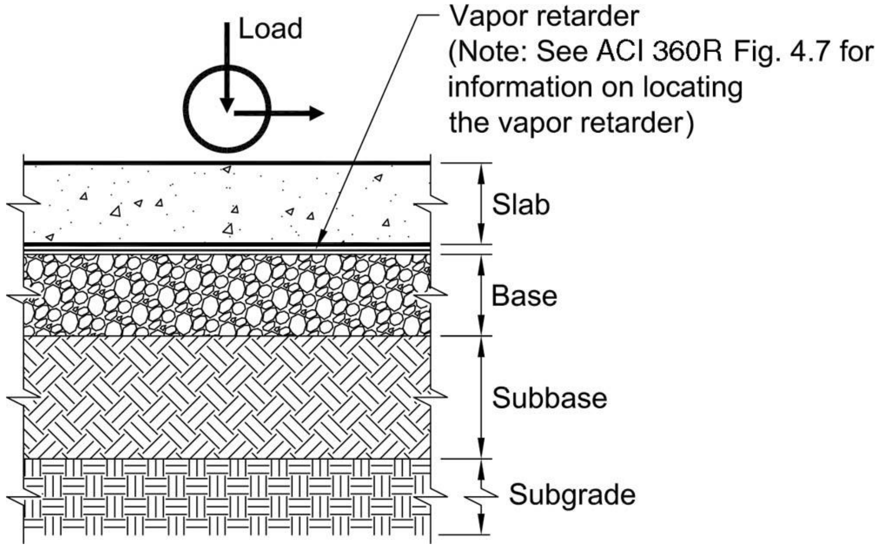
The design process for the working stress models is based on determining the slab-on-ground thickness for the critical moving load condition and increasing the thickness, where required, for the stationary loads. The slab-on-ground thickness is usually calculated for each load condition and the most critical will control the design. Working stresses have been established empirically based on experience and past performance and they include stresses induced by temperature gradients and other environmental effects. Reinforcement may be added after the slab thickness is determined to reduce crack widths due to shrinkage and temperature; reduce curling and warping; decrease the slab thickness (COE method); and increase the joint spacing. Note that the WRI method assumes the use of reinforcement.

The finite element (FE) analysis method (Chapter 4 Section 4-12) permits the analysis of multiple loading conditions with different subgrade reactions in the same model. The slab-on-ground may be designed as plain or reinforced concrete according to ACI 318 using the strength design methodology. The load factors should be used in the FE analysis. Plain slabs-on-ground are designed according to Chapter 14 of ACI 318. Reinforced slabs-on-ground are designed according to the section strength requirements in ACI 318. Slabs-on-ground supported on piles (Chapter 4 Section 4-13) are reinforced and designed per ACI 318.

1-4 SLAB SUPPORT SYSTEM.

The slab-on-ground support system consists usually of subgrade and probably an optional subbase layer (refer to Figure 1-1). The top section of the subgrade should be of uniform material and density and free of abrupt changes from soft to hard in its structure. If the geotechnical engineer determines, however, that poor topsoil exists, then it should be removed and replaced with compacted properly graded soil of uniform material and density to provide a consistent subgrade support system for the concrete slab-on-ground (refer to Figure 1-1 and Chapter 2). In expeditionary circumstances, however, a slab-on-ground may be directly supported on the existing subbase.

Figure 1-1 **Slab Support System Terminology**



1-5 SLAB TYPES.

There are seven design choices for slab-on-ground construction. In this manual, the first five types are addressed. (Table 1-2 lists all seven types with the advantages and the disadvantages for each type):

1-5.1 Plain Concrete Slabs-on-Ground.

The slabs-on-ground are not reinforced, but have joints strengthened with positive load transfer mechanisms, if required to transfer shear forces between two adjacent concrete panels and to improve joint performance. The thickness of plain slabs-on ground is determined using the COE, PCA, WRI, or FE methods. Joints are closely spaced to control shrinkage and temperature movement; refer to Chapter 6 for recommended joint spacings.

1-5.2 Lightly Reinforced Concrete Slabs-on-Ground.

Slabs-on-ground designed as plain concrete slabs-on-ground reinforced with deformed bars or welded-wire reinforcement added to limit crack widths due to shrinkage and temperature restraint and applied loads. Reinforcement ratios are less than 0.05%. The lightly reinforced slabs-on-ground enhance the performance of plain slabs-on-ground but do not change the slab thickness or joint spacing. Positive load transfer may be required at construction and contraction joints depending on the loading type and joint transfer efficiency.

1-5.3 Reinforced Concrete Slabs-on-Ground.

Slabs-on-ground designed as plain concrete slabs-on-ground reinforced with deformed bars or welded-wire reinforcement to increase the joint spacing for slabs designed by the COE, PCA, or WRI methods or to decrease the slab thickness for slabs designed by the COE method. Reinforcement ratios are between $0.05 \leq \rho \leq 0.5\%$.

Note that slabs-on-ground with $\rho > 0.5\%$ continuous reinforcement in both directions do not need contraction joints.

1-5.4 Steel-Fiber Reinforced Concrete Slabs-on-Ground.

Slabs-on-ground with steel fibers added in the concrete mixture will improve resistance to impact and fatigue. The contractor should be aware that concrete mixing, placement, and finishing may require adjustments.

1-5.5 Structural Slabs-On-Ground.

Structural reinforced concrete slabs-on-ground that transmit vertical loads such as mezzanine loads or lateral forces from other portions of the structure are designed by the structural concrete code, ACI 318. They may span to supports; refer to Chapter 5 Section 5-13. They are structurally reinforced in one- or two-layers of reinforcement; refer to Chapter 5 Section 5-14 and Appendix C. Structural slabs-on-ground do not have contraction joints.

1-5.6 Prestressed Concrete Slabs-on-Ground.

Prestressed concrete slabs-on-ground reduce/prevent cracking due to shrinkage and temperature restraint and applied loads. These slabs consist of:

- Shrinkage-compensating concrete (cement expands during curing which pretensions the reinforcement in the slab; and
- Post-tensioned (prestressed) slabs-on-ground.

Prestressed slabs-on-ground are not addressed in this manual.

1-5.7 Synthetic-Fiber Reinforced Concrete Slabs-on-Ground.

Synthetic-fiber reinforced concrete slabs-on-ground help reduce plastic shrinkage cracking and increased resistance to impact and fatigue if macrosynthetic fibers are used. Joint spacing is the same as unreinforced slabs-on-ground. This type of slab-on-ground reinforcement is not addressed in this manual.

Table 1-2 General Comparison of Slab Types (adapted from ACI 360R Table 3.1)

Slab type	Advantages	Disadvantages
Plain	• 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.
Lightly reinforced	• Reinforcement is used to limit crack width.	• More expensive than a plain slab.
Reinforced	• Increase the joint spacing	• 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	• Sawcut contract 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.
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.

Slab type	Advantages	Disadvantages
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.
Shrinkage-compensating concrete (not addressed in this manual)	• 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 (not addressed in this manual)	• 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.
Synthetic fiber-reinforced concrete (not addressed in this manual)	• 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.

1-6 GLOSSARY

Appendix E contains notations and terms.

1-7 REFERENCES.

Appendix F contains a list of references used in this document. The publication date of the code or standard is not included in this document. Unless otherwise specified, the most recent edition of the referenced publication applies.

This Page Intentionally Left Blank

CHAPTER 2 SITE INVESTIGATION AND EVALUATION

2-1 GENERAL.

Geotechnical work is performed to investigate and evaluate the site soil conditions for adequacy to support a slab-on-ground for a project. A geotechnical engineer provides the SER with a geotechnical report containing the required design parameters to design a slab-on-ground properly and adequately. The report will include directions and recommendations to improve the existing subgrade condition, if required, and suggest proper material and thickness for a subbase, if needed. The project construction documents usually reference the geotechnical report or incorporates relevant information extracted from it.

The existing grade of a planned slab-on-ground is generally not at the desired elevation or slope before construction. Also, the existing soil may not be uniform, have the desired strength, or proper physical properties to support the planned slab-on-ground. Therefore, some cut-and-fill will be required and soil testing is performed prior to slab-on-ground construction. If the on-site soil, which is preferable from an economical perspective, does not meet the necessary properties, imported soil is hauled to the site. Fill is usually placed in compacted layers of 6 to 9 inches (150 to 230 millimeters) or as recommended by the geotechnical engineer.

The SER establishes the design factors including the load conditions a slab-on-ground will be subjected to. This information is then processed by the geotechnical engineer to determine the adequacy of the subgrade and if unsuitable soil conditions exist. Therefore, for the geotechnical engineer to perform the soil investigation and evaluation properly, the SER should provide the following information as a minimum:

- Facility use and proposed floor elevation
- Type and magnitude of anticipated loads; moving and long-term loads (refer to Chapter 4)
- Frequency of moving load traveling on the slab-on-ground
- Area and geometry of loaded area
- Environmental conditions of the building space especially if floor covering will be provided (office type facilities)
- Floor tolerances, levelness and flatness, criteria (refer to Chapter 7)
- Sensitivity to cracking, soil settlement, and sloping of slab-on-ground if equipment is placed on it
- Floor-covering requirements.

The geotechnical engineer will submit the findings in a report, which should include, as a minimum, the following information:

- Soil properties—that is, type of soil, allowable soil bearing pressure
- Subgrade classification

- Recommended modulus of subgrade reaction
- Design of the slab-on-ground support system
- Site preparation recommendation
- Water table level, if existing
- Climatic conditions—that is, frost depth, construction of freezer room
- Inspection and testing of the slab-on-ground support system.

2-2 SOIL CLASSIFICATION.

The subgrade provides a foundation to a slab-on-ground and to the base courses, if required. The performance of the slab-on-ground during its service life will depend on the uniformity and bearing strength of the subgrade. Therefore, it is prudent to investigate the subgrade to assess the maximum support potential of the specific subgrade.

2-2.1 Initial Investigation.

Preliminary investigations of subgrade conditions should be performed to determine the engineering characteristics of the subgrade soils and the extent of peculiarities of the proposed site. The general suitability of the subgrade soils is based on classification of the soil, moisture density relationships, expansive characteristics, susceptibility to pumping, and susceptibility to detrimental frost action. A study of the service history of existing floor slabs on similar subgrade materials in the locality of the proposed site should be made if possible. Additional factors to be considered are groundwater, soil capillarity, topography, drainage conditions, and seasonal changes.

2-2.2 Exploration and Classification.

The soil on which a slab-on-ground is supported should be identified and classified for its suitability as a subgrade. The soil can be classified per laboratory testing following ASTM D2487, which is based on laboratory determination of particle-size characteristics, liquid limit, and plasticity index, as presented in Table 2-1 and Figure 2-1 and 2-2. The soil can be also classified per ASTM D2488, which is based on visual examination and manual tests. The latter method is subjective and less reliable.

If frozen soil is encountered, then ASTM D4083 should be used in collaboration with ASTM D2487. If, however, field reconnaissance and analysis of existing subsurface information are insufficient to provide the necessary data for slab-on-ground design, an exploration program should be initiated according to UFC 3-220-01. Some of the tests and test methods that are helpful for soil classification are:

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

Although the standard Proctor compaction test (ASTM D698) and modified Proctor compaction test (ASTM D1557) are not considered for soil classification, but the moisture-density relationship obtained from those tests are useful in assessing a soil subgrade or subbase.

Table 2-1 Soil Classification Chart (adopted from ASTM D2487 Table 1)

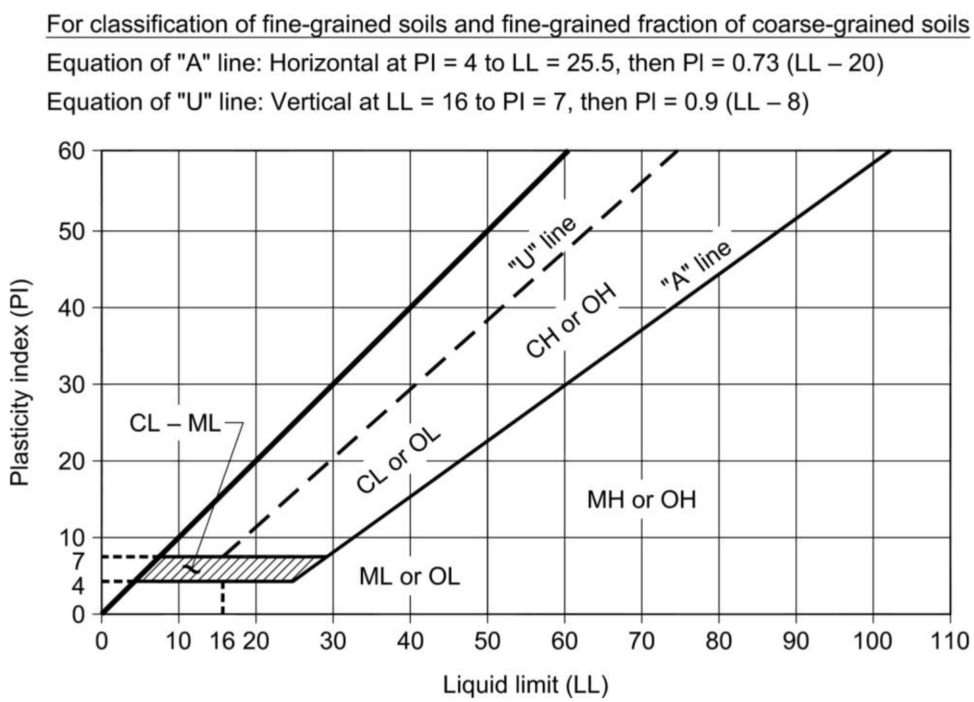
Criteria for Assigning Group Symbols and Group Names Using Laboratory Tests[A]				Soil Classification	
				Group Symbol	Group Name[B]
COARSE-GRAINED SOILS More than 50 % retained on No. 200 sieve	Gravels (More than 50 % of coarse fraction retained on No. 4 sieve)	Clean Gravels (Less than 5 % fines[C])	$Cu \geq 4.0$ and $1 \leq Cc \leq 3.0$[D]	GW	Well-graded gravel[E]
			$Cu < 4.0$ and/or $[Cc < 1$ or $Cc > 3.0]$[D]	GP	Poorly graded gravel[E]
		Gravels with Fines (More than 12 % fines[C])	Fines classify as ML or MH	GM	Silty gravel[E,F,G]
			Fines classify as CL or CH	GC	Clayey gravel[E,F,G]
	Sands (50 % or more of coarse fraction passes No. 4 sieve)	Clean Sands (Less than 5 % fines[H])	$Cu \geq 6.0$ and $1.0 \leq Cc \leq 3.0$[D]	SW	Well-graded sand[I]
			$Cu < 6.0$ and/or $[Cc < 1.0$ or $Cc > 3.0]$[D]	SP	Poorly graded sand[I]
		Sands with Fines (More than 12 % fines[H])	Fines classify as ML or MH	SM	Silty sand[F,G,I]
			Fines classify as CL or CH	SC	Clayey sand[F,G,I]
FINE-GRAINED SOILS 50 % or more passes the No. 200 sieve	Silts and Clays Liquid limit less than 50	inorganic	$PI > 7$ and plots on or above “A” line[J]	CL	Lean clay[K,L,M]
			$PI < 4$ or plots below “A” line[J]	ML	Silt [K,L,M]
		organic	Liquid limit − oven dried/Liquid limit − not dried < 0.75	OL	Organic clay[K,L,M,N] Organic silt[K,L,M,O]
	Silts and Clays Liquid limit 50 or more	inorganic	PI plots on or above “A” line	CH	Fat clay[K,L,M]
			PI plots below “A” line	MH	Elastic silt[K,L,M]
		organic	Liquid limit − oven dried/Liquid limit − not dried < 0.75	OH	Organic clay[K,L,M,P] Organic silt[K,L,M,Q]
HIGHLY ORGANIC SOILS	Primarily organic matter, dark in color, and organic odor			PT	Peat

(A) Based on the material passing the 3-in. (75-mm) sieve.
(B) If field sample contained cobbles or boulders, or both, add “with cobbles or boulders, or both” to group name.
(C) Gravels with 5 to 12 % fines require dual symbols:
GW-GM well-graded gravel with silt
GW-GC well-graded gravel with clay
GP-GM poorly graded gravel with silt
GP-GC poorly graded gravel with clay

(D) $Cu = D_{60} / D_{10} \quad Cc = \dfrac{(D_{30})^2}{D_{10} \times D_{60}}$

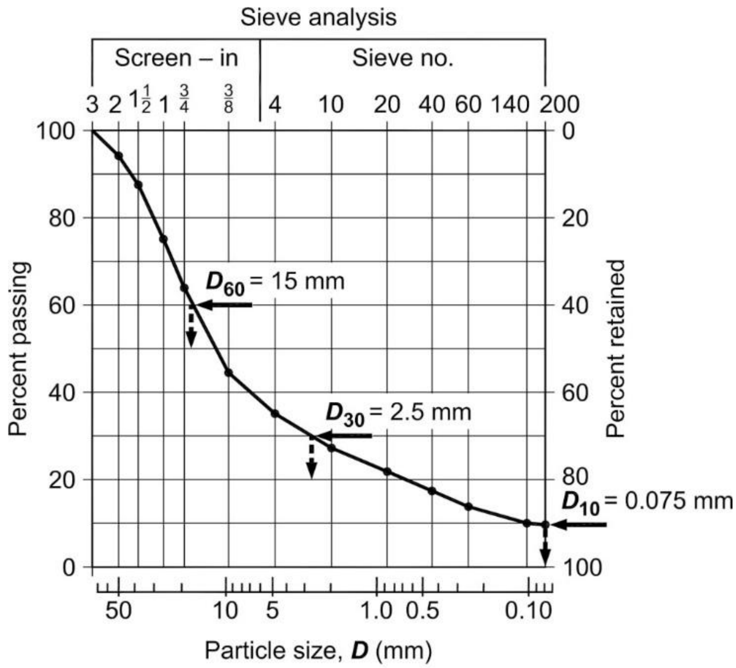
(E) If soil contains ≥15 % sand, add "with sand" to group name.
(F) If fines classify as CL-ML, use dual symbol GC-GM, or SC-SM.
(G) If fines are organic, add "with organic fines" to group name.
(H) Sands with 5 to 12 % fines require dual symbols**:**
SW-SM well-graded sand with silt
SW-SC well-graded sand with clay
SP-SM poorly graded sand with silt
SP-SC poorly graded sand with clay
(I) If soil contains ≥15 % gravel, add "with gravel" to group name.
(J) If Atterberg limits plot in hatched area, soil is a CL-ML, silty clay.
(K) If soil contains 15 to <30 % plus No. 200, add "with sand" or "with gravel," whichever is predominant.
(L) If soil contains ≥30% plus No. 200, predominantly sand, add "sandy" to group name.
(M) If soil contains ≥30% plus No. 200, predominantly gravel, add "gravelly" to group name.
(N) PI ≥ 4 and plots on or above "A" line.
(O) PI < 4 or plots below "A" line.
(P) PI plots on or above "A" line.
(Q) PI plots below "A" line.

Figure 2-1 **Plasticity Chart (adopted from ASTM D2487 Figure 4)**



NOTE: The "U" line in Figure 3-1 has been empirically determined and represents the approximate "upper limit" for natural soils. Any test results that fall above or to the left of the "U" line should be verified.

Figure 2-2 **Cumulative Particle-Size Plot (adopted from ASTM D2487 Figure 5)**



$$Cu = \frac{\boldsymbol{D_{60}}}{\boldsymbol{D_{10}}} = \frac{15}{0.075} = 200 \qquad Cc = \frac{(\boldsymbol{D_{30}})^2}{\boldsymbol{D_{10}} \times \boldsymbol{D_{60}}} = \frac{(2.5)^2}{0.075 \times 15} = 5.6$$

NOTE: 1 inch = 25.4 millimeter

2-3 SUBGRADE.

Following the soil identification and classification, the soil strength-deformation properties are then evaluated to ensure that an adequate support system for a slab-on-ground exists. Those properties are:

- Allowable soil bearing capacity (allowable soil pressure)
- Soil compressibility of cohesive soils
- Modulus of subgrade reaction of soil, *k*

The allowable soil bearing capacity (pressure) is the ultimate soil-bearing capacity divided by a factor of safety. It is used in foundation design to prevent shear failure or excessive settlement of a soil subjected to sustained loads, heavy loads, or both. Allowable soil pressure may be based on: 1) laboratory strength tests (ASTM D2850, ASTM D2166); 2) field tests (ASTM D3441); 3) soil classification; or 4) moisture-density-strength relationships.

Soil compressibility of cohesive soils determines the potential amount of long-term settlement under an imposed load (ASTM D4546). The modulus of subgrade, *k*, also known as Westergaard's modulus of subgrade reaction, is used as a soil parameter in the design of slabs-on-ground. It is appropriate for slabs-on-ground not supporting concentrated loads such as columns or load-bearing walls. A reliable correlation does not exist between the three soil deformation properties.

2-3.1 Resilient Modulus, M_R.

The American Association of State Highway Transportation Officials (AASHTO) (T307) has developed a design procedure for rigid pavements (slabs-on-ground) using a measure of the assumed elastic property of soil considering its nonlinear characteristics called resilient modulus, M_R. 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 value M_R can be evaluated from an empirical relationship using the California bearing ratio (CBR) test value (ASTM D1883) (Heukelom and Klomp 1962). Theoretical relationships were developed between modulus of subgrade reaction, k, values and the resilient modulus of subgrade, M_R (ACI 360R). The k-values obtained from measured CBR and M_R data using AASHTO relationships can yield unrealistically high values (ACI 360R); refer to Figure 2-3.

2-3.2 Modulus of Subgrade Reaction.

Concrete slabs-on-ground are relatively rigid compared to the subgrade. Therefore, loads from forklift wheels or other concentrated loads such as light loaded posts are spread over larger areas and pressure on subgrade is lower. Hence, strong subgrades are generally not necessarily required as a support for slabs-on-ground.

For the design of slabs-on-ground in industrial and warehouse facilities that are supporting moving loads, the parameter modulus of subgrade, k, is commonly used. It is a spring constant that assumes linear relationship between load and deformation from the subgrade under temporary and small deflections usually 0.05 inches (1 millimeter) or less and is expressed by:

Equation 2-1. [Modulus of Subgrade Reaction]

$$k = \frac{\text{pressure}}{\text{deflection}} = \frac{q}{\delta}$$

The modulus of subgrade is obtained from the plate load test (ASTM D1196), which is usually used for highway and airport projects and sometimes for heavy industrial slabs-on-ground. For most slab-on-ground construction, the plate load test is typically not used. The k-value unit is given in pounds per square inch per inch (lb/in.^{2}/in.) (megapascal per meter [MPa/m]) or commonly used units in the industry of pounds per cubic inch (pci). The modulus of subgrade reaction is not a soil property but a function of:

- Elastic property of the soil due to soil consolidation from sustained loading. It is measured at both the initial response and the long-term response
- Magnitude and distribution of the loading that influences long-term consolidation settlement

- Size and shape of loaded area
- Stiffness of the slab, which spreads loads over larger areas and results in lower soil bearing pressure

The modulus of subgrade, *k*, for slabs-on-ground does not reflect the effect of compressible soil layers within the subgrade. It is, however, the correct factor to use for wheel loads and other concentrated loads because soil pressures under most slabs-on-ground of adequate thickness are not excessive. For heavy concentrated or distributed loads, such as steel coils or heavy equipment, when placed or stored on a slab-on-ground, the pressure transmitted to the subgrade will be significant, and potential soil consolidation should be considered to determine if other shear failure or excessive settlement might occur. Therefore, the SER must present the geotechnical engineer with the magnitude of the concentrated loads, distributed loads, or both, so that the geotechnical report will provide recommendations for site design and possible settlement values.

The *k*-value used for design is that obtained at the top of the subgrade or subbase. The combined subbase and subgrade for slabs-on-ground supporting heavy traffic loads, such as airplanes, should have a minimum design *k*-value of 200 pci (54 MPa/m) to prevent excessive permanent deformation of the subgrade due to slab-on-ground corner deflections. A subbase course of sufficient thickness and quality should be used to achieve this modulus. However, in no case should design be based on a *k*-value greater than 500 pci (135 MPa/m) per UFC 3-260-02 Chapter 12. For office type buildings and typical forklift traffic, lower modulus of subgrade reaction can be used-refer to Appendix B examples.

If a subgrade has a high degree of saturation and low permeability, then a subbase material that is resistant to the detrimental effects of moisture should be used. A free-draining granular subbase course may be used to increase the subgrade *k*-value to the minimum acceptable *k*-value of 200 pci (54 MPa/m).

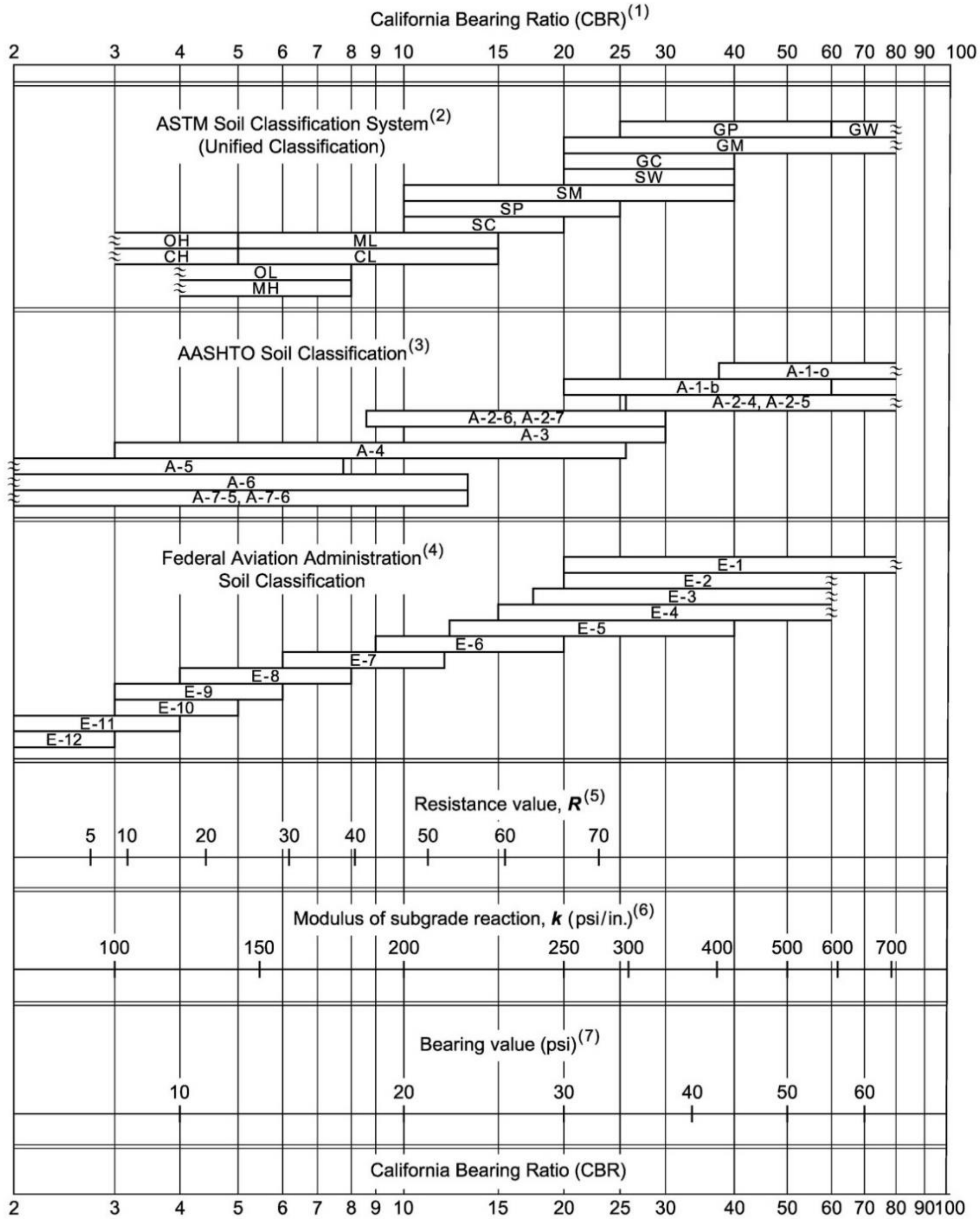
Where performance data from existing slabs-on-ground are available, adequate values for *k* usually can be estimated on the basis of soil type, drainage conditions, and frost conditions that exist at the proposed site. Table 2-2 lists typical values of modulus of subgrade reaction for various soil types and moisture contents. Figure 2-3 was developed by the Corps of Engineers (COE). It presents empirical relationships between soil classification type, CBR, bearing, and *k*-values. The values in both the table and figure should be considered as a guide only, and their use in lieu of the field plate load test is left to the discretion of the SER. The fact that the materials are shown in the table does not indicate suitability for use. Suitability must be determined for the specific job conditions.

Table 2-2 Typical Values of Modulus of Subgrade Reaction

Types of Materials	Modulus of Subgrade Reaction, *k*, lb/in.^{2}/in. (kPa/mm) for Moisture Contents of							
	1 to 4%	5 to 8%	9 to 12%	13 to 16%	17 to 20%	21 to 24%	25 to 28%	over 29%
Silts and clays Liquid limit > 50 (OH, CH, MH)	—	175 (47.5)	150 (40.7)	125 (33.9)	100 (27.1)	75 (20.4)	50 (13.6)	25 (6.8)
Silts and clays Liquid limit < 50 (OH, CL, ML)	—	200 (54.3)	175 (47.5)	150 (40.7)	125 (33.9)	100 (27.1)	75 (20.4)	50 (13.6)
Silty and clayey sands (SM & SC)	300 (81.4)	250 (67.9)	225 (61.1)	200 (54.3)	150 (40.7)	—	—	—
Gravelly sands (SW & SP)	300+ (81.4+)	300 (81.4)	250 (67.9)	—	—	—	—	—
Silty and clayey gravels (GM & GC)	300+ (81.4+)	300+ (81.4+)	300 (81.4)	250 (67.9)	—	—	—	—
Gravel and sandy gravels (GW & GP)	300+ (81.4+)	300+ (81.4+)	—	—	—	—	—	—

NOTE: *k*-values shown are typical for materials having dry densities equal to 90 to 95% of the maximum CE 55 density. For materials having dry densities less than 90% of maximum CE 55 density, values should be reduced by 50 lb/in.^{2}/in. (13.6 kPa/mm), except that a *k* of 25 lb/in.^{2}/in. (6.8 kPa/mm) will be the minimum used for design. Slab-on-ground are not generally placed directly on unimproved organic or expansive soils.

Figure 2-3 **Approximate Interrelationships of Soil Classifications and Bearing Values (PCA 1988). (Note: 1 psi/in. = 0.271 kPa/mm; 1 psi = 6.90 kPa.)**



(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 376-392.1.50

(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.

Example for presenting the slab-on-ground design criteria in the project construction documents is presented below:

1. SLAB-ON-GROUND DESIGN CRITERIA
2. MINIMUM REQUIRED MODULUS OF SUBGRADE REACTION FOR WIDE AREA RACK LOADING AND UNIFORM STORAGE LOADING.................. 200 PCI (54.3 MPa/m)
3. MINIMUM REQUIRED MODULUS OF SUBGRADE REACTION FOR LIFT-TRUCK LOADING............. 250 PCI (67.9 MPa/m)
4. UNIFORM STORAGE LOAD ....925 PSF (44 kPa)
5. LIFT-TRUCK FRONT AXLE LOAD ....15,500 LB (69,000 N) (SINGLE WHEELS SPACED 33 IN.)

If the soil classification reveals that the soil is poor, then an economical study should follow to determine whether the existing subgrade can be improved by compaction, stabilization, or strengthened by designing base courses, if previous experience of the slab-on-ground performance is not available.

2-4 SITE PREPARATION RECOMMENDATION.

The soil-support system is rarely uniform and some soil work is generally required to produce a more uniform surface to support the slab-on-ground. Therefore, the specifications, based on the geotechnical report, should direct the contractor to strip the topsoil of organic material, debris, and frozen material, and properly compact the existing soil. Hard and soft pockets of soil, which are usually located by proof-rolling or other means, should be removed and replaced with properly compacted soil. If deeper soft areas or buried debris is suspected, then borings, test pits, resistivity, or other procedures may be required. This information will help determine whether to use the existing subgrade, improve it by compaction or stabilization, design a subbase course, or vary the thickness of these layers.

2-4.1 Proof-Rolling and Compaction.

Proof-rolling is usually the action of driving a loaded vehicle in a grid pattern over the subgrade in an attempt to locate soft and compressible areas at or near the surface. The geotechnical engineer should recommend the type of equipment to use to proof-roll at least the upper foot (300 millimeters) of subgrade by sizing the wheel load of the equipment. In general, 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. Areas of poor support should be removed and replaced with compacted material to provide a more uniform and firmer subgrade. Guidelines for proof-rolling are given in ACI 302.1R.

Compaction improves stability of majority of subgrade soils and provides a more uniform foundation for the floor slabs or subbase course. The soil is densified by using compaction equipment such as a sheepsfoot, rubber tire, or vibratory rollers. CRD-C653-95, Compaction Effort, CE 55 relative compaction, should be applied to determine the compaction characteristics of the subgrade soils. CE 55 relative compaction implies 55 blows per layer and a compaction effort of 55,000 ft-lb/ft^3 of compacted soil. During construction, prolonged exposure of the subgrade to the atmosphere may allow overwetting, drying, or both, and therefore should not be allowed.

Contract documents, based on the geotechnical report, should specify the maximum lift thickness of the compacted fill layer. Also, the requirements for moisture and density based on the fill material should be included. The specified range of density should be around 100 ± 5% of the standard Proctor maximum density, or 95 ± 5% of the modified Proctor maximum dry density to achieve a more uniform subgrade modulus, k, and stiffer soil response. The range specified, however, should be compatible with the soil type, soil uniformity, contractor's operation, and project needs. For example, if clay soil with a plasticity index of 20 or higher is encountered on the job site, then a lower density range should be specified—92 ± 4% of the standard Proctor maximum dry density—which is often used to control volume changes.

2-4.2 Cut Sections.

With the exception of areas of special soil, the top 6 inches (150 millimeters) of subgrade in cut sections should be scarified and moistened to approximately optimum moisture content and compacted. Cohesive subgrade soils should be compacted to a minimum of 90% of CE 55 maximum density and cohesionless soils to a minimum of 95% of CE 55 maximum density.

2-4.3 Fill Sections.

The geotechnical report provides information on the maximum allowable lift thicknesses of the compacted fill layer. Also, the requirements for moisture and density based on the fill material should be included. With the exception of fill composed of special soils, fills composed of cohesive materials should be compacted to minimum of 90% of CE 55 maximum and all fills composed of cohesionless materials should be compacted to a minimum of 95% of CE 55 maximum density. Some adjustment for compaction requirements may be necessary for fills of expansive soils.

Large fills will add a surcharge load to the subsurface soils, which can cause differential settlement. The risk of settlement should be evaluated by the geotechnical engineer to control settlement within acceptable limits based on the use of the slab-on-ground. Also sloping exterior finish grade away from the slab-on-ground to drain surface water away from and around the slab-on-ground should be considered.

2-4.4 Cut-to-Fill Sections.

When a rigid floor slab is located partially on a fill area and partially on a cut area, the compaction requirements set forth in the preceding paragraphs should be followed. The depth of subgrade compaction in the cut area should be increased to 12 inches (300 millimeter).

2-4.5 Non-uniformity.

Where it is not possible to create uniform subgrade conditions by the methods described herein, the slab design can be varied throughout the project to maximize economy. Concrete flexural strength, percent reinforcing steel, and slab thickness can be adjusted to provide a design that is balanced in terms of service life. The specific combinations to be used will depend upon local conditions and costs, and selection of design alternatives is left to the discretion of the design engineer.

2-4.6 Special Soils (Problematic Soils).

Although compaction increases the stability and strength of most soils, some soil types show a marked decrease in stability when scarified, worked, and rolled. Also, there are some soils that shrink excessively during dry periods and expand excessively when allowed to absorb moisture. In general, special soils are highly expansive, highly compressible, or do not provide reasonably uniform support. Usually, these soils are inorganic clays of relatively high plasticity, classified as CH soils. Special types of soils are discussed in UFC 3-220-01

2-4.7 Backfilling.

Special care should be exercised in backfill areas around walls and columns to ensure compliance with compaction requirements outlined in the above paragraphs. Backfilling around walls and columns should be performed with pneumatic tampers, gasoline-powered tampers, and other mechanized hand-operated devices. Soil moisture content and lift thickness should be carefully controlled to ensure that compaction requirements are met through the full depth of the backfill.

2-4.8 Treatment of Unsuitable Materials.

Soils designated as unsatisfactory for subgrade use by the geotechnical engineer should be removed and replaced. The depth to which such undesirable soils should be removed depends on the soil type, drainage conditions, type of material stored, magnitude of tolerable differential settlement, and depth of freezing-temperature penetration. The depth of removal and replacement should be determined by the geotechnical engineer on the basis of judgment, experience, and with due consideration of the traffic to be served as well as the costs involved. Unsatisfactory or undesirable subgrade soils can, in some cases, be improved economically by chemical stabilization—adding chemicals that combine with the soil. Cement, fly ash, lime, or certain chemical additives are such materials when combined with soil, the characteristics of the composite material become suitable for use as subgrade. Criteria for soil stabilization are given in UFC 3-250-11. Subgrade stabilization, however, should not be attempted unless the cost reflects corresponding savings in subbase course, slabs-on-ground, or drainage facilities construction and is approved by HQDA (DAEN-ECE-G) Washington, DC 2031 4-1000 or Headquarters, Air Force Engineering Services Center (DEMP), Tyndall AFB, FL 32403.

Generally, portland cement, lime, bitumen, or fly ash is mixed into the soil substrata with water and the mixture is recompacted (refer to Table 2-3). 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 and analyze the soil conditions before chemical stabilization is used.

Table 2-3 **Soil Stabilization with Chemical Admixtures (ACI 360R)**

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 with surface cover.	Forms stabilized subgrade or base course. 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	3 to 5% bitumen in the form of cutback asphalt emulsion, or liquid tars for sandy soils. 6 to 8% asphalt emulsions and light tars for fine-grained materials. For coarse-grained soils, add anti-strip compounds to promote particle coating by bitumen.	Pulverize soil, mix with bitumen, solvent is aerated, and mixture compacted. 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	4 to 8%. Fly ash, between 10 and 20%, may be added to increase pozzolanic reaction.	Spread dry lime mixture with soil by pulvi-mixers or discs, compact moisture 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).

Subgrade support can be considerably improved by installing a cement-treated subbase (soil cement), controlled low-strength material (CLSM), or lean concrete subbase. Generally, cement-treated and lean concrete subbases are 4 to 6 inches (100 to 150 millimeters) thick. A modulus of subgrade reaction of 400 to 500 pound per square inch/inch (108 to 135 megapascal per meter) can be used in calculating the required thickness of a slab-on-ground placed directly on lean concrete and cement treated roller-compacted subbases.

Where subgrade strength is low, usually having a CBR of less than 5, then it may be necessary to improve the subgrade chemically, mechanically, or by replacement with suitable subgrade material. When the CBR is less than 3, then it is necessary to improve the subgrade through stabilization or replacement with suitable subgrade material. Subgrade stabilization should also be considered if one of the following conditions exist; poor drainage or need for a stable working platform. For design of slab-on-ground thickness supported on modified soil foundation, refer to Chapter 5 Section 5-8.

2-4.9 Subbase course.

The slab-on-ground is sometimes directly supported on the subgrade if the existing soil is of uniform strength and has the necessary physical properties. However, the existing topsoil is normally removed and replaced with compacted soil to provide a uniform subgrade for the concrete slab. If, however, the grading of a compaction operation does not produce a uniform subgrade, a granular subbase is proposed (Figure 1-1).

The subbase will provide a cushion and a more uniform slab-on-ground support. Selection of crushed rock or soils in the well-graded gravel (GW) and poorly graded gravel (GP) groups may appear costly as a subbase material, but the selection of these granular materials has distinct advantages as presented in Section 2-4.9.1. The use of sand for subbase is not recommended for the following two reasons: 1) difficulty in maintaining the subbase elevation; and 2) potential integration of sand into the concrete mixture.

2-4.9.1 Requirements.

Subbase course provides several benefits during the construction process and after the slab-on-ground is placed in service such that contractors build them even if contract documents do not require them for the following reasons:

- Produces more uniform support by distributing minor subgrade defects
- Provides a suitable working platform for the construction operation, especially during adverse weather conditions
- Improves modulus of subgrade resistance
- Protects against detrimental frost action, frost-heave
- Transmits the load from the slab-on-ground to the subgrade, thus improving the quality of support from the underlying soil
- Serves as a capillary break, reducing moisture migration toward the bottom of the slab-on-ground

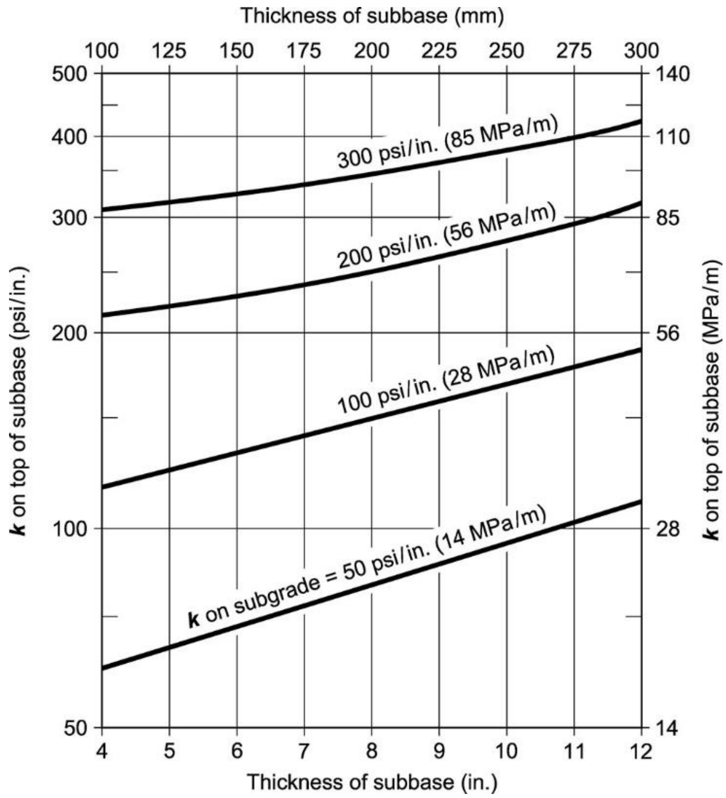
- Improves support to cohesive soils that are susceptible to reduced bearing support with an increase in moisture content
- Controls volumetric stability if subgrade materials are expansive
- Aids in controlling volume changes for expansive or frost-susceptible subgrade soils
- Adds resistance to erosion (pumping) under heavy loads
- Provides appropriate drainage for the subbase/subgrade system used

If the SER determines that a subbase course is essential to address one of the above-mentioned applications, then an economic study is required to establish subbase course requirements in slab-on-ground design. The economic study will typically include costs of subbase course materials such as hauling and required slab-on-ground thickness with and without subbase course. The use of a subbase with a base course usually represents an economical alternative for construction on a poor subgrade. Consideration should also be given to the use of the slab-on-ground—that is, what material is to be stored and what operations are likely to occur on the slab-on-ground. These considerations will also have an impact on whether to include a subbase course, as some of these factors can be better controlled through proper subgrade preparation treatments. Refer to ACI 302.1R for more in-depth discussions.

2-4.9.2 Compaction.

The subbase course material should be properly compacted in accordance with the criteria presented in Section 2-4 and should have high strength and low compressibility. Effective compaction is achieved at the optimum moisture content, which corresponds to the maximum dry density of the subbase material. Using high-quality and well-compacted granular subbase under a slab-on-ground will increase the modulus of subgrade, *k*. Further, increasing the subbase course will increase the modulus of subgrade, *k*, value. From Figure 2-4, one can conclude that increasing the subbase thickness for lower modulus-of-subgrade is more effective than for higher modulus-of-subgrade values (ACI 360R).

Figure 2-4 **Effect of Subbase Thickness on Design Modulus of Subgrade Reaction**



Note: 1 lb/in.^{2}/in. = 0.2714 MPa/m; 1 in. = 25.4 mm.

2-4.9.3 Drainage.

Adverse moisture conditions resulting from high water table and subsoils subject to capillary action can cause damage to floor covering and stored material. If the subgrade soils provide for movement of water by capillary flow (CH, CL, MH, and ML types) and the groundwater table is less than 5 feet (1500 millimeters) from the final grade, a minimum thickness of 6 inches (150 millimeters) of free-draining subbase course should be provided. Positive drainage is to be provided to ensure against water being trapped beneath the concrete slab-on-ground. The floor should be protected against the migration of water vapor through the slab and joints. Water vapor damage is to be prevented by an impermeable membrane placed on the subgrade prior to concrete placement; refer to Chapter 7 Section 7-4. Such vapor retarders must be installed even in conjunction with a subbase course if moisture-susceptible floor coverings or conduits are present. A subbase course for drainage is not required when groundwater table is deep enough and capillary action is inconsequential.

2-4.9.4 Materials.

If conditions indicate that a subbase course is desirable, a thorough investigation should be made to determine the source, quantity, and characteristics of the available materials. A study should be made to determine the economical thickness of material for a subbase course that will meet the requirements. The subbase course may consist of natural materials, processed materials, or stabilized materials as defined in UFC 3-250-11. The material selected should be the one that best accomplishes the intended purpose of the subbase course. In general, the subbase course material should be well-graded, high-stability material. UFC 3-250-01 and UFC 3-260-02 provide requirements for base courses for additional support and frost action. If the subbase course is for drainage, the maximum particle size must be 1-1/2 inches (38 millimeters) and minimum particle size must be the No. 4 (4.75 mm) sieve size. If a free-draining, open-graded subbase is used, a filter layer can be placed under the subbase course to prevent pumping action and subgrade intrusion. Coarse aggregate must have a percentage of wear by the Los Angeles abrasion test of not more than 50.

Uniform high-quality materials should be used. Weakly cemented rocks and most shales should not be used; an exception would be baked shales occurring adjacent to intrusive dikes. Durability will be checked if the subbase aggregate will be exposed to frost. Aggregates that break down excessively when subjected to freezing-and-thawing cycles will not be used.

Subbase materials should be a clean, densely graded, granular material with a balanced fine content. It should produce an easily constructed, low-friction surface while minimizing movement/flow of moisture from below.

2-4.9.5 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 material 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 D6913)
- Plasticity (ASTM D4318)
- 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)
- 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)
- Nuclear densometer (ASTM D3017 and D6938)

2-4.9.6 Special Slab-on-Ground Support Problems.

Soils with a plasticity index of 15 or higher may have a potential for volume change that should be considered—refer to Table 2-1, Figure 2-1, and Figure 2-2. Silts, clays, and some fine sands can be susceptible to frost action. They can experience large volume changes, which may result in heave of the soil and lose support due to saturation upon thawing. Therefore, the subbase should be free of frost before concrete placement and be able to support construction traffic including concrete trucks. There are three conditions present when this issue occurs:

1. Soil temperature below freezing
2. Water table close to the frost level
3. A soil able to transmit water from the water table into the frost zone by capillary action.

Possible solutions include: 1) lowering the water table; 2) providing a barrier; 3) using a subbase or subgrade soil that is not frost-susceptible; or 4) installing properly designed insulation. Volume changes due to frost action occur at building perimeters and under freezer areas. Therefore, in cold climate regions, it is good practice to place insulation below the slab-on-ground on subgrade at ends adjacent to exterior foundation and walls. The insulation is placed over a distance of 24 to 36 inches (600 to 900 millimeter) from the exterior foundation or walls and sometimes vertically along the grade beam or exterior foundation to lessen heat loss.

2-5 ENVIRONMENTAL CONDITIONS.

The environmental exposure of a slab-on-ground is a concern because there is a potential for humidity, temperature changes, and volume changes such as shrink and swell of soils. Some of the environmental impacts could be addressed such as thermal effects, which could be reduced if a slab-on-ground is constructed after the building is enclosed. However, most slabs-on-ground are constructed before building enclosure and, therefore, environmental factors should be considered in the construction sequence. Also, thermal effects during service life of slab-on-ground should be addressed as well.

2-5.1 Freezing and Thawing.

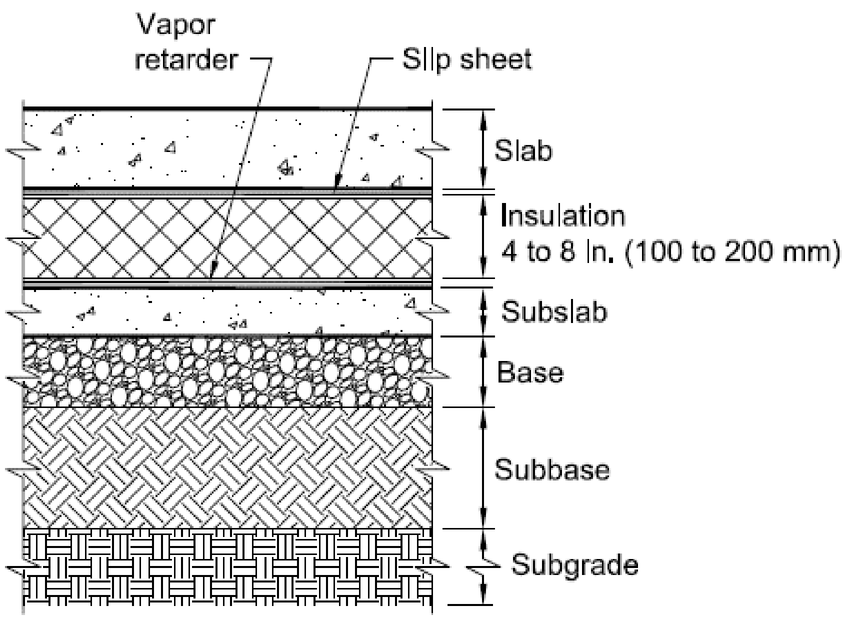
Special additional design considerations and measures are necessary where freezing and thawing can occur in underlying soils. The effects of such occurrences, which are termed “frost action,” include surface heaving during freezing and loss of bearing capacity upon thawing. Detrimental frost action is the result of the development, thawing of segregated ice in underlying soils, or both. Potential difficulties from frost action exist whenever a source of water is available to a frost-susceptible soil that is subject to sub-freezing temperatures during a portion of the year. Conditions necessary for the development of ice segregation in soils, together with a description of the ice segregation process and the detrimental effects of frost action, are given in UFC 3-260-02.

2-5.2 Cold Storage Facilities.

A different problem is encountered in cold storage facilities where a structure in contact with the ground is maintained at sub-freezing temperature. Hence, frost action under such structures is a long-term rather than a seasonal phenomenon, and deep frost penetration will eventually occur, even in areas where sub-freezing ground temperatures are not naturally experienced, unless insulation or provisions for circulation of warm air beneath the slab-on-ground are provided in design.

An insulation layer is typically installed between a sub-slab or mud-slab and the slab-on-ground. The sub-slab is constructed on base courses to prevent subgrade frost heave in a freezer warehouse. A vapor retarder must be placed directly below the insulation (refer to Figure 2-5). It should be kept in mind that insulation will merely slow frost penetration into subbase and subgrade soils; soil freezing and heaving could still occur. Therefore, heat return conduits are installed in the sub-slab to mitigate soil freezing and heaving. The American Society of Heating, Refrigerating, and Air-Conditioning Engineering *ASHRAE Handbook and Product Directory, Equipment,* and *Applications* provides additional information and guidance.

Figure 2-5 **Typical Slab-on-Ground Construction for Refrigerated Building**



The insulation layer is 4 to 8 inches (100 to 200 millimeters) thick and provides some rigidity to the system. It is, however, important to note that the subgrade modulus values published by suppliers of rigid insulation are typically calculated using ASTM D1671, which provides higher *k*-values for the system than the plate bearing test (ASTM D1196) previously discussed in Section 2-3.2. These higher values should not be used in determining the concrete slab-on-ground thickness, as they can result in inadequate slab thicknesses. If the actual *k*-value of the soil is not known, it is then recommended to use a value between 75 to 100 pounds per square inch per inch (20 to 27 megapascal per meter).

2-5.3 Permafrost.

Because construction alters the existing thermal regime in the ground, an additional problem is encountered in regions where heat flow from the facility can result in the progressive thawing of perennially frozen ground (permafrost). Thermal degradation of permafrost, which contains masses of ice, will result in subsidence as well as reduction in bearing capacity. Both can be severe. Ventilated foundation is usually employed as an effective and economical means of maintaining a stable thermal regime in permafrost under slabs-on-ground. Provision is made for ducted circulation of cold winter air between the insulated floor and underlying ground. The air circulation serves to carry away the heat both from the foundation and the overlying building, freezing back the upper layers of soil that were thawed the preceding summer. The characteristics of permafrost and engineering principles in permafrost regions are described in UFC 3-130-01 and UFC 3-130-04.

2-5.4 Applicable Technical Manuals.

Where freezing and/or thawing can occur in underlying soils, slab design will be in accordance, as applicable, with UFC 3-260-02 and UFC-130-04. Thermal computation procedures are detailed in UFC 3-130-06.

2-6 SUMMARY.

1. The geotechnical engineer must provide the soil design parameters and site work required based on design parameters prepared by the SER.
2. The *k*-value for the slab-on-ground design reflect the response of the subgrade under temporary (elastic) conditions and small settlements.
3. Soil compressibility and bearing capacity values are used to predict and limit differential settlements.
4. Project specifications should direct the contractor to strip the topsoil of organic material, debris, and frozen material, and properly compact the existing subgrade.
5. Slab-on-ground must be supported on well-compacted subgrade/subbase and be of uniform strength.
6. Subbase course is provided if subgrade is poor and its strength needs to be increased.
7. As the modulus of subgrade reaction increases, reduction in slab-on-ground thickness decreases at smaller increments.

CHAPTER 3 DETERMINATION OF SLAB-ON-GROUND LOADS

3-1 LOAD CATEGORIES.

Slabs-on-ground are subjected to several types of loadings. They vary from concentrated to linearly distributed to uniformly distributed, stationary, and moving loads. These loads are applied either individually or in combination; some are listed below:

- Vehicle wheel loads: trucks, forklifts
- Aircraft loads
- Distributed loads
- Line and strip loads: walls
- Concentrated loads: rack loads
- Construction loads
- Environmental effect

3-2 STRESSES.

The structural design of a concrete slab-on-ground is primarily controlled by the stresses caused by moving live loads (mainly vehicles, forklifts, and airplanes) and in some cases by stationary (distributed, line, or concentrated) loads. Stresses in slabs-on-ground resulting from vehicular loads are a function of slab-on-ground thickness, *h*, vehicle weight, *P*, and weight distribution, *w*, vehicle wheel spacing, *s*, or track configuration, modulus of elasticity, *E*, and Poisson's ratio, ν, of concrete, modulus of subgrade reaction, *k*, of supporting material, and construction method and quality. The volume of traffic during the design life is important for fatigue considerations. The slab-on-ground design procedure presented herein is based on limiting the critical tensile stresses produced within the slab by the vehicle loading, as in UFC 3-250-01 and UFC 3-260-02. Correlation studies between theory, small-scale model studies, and full-scale accelerated traffic tests have shown that maximum tensile stresses in slabs-on-ground will occur when vehicle wheels are tangent to a free edge (Westergaard 1925a). Stresses for the condition of the vehicle wheels tangent to an interior joint where the two slabs are tied together are less severe than at a free edge because of the load transfer across the two adjacent slabs. In the case of slabs-on-ground, the design can be based on the control of stress at interior joints. Exceptions to this assumption for interior joint loading occur when a wheel is placed at the edge, at doorways, or near a free edge at a wall.

3-3 TRANSIENT/VEHICLE-IMPOSED LOADS.

For determining slab-on-ground design requirements, military vehicles have been divided into three general classifications: 1) forklifts; 2) other pneumatic and solid-tired vehicles; and 3) tracked vehicles. The relative severity of a given load within one of the three classifications is determined by establishing a relationship between the applied load and a standard loading. Slab-on-ground design requirements are then established in terms of the standard load. Other stresses, such as restraint stresses resulting from thermal expansion and contraction of the concrete slab and warping stresses resulting from moisture and temperature gradients within the slab, due to their cyclic nature, will at times be added to the moving live load stresses. A provision for these stresses that are not induced by wheel loads is made by safety factors developed empirically from full-scale accelerated traffic tests and from the observed performance of pavements under actual service conditions.

The following traffic data are required to determine the slab-on-ground thickness requirements:

- Types of vehicles
- Wheel loads, including the maximum single-axle and tandem-axle loading for trucks, forklifts, and tracked vehicles
- The average daily volume of traffic (ADV) by vehicle type that, in turn, determines the total traffic volume anticipated during the design life of the slab-on-ground
- Wheel contact area
- Distance between loaded wheels

For slabs-on-ground, the magnitude of the axle load is of far greater importance than the gross weight. Axle spacings generally are large enough so that there is little or no interaction between axles. Forklift traffic is expressed in terms of maximum axle load. Under maximum load conditions, weight carried by the drive axle of a forklift is normally 87 to 94% of the total gross weight of the loaded vehicle. Full-scale experiments have shown that changes as little as 10% in the magnitude of axle loading are equivalent to changes of 300 to 400% in the number of load repetitions.

For tracked vehicles, the gross weight is evenly divided between two tracks, and the severity of the load can easily be expressed in terms of gross weight.

3-3.1 Traffic Distribution.

To aid in evaluating traffic for the purposes of slab-on-ground design per the Corps of Engineers (COE) method, refer to Chapter 5 Section 5-4.1. Typical forklifts have been divided into six categories as follows per Table 3-1.

Table 3-1 Forklift Category Based on Axle Load

Forklift category	Forklift maximum axle load, kip (kN)	Maximum load capacity, kip (kN)
I	5 to 10 (22.2 to 44.5)	2 to 4 (8.9 to 17.8)
II	10 to 15 (44.5 to 66.7)	4 to 6 (17.8 to 26.7)
III	15 to 25 (66.7 to 111.2)	6 to 10 (26.7 to 44.5)
IV	25 to 36 (111.2 to 160.1)	10 to 16 (44.5 to 71.2)
V	36 to 43 (160.1 to 191.3)	16 to 20 (71.2 to 89)
VI	43 to 120 (191.3 to 533.8)	20 to 52 (89 to 231.3)

When forklifts have axle loads less than 5000 pounds (22,240 Newton) and the stationary live loads are less than 400 pounds per square foot (19.2 kilopascal [1952 kilogram per meter square]), the floor slab-on-ground should be designed in accordance with UFC 3-301-01. Vehicles other than forklifts such as conventional trucks shall be evaluated by considering each axle as one forklift axle of approximate weight. For example, a three-axle truck with axle loads of 6000, 14,000, and 14,000 pounds (26,700, 62,300, and 62,300 Newton) will be considered as three forklift axles—one in Category I and two in Category II, Table 3-1. Tracked vehicles are categorized as per Table 3-2.

Table 3-2 Tracked Vehicles Categories Based on Gross Weight

Forklift category	Tracked vehicles maximum gross weight, kip (kN)
I	Less than 40 (178)
II	40 to 60 (178 to 267)
III	60 to 90 (178 to 400.3)
IV	90 to 120 (400.3 to 533.8)

Categories for tracked vehicles may be substituted for the same category for forklifts.

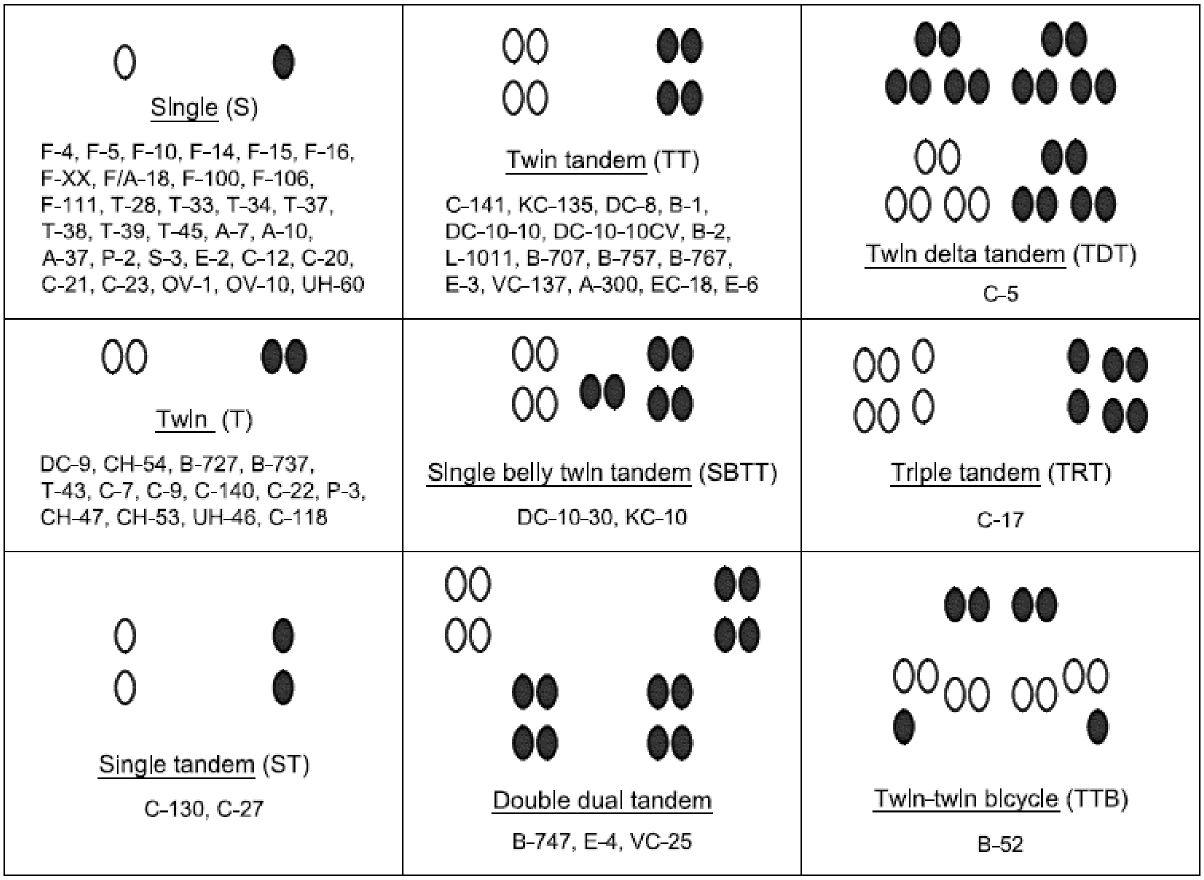
3-3.2 Aircraft Loads

Factors that must be considered in slab-on-ground thickness design for aircraft loads are the landing gear configuration, weight distribution, gear loads, number of wheels, wheel spacing, tire width, and tire inflation pressure. These characteristics are different for each aircraft and will result in a different slab-on-ground response. Aircraft expected to use the facility over the design period shall be considered in the slab-on-ground thickness design.

3-3.2.1 Aircraft Type.

A landing gear assembly shall consist of a single wheel for smaller aircraft, or dual and dual tandem wheels for larger aircraft. Figure 3-1 illustrates the various multi-wheel landing gear assemblies and lists typical aircraft for each.

Figure 3-1 **Loading Gear Assemblies**



3-3.2.2 Design Weight.

The maximum static gear loads are used for slab-on-ground thickness design. Table 3-3 presents the design gear loads and other characteristics for Air Force Navy and Marine Corps aircraft. To use the design curves in Chapter 5, the design gear load must be converted to the design gross aircraft weight (typically, the maximum gross take-off weight) by assuming that 95% of the gross aircraft weight is carried by the main gears. The design gear loads given in Table 3-3 represent the maximum static gear loads expected to be applied to a slab-on-ground.

Table 3-3 Aircraft Characteristics and Design Loadings

Aircraft Characteristics and Design Loadings

Type	DOD Designation	Type of Loading Gear	Design Gear Load (lb)	Design Tire Pressure (psi)	Pass/Coverage[3]		Empty Weight (lb)	Maximum Take-off Weight (lb)	Wing Span (ft)	Length (ft)	Wheel Base (in.)	Tread (in.)	Main Gear Tire Spacing	
					Chan.	Unchan.							A (in.)[4]	B (in.)[5]
Attack	A-3B	S	37,000	245	3.48	14.96		78,000	72.5	76.4			–	–
	A-4M	S	12,500	200	11.63	23.26	10,500	24,500	27.5	41.25	160.5	93.5	–	–
	A-5	S	29,500	300	9.27	18.54	38,000	80,000	53.3	76.5	264.0	150.5	–	–
	RA-5C	S	38,000	350	8.82	17.64	38,800	81,700	53.3	76.5	264.0	150.5	–	–
	A-6E	S	28,700	200	7.67	15.35	36,600	60,400	53.0	55.75	206.0	132.0	–	–
	A-7K	S	21,000	200	8.97	13.91	21,800	42,000	38.7	46.1	188.1	113.9	–	–
	AV-8B	Special	15,000	125	3.89	7.47	12,000	24,000	30.3	45.7	135.0			
Fighter	F-4E	S	22,500	300	13.70	27.39	31,800	58,000	38.4	58.3	279.0	215.0	–	–
	F-8E	S	18,000	265	13.69	27.39	19,700	34,300	85.7	54.5			–	–
	F-14	S	30,000	240	8.58	17.00	36,700	72,600	64.1	61.98	276.5	192.0	–	–
	F/A-18	S	21,000	200	8.22	16.44	30,000	51,900	40.4	56.0	213.7		–	–
Trainer	T-1	S	9,000	200	13.69	27.39							–	–
	T-2C	S	7,000	165	14.10	28.20	8,000	14,000	37.9	38.8	155.0	221.0	–	–
	TC-4C	T		123				36,000	78.3	67.9		290.0	–	–
	TA-4F/J	S		350				24,500	27.5	46.2			–	–
	T-39A	S	9,000	165	12.45	24.89	10,000	18,700	44.4	43.8	174.0	86.0	–	–
	T-28D	S	4,300	60	10.85	21.02	6,700	9,000	41.0	33.0	144.0	162.0	–	–
	T-34C	S	1,500	60			2,200	3,000	33.3	28.8			–	–
	T-44A	S	4,500	90	12.99	24.75	6,300	9,600	50.3	35.5	147.5	153.0	–	–
	T-45A	S		125	11.68	22.31		14,500	30.8	39.3	170.0	154.0	–	–
Patrol	P-3C	TT	68,000	190	3.45	6.49	66,200	143,000	99.7	116.8	357.0	374.0	26.0	–
	S-3A	S	19,000	245	10.43	20.87	26,864	46,000	68.7	53.3	225.0	165.0	–	–
Transport and Tanker	C-1A	S		142			20,640	26,800	69.7	42.3	106.9	222.0	–	–
	C-2A	S		235	7.91	15.69		60,000	80.6	56.8	278.4	234.0	–	–
	C-5A	TDT	190,000	115	0.83	1.05	318,000	837,000	222.7	247.8	765.1	449.5		
	C-17	TRT	260,000		1.37	1.9	279,000	580,000	2088.0	2038.0			–	–
	C-121	T	81,000	170	3.45	6.18			123.0	113.6	599.0	336.0	28.0	–
	C-130	ST	84,000	95	4.36	8.56	72,000	175,000	132.6	97.8	388.0	171.0	–	60.0
	KC-10	SBTT	212,000	181	3.77	5.59	271,000	599,000	165.3	182.3	869.0	416.0	–	–
	KC-135	TT	142,000	155	3.37	5.97	104,300	301,600	130.8	136.3	708.0	265.0	35.8	59.8
	C-141B	TT	155,000	180	3.49	6.25	140,000	344,900	160.0	145.0	678.7	251.0	32.5	48.0
	C-9B	T	51,300	152	3.85	7.18	62,000	108,000	93.3	119.3	638.5	196.0	25.0	–
	C-117	S	15,300	56	5.56	11.11		36,800	85.0	64.4	440.0	222.0	–	–
	C-118A	T	54,300	124	3.48	6.39	59,000	112,000	117.5	106.8	432.0	296.5	29.0	–
Bomber	B-52	TTB	250,000	240	1.58	2.15	230,000	480,000	185.0	162.0	597.0	136.0	62.0	–

(Continued)

S – Single Tricycle, T – Dual Tricycle, TDT – Twin Delta Tandem, ST – Single Tandem Tricycle, TT – Dual Tandem Tricycle

NOTES:
1. Blank spaces indicate data not readily available.
2. This data represents the best available figures at the time of publication. The user should update this information for later models of the design aircraft.
3. Values given are for rigid and flexible pavements. Pass to Coverage Ratios for flexible pavements for aircraft with Dual Tandem Tricycle Gear are equal to one-half the value shown. All Tandem Wheel Aircraft produce only one maximum stress for each pass of the gear for rigid pavements.
4. A represents the transverse tire spacing on one main gear.
5. B represents the longitudinal tire spacing on one main gear.

Table 3-3 (continued)

Type	DOD Designation	Type of Loading Gear	Design Gear Load (lb)	Design Tire Pressure (psi)	Pass/Coverage[3] Chan.	Pass/Coverage[3] Unchan.	Empty Weight (lb)	Maximum Take-off Weight (lb)	Wing Span (ft)	Length (ft)	Wheel Base (in.)	Tread (in.)	Main Gear Tire Spacing A (in.)[4]	Main Gear Tire Spacing B (in.)[5]
Commercial	B-707	TT	157,000	180	3.30	5.87	146,400	333,600	145.8	152.9	708.0	265.0	34.5	56.0
	B-727	T	98,000	150	3.30	5.88	101,500	209,500	108.0	153.6	760.0	225.0	34.0	--
	B-737	T	54,000	150	3.20	5.80	60,500	125,000	93.0	100.0	447.0	206.0	30.5	--
	B-747	DDT	190,000	195	3.84	5.43	363,000	778,000	195.7	231.3	1,008.0	434.0	43.25	54.0
	B-757-200	TT	105,000	170	3.30	5.88	129,900	220,000	124.5	155.3				
	B-767-200	TT	143,000	183	3.71	6.05	180,540	300,000	156.3	159.1				
	DC-8	TT	172,000	196	3.19	5.82		350,000	148.5	187.4	930.0	250.0	30.0	55.0
	DC-9 Series 10	T	57,000	170	3.61	6.73	50,840	90,500	89.4	104.4	524.4	196.8	24.0	--
	DC-10 Series 30	TT	210,500	165	3.77	5.61	267,197	572,000	165.3	181.6	868.6	429.0	54.0	64.0
	(Center Dual)		91,100	140	2.63	3.96	248,485	466,000						
	L-1011-200	TT	219,000	165	3.66	5.57	249,100	450,000	155.3	177.8	840.0	432.0	52.0	70.0
Early Warning	E-1B	S		151				27,400	72.3	45.2			–	–
	E-2C	S	24,500	260	8.58	17.00	38,100	51,900	80.6	57.6	278.0	233.8	--	--
	E-3A	TT	155,000	180	3.30	5.87	88,000	325,000	145.8	152.9	708.0	265.0	34.5	56.0
	EA-6B	S		230				61,500	53.0	59.8			--	--
	EP-3E	T						142,000	99.7	105.9			--	--
	ES-3A	S		245			34,000	52,500	68.7	53.3	225.0	165.0	--	--
Reconnaissance	UC-12M	S		64				13,500	54.5	43.8	179.4	206.0	--	--
Rotary Wing	AH-1W						10,200	14,750	48.0	58.0	146.4	84.0	--	--
	CH-46E	T			8.01	15.22	16,000	24,300	51.0	84.3	297.6	176.4	20.0	–
	CH-53E	T	26,558	165			33,226	69,750	79.0	90.0	327.0	156.0		
	HH-3A	T						19,100	62.0	72.9	282.5	156.0	--	--
	HH-60H	S			11.94	19.49		21,880	53.7	64.8		104.0	--	--
	MH-53E	T			5.23	9.53	36,745	69,750	79.0	99.0		156.0	15.0	--
	RH-53D	T			5.23	9.53		42,000	72.2	88.6		156.0	15.0	--
	SH-3H	T						21,000	62.0	72.9	282.5	156.0	--	--
	SH-60F	S			11.94	19.49		21,880	53.7	64.9		104.0	–	--
	TH-57B/C							3,350	33.3	39.2	56.5	75.5	–	–
	UH-1N							10,500	48.0	57.3		109.0	–	–
	UH-3H							21,000	62.0	72.9	282.5		–	–
	UH-46E	T	9,800	150			12,550	22,800	51.0	84.4	298.0	176.4		
	VH-3A							19,100	62.0	72.9		156.0	--	--
VTOL	MV-22	T		117	4.72	8.66		57,000	1014.6	747.2	3000.0	156.0	--	--
Helicopter	CH-53K	T	27,000				33,200	88,000	99	99	154			

3-3.2.3 Use of Other Gear Loads in Design.

Gear loads other than those listed in Table 3-3 may be used for design when required. Because certain areas of an airfield (for example, runway shoulders, runway overruns) do not normally carry fully loaded aircraft, they do not need to be designed for the maximum gross weight.

3-3.2.4 Hangar Slab-on-Ground.

Aircraft in hangars are not normally loaded with cargo, fuel, or armaments. Hangar floors shall be designed for the empty weight of the aircraft. When exact data are not available, 60% of the maximum gross weight of the aircraft is used. Aircraft hangar slabs-on-ground are not designed for jacking loads as long as the footprint of the jack is equal to or greater than the contact area of the combined tires on the aircraft gear being elevated.

3-3.2.5 Standard Design Aircraft.

One aircraft in each gear assembly group has been designated the representative aircraft for that group. Table 3-4 identifies five standard aircraft types that are to be used as default values in the design of slabs-on-ground only when site specific aircraft loadings are not available.

Table 3-4 Standard Design Aircraft Types

Landing gear assembly	Representative aircraft	Tire pressure, psi (MPa)	Design gear load, lb (kg)
Single	F-14	240 (1.65)	30,000 (13,608)
Dual	P-3	190 (1.31)	68,000 (30,845)
Single tandem	C-130	95 (0.65)	84,000 (38,100)
Dual tandem	C-141	180 (1.24)	155,000 (70,310)
Twin delta tandem	C-5A	115 (0.79)	190,000 (86,190)

3-3.3 Wheel Contact Area.

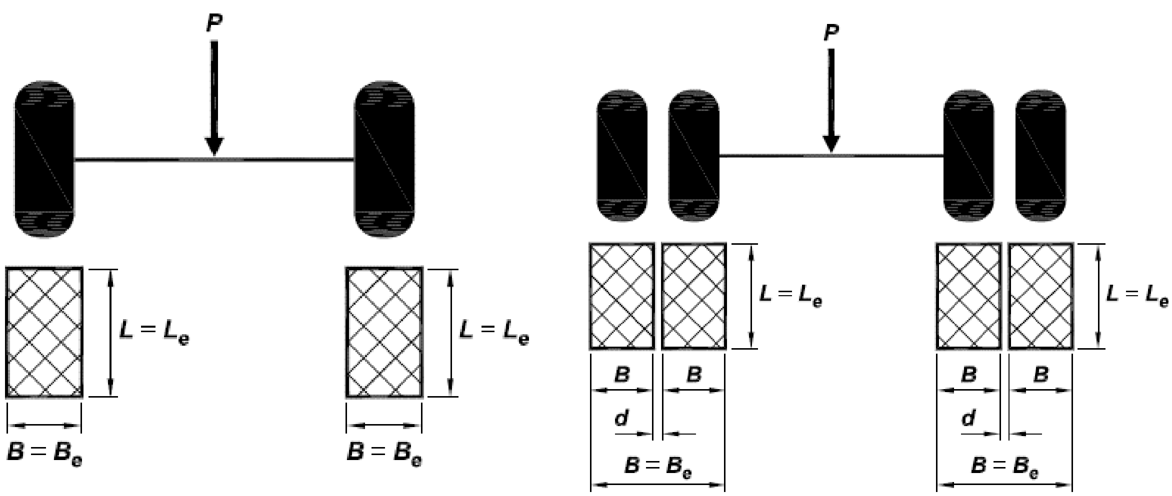
This information is required for the Portland Cement Association (PCA), Wire Reinforcement Institute (WRI), and the finite element (FE) methods; refer to Chapter 5. Wheel contact area for vehicular traffic or aircrafts can be single wheel or multiple wheels. A single tire contact area is conservatively approximated by dividing the tire load by the tire pressure (Packard 1996). The type of tire has an effect on the pressure to which the slab-on-ground is subjected to, as presented in Table 3-5 for vehicular loads.

Table 3-5 Range of Pressure per Tire Type

Tire type	Pressure
Pneumatic non-steel-cord	85 to 100 psi (0.6 to 0.7 MPa)
Steel-cord	90 to 120 psi (0.6 to 0.8 MPa)
Standard solid and cushion solid rubber	180 to 250 psi (1.2 to 1.7 MPa)
Polyurethane	>1000 psi (> 6.9 MPa)

Dual tires' effective contact area can be conservatively estimated by summing the contact area of each individual tire contact area and the area between them (Figure 3-2). When there is no information on the number of wheels or wheel spacings, then the engineer can conservatively assume a single equivalent wheel load and contact area.

Figure 3-2 **Equivalent Contact Area of Single- and Dual-Tire Vehicles**



(a) Single tire contact area approximation (b) Dual tire contact area approximation

3-4 DISTRIBUTED LIVE LOADS.

Slabs-on-ground should have adequate strength to support structural distributed live loads. The variables that affect slabs-on-ground design that are subjected to distributed loads are (ACI 360R):

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

The maximum allowable distributed live load is limited by both the positive bending moment stress under the load and the negative bending moment stresses occurring at some distance from the load.

3-4.1 Positive Bending Moments.

Stresses due to positive bending moment are relatively simple to compute by using Westergaard's analysis of elastically supported plates (Westergaard 1925b). An appropriate factor of safety is applied to determine allowable stresses due to these loads. Environmentally imposed stresses must also be accounted for when considering distributed loads.

3-4.2 Negative Bending Moments.

The effect of negative bending stress is more difficult to determine. A slab on an elastic subgrade will deform under loading similar to a damped sine curve in which the amplitude or deformation of successive cycles at a distance from the loading position decreases asymptotically to zero. Thus, there exists some critical aisle width where the damped sine curves from parallel loading areas are in phase and additive. In this situation, the negative bending moment stresses will become significant and must be considered. Therefore, allowable distributed live loads were established to include the effects of negative moment bending stresses. These calculations are reflected in the tabulated values of allowable distributed live loads (Chapter 5 Section 5-5).

Positive and negative bending moments are indirectly incorporated into the classical design methods charts (COE, PCA, and WRI). The SER must, however, design the slab-on-ground per ACI 318 for the obtained forces (bending moments and shear forces) when FE analysis method is applied, refer to Chapter 5 Section 5-12.

3-5 WALL LOADS.

Line or strip loads are usually wall loads supported on slab-on-ground. Slabs-on-ground should have adequate thickness to carry wall loads—refer to Chapter 5 Section 5-6 for minimum required slabs-on-ground thickness to support the imposed wall/strip load. Factors affecting the design of slab-on-ground subjected to line and strip loads (ACI 360R):

- Maximum load intensity
- Load duration
- Width and 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
- 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.

Walls weigh from several hundred to several thousand pounds per linear foot (from more than 1500 newton per meter to several tens of thousands newton per meter). The design table used for determining thicknesses required under walls is developed by Staab (1980) and is based on the theory of a beam on a liquid foundation subjected to concentrated loads. Three loading conditions are considered: 1) loads at the center of the slab; 2) loads at a joint; and 3) loads at the edge of the slab. The widths of thickened slabs are developed together with the recommended transitions. There are situations where a wall is placed on a new thickened slab or on an existing concrete slab-on-ground if analysis reveals that the existing slab-on-ground thickness is adequate to support the new line load. Influence charts can be used for strip and wall loads if length of the load contact area is 4ℓ or 6ℓ, where ℓ is defined by (Packard 1996); refer to Chapter 5 Equation 5-2.

3-6 CONCENTRATED LOADS.

Concentrated loads are usually static loads and are applied such as posts of storage racks that are assembled in narrow aisles. The racks could reach heights of 80 feet (24 meters) and higher and can exert concentrated loads of 40,000 pounds (180,000 Newtons). The SER must consider long-term soil settlement in the design of the slab-on-ground that is subjected to high rack post loads.

The variables that affect and must be considered in the design of slabs-on-ground subjected to concentrated loads are (ACI 360R):

- 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
- Area of contact between post base plate and slab.

3-7 CONSTRUCTION LOADS.

The slab-on-ground may be subjected to various loadings during the construction phase. This is critical especially if the slab-on-ground was recently placed and opened to traffic before it attained its full strength or was subjected to loading exceeding its design load. Common construction loads are:

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

The SER must anticipate these construction loads and consider them in the design process and direct the contractor when the slab-on-ground can be subjected to such loads. The SER needs to instruct the contractor to limit construction loads near free edges or slab corners. This type of loading should be addressed at the preconstruction meeting; refer to Chapter 7 Section 7-2.

3-8 ENVIRONMENTAL FACTORS

Thermal changes, reduction in humidity, and expansive soils produce flexural stresses that should be considered in addition to the flexural stresses in slabs-on-ground produced by the applied loads. Moisture changes in the slab-on-ground produce stresses that will affect curling due to the different shrinkage rates between the top and bottom of the slab-on-ground and are particularly important for exterior slabs and for slabs constructed before the building is enclosed. These changes produce flexural stresses that result in the slab-on-ground lifting off the subgrade—curling. The restraint stresses can be ignored in short slabs-on-ground. When the joint spacing recommendations obtained from Figure 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. If built, then reinforcement should be provided at such restraints to limit slab crack widths.

3-9 UNUSUAL LOADS.

Information regarding slab-on-ground requirements for special-purpose ordnance, engineer, or transport vehicles producing loads significantly greater than those defined herein should be requested from Headquarters, Department of the Army (HQDA) (DAEN-ECE-G), Washington, DC 20315-1000 or Headquarters, Air Force Engineering and Services Center (DEMP), Tyndall MB, FL 32403.

For unusual loads, slabs-on-ground forces, deflections, and soil-bearing pressures can be determined by finite element analysis, refer to Chapter 5 Section 5-12.

3-10 FACTORS OF SAFETY.

For nonstructural slabs-on-ground, the factors of safety are used to reduce to an acceptable level the potential of serviceability failure. As the ratio of the actual flexural stress to the modulus of rupture decreases, the slab can withstand more load repetitions before failure (Table 3-6). For a stress ratio less than 0.45, the concrete slab-on-ground can withstand an unlimited number of load repetitions without fatigue cracking. The safety factor is taken as the inverse of the stress ratio. For example, if the stress ratio is 0.57, then the factor of safety to be considered is SF = 1/0.57 = 1.75 with approximately 71,300 allowable load repetitions on the slab-on-ground, and for a stress ratio of 0.45, the SF = 1/0.45 = 2.2. A safety factor, however, of 2.0 has been usually used in the industry. In general, the SER selects the factor of safety based on several considerations. Some of the main factors are:

- Loss of slab-on-ground use and the cost for repairing the affected areas in an active facility

- Subjecting the slab-on-ground to loading at an early stage
- Anticipated frequency, repetition of load, and traffic patterns to allow consideration of fatigue cracking

Table 3-6 Stress Ratio versus Allowable Load Repetitions (PCA Fatigue Curve)*

Stress ratio	Allowable load repetitions	Stress ratio	Allowable load repetitions
< 0.45	unlimited		
0.45	62,790,761	0.74	630
0.46	14,335,236	0.75	477
0.47	5,202,474	0.76	361
0.48	2,402,754	0.77	274
0.49	1,286,914	0.78	207
0.50	762,043	0.79	157
0.51	485,184	0.80	119
0.52	326,334	0.81	90
0.53	229,127	0.82	68
0.54	166,533	0.83	52
0.55	174,523	0.84	52
0.56	94,065	0.85	30
0.57	71,229	0.86	22
0.58	53,937	0.87	17
0.59	40,842	0.88	13
0.60	30,927	0.89	10
0.61	23,419	0.90	7
0.62	17,733	0.91	6
0.63	13,428	0.92	4
0.64	10,168	0.93	3
0.65	7,700	0.94	2
0.66	5,830	0.95	2
0.67	4,415	0.96	1
0.68	3,343	0.97	1
0.69	2,532	0.98	1
0.70	1,917	0.99	1
0.71	1,452	1.0	0
0.72	1,099	>1.00	0

*Thickness Design for Concrete Highway and Street Pavements, EB109.01P, Portland Cement Association, Skokie, IL 1984.

The factor of safety is normally accounted for only in the allowable flexural stress in the concrete slab-on-ground. Table 3-7 shows recommended ranges for factors of safety for several types of slab-on-ground loading.

Table 3-7 Factors of Safety Used in Design of Various Types of Loading

Load type	Occasional used factors of safety	Minimum recommended factors of safety
Moving wheel loads	1.4 to 2.0 and greater	2.0
Concentrated (rack and post) loads	Higher under special circumstances	2.0 – 5.0
Uniform loads	1.4 is lower limit	2.0
Line and strip loads	2.0 is conservative upper limits*	2.0
Construction loads	—	1.7

Notes: Follow appropriate building code requirements when considering a line load to be a structural load due to building function. For high stress ratio, use higher safety factor values.

3-11 SUMMARY.

1. Forklift specifications, wheel loads, and spacing are obtained from the forklift manufacturer.
2. Airplane loads are obtained from Table 3-3 and landing gear assemblies from Figure 3-1.
3. For moving loads, axle loads are more important than gross weight of vehicle, except for tracked vehicles, where the gross weight is evenly divided between the two tracks.
4. A 10% change in the magnitude of axle loading are equivalent to changes of 300 to 400% in the number of load repetitions.
5. Where stationary loads control the slab-on-ground design thickness, it must be thickened at those locations—areas with a transition between the thickened area and typical slab-on-ground thickness.
6. A recommended factor of safety for the design of slabs-on-ground is 2, but the SER must exercise engineering judgment; refer to Table 3-7.

This Page Intentionally Left Blank

CHAPTER 4 CONCRETE MIXTURE

4-1 INTRODUCTION.

The structural engineer of record (SER) specifies the concrete compressive strength, water cementitious materials ratio (*w/cm*), and slump for the concrete mixture design of the slab-on-ground. There are, however, other factors to consider when specifying the concrete mixture design such as; workability, finishability, and low shrinkage. The objective is to produce a serviceable surface that can be operated by the owner.

The specified concrete compressive strength should be only as high as to resist the applied loads without failure. Maximum particle size and quality of the coarse aggregate will have a pronounced effect on concrete strength, as will the gradation of the blended coarse and fine aggregate. Specified concrete strength should be sufficient to provide high wear resistance properties, constructability, and a reasonably high flexural stress to attain the greatest economy in the design.

4-2 CONCRETE STRENGTH.

The minimum required concrete compressive strength for slabs-on-ground in pedestrian areas, such as offices, should not be less than 3000 pounds per square inch (21 megapascal). For industrial floors subject to heavy vehicular traffic with pneumatic tires, the minimum recommended concrete compressive strength should not be less than 4000 pounds per square inch (28 megapascal). For slabs-on-ground subjected to abrasive traffic such as steel/hard wheels, the minimum recommended concrete compressive strength is 5000 pounds per square inch (35 megapascal). Although high-strength concrete has been successfully used in the field (Hansen et al. 2001), it is in general not recommended for several reasons, among them: higher-strength concrete can increase warping problems due to an increase in stiffness and reduced creep, an increase linear drying shrinkage, and can be difficult to finish.

4-3 CONCRETE QUALITY.

Concrete slabs-on-ground are nonstructural elements, yet the failure of them may result in expensive repairs and interruption of the operations in the facility. Therefore, the quality of concrete is important to the service life of a slab-on-ground to carry the anticipated loads and resist wear.

The ingredients that are included and proportioned in a concrete mixture design affect the quality and performance of the slab-on-ground. One of goals of a concrete mixture design is to develop concrete mixture proportions that have low shrinkage characteristics and are workable, finishable, and provide a serviceable surface (ACI 360R). The SER must be knowledgeable in the materials used in a slab-on-ground concrete mixtures and the adverse effects of some of the materials, when used, must be addressed during the preconstruction meeting; refer to Chapter 7 Section 7-2. Below is a brief description of the quality of each of the main ingredients.

4-3.1 Water.

Water used in concrete mixture must be potable. Non-potable water can be used if testing of 2-inch (50-millimeter) mortar cubes shows 7- and 28-day strengths are at least equal to 90% of the strength of cubes used from similar mixture using distilled water and tested in accordance with ASTM C109/C109M. For additional information on mixing water, refer to ACI 301.

4-3.2 Cement.

Cement type I/II satisfying ASTM C150/C150M is the common cement used in slabs-on-ground. Other types of cements are used when special conditions exist such as sulfate in the ground. Cement Types II and V are used with low *w/cm* for moderate and high sulfate resistance, respectively. The minimum amount of cementitious material to be used for a slab-on-ground should not be less than the amount shown in Table 4-1 (ACI 302.1R Table 8.4.1b):

Table 4-1 Recommended Cementitious Material Contents for Concrete Floors

Nominal maximum-size aggregate*, in. (mm)	Cementitious material content†, lb/yd^3 (kg/m^3)
1-1/2 (37.5)	470 to 560 (280 to 330)
1 (25)	520 to 610 (310 to 360)
3/4 (19)	540 to 630 (320 to 375)
1/2 (12.5)	590 to 680 (350 to 405)
3/8 (9.5)	610 to 700 (360 to 415)

*For normalweight aggregates.
†Minimum 400 lb/yd^3 (240 kg/m^3) portland cement content recommended for trowel finished slabs-on-ground. Refer to ACI 318 for minimum portland cement requirements for structural applications.

4-3.3 Blended Hydraulic Cement.

Blended hydraulic cements are composed of two or more of the following uniformly blended materials; portland cement, slag cement, fly ash, and other pozzolans, and hydrate lime. This type of cement should conform to ASTM C595/C595M. But sometimes this type of cements may be unsuitable on a project because of excessive shrinkage and significant retardation. In general, adding supplemental cementitious materials (SCMs) to a concrete mixture will provide following benefits:

1. Improves long-term strength. Will continue to increase beyond the 28-day strength
2. Reduces permeability, which will have an effect and improves long-term durability
3. Most SCMs will improve workability
4. Reduces cement content

4-3.4 Pozzolans.

Pozzolans such as fly ash, silica fume, and slag are natural materials that conform to ASTM C618 that also include metakaolin, clays, shells, opaline cherts, volcanic tuffs, and pumicities. The effect of pozzolans in a concrete mixture, except for silica fume, tend to extend the setting time of the concrete mixture, reduce heat of hydration, result in less drying shrinkage cracking, and delays strength gain. Pozzolans can also result in a different concrete color from that produced if portland cement is the only cementitious component.

Fly ash, Class C and F, conforming to ASTM C618 is often used in concrete mixtures replacing up to 20% of portland cement. It increases workability and delays setting time, which is beneficial in hot weather, aids when pumping concrete, results in reducing the water content in a mixture, and helps in reducing curling. Fly ash also increases concrete mixture strength and improves durability by enhancing resistance to sulfate attack, alkali-silica reactivity, and efflorescence. In addition to the above-mentioned advantages, SCMs are added to concrete mixtures to aid in pumpability and finishability and improve the overall hardened properties of concrete through hydraulic or pozzolanic activity, or both.

The SER should be aware that an increase in the cementitious content can have an adverse effect on the concrete’s shrinkage characteristics and stiffness or modulus of elasticity. If an exposed warehouse slab-on-ground is subjected to heavy wheel traffic or forklifts with steel wheels, then fly ash should not be used because of the potential for dusting. A summary of the effects of SCMs on a concrete mixture are provided in Table 4-2 (Taylor 2014); also refer to Appendix C.

Table 4-2 Summary of Side Effects and Interactions of SCMs

Properties	Supplementary Cementitious Material					
	Fly ash Class F	Fly ash Class C	Slag cement	Silica fume	Metakaolin	Limestone
Workability	Significantly improved	Improved	Neutral/ improved	Improved at low dose (<5%), decreased at high dose	Decreased	Slightly improved
Air void system	May be difficult to entrain air with high LOI*	Neutral	Neutral	May be difficult to entrain air	May be difficult to entrain air	Neutral
Setting	Delayed	Slightly delayed	Slightly delayed	Accelerated	Neutral	Neutral
Incompatibility	Low risk	Some risk	Low risk	Low risk	Low risk	Low risk
Strength gain	Slower but continues longer	Slightly slower but continues longer	Slightly slower but continues longer	Accelerated initially	Accelerated initially	Neutral
Stiffness	Related to strength					
Heat generation	Lower	Slightly lower	Slightly lower	Higher	Slightly higher	Slightly lower
Shrinkage	Neutral	Reduced	Neutral	Increased	Increased	Neutral
Permeability	Improved over time	Improved over time	Improved over time	Improved	Improved	Neutral
ASR	Improved		Improved at sufficient dosage	Slightly improved	Improved	Neutral
Sulfate attack	Improved	Improved at sufficient dosage	Improved at high dosages	Neutral	Neutral	May be worse at high dosages in very cold environments
Corrosion Resistance	Slightly improved	Slightly improved	Improved	Improved	Improved	Neutral

*LOI—Loss of ignition.

4-4 COARSE AGGREGATE.

Coarse aggregate greatly influences the shrinkage potential of a slab-on-ground. It also affects the risk and magnitude of concrete random cracking, joint spalling, and panel edge curling or warping. Therefore, SER should specify the maximum aggregate size possible with proper gradation. Maximum aggregate size used in a mixture should not exceed 1-1/2 inch (38 millimeter) or one-third the slab-on-ground thickness. In general, for normal applications, the SER should specify coarse aggregates not less than 0.75 inch (20 millimeter) in size). For a concrete mixture with steel fibers added, the maximum aggregate size should fall between 3/8 and 3/4 inch (9.5 and 520 millimeter); refer to Chapter 5 Section 5-10. Quality, quantity, and gradation of coarse aggregate are considered the largest individual factors affecting concrete shrinkage and, ultimately, joint spalling, warping, and concrete cracking.

Pea gravel or river gravel, which is naturally smooth and round, has a lower surface area than crushed stone. The particle shape and surface texture will decrease the amount of paste required to cover each individual particle. The amount of total water necessary to produce a given workability is also reduced—generally up to 10% less for concrete containing smooth gravel versus the same mixture containing crushed limestone. The paste to aggregate bond strength, however, is less for the smooth gravel than for a crushed aggregate, requiring more cementitious materials for concrete containing gravel aggregate to meet equivalent strength requirements, which will increase shrinkage (Harrison 2004). Pea gravel should not be used in concrete mixture for slabs-on-ground.

4-5 FINE AGGREGATE.

Fine aggregate is composed of natural sand, manufactured sand, or a combination of the two. Fine aggregate fills voids between coarse aggregate particles in concrete to produce a densely packed mixture. Fine aggregate grading is an important characteristic, as it impacts water demand, workability, bleeding, and finishability. Fine grading specifications ASTM C33/C33M and C387/C387M are acceptable. However, for slabs-on-ground, Table 4-3 presents the preferred grading specification as proposed in ACI 302.1R Table 8.5.1. Aggregate quality should be in compliance with ASTM C33/C33M and C330/C330M.

Table 4-3 Preferred Grading of Fine Aggregates for Slabs-on-Ground (ACI 302.1R Table 8.5.1)

Sieve designations		Percent passing		
Standard	Alternative	Normalweight aggregate	Lightweight aggregate	Heavy-duty toppings, Class 7 floors
9.5 mm	3/8 in.	100	100	100
4.75 mm	No. 4	85 to 100	85 to 100	95 to 100
2.36 mm	No. 8	80 to 90	—	65 to 80
1.18 mm	No. 16	50 to 75	40 to 80	45 to 65
600 μm	No. 30	30 to 50	30 to 65	25 to 45
300 μm	No. 50	10 to 20	10 to 35	5 to 15
150 μm	No. 100	2 to 5	5 to 20	0 to 5

4-6 CHEMICAL ADMIXTURES.

Chemical admixtures, meeting the requirements of ASTM C494/C494M, are used in concrete mixtures because they offer specific desired changes in the properties of concrete mixtures; refer to ACI 212.3R. They are used to modify particular properties of fresh or hardened concrete when applied singularly or in combination. Some of the improved fresh concrete properties are:

1. Increased workability/slump without increasing the water content

2. Improved placing and finishing during hot or cold weather construction
3. Improved setting and finishing characteristics
4. Reduced bleeding

Some of the improved characteristics of hardened concrete when applying admixtures are:

1. Decreased permeability and improve durability
2. Increased bond to steel reinforcement and between existing and new concrete
3. Corrosion inhibition of embedded metal
4. Reduced drying shrinkage and curling
5. Reduced number and width of cracking
6. Increased strength and durability

The admixtures used in a concrete mixture are:

1. Accelerating
2. Air-entraining
3. Retarding
4. Shrinkage reducing
5. High-range water-reducing (superplasticizing)
6. Water-reducing

Air-entraining admixtures have their own ASTM specification (ASTM C260/C260M). Some of the admixtures may have undesirable effects; for example, certain water-reducing admixtures can increase concrete shrinkage (Whiting and Dziedzic 1992). For more information on the effects of commonly used admixtures, including water-reducing, retarding, accelerating, and superplasticizing, or combinations of the above, refer to ACI 212.3R.

4-7 SURFACE TREATMENTS.

Although technically not an internal ingredient of concrete, surface treatments on concrete floors are commonly used to enhance the performance of the wear surface. Surface treatments can be used for curing purposes or to harden the wearing surface. Refer to ACI 515.2R and ACI 515.3R for selecting the suitable protective treatments and for surface preparation for application of protection systems for concrete.

4-8 SUMMARY.

1. The quality of concrete is improved by using supplemental cementitious material and admixtures—refer to Table 4-2 and Section 4-3.4, respectively.
2. Specified concrete compressive strength for slabs-on-ground design supporting moving loads with pneumatic tires should not be less than 4000 pounds per square inch (28 megapascal).
3. Specified concrete compressive strength for slabs-on-ground design supporting abrasive traffic with steel/hard wheels should not be less than 5000 pounds per square inch (35 megapascal).
4. Maximum specified aggregate size should not be greater than 1-1/2 inch (38 millimeter) or one-third the slab-on-ground thickness.
5. When steel fibers are added to the concrete mixture, maximum aggregate size is limited to 3/4 inch (20 millimeter).

This Page Intentionally Left Blank

CHAPTER 5 DESIGN PROCEDURE

5-1 GENERAL.

There are several factors that have a considerable effect on determining the design thickness of a concrete slab-on-ground and can be divided into above and below slab-on-ground factors. The type, strength, and uniformity of the subgrade or subbase are the below slab-on-ground factors and are discussed in Chapter 2. The type of loads, magnitude of loads, and frequency of moving loads travel are the above slab-on-ground factors and are addressed in Chapter 3. The concrete mixture design and strength of the slab-on-ground is discussed in Chapter 4.

In this chapter, the SER will determine the key factor in the design of a slab-on-ground—its thickness, *h*. Three classical design methods and the finite element (FE) method are available to engineers for determining the slab-on-ground thickness. The classical design methods are: Corps of Engineers (COE), Portland Cement Association (PCA), and Wire Reinforcement Institute (WRI). They are based on continuous support to the slab-on-ground and uniform modulus of subgrade strength, *k*. The slab thickness calculation is insensitive to minor changes in *k*-values; therefore, it is not critical to obtain an accurate *k*-value. It is, however, directly related to the strength of concrete defined by the concrete flexural strength, f_r, which is measured in accordance with ASTM C78 and calculated from the following empirical equation:

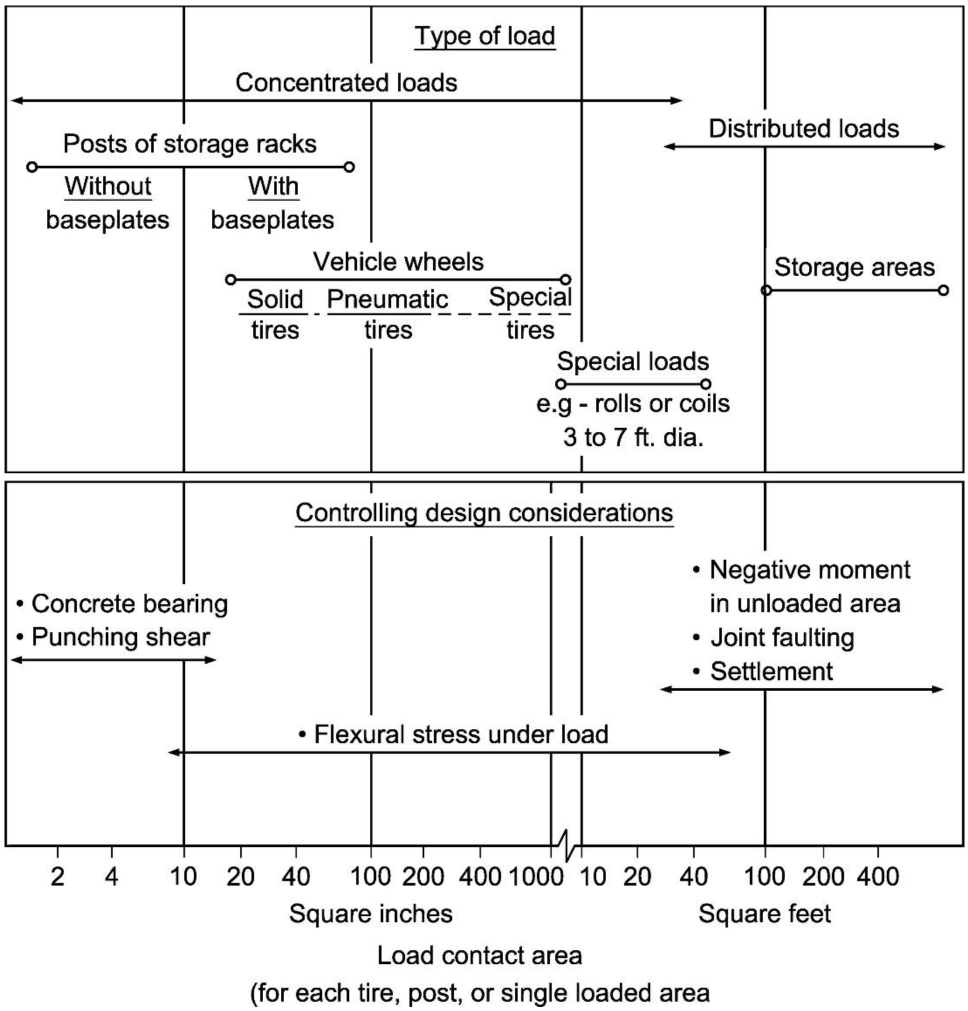
Equation 5-1. [Concrete Flexural Strength]

$$f_r = \alpha\sqrt{f_c'} \quad \text{psi (MPa)}$$

where the factor α varies between 7.5 and 9. The COE and WRI methods use a value equal to 7.5, while PCA method uses a value equal to 9. For heavy loading, however, it is recommended to use the lower factor of 7.5 with a factor of safety equal to 2; refer to Section 3-10. The FE method, Section 5-12, unlike the classical methods, does allow for variable modulus of subgrade in the analysis.

Slabs-on-ground are designed for the critical load or load combinations that generate the maximum stress and maintain surface cracking at an acceptable level. Typically, forklifts control the flexural design of slabs-on-ground, storage racks control punching shear and concrete bearing design, while distributed live loads control negative moment design in aisles between distributed loads, dowels at joints, and settlement of slabs-on-ground; refer to Figure 5-1 (Packard 1996). Accordingly, the SER will design the overall slab-on-ground thickness for the allowable moving load that controls flexural stresses. The SER will then check for punching shear of concentrated, line, and distributed loads at localized areas where constructed, applied, or both, verifies that excessive settlement does not occur below a stationary load, and ensures that cracks are not developed in aisles between distributed loads. The design procedure covers subgrade conditions, steel reinforcement, and various details such as jointing, dowels (Chapter 6), and the inclusion of vapor retarder, if needed (Chapter 7 Section 7-4).

Figure 5-1 **Controlling Design Consideration depends on Size of Load Contact Area (Packard 1996)**



NOTE: 1 in.^{2} = 645.2 mm^2; 1 ft^2 = 0.0929 m^2.

5-2 COMPARISON BETWEEN THE THREE CLASSICAL DESIGN METHODS—COE, PCA, AND WRI.

The three classical design methods—COE, PCA, and WRI—assume uniform and continuous support to the slab-on-ground. The nomographs for the three methods were developed by modeling the soil beneath the slab-on-ground using the Winkler foundation approach (Winkler 1867). Therefore, the three methods implement a uniform modulus of subgrade reaction, *k*, value in design obtained from soil testing, from adjacent projects with known *k*-values, or by approximate mathematical expressions in the design of a slab-on-ground; refer to Chapter 2.

5-2.1 United States Army Corps of Engineers (COE).

The COE design method is based on Westergaard's (1925b) formula for free edge stress with some joint transfer ability through aggregate interlock; refer to Chapter 6 Section 6-6.1. The method is mainly directed toward the design of heavy axle loadings, such as heavy forklifts up to 120,000 pounds (533,800 Newton); refer to Table 3-1. For airplanes, refer to Tables 3-3 and 3-4. The design assumes plain concrete slab-on-ground, but the use of steel reinforcement is implied for excessive applied loads or if slab-on-ground thickness is restricted.

5-2.2 Portland Cement Association (PCA).

The PCA design method is based on Westergaard's equations developed in the early 1900s (Westergaard 1925a,b). It is mainly directed toward the design of industrial facilities subjected to forklift and other vehicular traffic. The slabs are designed as plain concrete slabs-on-ground supporting single- and dual-wheel axle loads, uniform loads with fixed or variable locations, and rack support post loading. Post load rack curves were developed for a specific modulus of subgrade reaction, *k*, value based on Hetenyi's (1946) method. The slab-on-ground can be lightly reinforced to resist shrinkage and temperature effects only and is considered optional; refer to Section 6-9. The PCA design concept is based on loads applied to the interior slab-on-ground panel, away from edges with full load transfer at joints. The PCA method was later further developed to consider joint transfer effects (Chapter 6 Section 6-6) and nomographs for slabs-on-ground with no load transfer at joints were developed (Tarr and Farny 2008).

5-2.3 Wire Reinforcement Institute (WRI).

The WRI method is based on the work of Panak (1973, 1975), which is considered a step toward developing a rational design procedure for the design of slabs-on-ground. Similar to the PCA method, this method is also based on loads applied in the interior slab-on-ground panel away from edges. The method provides an approach to select slab-on-ground thickness for single-wheel axle loads and uniform loads with aisles. WRI nomographs include the effects of relative slab stiffness with respect to the subgrade. Unlike the other classical design methods, steel reinforcement is assumed in the design process.

5-3 DESIGN METHODS.

Although the three classical slab-on-ground design methods are still referenced and available to the design profession, most engineers have migrated toward the FE method for the design of slabs-on-ground (Section 5-12). FEM software programs are widely available and slabs-on-ground can be modeled quickly. This rational approach calculates the actual stresses, unlike the classical design methods that are based on assumptions and approximate nomographs. Each of the design methods is discussed below for the different loads: moving/vehicle; distributed; line/wall; and concentrated/column. Table 5-1 records the design methods applicable to each of the loading type.

Table 5-1 Applicable Design Methods for Different Types of Loadings.

Loading type		Design methods			
		COE	PCA	WRI	FEM
Moving load					
Forklift		x	x	x	x
Vehicles		x	x	x	x
Tracked vehicles		x			x
airplanes		x			x
Distributed loads	without aisles	x	x	x	x
	with aisles		x	x	x
Line/wall loads		x	x	x	x
Concentrated loads (racks)			x		x

5-4 MOVING/VEHICLE LOADS.

Chapter 3 Section 3-3 presents the axle loads for different moving axle categories and aircraft gear assemblies. Forklift axle loads are usually obtained from manufacturers. The moving load design assumes a static load situated at strategic locations to result in the maximum flexure and shear stresses within a slab-on-ground. This usually occurs when the load is situated close to a slab-on-ground edge panel or corner; refer to Figure 5-2, where ℓ is the critical distance or radius of relative stiffness (Equation 5-2), and *a* is the equivalent radius of contact area of the load, which is calculated from Equation 5-3.

Equation 5-2. [Radius of Relative Stiffness]

$$\ell = \sqrt[4]{\frac{E_C h^3}{12(1-\nu^2)k}}$$

Equation 5-3. [Radius of Contact Area]

$$a = \sqrt{\frac{A_{cont} \times 4}{\pi}} \quad \text{inch (millimeter)}$$

and

$$A_{cont} = \frac{\text{load on tire}}{\text{tire pressure}} \quad \text{square inch (square millimeter)}$$

If the tire pressure value is not available, an approximate value can be obtained from Table 3-5.

5-4.1 Corps of Engineering (COE) Design Method.

This method is developed for loads applied at the edges of slabs-on-ground concrete panels; refer to Figure 5-2. To satisfy requirements of different types of vehicles and traffic volumes, Category I, II, and III traffic has been expressed in terms of equivalent operations of a basic axle loading; refer to Chapter 3 Section 3-3.1. The basic loading was assumed to be an 18,000-pound (80,100 Newton) single-axle load with two sets of dual wheels spaced 58-1/2 inches (1490 millimeters) apart with 13-1/2 inches (340 millimeters) between dual wheels. It should be noted that the basic loading was arbitrarily selected to provide a reasonable spread in the loadings and traffic volumes likely to be encountered under normal conditions. A design index (DI) was devised that expresses varying axle loads and traffic volume in terms of relative severity. The DI ranges from 1 to 10, with the higher number indicating a more severe design requirement. The basic loading described above was used to assign and rank the DIs. More information concerning the DI can be found in UFC 3-250-01 and UFC 3-260-02. Table 5-2 presents the DIs for various traffic volumes. Thickness requirements for unreinforced slabs-on-ground for the ten DIs are calculated from the nomograph (Figure 5-3). The slab-on-ground thickness requirements are functions of concrete strength, subgrade modulus, and DI. The curves are based on an impact factor of 25%, a concrete modulus of elasticity of 4,000,000 pounds per square inch (27,600 megapascal), joint transfer coefficient of 0.75 (refer to Chapter 6 Section 6-6 for discussion on load transfer efficiency at a joint), a Poisson's ratio of 0.2, and a factor of safety of 2.

Figure 5-2 **Possible Loading Locations**

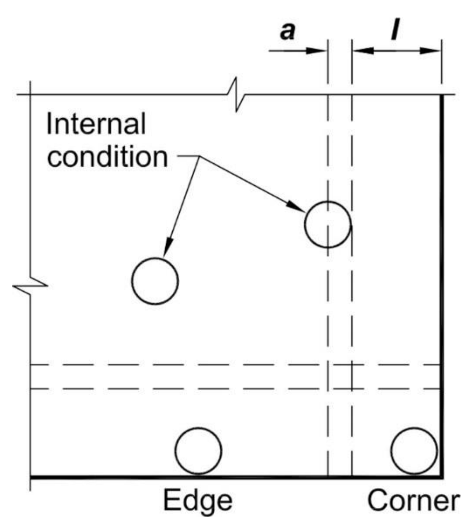
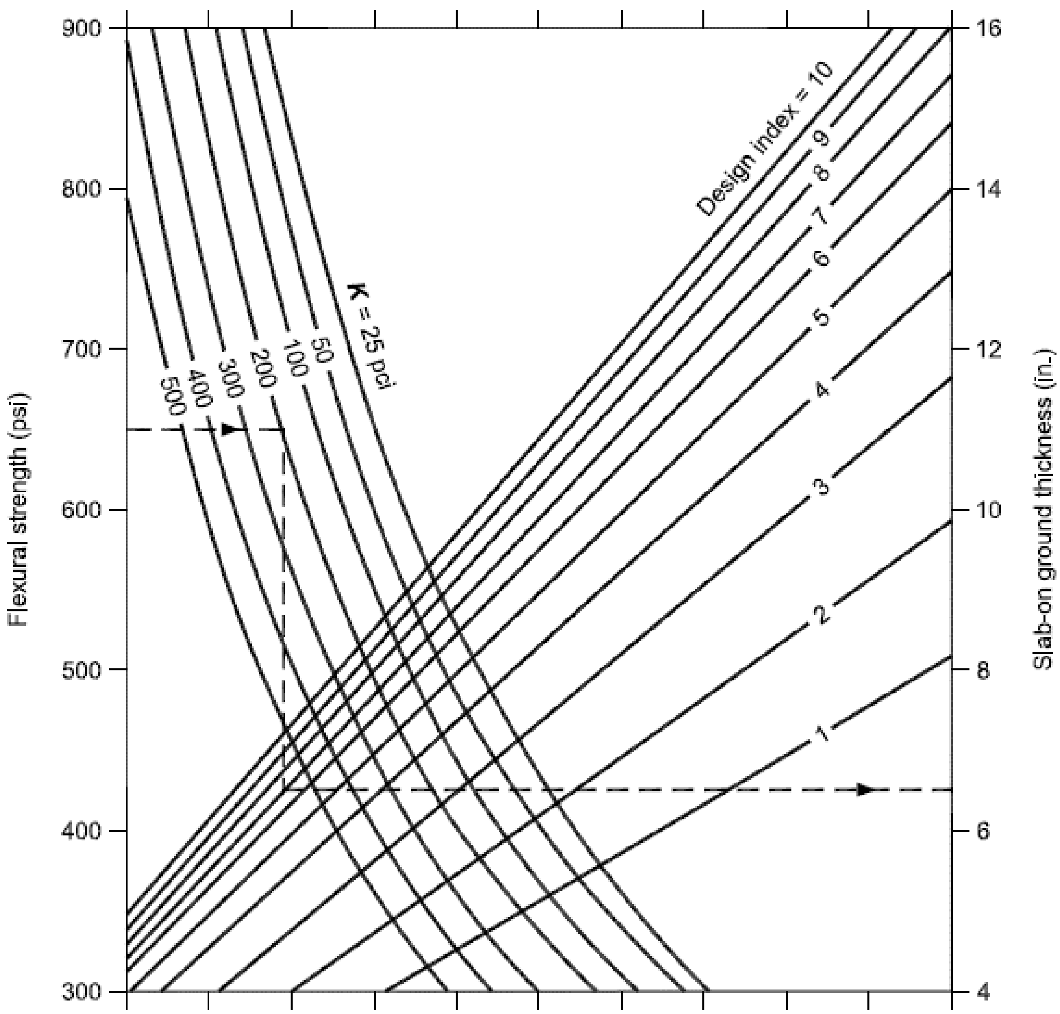


Table 5-2 Traffic Categories for Design Index

Maximum operations per day over 25 years	Load	Design index
50	10-kip (44 kN) axle-load forklift truck	4
250	10-kip (44 kN) axle-load forklift truck	5
10	16-kip (67 kN) axle-load forklift truck	
250	10-kip (44 kN) axle-load forklift truck	7
100	16-kip (67 kN) axle-load forklift truck	
250	16-kip (67 kN) axle-load forklift truck	8
5	26-kip (111 kN) axle-load forklift	

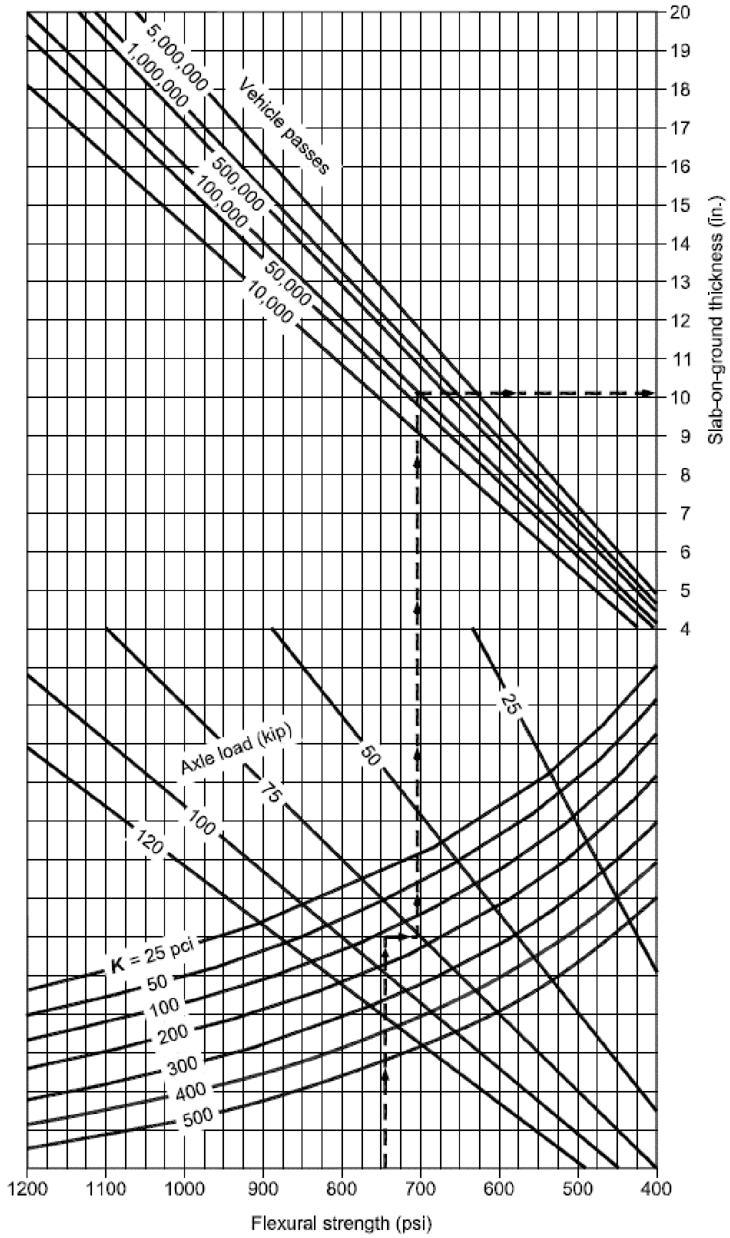
Figure 5-3 **Design Curves for Concrete Slabs-on-Ground by Design Index**



Note: 1 inch = 25.4 millimeter, 1 pounds per square inch (psi) = 0.00689 megapascal (MPa), and 100 pounds per square inch per inch (lb/in.^{2}/in.) = 27.1 megapascal per meter (MPa/m).

Larger forklifts having axle loads greater than 25,000 pounds (111,000 Newtons) are treated separately. The required slab thickness for slabs-on-ground designed for these loads are not significantly affected by vehicles having axle loads less than 25,000 pounds (111,000 Newtons). The thickness requirements for these heavier loads are shown in Figure 5-4. Airplane loads parked on slabs-on-ground may be designed following the method described above by taking the equivalent contact area of landing gear assembly. As an alternative, the slab-on-ground can be designed per the method described in UFC-3-260-02 Chapters 13 and 14.

Figure 5-4 **Design Curves for Concrete Slabs-on-Ground for Heavy Forklifts.**



Note: 1 inch = 25.4 millimeter, 1 pounds per square inch (psi) = 0.00689 megapascal (MPa), and 100 pounds per square inch per inch (lb/in.^{2}/in.) = 27.1 megapascal per meter (MPa/m)

Following are the main steps to design a slab-on-ground using the COE charts; for illustration purposes the following values are assumed as an example only: f_r = 650 lb/in.^{2} (4.48 MPa), k = 200 lb/in.^{2}/in. (54.3 MPa/m), and DI =7, use Figure 5-3:

- Enter chart at left with a flexural strength, f_r value of 650 pounds per square inch (4.48 Megapascal);
- Move right to subgrade modulus, k, value 200 pounds per cubic inch (54.3 megapascal per meter);
- Move up or down to curve corresponding to the determined DI 7;
- Move right to read the minimum suggested slab-on-ground thickness value, h, 6.5 inch (165 millimeter).

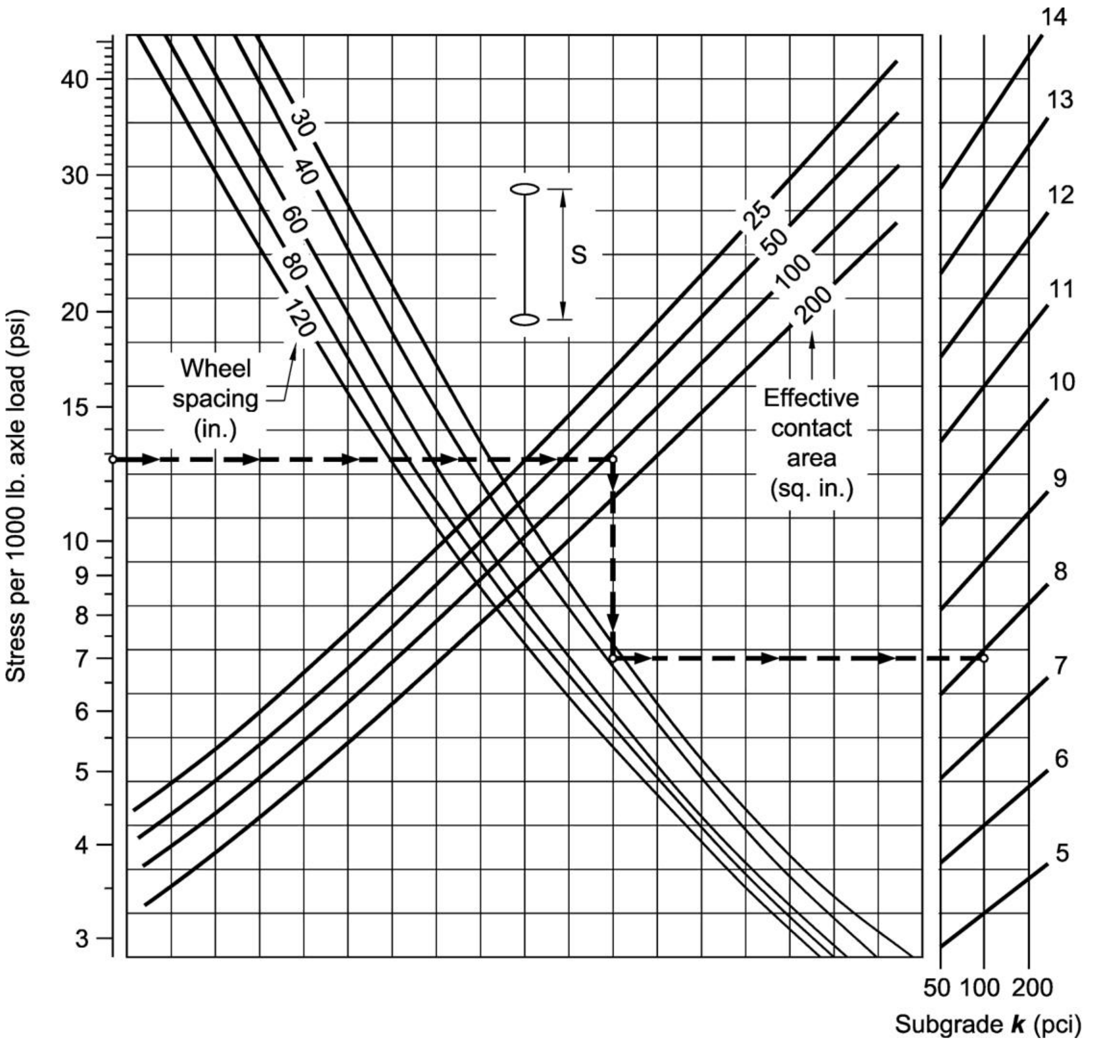
When values used fall outside the bounds of the curves, the curves will have to be extrapolated in order to come up with a value for the thickness of the slab. Refer to Appendix B Section B-1 for solved examples using the COE method for forklift trucks with single wheel axle loading.

5-4.2 Portland Cement Association (PCA) Design Method.

The Portland Cement Association (PCA) design method is for internal loads only applied away from edges and corners of slabs-on-ground panels (Figure 5-2) assuming full load transfer at joints. The PCA method was later developed to include the joint factor, JF, effect, refer to Chapter 6, Section 6-6.2.1. The method is based on determining the flexural strength of concrete, f_r, vehicle effective wheel contact area, A_{cont}, wheel spacing, s, and the modulus of subgrade reaction of soil, k, a predetermined factor of safety, SF – refer to Chapter 3 Section 3.10. Other assumed values used to develop the charts are Poisson's ratio, (ν = 0.15), and the concrete modulus of elasticity, E_c = 4,000,000 pounds per square inch (27,600 megapascal).

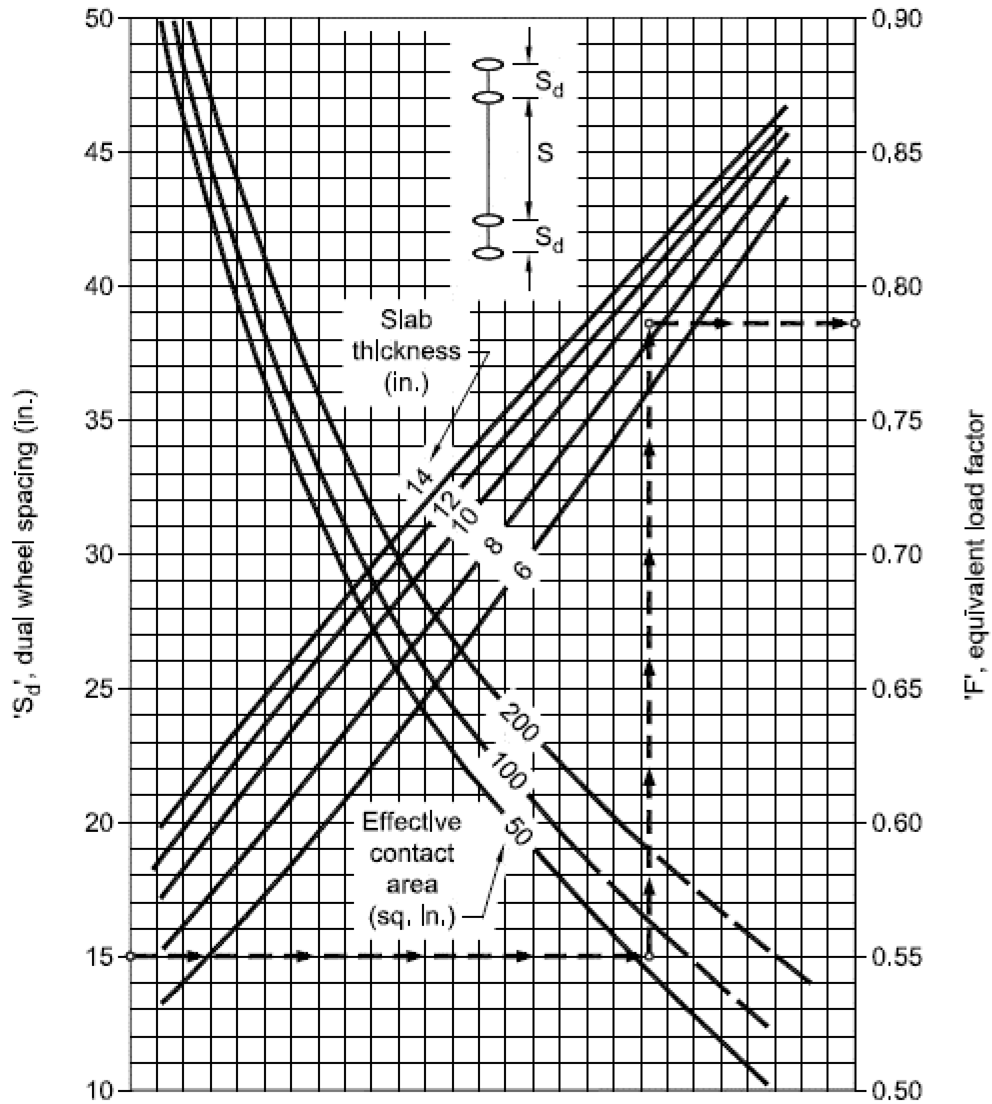
The developed nomographs will provide the required slab-on-ground thickness for single-wheel axle—refer to Figure 5-5 and for dual-wheels axle, refer to Figure 5-6. Figure 5-7 is used in conjunction with Figure 5-5 and 5-6 to obtain the effective load contact area and assumed slab-on-ground thickness.

Figure 5-5 **Design Chart for Axles with Single Wheels—Complete Load Transfer at Joint**



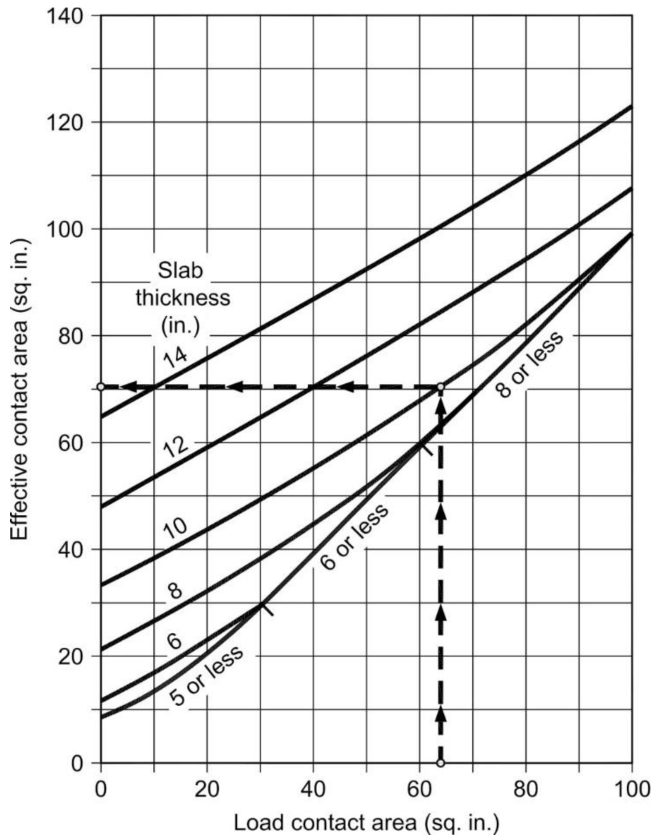
Note: 1 inch = 25.4 millimeter, 1 square inch (in.^{2}) = 645 square millimeter (mm^2), 1000 pound (lb) = 4448 Newton (N), and 100 pounds per square inch per inch (lb/in.^{2}/in.) = 27.1 megapascal per meter (MPa/m)

Figure 5-6 **Design Chart for Axles with Dual Wheels**



Note: 1 inch = 25.4 millimeter and 1 square inch (in.^{2}) = 645 square millimeter (mm^2)

Figure 5-7 **Effective Load Contact Area Depends on Slab-on-Ground Thickness (adopted from PCA).**



Note: 1 inch = 25.4 millimeter and 1 square inch (in.^{2}) = 645 square millimeter (mm^2)

Following are the main steps to design a slab-on-ground using the PCA nomograph; values used are for illustration purposes only, refer to Figure 5-5:

- Calculate the flexural concrete strength, f_r, 524 pounds per square inch (3.3 megapascal);
- Determine a factor of safety, assume SF = 2
- Calculate concrete working stress; f_r/SF = 524 psi/2 = 262 psi (1.8 MPa)
- Determine joint transfer factor JF = 1, refer to Chapter 6 Section 6-6.2.1 for further discussion on joint load transfer.
- Slab stress per 1000 pounds (4448 Newton) assume an axle load of 20,300 pounds (90,300 Newton): 262/20.3 = 12.9 psi/1000 lb (0.09 megapascal/4448 Newton)
- Enter Figure 5-5 at left with stress of 12.9 psi (0.09 megapascal)
- Move right to effective contact area of 100 square inch (64,516 square millimeter)
- Move up/down to wheel spacing of 40 inch (1016 millimeter)

- Move right to read the minimum recommended slab thickness of 7.9 inch (199 millimeter) for a modulus of subgrade of 100 pounds per cubic inch (27.1 megapascal per meter).
- The SER would choose 8.0 inch (200 millimeter) thick slab-on-ground.

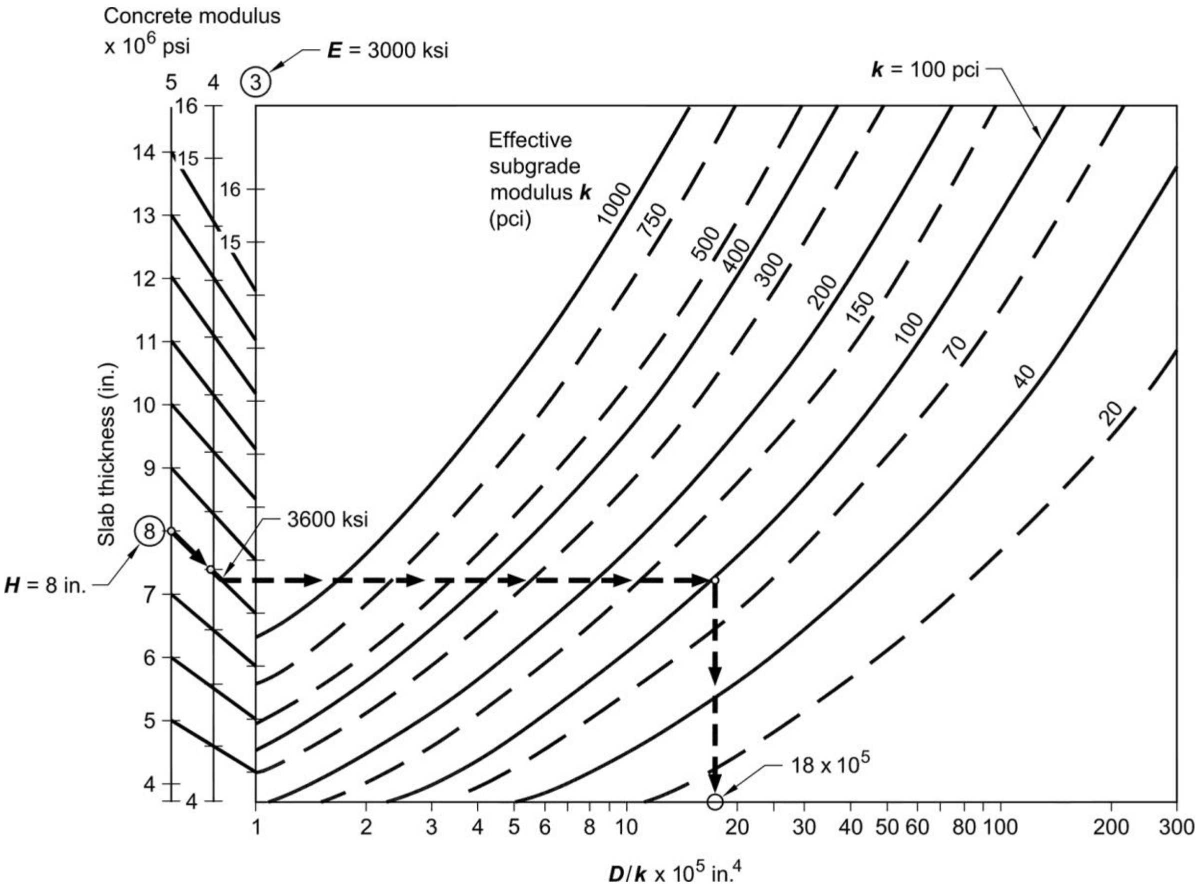
When determining the slab-on-ground thickness for dual wheels, Figure 5-7 is used to obtain an equivalent factor based on an assumed slab-on-ground thickness, which is then multiplied with the dual-wheel axle load to obtain the equivalent single-wheel axle load. This value along with calculated values presented above for single-axle vehicle are then used in Figure 5-5 to arrive at the minimum recommended thickness.

If the obtained slab-on-ground thickness for the dual-wheel axle load is too far off from the initially estimated thickness, then the process is repeated by choosing a value closer to the one obtained from Figure 5-5 until a convergence is reached. Refer to Appendix B Section B-2 for solved examples using the PCA method for forklift trucks with single and dual wheel(s).

5-4.3 Wire Reinforcement Institute (WRI) Design Method

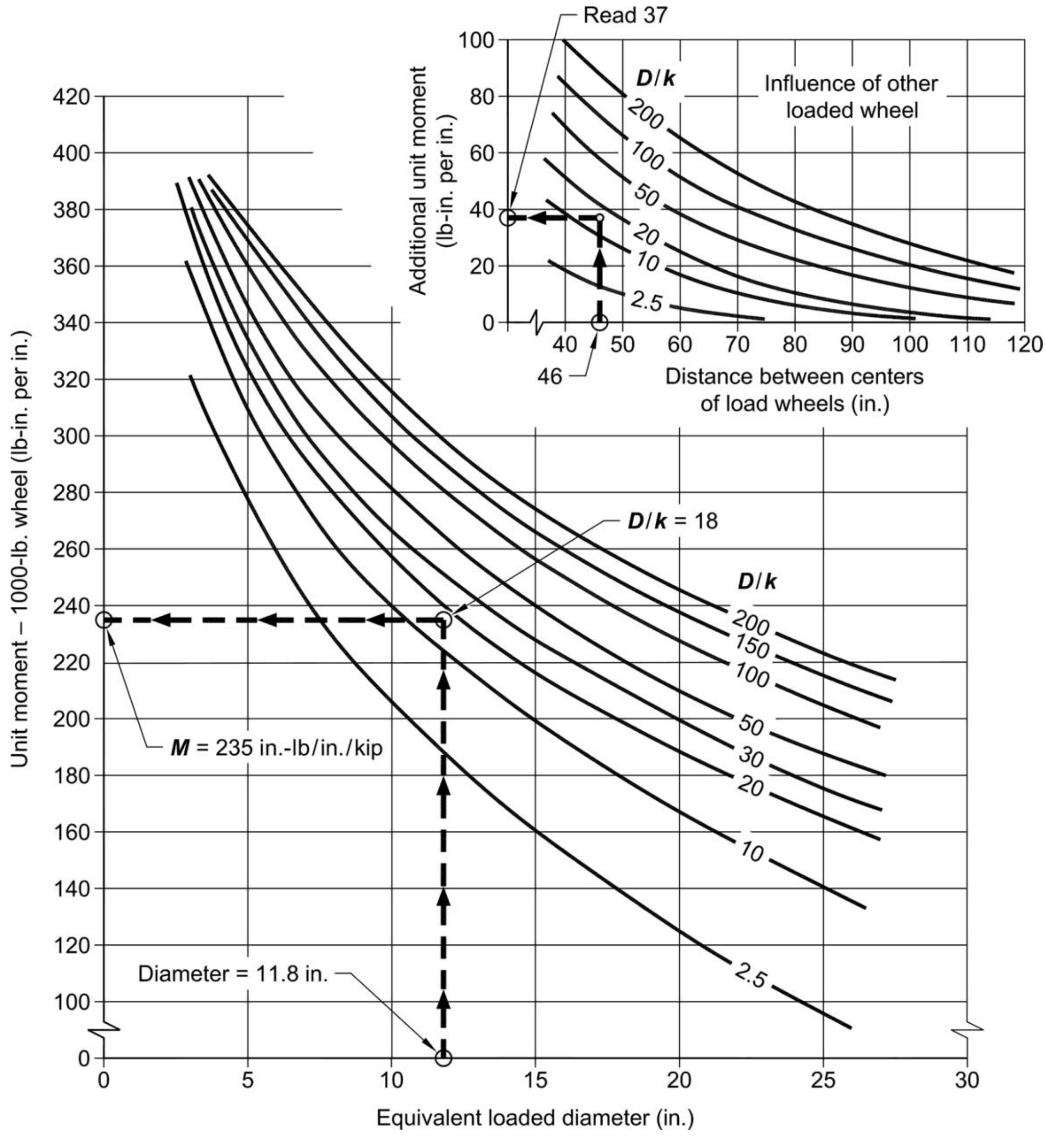
The Wire Reinforcement Institute (WRI) design method is for loads applied away from edges and corners of slabs-on-ground, refer to Figure 5-2. The slab-on-ground is lightly reinforced or reinforced with steel wire mesh mats, refer to Chapter 1, Section 1-7 for definition of lightly- and reinforced slab-on-ground. The method is based on obtaining the slab stiffness factor, D/k, modulus of elasticity, E_c, subgrade modulus, k, trial slab thickness, h, diameter of equivalent loaded area (Equation 5-3), distance between wheels, s, flexural strength, f_r, (Equation 5-1) and working stress by dividing the flexural strength by a predetermined factor of safety, SF, refer to Chapter 3 Section 3-10. Slab-on-ground thickness is obtained from nomographs incorporating all the different variables listed above, Figures 5-8 through 5-10 (ACI 360R, Appendix 2).

Figure 5-8 **Subgrade and Slab Stiffness Relationship**



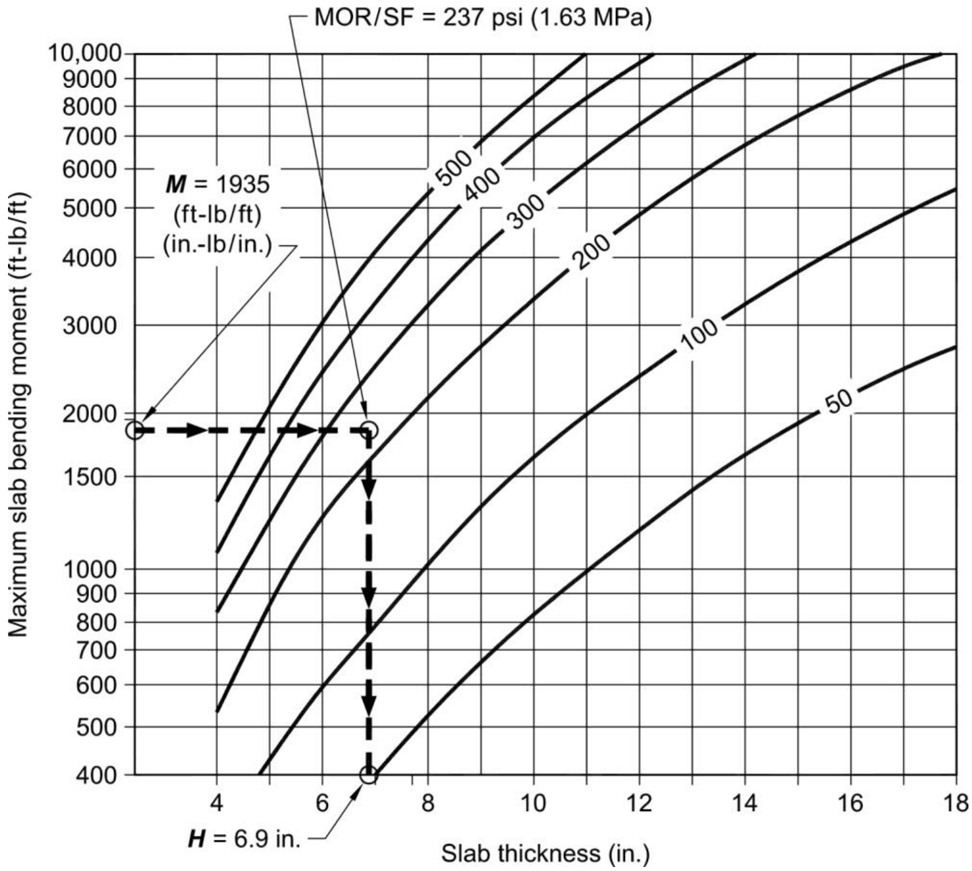
Note: 1 inch = 25.4 millimeter, 1 pounds per square inch (psi) = 0.00689 megapascal (MPa) and 100 pounds per square inch per inch (lb/in.^{2}/in.) = 27.1 megapascal per meter (MPa/m).

Figure 5-9 **Wheel Loading Design Chart**



Note: 1 inch = 25.4 millimeter, 1 pounds per square inch (psi) = 0.00689 megapascal (MPa), 100 pounds per square inch per inch (lb/in.^{2}/in.) = 27.1 megapascal per meter (MPa/m), 1 inch pound per inch (in.-lb/in.) = 4.448 Newton meter per meter (N·m/m), and 1 inch pound per inch per kip (in.-lb/in./kip) = 0.001 Newton meter per meter per kilo Newton (N·m/m/kN).

Figure 5-10 **Slab Tensile Stress Charts**



Note: 1 inch = 25.4 millimeter, 1 pounds per square inch (psi) = 0.00689 megapascal (MPa), 100 pounds per square inch per inch (lb/in.^{2}/in.) = 27.1 megapascal per meter (MPa/m), 100 inch pound per inch (in.-lb/in.) = 4.448 Newton meter per meter (N·m/m), and 1 inch pound per inch per kip (in.-lb/in./kip) = 0.001 Newton meter per meter per kilo Newton (N·m/m/kN).

Following are the main steps to design a slab-on-ground using the WRI charts; values used are for illustration purposes only, refer to Figure 5-8 through 5-10:

- Assume a slab-on-ground thickness, inch (millimeter); say, 8 inch (200 millimeter)
- Enter Figure 5-8 with 8 inch (200 millimeter) slab-on-ground thickness. Move along the sloped line to reach the concrete modulus, *E*, of 3,600,000 pounds per square inch (24,800 megapascal);
- Move right to effective subgrade modulus, *k*, of 100 pounds per cubic inch (27.1 megapascal per meter)
- Move down to read D/k = 18 x 10^5 in.^{4} (7.5 x 10^{11} mm^4)
- Calculate the diameter of the equivalent circle of wheel contact area = 110 in.^{2} (64,500 mm^2) from Equation 5-3; a = 11.8 inch (299 millimeter)
- Enter Figure 5-9 with a =11.8 inch (299 millimeter) move up to intersect D/k = 18 x 10^5 in.^{4} (7.5 x 10^{11} mm^4)

- Move to the left and read the basic bending moment of 235 inch pound per inch (1045 Newton meter per meter)
- Enter the smaller design chart of Figure 5-9 enter with wheel spacing s = 46 inch (1168 millimeter) move up until line intersects with $D/k = 18 \times 10^5$ in.^{4} (7.5×10^{11} mm^4)
- Move left and read additional moment due to the other wheel as 37-inch pound per inch (165 Newton meter per meter) of width kip (Newton) of wheel load. This results in:

  Total moment = 235 + 37 = 272-inch pound per inch per 1000 pounds (1210 Newton meter per meter per 4448 Newton)

  Axle load = 14,600 pounds (64,944 Newton)

  Wheel load = 7300 pounds (62,472 Newton)

  Design moment = 272 x 7.3 = 1985 foot pound per foot (8834 Newton meter per meter)

- Enter Figure 5-10 with design moment move right to 190 pounds per square inch (1.31 megapascal); $f_r/\text{SF} = 7.5\sqrt{4000}/2$ = 237 pounds per square inch (1.63 megapascal)
- Move down and read recommended minimum slab-on-ground thickness of 6.9 inch (175 millimeter).

This slab-on-ground thickness is then compared to the initial assumed thickness. If the difference is substantial, then the process is repeated using a revised slab-on-ground thickness until the difference between the assumed and the obtained thickness from Figure 5-10 is minimal and acceptable to the SER.

In the above example, the SER would revise the initial slab-on-ground thickness to 7 inch (180 millimeter). Repeating the steps above, a 7.0-inch (180 millimeter) slab-on-ground thickness is required. Therefore, the SER would use a 7 inch (180 millimeter) thick slab-on-ground. Refer to Appendix B Section B-3 for a solved example using the WRI method for forklift trucks.

5-5 DISTRIBUTED LIVE LOADS.

Distributed live loads are placed directly on slabs-on-ground with specified aisles or no aisles between the pallets. The main objective of the design is to prevent high top tension stresses (negative moments) from occurring in the aisles between the distributed loads as they may result in concrete cracking and render the slab-on-ground not functional in the aisles. The top (negative) flexural moment in an aisle without joints between distributed loaded areas can be as high as twice the flexural moment in the slab-on-ground beneath the distributed loaded areas. Distributed loads, in general, produce less flexural stresses in slabs-on-ground than concentrated loads and can also result in excessive undesirable settlement due to consolidation of subgrade below the loads, which should be prevented.

The three classical methods cover distributed loads on slabs-on-ground, refer to Table 5-1. The PCA and WRI methods, as in the case of moving loads, address distributed live loads imposed on slab-on-ground interior, whereas the COE method addresses distributed live loads placed at slab-on-ground edges or joints, which will produce lower allowable distributed loads than the other two methods, PCA and WRI. Distributed live loads are expressed in terms of maximum allowable pounds per square foot (Newtons per square meter).

5-5.1 COE Method.

The method is used to determine the allowable loads based on the concrete flexural strength, the slab-on-ground thickness, and the modulus of subgrade reaction. COE method assumes distributed loads are placed randomly on a slab-on-ground; aisle widths between distributed loads are not considered. Table 5-3 lists values for maximum allowable distributed live loads with a factor of safety equal to 2. Equation 5-4 can be used to find allowable loads for combinations of values of f'_c, h, k, and SF not given in Table 5-3.

Equation 5-4. [COE Method - Allowable Distributed Loads]

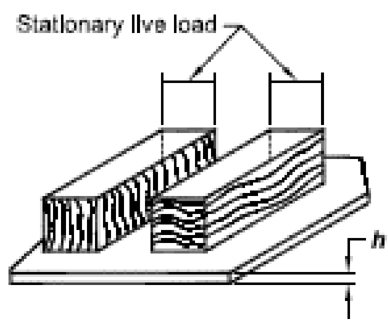
$$w = 257.876 \frac{f_r}{\mathrm{SF}} \sqrt{\frac{kh}{E_C}} \quad \text{(in.-lb)}$$

$$w = 57.15 \frac{f_r}{\mathrm{SF}} \sqrt{\frac{kh}{E_C}} \quad \text{(SI)}$$

The engineer can obtain the allowable distributed load a slab-on-ground is able to support by entering Table 5-3 with the flexural strength and the slab-on-ground thickness. Or if the distributed load is known, the engineer can enter Table 5-3 with the flexural strength and a distributed live load equal to or greater than the given distributed allowable load; the minimum slab thickness can then be read from the left column. Based on the modulus of subgrade reaction, the load is adjusted using the constant factor given in the note below Table 5-3.

Table 5-3 Maximum Allowable Stationary/Distributed Live Load

Slab thickness, inches (millimeter)	Stationary live load *w*, lb/ft^2 (kPa), for the following flexural strengths of concrete			
	550 lb/in.^{2} (3.8)	600 lb/in.^{2} (4.1)	650 lb/in.^{2} (4.5)	700 lb/in.^{2} (4.8)
6 (150)	868 (42)	947 (45)	1026 (49)	1105 (53)
7 (175)	938 (45)	1023 (49)	1109 (53)	1194 (57)
8 (200)	1003 (48)	1094 (52)	1185 (57)	1276 (61)
9 (225)	1064 (51)	1160 (55)	1257 (60)	1354 (65)
10 (250)	1121 (54)	1223 (58)	1325 (63)	1427 (68)
11 (275)	1176 (56)	1283 (61)	1390 (67)	1497 (72)
12 (300)	1228 (59)	1340 (64)	1452 (70)	1563 (75)
14 (350)	1326 (63)	1447 (69)	1568 (75)	1689 (81)
16 (400)	1418 (68)	1547 (73)	1676 (80)	1805 (86)
18 (450)	1504 (72)	1641 (78)	1778 (85)	1915 (92)
20 (450)	1586 (76)	1730 (82)	1874 (90)	2018 (97)



NOTE: Stationary live loads tabulated above are based on a modulus of subgrade reaction (*k*) of 100 lb/in.^{2}/in. (27.1 megapascal per meter). Maximum allowable stationary live loads for other moduli of subgrade reaction will be computed by multiplying the above—tabulated loads by a constant factor. Constants for other subgrade moduli are tabulated below.

Modulus of subgrade reaction	25 (6.8)	50 (13.6)	100 (27.1)	200 (54.3)	300 (81.4)
Constant factor	0.5	0.7	1.0	1.4	1.7

For other modulus of subgrade reaction values, the constant values may be found from the expression $\sqrt{k/100}$ ($\sqrt{k/27.1}$).

Further safety may be obtained by reducing allowable extreme fiber stress to a smaller percentage of the concrete flexural strength have been presented by Grieb and Werner (1962), Waddell (1968), and Hammitt (1974). For very heavy distributed live loads, the slab-on-ground thickness obtained from Equation 5-4 may control the design thickness of the slab-on-ground. The design should be examined for the possibility of differential settlements, which could result from nonuniform subgrade support. Also, consideration of the effects of long-term overall settlement for stationary distributed live loads may be necessary for compressible soils.

5-5.2 PCA Method.

This method is based on work done by Rice (1957) where he derived an expression for the critical negative moment (top of slab-on-ground) and deflection in the slab-on-ground, M_c, that occurs at the center of an aisle:

Equation 5-5. [PCA Method]

$$M_c = \frac{w}{2\lambda^2} e^{-\lambda c} \sin(\lambda c)$$

Equation 5-6. [PCA Method]

$$y = (w/k)^{-\lambda c} \cos(\lambda c)$$

where $\lambda = \sqrt[4]{k/(4E_c I)}$, in.$^{-1}$ (m^{-1}).

A distributed load placed on both sides of an aisle, will produce a maximum moment at aisle's center top surface (zero shear) and will cause upward deflection at that location, Equation 5-5. Multiplying the critical negative moment by a factor of safety, the engineer will ensure that the designed slab-on-ground will not crack due to the applied distributed loads. If the location of the distributed loads is permanent, a construction or a contraction joint, if feasible, can be provided in the middle of the aisle thus releasing the stresses and preventing objectionable cracks from becoming visible. To prevent warping or upward movement of the slab-on-ground at the created joint, the engineer must provide adequate dowels to transfer the loads across the joint, refer to Chapter 6). PCA similar to COE method provides tables that will help the engineer determine the allowable distributed live loads that can be placed on the slab-on-ground, refer to Tables 5-4 and 5-5. Table 5-4 is used if the location of the distributed load is not fixed, similar to the COE method.

Table 5-4 Allowable Distributed Loads for Unjointed Aisle with Nonuniform Loading Variable Layout (Packard 1996)

Slab thickness, in. (mm)	Subgrade *k*,* lb/in.^{2}/in. (MPa/m)	Allowable load, lb/ft^2† (kPa) Concrete flexural strength, psi (MPa) 550 (3.8)	600 (4.1)	650 (4.5)	700 (4.8)
5 (125)	50 (13.5)	535 (25.6)	585 (28.0)	635 (30.4)	685 (32.8)
	100 (27.1)	760 (36.4)	830 (36.4)	900 (43.1)	965 (46.2)
	200 (54.3)	1075 (51.5)	1175 (56.3)	1270 (60.8)	1370 (65.6)
6 (150)	50 (13.5)	585 (28.0)	640 (30.6)	695 (33.3)	750 (35.9)
	100 (27.1)	830 (39.7)	905 (43.3)	980 (46.9)	1055 (50.5)
	200 (54.3)	1175 (56.3)	1280 (61.3)	1390 (66.6)	1495 (71.6)
8 (200)	50 (13.5)	680 (32.6)	740 (35.4)	800 (38.3)	865 (41.4)
	100 (27.1)	960 (46.0)	1045 (50.0)	1135 (54.3)	1220 (58.4)
	200 (54.3)	1355 (64.9)	1480 (70.9)	1603 (76.8)	1725 (82.6)
10 (250)	50 (13.5)	760 (36.4)	830 (39.7)	895 (42.9)	965 (46.2)
	100 (27.1)	1070 (51.2)	1170 (56.0)	1265 (60.6)	1365 (65.4)
	200 (54.3)	1515 (72.5)	1655 (79.2)	1790 (85.7)	1930 (92.4)
12 (300)	50 (13.5)	830 (39.7)	905 (43.3)	980 (46.9)	1055 (50.5)
	100 (27.1)	1175 (56.3)	1280 (61.3)	1390 (66.6)	1495 (71.6)
	200 (54.3)	1660 (79.5)	1810 (86.7)	1965 (94.1)	2115 (101.5)
14 (350)	50 (13.5)	895 (42.9)	980 (46.9)	1060 (50.8)	1140 (54.6)
	100 (27.1)	1270 (60.8)	1385 (66.3)	1500 (71.8)	1615 (77.3)
	200 (54.3)	1795 (85.9)	1960 (93.8)	2120 (101.5)	2285 (109.4)

**k*, modulus of subgrade; disregard increase in k due to subbase.
†For allowable stress equal to 1/2 flexural strength.
Based on aisle and load widths giving maximum stress.

If the distributed load location will not change during the service life of the slab-on-ground, permanently fixed, then Table 5-5 is used to provide the allowable distributed loads based on aisle width and for specific modulus of subgrade. Different modulus of subgrade will have different values as shown in Table 5-5 (Packard 1996). Table 5-5 results in higher distributed loads than Table 5-4.

Table 5-5 Allowable Distributed Loads, Unjointed Aisles, Uniform Loading, and Variable Layout (Packard 1996)

Slab thickness, inch	Working stress, psi	Critical aisle width*, ft	Allowable load, lb/ft²					
			At critical aisle width	At other aisle widths				
				6 ft aisle	8 ft aisle	10 ft aisle	12 ft aisle	14 ft aisle
Subgrade k = 50 lb/in.²/in.†								
5	300	5.6	610	615	670	815	1050	1215
	350	5.6	710	715	785	950	1225	1420
	400	5.6	815	820	895	1085	1400	1620
6	300	6.4	670	675	695	780	945	1175
	350	6.4	785	785	810	910	1100	1370
	400	6.4	895	895	925	1040	1260	1570
8	300	8.0	770	800	770	800	880	1010
	350	8.0	900	935	900	935	1025	1180
	400	8.0	1025	1070	1025	1065	1175	1350
10	300	9.4	845	930	855	850	885	960
	350	9.4	985	1085	1000	990	1035	1120
	400	9.4	1130	1240	1145	1135	1185	1285
12	300	10.8	915	1065	955	915	925	965
	350	10.8	1065	1240	1115	1070	1080	1125
	400	10.8	1220	1420	1270	1220	1230	1290
14	300	12.1	980	1225	1070	1000	980	995
	350	12.1	1145	1430	1245	1170	1145	1160
	400	12.1	1310	1630	1425	1335	1310	1330
Subgrade k = 100 lb/in. ²/in.†								
5	300	4.7	865	900	1090	1470	1745	1810
	350	4.7	1010	1050	1270	1715	2035	2115
	400	4.7	1155	1200	1455	1955	2325	2415
6	300	5.4	950	955	1065	1320	1700	1925
	350	5.4	1105	1115	1245	1540	1985	2245
	400	5.4	1265	1275	1420	1760	2270	2565
8	300	6.7	1095	1105	1120	1240	1465	1815
	350	6.7	1280	1285	1305	1445	1705	2120
	400	6.7	1460	1470	1495	1650	1950	2420
10	300	7.9	1215	1265	1215	1270	1395	1610
	350	7.9	1420	1475	1420	1480	1630	1880
	400	7.9	1625	1645	1625	1690	1860	2150
12	300	9.1	1320	1425	1325	1330	1400	1535
	350	9.1	1540	1665	1545	1550	1635	1795
	400	9.1	1755	1900	1770	1770	1865	2050
14	300	10.2	1405	1590	1445	1405	1435	1525
	350	10.2	1640	1855	1685	1640	1675	1775
	400	10.2	1875	2120	1925	1875	1915	2030
Subgrade k = 200 lb/in. ²/in.†								
5	300	4.0	1225	1400	1930	2450	2565	2520
	350	4.0	1425	1630	2255	2860	2990	2940
	400	4.0	1630	1865	2575	3270	3420	3360
6	300	4.5	1340	1415	1755	2395	2740	2810
	350	4.5	1565	1650	2050	2800	3200	3275
	400	4.5	1785	1890	2345	3190	3655	3745
8	300	5.6	1550	1550	1695	2045	2635	3070
	350	5.6	1810	1810	1980	2385	3075	3580
	400	5.6	2065	2070	2615	2730	3515	4095
10	300	6.6	1730	1745	1775	1965	2330	2895
	350	6.6	2020	2035	2070	2290	2715	3300
	400	6.6	2310	2325	2365	2620	3105	3860
12	300	7.6	1890	1945	1895	1995	2230	2610
	350	7.6	2205	2270	2210	2330	2600	3045
	400	7.6	2520	2595	2525	2660	2972	3480
14	300	8.6	2025	2150	2030	2065	2210	2480
	350	8.6	2360	2510	2365	2405	2580	2890
	400	8.6	2700	2870	2705	2750	2950	3305

*Critical aisle width equals 2.209 times the radius of relative stiffness.
†*k* of subgrade; disregard increase in *k* due to subbase.
Notes: Assumed load width = 300 in.; allowable load varies only slightly for other load widths. Allowable stress = ½ flexural strength.
Conversion factors: 1 in. = 25.4 mm; 1 ft = 300 mm; 100 lb/in. ²/in. = 27.1 MPa/m; 1 lb/ft² = 0.048 kPa

The values presented in Table 5-4 are based on a factor of safety equal to 2, which can be conservative. For other factor of safety values, the following equation can be applied, Equation 5-7:

Equation 5-7. [PCA Method - Factor of Safety Values]

$$w = 0.123 \frac{f_r}{\mathrm{SF}} \sqrt{kh} \qquad (\mathrm{lb/ft^2})$$

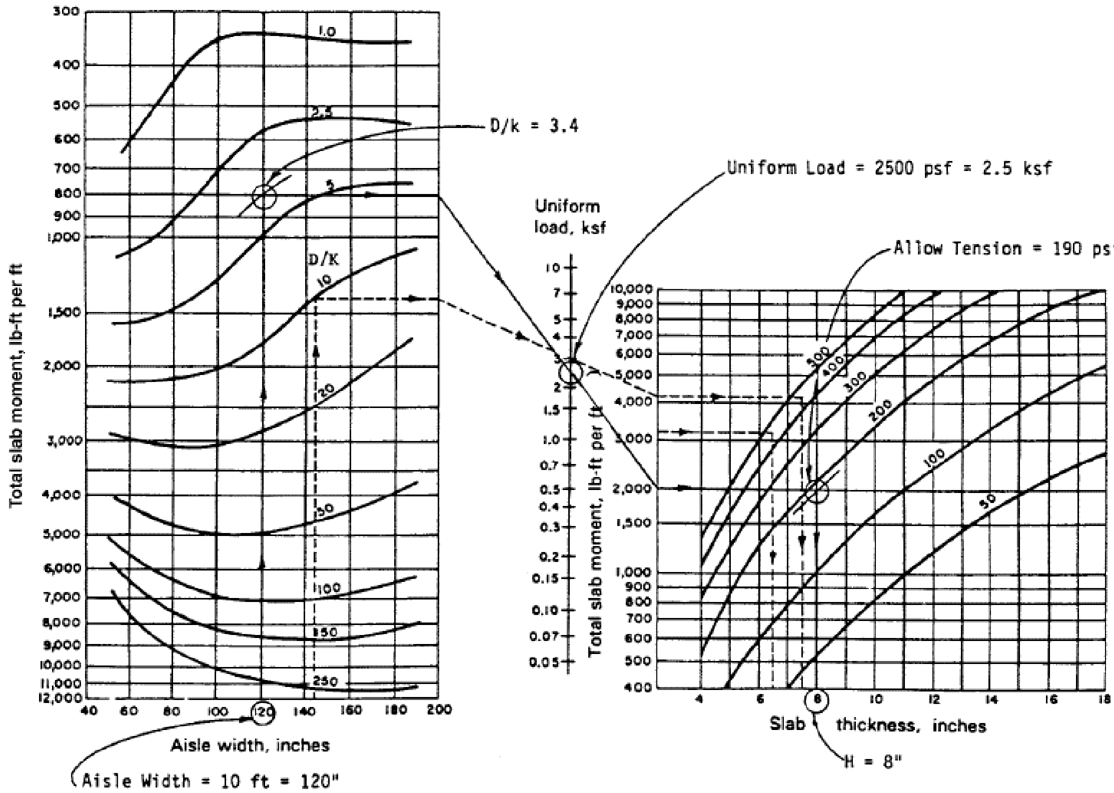
$$w = 0.00033 \frac{f_r}{\mathrm{SF}} \sqrt{kh} \qquad (\mathrm{kPa})$$

5-5.3 WRI Method.

This method relies on nomographs developed from the moving load charts. The SER will determine the slab stiffness *D/k* as shown above, Figure 5-8. Entering Figure 5-11(a) with the known aisle width, moving up and intersecting the obtained slab stiffness, then moving right to the plot edge, and down through the known uniform load value to the left-hand edge of the next nomograph Figure 5-11(b). From there move horizontally to the allowable stress and then down to read the minimum recommended slab-on-ground thickness.

This slab-on-ground thickness is then compared to the initial assumed thickness. If the difference is substantial, then the process is repeated using a revised slab-on-ground thickness until convergence between the assumed and the obtained thickness from Figure 5-11(b) is acceptable to the SER.

Figure 5-11 **Uniform Load Design and Slab Tensile Stress Charts Used with WRI Design Procedure**



(a) Calculation of slab-on-ground stiffness, *D/k* (b) Calculation of slab-on-ground thickness

Note: 1 inch = 25.4 millimeter, 1 pounds per square inch (psi) = 0.00689 megapascal (MPa), 1 inch pound per inch (ft-lb/ft) = 4.448 Newton meter per meter (N•m/m), and 1 kilo pound per square foot (ksf) = 47.88 kilopascal (kPa).

5-6 LINE/WALL LOADING.

A line or strip load is a relatively narrow uniformly distributed load. For a load to be considered a line or strip load, its width should be less than one-third of the radius of relative slab stiffness given by Equation 5-2. When the calculated radius of relative slab stiffness and the load width are within 15% of one another, then consider the load as uniform load. When the load width falls approximately between the two ranges (greater than 1/3ℓ and less than 15%ℓ), then review the stresses produced by line loading and uniform load (ACI 360R). Stationary-partition loads are expressed in terms of pounds per linear foot (Newtons per meter).

5-6.1 COE Method.

The allowable loads are given in Tables 5-6 and 5-7 for loads away from free edge and at free edge, respectively. The method used to determine thickness *h* of the thickened slab-on-ground is based on the concrete flexural strength, f_r, the load, and the modulus of subgrade reaction, *k*. Entering Tables 5-6 and 5-7 with the flexural strength of the concrete and the load, the concrete thickness is selected based on a modulus of subgrade reaction of 100 pounds per square inch per inch (27.1 megapascal per meter). The thickness is adjusted using the constant factor given in the note (Table 5-6), for other subgrade moduli.

Tables 5-6 and 5-7 present the minimum thicknesses of thickened slabs for various wall loads. The equations used to calculate these values are included in Appendix A. When the required slab thickness for line loads exceeds that required for moving or distributed loads, the slab should be thickened in accordance with Figure 5-12(a) for a line located away from a slab edge. The safety factor for the design was considered by using a reduced allowable tensile stress of the concrete, f_r, which was computed using the following equation

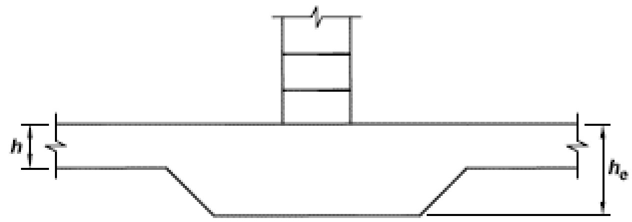
$f_r/SF = 1.6\sqrt{f_c'}$ pounds per square inch ($0.133\sqrt{f_c'}$ megapascal).

The slab under the wall is widened such that the stress in the thinner slab-on-ground section at the start of transition does not exceed the allowable tensile stress of

$1.6\sqrt{f_c'}$ ($0.133\sqrt{f_c'}$).

The recommended slope of the transition is constructed at 3 horizontal to 1 vertical. Figure 5-12(b) shows a slab loaded near a keyed or doweled edge and Figure 5-12(c) shows a recommended slab thickening for a slab loaded near a free edge. The width of the thickened edge varies depending upon the width of the wall. If line/wall loads exceed the tabulated values shown in Tables 5-6 or 5-7, isolated wall footings should be provided.

Table 5-6 Minimum Thickness of Thickened Floor slab for Wall Load Near Center of Slab or Near Keyed or Doweled Joint



Thickness of thickened floor slab, h_e, inches (millimeters)	Slab line load capacity P, lb/lin ft (N/lin m)			
	Flexural strength of concrete*, psi (MPa)			
	550 (3.79)	600 (4.14)	650 (4.48)	700 (4.83)
4 (100)	425 (6202)	455 (6640)	485 (7078)	510 (7443)
5 (125)	565 (8246)	600 (8756)	640 (9340)	675 (9851)
6 (150)	710 (10,362)	755 (11,018)	805 (11,748)	850 (12,405)
7 (175)	860 (12,551)	920 (13,426)	975 (14,229)	1030 (15,032)
8 (200)	1015 (14,813)	1080 (15,761)	1150 (16,783)	1215 (17,732)
9 (225)	1175 (17,147)	1255 (18,315)	1330 (19,410)	1410 (20,577)
10 (250)	1340 (19,556)	1430 (20,869)	1520 (22,183)	1605 (23,423)

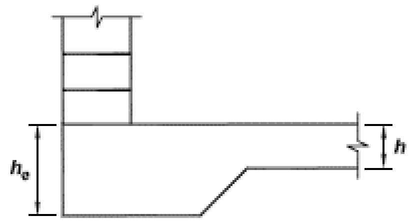
NOTE: The allowable wall loads are based on a modulus of subgrade reaction (k) of 100 pounds per square inch per inch (27.1 megapascal per meter). The thickness of the thickened slab will be computed by multiplying the above thick— nesses by a constant factor. Constants for other subgrade moduli are tabulated below.

Modulus of subgrade reaction (k)	25 (6.8)	50 (13.6)	100 (27.1)	200 (54.2)	300 (81.3)
Constant factor	1.3	1.1	1.0	0.9	0.8

For other modulus of subgrade reaction values the constant values may be found from $\sqrt[5]{100/k}$ $\left(\sqrt[5]{27.1/k}\right)$

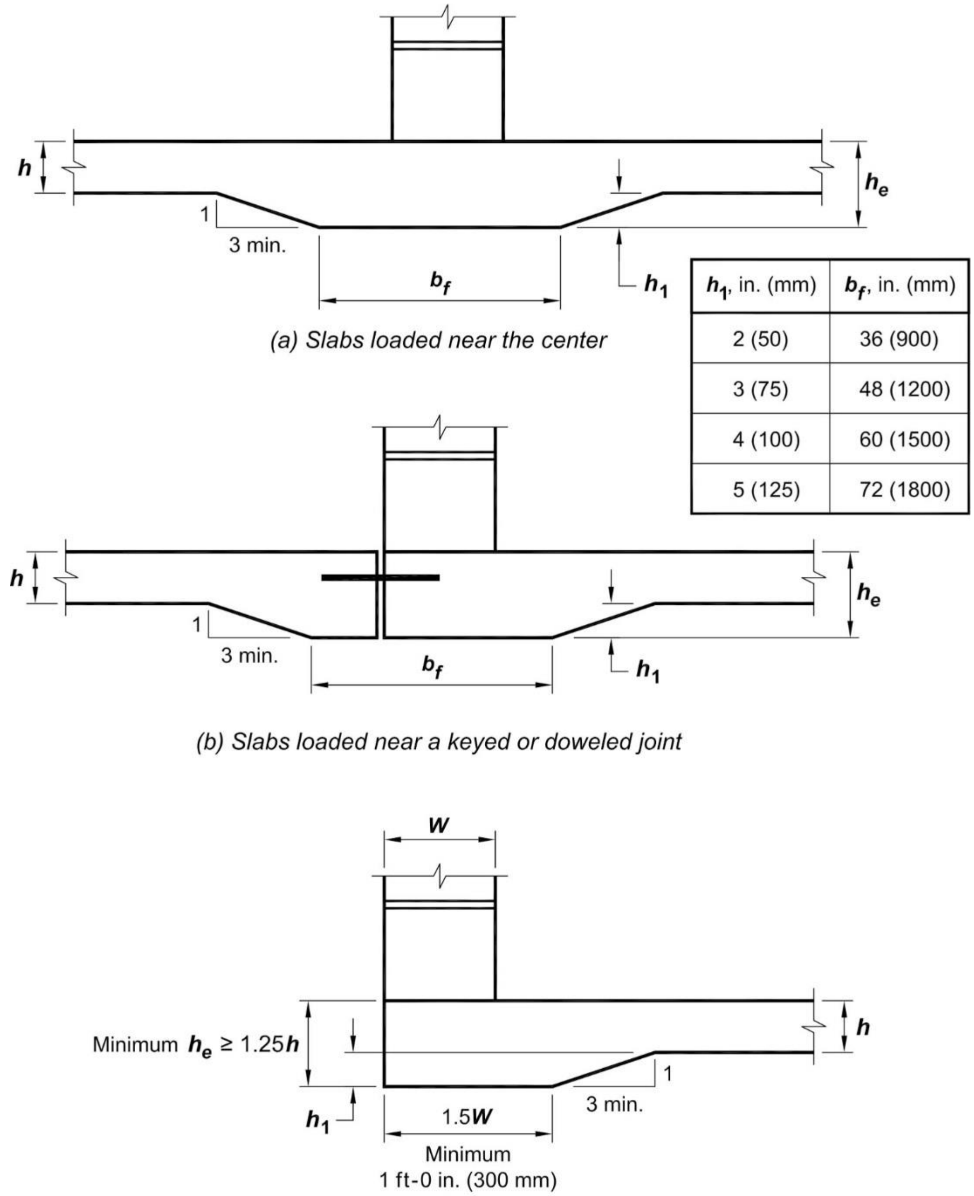
[a]For this application the flexural strength of concrete was assumed equal to $9\sqrt{f_c'}$ $(0.75\sqrt{f_c'})$, where f_c' is the specified compressive strength of concrete, lb/in.^{2}(N/mm^2).

Table 5-7 Maximum Allowable Wall Load Near Free Edge



Thickness of Thickened Slab, h_e, inches (millimeter)	Slab Line Load Capacity, *P*, lb/lin ft (N/lin m) Flexural Strength, of Concrete, lb/in.^{2} (MPa)			
	550 (3.79)	**600 (4.14)**	**650 (4.48)**	**700 (4.83)**
4 (100)	330 (4816)	355 (5181)	375 (5473)	395 (5765)
5 (125)	435 (6348)	465 (6786)	495 (7224)	525 (7662)
6 (150)	550 (8027)	585 (8537)	620 (9048)	660 (9632)
7 (175)	665 (9705)	710 (10,362)	755 (11,018)	800 (11,675)
8 (200)	785 (11,456)	840 (12,259)	890 (12.989)	945 (13,791)
9 (230)	910 (13,280)	975 (14,229)	1,035 (15,105)	1,090 (15,907)
10 (300)	1,040 (15,178)	1,110 (16,199)	1,180 (17,221)	1,245 (18,169)

Figure 5-12 **Widths of Thickened Slabs and Slab Edge Conditions under Wall Loads**



(a) Slabs loaded near the center

h_1, in. (mm)	b_f, in. (mm)
2 (50)	36 (900)
3 (75)	48 (1200)
4 (100)	60 (1500)
5 (125)	72 (1800)

(b) Slabs loaded near a keyed or doweled joint

(c) Slabs loaded near a free edge

5-6.2 PCA and WRI Methods.

Both PCA and WRI methods do not provide tables, charts, or equations to calculate the slab-on-ground thickness when subjected to wall loading.

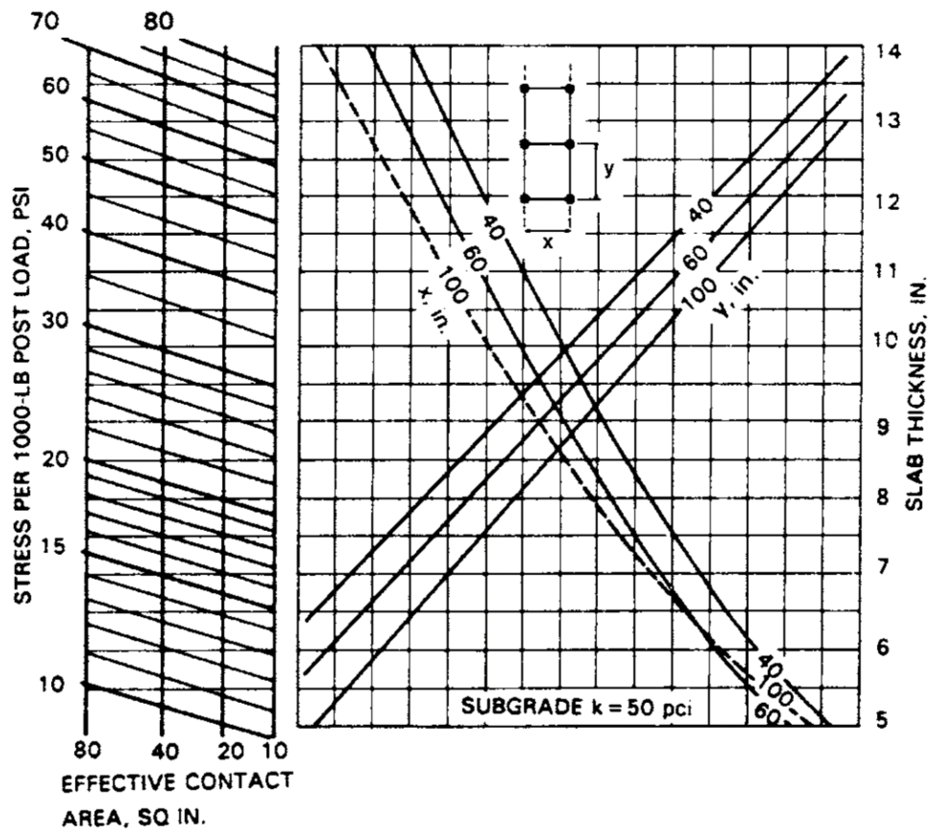
5-7 CONCENTRATED LOADS.

In general, flexure controls the concrete slab-on-ground design for concentrated loads. Bearing stresses and shear stresses at the bearing plates, however, must be also checked in accordance with ACI 318 to prevent punching shear failure.

The COE method does not provide an approach to calculate the slab-on-ground thickness subjected to concentrated loads, refer to Table 5-3.

The PCA method modified and expanded the design of the wheel nomographs, Figure 5-5, to post loads for different moduli of subgrade, *k*, refer to Figure 5-13. The SER must consider the rack posts proximities to slab-on-ground joints as they may control the design of a slab-on-ground.

Figure 5-13 **The PCA Design Chart for Post Loads when Subgrade Modulus is 100 psi/in. (27.1 MPa/m)**



The WRI method does not have specific nomographs to determine slab-on-ground thickness for concentrated loads. However, by using a single wheel load, which represents an equivalent concentrated load, the same moving load charts can be used. The additional step to obtain the secondary moment, the influence of the second wheel, is omitted.

5-8 DESIGN PROCEDURES FOR STABILIZED FOUNDATIONS.

The stabilized or modified design method applies to the COE method only. A stabilized soil is one that shows improvement in load-carrying capability and durability characteristics. A modified soil is one that shows improvement in its construction characteristics but does not show an increase in the strength of the soil sufficiently to qualify as a stabilized soil. The principal benefits of soil modification or stabilization include a stable all-weather construction platform, a reduction of rigid slab-on-ground thickness requirements when applicable, swell potential, and susceptibility to pumping and strength loss due to moisture.

The design of the stabilized or modified layers will follow UFC 3-250-11 and UFC 3-260-02. To qualify as a stabilized layer, the stabilized material must meet the unconfined compressive strength and durability requirements in UFC 3-250-11; otherwise, the layer is considered modified.

The thickness requirements for a rigid slab-on-ground on a modified soil foundation will be designed as if the layer is unbounded using the *k*-value measured on top of the modified soil layer. For stabilized soil layers, the treated layer will be considered a low-strength base. The slab-on-ground will be considered an overlay with a thickness determined using the following modified, partially bonded rigid slab-on-ground design equation (Equation 5-8):

Equation 5-8. [Rigid Slab-on-Ground Design]

$$h_o = \sqrt[1.4]{h^{1.4} - \left(\left[\sqrt[3]{\frac{f_r}{E_c}} \right] h_s \right)^{1.4}} \quad \text{inch (millimeter)}$$

where in this equation h, is taken as the thickness of rigid slab-on-ground from the design nomograph (Figure 5-3) based on the *k*-value of unbound material, inches (millimeters) and E_c is taken equal to 4 x 10^6 psi (27,575 MPa). For other methods recommend testing for the *k*-values at the top of the modified soil and use it in the design of the slab-on-ground thickness.

5-9 STEEL REINFORCEMENT.

Slab-on-ground shrinkage and temperature reinforcement is usually placed in the upper third of a slab-on-ground to be effective. Reinforcement may be welded-wire fabric or deformed bar mats arranged in a square or rectangular grid. The advantages in using steel reinforcement include: (a) allows for wider spacing between contraction joints; (b) controls the width of crack openings, with the result that load transmission is maintained at a high level at these points and objectionable material is prevented from infiltrating the cracks; (c) adds strength to the slab-on-ground by providing flexural strength and stability at cracked sections; (d) restrains warping by placing reinforcement in the upper half of slab-on-ground to restrain drying shrinkage; (e) adds impact resistance; (f) reduces differential settlement due to nonuniform support or frost heave is reduced materially, and (g) may reduce future maintenance. The minimum reinforcement area to control shrinkage, using bars or welded-wire mats, can be calculated by the subgrade drag method, Chapter 6 Section 6-2.3.2.

Steel reinforcement in structural slabs-on-ground is generally placed in one or two layers to increase the slab’s load capacity in addition to controlling crack widths and allows for hairline cracks. Reinforcement also allows for increased joint spacings or the elimination of contraction joints between construction joints.

Steel fibers, as with steel bar and wire reinforcement, will not prevent cracks but can limit crack widths and distribute them more evenly if a sufficient amount of steel fibers and an appropriate joint spacing are used. Steel fibers are usually included to the concrete mixture design of nonstructural and structural slabs-on-ground to improve mainly the impact resistance; refer to Section 5-10.

5-9.1 Subgrade Conditions.

Reinforced concrete slab-on-ground have enough capacity to span limited soft spots in the subgrade or subbase, which may occur due to moisture after concrete placement. If soft spots are encountered prior to concrete placement, then such areas must be repaired. Reinforcement can be also used to control cracking in rigid slabs-on-ground found on subgrades where differential vertical movement is a possibility (for example, foundations with definite or borderline frost susceptibility that cannot feasibly be made to conform to conventional frost design requirements).

5-9.2 Economic Considerations.

For the general case, lightly reinforced slabs-on-ground will not be economically competitive with plain slabs-on-ground of equal load-carrying capacity, even though a reduction in slab-on-ground thickness is possible. Alternate bids, however, should be invited if reasonable doubt exists.

5-9.3 Other Uses.

If slab-on-ground reinforcement is considered for reasons other than shrinkage and temperature or strength, a report containing a justification of the need for reinforcement must be prepared and submitted for approval to HQDA (DAEN-ECE-G), Washington, DC 20316-1000, or Headquarters, Air Force Engineering and Services Center (DEMP), Tyndall AFB, FL 32403.

Guidance relative to the use of reinforcement in slabs-on-ground, which apply to the three classical methods, is discussed below.

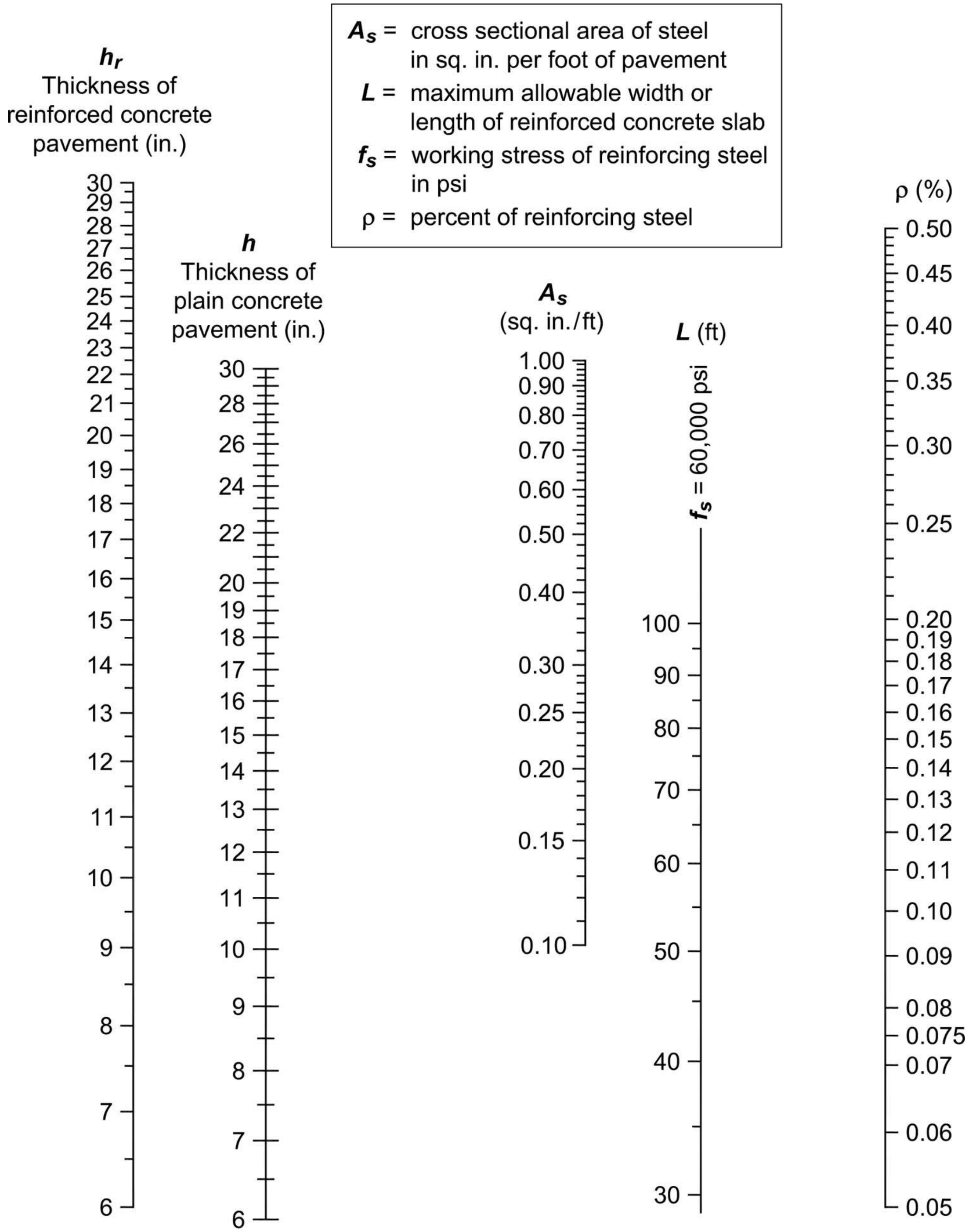
5-9.4 Slab-on-Ground Reinforcement Design per the COE Method.

The design procedure for reinforced concrete slabs-on-ground uses the principle of allowing a reduction in the required thickness of unreinforced concrete slab-on-ground due to the presence of the steel developed empirically from a limited number of prototype test pavements subjected to accelerated traffic testing. Although it is anticipated that some cracking will occur in the slab-on-ground under the design traffic loadings, the steel reinforcement will hold the cracks tightly closed. The reinforcement will prevent spalling or faulting at the cracks and provide a serviceable slab-on-ground during the anticipated design life. Essentially, the design method consists of determining the percentage of steel required, the thickness of the reinforced slab-on-ground, and the maximum allowable length of the slabs. Figure 5-14 presents a graphic solution for the design of reinforced slabs-on-ground. Because the thickness of a reinforced slab-on-ground is a function of the percentage of steel reinforcement, the SER may determine the required percentage of steel for a predetermined thickness of slab-on-ground or determine the required thickness of slab-on-ground for a predetermined percentage of steel. In either case, it is necessary to first determine the required thickness of unreinforced slab-on-ground by the method outlined previously (Section 5-4.1). The exact thickness (to the nearest 1/10 inch (2.5 millimeters)) of the slab-on-ground, h, is used to enter the nomograph in Figure 5-14. A straight line is then drawn from the value of h to the value selected for the thickness of reinforced slab-on-ground, h_r, and extended to the required percentage of reinforcing steel, ρ, or drawn from the value h to the value selected for the percentage of reinforcing steel, and extended to the thickness h_r. The thickness h_r will always be equal to or less than the thickness h.

5-9.4.1 Thickness Design on Stabilized Base or Subgrade.

This method is used by the COE method only and not covered by the other two methods, PCA and WRI. To determine the thickness requirements for reinforced concrete slabs-on-ground on a stabilized foundation, it is first necessary to determine the thickness of unreinforced concrete slab-on-ground required for the design conditions. This thickness of unreinforced slab-on-ground is determined by the procedures set forth in Section 5-8. Figure 5-14 is entered with the values of h, h_r, and ρ.

Figure 5-14 **Design Thickness for Reinforced Slabs-on-Ground**



Reinforced concrete pavement design

Note: Minimum thickness of reinforced concrete floor slabs will be 6 in.

Note: 1 inch = 25.4 millimeter and 1 square inch per foot = 645 square millimeter per 300 millimeters.

5-9.4.2 Limitations.

The design criteria for reinforced concrete slabs-on-ground are subject to the following limitations:

1. No reduction in the required thickness of unreinforced slabs-on-ground should be allowed for percentages of steel less than 0.05%.
2. No further reduction in the required thickness of unreinforced slabs-on-ground should be allowed over that indicated in Figure 5-14 for 0.50% steel, regardless of the percentage of steel used.
3. The minimum thickness of reinforced slabs-on-ground should be 6 inches (150 millimeters).

5-9.5 Steel Specifications.

The reinforcing steel for slabs-on-ground can be either deformed bars or welded-wire fabric. Deformed bars must conform to ASTM A615 or A706. Welded deformed bar mats must conform to ASTM A184; deformed bars used in welded deformed bar mats must conform to ASTM A615 or A706.

Deformed wire, plain wire, welded deformed wire reinforcement, and welded plain wire reinforcement must conform to ASTM A1064. Note that the yield strength of nonprestressed bars and wires must be determined by either method (ACI 318):

1. The offset method, using an offset of 0.2% in accordance with ASTM A370, or
2. The yield point by the half-of-force method, provided the nonprestressed bar or wire has a sharp-kneed or well-defined yield point.

5-9.5.1 Placement.

The following criteria regarding the maximum spacing of reinforcement should be observed. For welded-wire fabric, the maximum spacing of the longitudinal wires and transverse wires should not exceed 6 inches and 12 inches (150 millimeters and 300 millimeters), respectively; for bar mats, the maximum spacing of the longitudinal bars should not exceed 15 inches (380 millimeters) and three times the slab-on-ground thickness and for transverse bars not to exceed 30 inches (760 millimeters), respectively.

Irrespective of the reinforcement intended use, it must be spaced apart enough such that workers can step between bars or wires or it must be stiff enough to support workers placing concrete. Also, the steel must be supported, using chairs, at the proper position in the slab-on-ground. Design drawings should clearly show these details.

5-10 STEEL FIBER REINFORCEMENT DESIGN.

Steel fiber-reinforced concrete slabs-on-ground can be designed with the three classical design methods—COE, PCA, and WRI (ACI 360R). Slab-on-ground structural properties are improved by adding steel fibers to the concrete mixture design, particularly tensile and flexural strength thus improving serviceability and durability. Some of the advantages are:

- Increased strain strength and flexural toughness over traditional reinforced slabs-on-ground
- Improved resistance to impact and fatigue loadings when compared to slabs reinforced with bars or mesh
- Random crack control in concrete after the mixture reaches a hardened state
- Uniform distribution within concrete, which helps distribute localized stresses
- Simple to construct

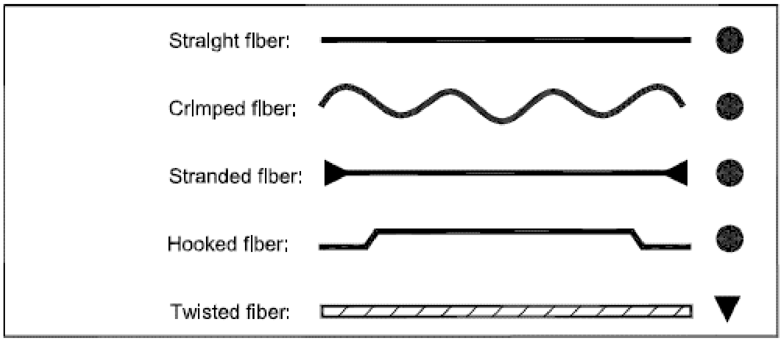
There are also some limitations for use of steel fibers in slabs-on-ground:

- 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
- Steel fibers can substitute reinforcement bars to a limit after which it will become uneconomical to use steel fibers

Several factors such as shape, size, volume, percentage, and distribution of fibers result in improvement in the mechanical properties of concrete with steel fibers over plain concrete.

ASTM A820/A820M, the standard specification for steel fibers for use in concrete, provides classification for five general types of steel fibers based primarily on the product or process used in their manufacture and should be referenced when specifying steel fibers: Type I: cold-drawn wire; Type II: cut sheet; Type III: melt-extracted; Type IV: mill cut; and Type V: modified cold-drawn wire. Steel fibers are typically anchored to concrete by different mechanisms: continuous deformations such as twists, dimples or crimps, end anchorage such as hooks, or simply bond for undeformed fibers (refer to Figure 5-15). Fiber geometry and anchorage significantly affects resistance to pullout forces and overall performance of steel fiber-reinforced concrete (SFRC). Plain, straight, and round steel fibers were found to develop weak bond and, consequently, low flexural strength.

Figure 5-15 **Shapes of Steel Fibers**



ASTM A820/A820M provides a lower limit for the average tensile strength of fiber material of not less than 50,000 pounds per square inch (345 megapascals). Typical steel fibers are made of low-carbon fibers that are either uncoated or galvanized; high-carbon steel fibers are typically used with concrete mixtures of 8000 psi (55 MPa) compressive strength and higher. Stainless steel fibers may be used when the concrete is exposed to extremely elevated temperatures.

As in the case with conventional reinforcement, the fibers do not prevent cracking, but serve to hold cracks tight such that the slab performs as intended during its service life. The degree of random crack control by the fibers is directly related to the fiber type and quantity.

5-10.1 Basis of Steel Fiber-Reinforced Concrete (SFRC) Slab-on-Ground Design.

The design of steel fiber-reinforced concrete (SFRC) slabs-on-ground is based upon limiting the ratio of the concrete flexural strength and the maximum tensile stress at the joint to a value found to give satisfactory performance in full-scale accelerated test tracks. The load is placed either parallel or normal to the edge of the slab. Because of the increased flexural strength and tenacity at cracks that develop in the fibrous concrete, the thickness can be significantly reduced. However, this results in a more flexible structure, which causes an increase in vertical deflections as well as in potential for densification, shear failures, or both, in the foundations; pumping of the subgrade material; and joint deterioration. ACI 360R presents two methods for calculating slabs-on-ground reinforced with steel fibers: the elastic method and the yield line method.

5-10.1.1 Elastic Method.

The elastic method is based on setting the allowable stress equal to the equivalent flexural strength of the composite steel FRC:

Equation 5-9. [Elastic Method – Allowable Bending Stress]

$$f_b = \frac{R_{e,3}}{100} f_r$$

Example 5-10.1.1

Use $R_{e,3}$ = 57 and f_r = 600 psi (4.14 MPa)

The allowable bending stress is then determined from Equation 5-9:

f_b = (57/100)(600 psi) = 342 psi (2.36 MPa)

In comparison, the allowable flexural strength of unreinforced concrete slab-on-ground with factor of safety = 2 is:

(0.5)(600 psi) = 300 psi (2.07 MPa) or a reduction of 14%.

5-10.1.2 Yield Line Method.

The yield line method is based on the redistribution of the maximum moments occurring at plastic hinges in slabs-on-ground. This method is based on work done by Meyerhof (1962) and Lösberg (1961). Slab-on-ground can be designed using this rational method, refer to ACI 360, ACI 544.6R, and TR34 for examples and further discussion.

5-10.2 Uses.

Although several types of fibers have been studied for concrete reinforcement, the design criteria presented herein are limited to steel fibrous concrete. The use of steel fibrous concrete requires the approval of HQDA (DAEN-ECE-G), Washington, DC 20316-1000; Headquarters, Air Force Engineering Services Center (DEMP), Tyndall AFB, FL 32403; or both. The use of SFRC slabs-on-ground should be based upon the economics involved.

5-10.3 Mixture Proportioning Considerations.

The design mixture proportioning of fibrous concrete will be determined by a laboratory study. The following are offered as guides and to establish limits where necessary for the use of the design criteria included herein.

1. The recommended addition of steel fibers to a concrete mixture design is in the range of 0.5 to 1% by volume (66 to 132 lb/yd^3 [39 to 78 kg/m^3]); refer to ACI 360R. Steel fibers will increase the number of cracks and reduce crack widths if they are added at volumes of 0.25 to 0.5% (33 to 66 lb/yd^3 (20 to 39 kg/m^3)). Steel fibers added at less than 0.5% by volume will not affect the concrete’s modulus of rupture. Regardless, steel fibers should not be added at less than 0.25 by volume. Steel fibers, when added to slabs-on-ground reinforced with continuous steel bars, will share the applied tensile forces and consequently further control crack widths.
2. The aspect ratio is determined as the ratio of the length to diameter of a steel fiber. Steel microfibers have typical diameters in the range of 0.01 to 0.05 inches (0.3 to 1.3 millimeters) and a length in the range of 0.5 to 2.5 inches (13 to 64 millimeter). The aspect ratio is limited to an optimum value to achieve good workability and strength. For handling and mixing of fibers, an aspect ratio of less than 60 is desirable, while for strength, an

aspect ratio of approximately 100 is desirable. Typically, for the same mixture proportions, as the fiber aspect ratio increases, so does the reinforcing performance.

3. In early applications, coarse aggregate larger than 0.75 inches (19 millimeters) was not recommended for SFRC. However, many successful placements have used aggregates as large as 1.5 inches (38 millimeters) (Rettberg 1986). Another method of improving SFRC workability is to use supplementary cementitious materials (SCMs) such as fly ash, slag, and silica fume in addition to or as a partial replacement of cement.

4. For proper mixing, it is important to have a uniform dispersion of the fibers and to prevent the segregation or balling of the fibers during mixing. Mixture adjustments may be required when steel fibers above approximately 0.33% by volume is used. Otherwise, there is no change to the conventional mixture proportions used by ready mixed concrete suppliers for the required concrete compressive strength when steel fibers are added. In these instances, more paste may be needed to provide better workability. Therefore, the fine-to-coarse aggregate ratio is adjusted upward accordingly. Combined aggregate grading for macrofiber FRC provided in Table 5-8 is borrowed from ACI 544.1R and is presented here for guidance only.

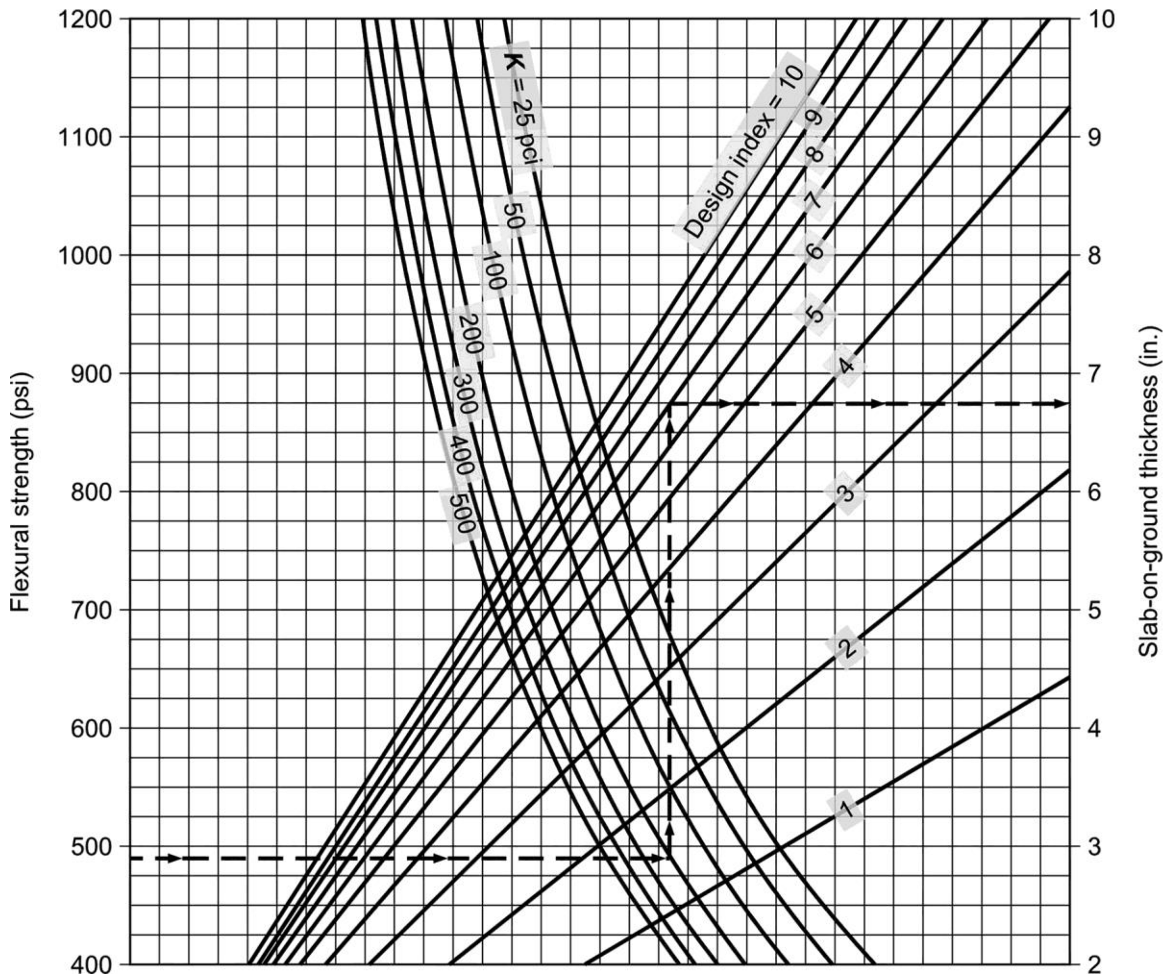
Table 5-8 Range of Proportions For Normalweight Steel Fiber-Reinforced Concrete (ACI 544.1R)

Mixture parameters	3/8 in. (9.5 mm) maximum size aggregate	3/4 in. (20 mm) maximum size aggregate	1-1/2 in. (38 mm) maximum size aggregate
Cementitious material, lb/yd^3 (kg/m^3)	600 to 1000 (356 to 593)	500 to 900 (297 to 534)	470 to 700 (279 to 415)
w/c	0.35 to 0.45	0.35 to 0.50	0.35 to 0.55
Percent of fine to coarse aggregate	45 to 60	45 to 55	40 to 55
Entrained air content, %	4 to 8	4 to 6	4 to 5
Fiber content, volume percent			
Deformed fiber	0.4 to 1.0	0.3 to 0.8	0.2 to 0.7
Smooth fiber	0.8 to 2.0	0.6 to 1.6	0.4 to 1.4

5-10.4 Thickness Determination.

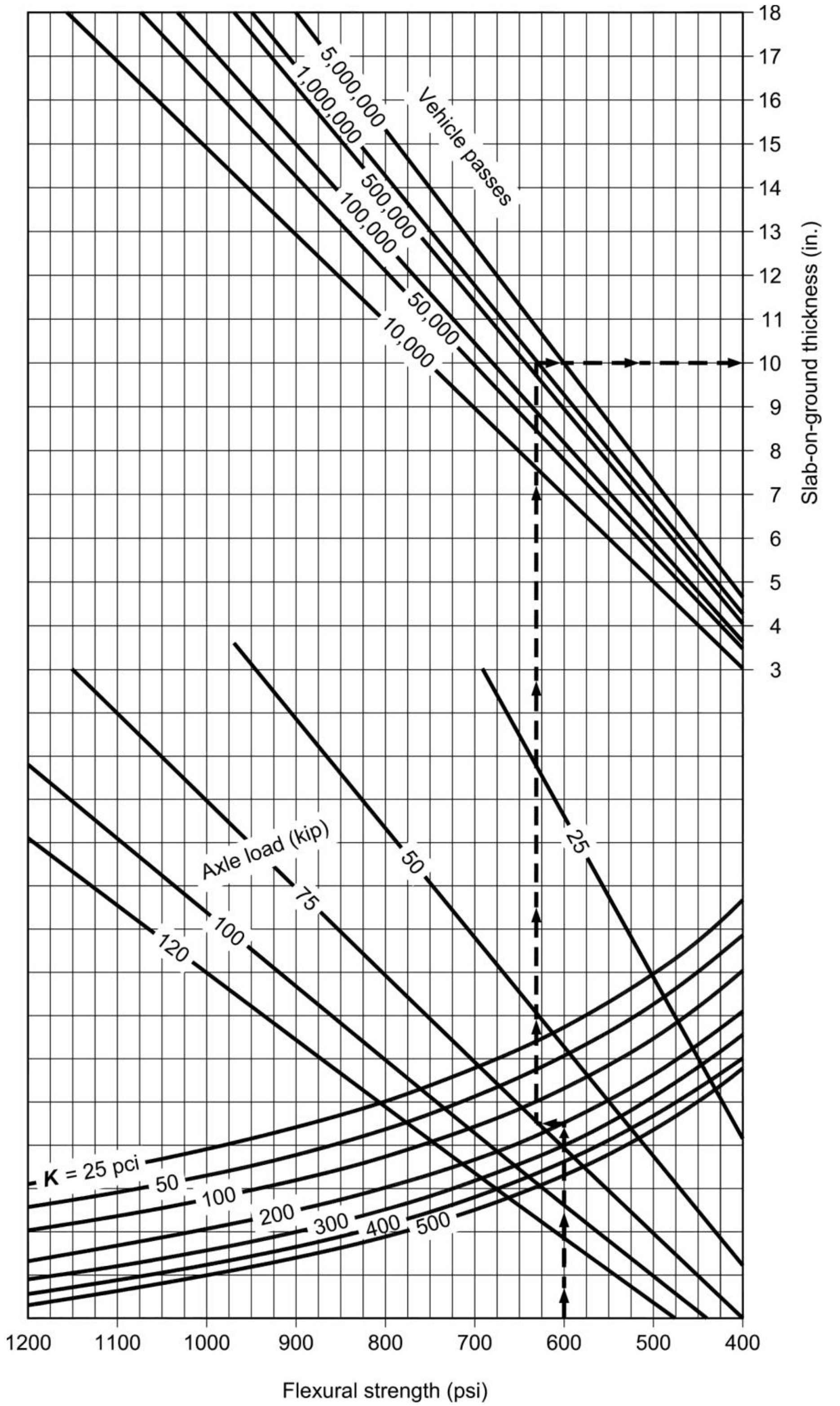
This approach, presented here with the associated nomographs, to determine the required thickness of SFRC slabs-on-ground is applicable to the COE method only. It is a function of the design concrete flexural strength, f_r, modulus of soil subgrade reaction, k, thickness, h, and flexural modulus of elasticity, E_{fs}, of stabilized material, if used; the vehicle or axle gross load; the volume of traffic; the type of traffic area; and the allowable vertical deflection. When stabilized material is not used, the required thickness, h, of SFRC is determined directly from the appropriate nomographs (Figure 5-16 and 5-17). If the base or subgrade is stabilized and meets the minimum strength requirements of UFC 3-250-11, the stabilized layer will be treated as a low-strength base and the slab-on-ground thickness is calculated from Equation 5-8. The resulting thickness h will be rounded up to the nearest half or full inch. The rounded thickness h will then be checked for allowable deflection in accordance with Section 5-10.5. The minimum thickness for SFRC slabs-on-ground is 4 inches (100 millimeters).

Figure 5-16 **Design Curves for Fiber-Reinforced Concrete Slab-on-Ground by Design Index**



Note: 1 inch = 25.4 millimeter, 1 pounds per square inch (psi) = 0.00689 megapascal (MPa), and 100 pounds per square inch per inch (lb/in.^{2}/in.) = 27.1 kilo megapascal per meter (MPa/m).

Figure 5-17 **Design Curves for Steel Fiber-reinforced Concrete Slabs-on-Ground for Heavy Forklifts.**

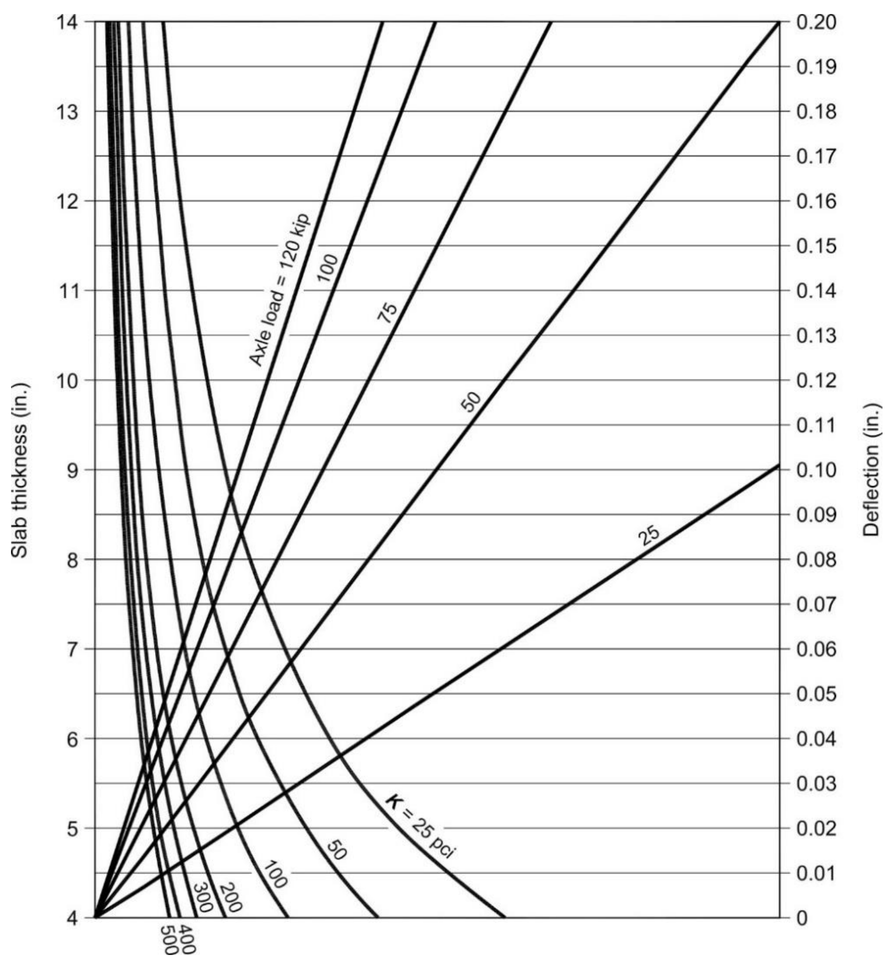


Note: 1 inch = 25.4 millimeter, 1 pounds per square inch (psi) = 0.00689 megapascal (MPa), and 100 pounds per square inch per inch (lb/in.^{2}/in.) = 27.1 megapascal per meter (kN/m^2/m).

5-10.5 Allowable Deflection for SFRC Slab-on-Ground.

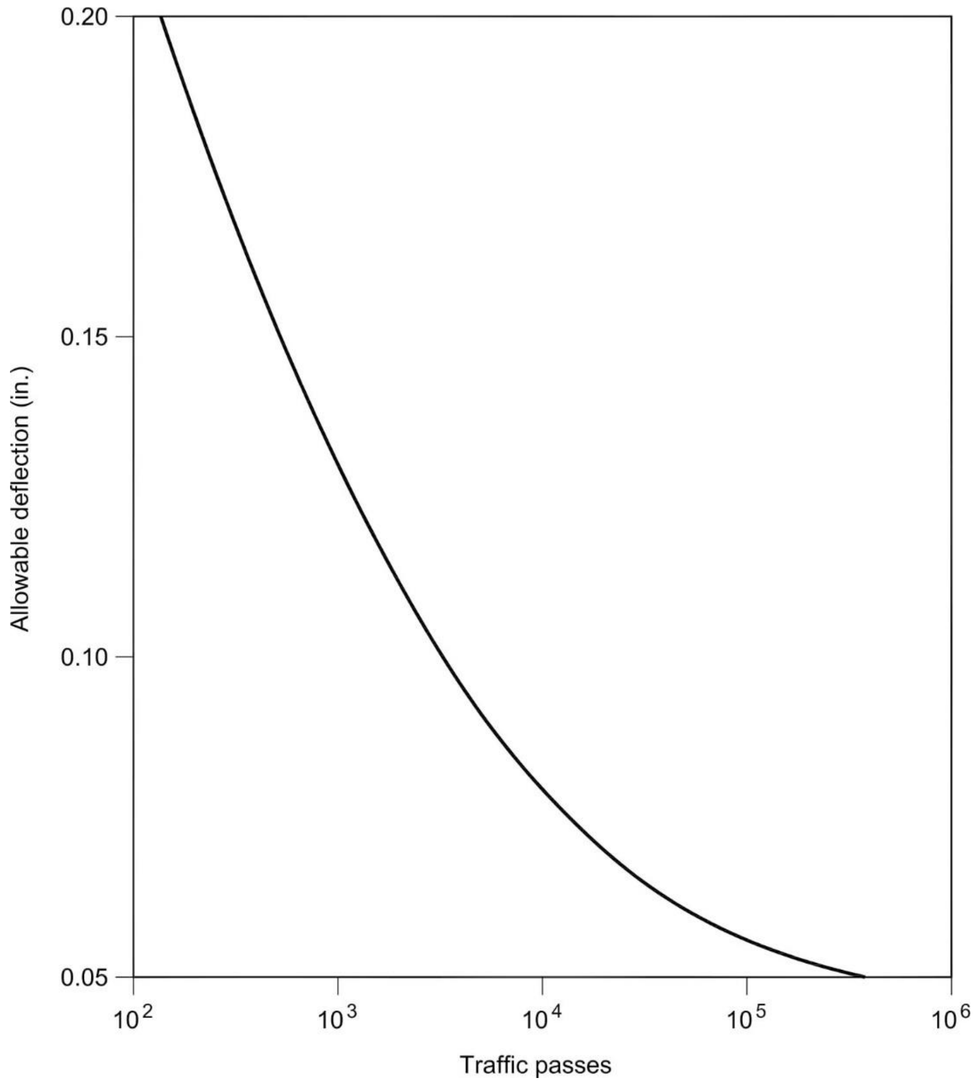
The elastic deflection that SFRC slabs-on-ground experience must be limited to prevent overstressing of the foundation material and thus premature failure of the slab-on-ground. Curves are provided for the computation of the vertical elastic deflection that a slab will experience when loaded; refer to Figure 5-18. Use of the curves requires three different inputs: slab thickness, *h*, modulus of subgrade reaction, *k*, and gross weight of the design vehicle, *P*. The slab thickness is determined from the guidelines of Section 5-4.1. The calculated vertical elastic deflection is then compared with appropriate allowable deflections determined from Figure 5-19. Deflections need not be checked for axle loads less than 25 kip (111 kN). If the calculated deflection is less than the allowable deflection, the thickness meets allowable deflection criteria and is acceptable. If the calculated deflection is larger than the allowable deflection, the thickness must be increased or a new design initiated with a different value for either f_r or k. The process must be repeated until a thickness based upon the limiting stress criterion will also have a calculated deflection below the allowable deflection.

Figure 5-18 **Deflection Curves for Steel Fiber-Reinforced Concrete Slabs-on-Ground**



Note: 1 inch = 25.4 millimeter, 1 kilo pound (kip) = 4.448 kilo Newton (kN), and 100 pounds per square inch per inch (lb/in.^{2}/in.) = 27.1 megapascal per meter (kN/m^2/m)

Figure 5-19 **Allowable Deflections for Steel Fiber-Reinforced Concrete Floor Slabs**



Note: 1 inch = 25.4 millimeter.

5-11 CONCRETE SLAB-ON-GROUND REINFORCED WITH FIBER-REINFORCED POLYMER (FRP) BARS.

There is limited or no research data on slabs-on-ground reinforced with FRP bars. ACI 440.1R Section A.2, however, provides some guidelines to reinforce slabs-on-ground with shrinkage and temperature FRP bars. The slabs-on-ground thickness is determined assuming the slab-on-ground is without reinforcement, plain, and the FRP bars are placed in the upper half of the slab-on-ground to resist shrinkage and temperature stresses. The FRP bars, as with steel bars, do not prevent cracking, but are added to limit crack widths and spacings and to provide a reserve strength after shrinkage or temperature cracking has occurred. The increase in the flexural capacity of the slab-on-ground is insignificant. Wider spacing between contraction joints is permitted but not recommended.

Using FRP bars, which are corrosion-resistant, would eliminate slab-on-ground concrete deterioration from corrosion of steel bars. They have a similar coefficient of thermal expansion to concrete, therefore, there is no differential in expansion between concrete and FRP bars, thus concrete pops and spalling is reduced. Other benefits are lower internal stresses in concrete during shrinkage and temperature changes and easier to demolish a slab-on-ground with FRP bars compared to one with steel bars because of the lower material properties in shear. The subgrade drag method for calculating the longitudinal bar area to resist shrinkage and temperature was expanded to include FRP bars, Chapter 6 Section 6-2.3.2. ACI 440.1R, however, stresses that "No experimental data have been reported on FRP slab-on-ground applications; research is required to validate this approach."

5-12 FINITE ELEMENT ANALYSIS METHOD.

Finite element (FE) analysis method is used by engineers to analyze and design slabs-on-ground. It is a rational approach that can accommodate the majority of loads being forklift, airplane, distributed, line, and concentrated loads, separately or in combination placed anywhere on a slab-on-ground. The SER should consider several factors when applying FEM: the element selected to model the slab-on-ground; the degree of mesh fineness; and the modulus of subgrade.

Steps to analyze a slab-on-ground using FE method are as follows:

1. Model slab-on-ground as bending plates
2. Subdivide the slab-on-ground into small bending plate elements. The size of the finite elements must be chosen appropriately with regard to the dimensions of the structure. The smaller the subdivision of the slab area, the higher the reliability of the analysis
3. The supporting soil is modeled as discrete, compression-only springs connected to the plate nodes

Slabs-on-ground are, in general, modeled as rectangular plate elements. For irregular-shaped slabs-on-ground, a combination of rectangular elements and other types of elements such as triangular elements are used.

The supporting soil is idealized as linear elastic continuum using Winkler's model (Winkler 1867). If the software used for analysis does not have the capability to calculate the vertical spring stiffness from the modulus of subgrade, then it will have to be entered manually. The compression-only vertical spring stiffness is calculated by multiplying the assumed subgrade modulus with the tributary area of the spring support system of the spring support elements (Equation 5-10).

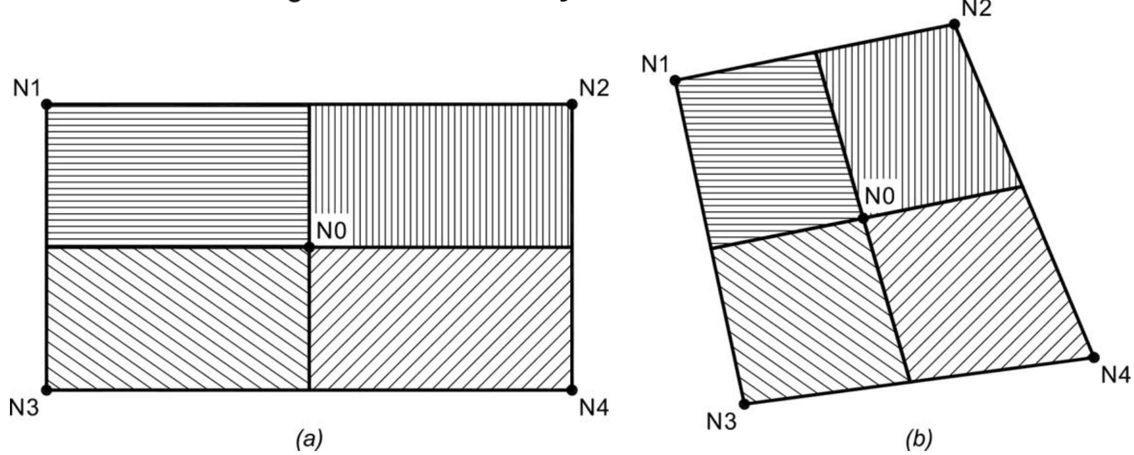
Equation 5-10. [Vertical Spring Stiffness]

$$k_i = k \times A_{trib}$$

where k_i is spring constant at i-th node; k is modulus of subgrade reaction; and $A_{i,trib}$ is tributary area of the i-th node.

The tributary area to a node depends on the shape of the element. For a perfect square rectangular plate, each node will influence exactly one-fourth of the plate surface area. However, for a generalized quadrilateral, the best practice would be to calculate the center of the mass of the plate and then draw the lines from that center point to the middle points of each side (refer to Figure 5-20).

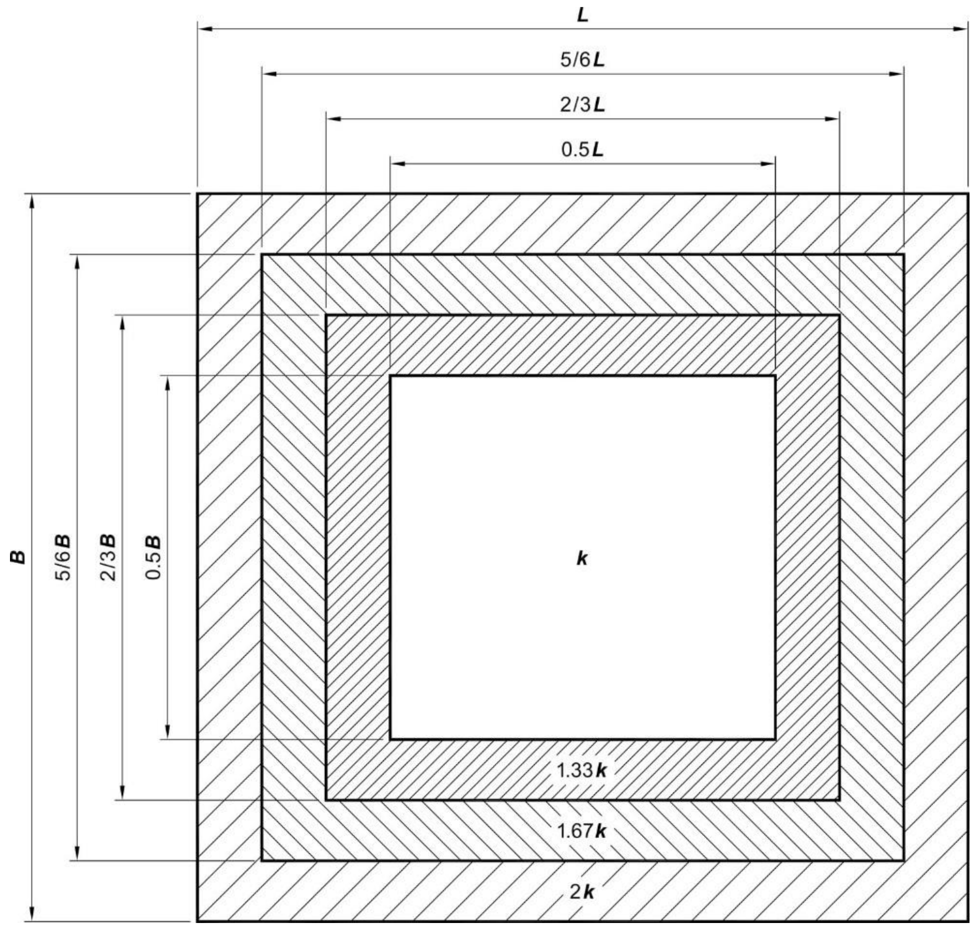
Figure 5-20 **Tributary Area to a Node**



The above-described tributary area calculation is used by the commercial software to calculate the linear spring constant. The program first calculates the tributary area for each node of the slab-on-ground and then multiplies the assigned modulus of subgrade reaction by the corresponding tributary area for each node to get the linear spring constant at each node.

The subgrade modulus, however, is not constant underneath a slab-on-ground. Therefore, increase the compression-only spring stiffness from the center of the slab-on-ground toward the perimeter of each panel. It is recommended to divide the supporting soil medium into several bands (usually three to six) and increase the subgrade reaction by 100% starting with k at the center to $2k$ at the edges of the slab; refer to Figure 5-21. Analyses have shown that the deflection profile matched the expected bowl shape soil settlement more accurately (Tribedi 2018). The slab-on-ground thickness and reinforcement is then calculated from the obtained FE analysis forces, flexural moment, and shear forces, following ACI 318 requirements.

Figure 5-21 **Subgrade Modulus Proposed Zones under a Slab-on-Ground Panel**



5-13 DESIGN MODEL FOR PILE-SUPPORTED FLOOR.

Where geotechnical investigations indicate that ground conditions are inadequate for a ground-supported floor, compressible or organic soil, and the economic study reveals that hauling and compacting good soil to replace existing soil or soil modification is economically not feasible, the slab-on-ground can be constructed on piles. The use of piles requires the approval of HQDA (DAEN-ECE-G), Washington, DC 20316-1000; Headquarters, Air Force Engineering Services Center (DEMP), Tyndall AFB, FL 32403; or both.

The SER should consider that the subgrade/subbase provides support to the concrete slab during construction until it has achieved adequate strength; after which, it is assumed that only piles provide the support. It is therefore necessary that while concrete is gaining strength, the subgrade/subbase provides a stable platform to resist deformation under construction traffic and loads and to provide a flat surface to enable the slab or mat as sometimes referred to, to undergo shrinkage without undue restraint.

Piles are constructed as cast-in-place concrete piles, driven piles of cylindrical or square precast concrete, steel piles, micropiles, or rammed aggregate piers (Geopier 2016).

Piles have relatively high stiffness compared to the surrounding soil; accordingly, the slab loads are resisted by the piles diminishing the uniform support condition of the slab-on-ground by the subgrade or bases. Therefore, the slab (mat) span needs to be limited to maintain a safe and economical design based on the pile capacity. Literature suggests maintaining a span-depth ratio of the slab between 8 and 20. However, it is preferable to maintain slab spans between 8 to 15 feet (2.5 to 5 meters) between piles and slab thickness between 7 and 16 inches (175 and 410 millimeters) thick (TR34).

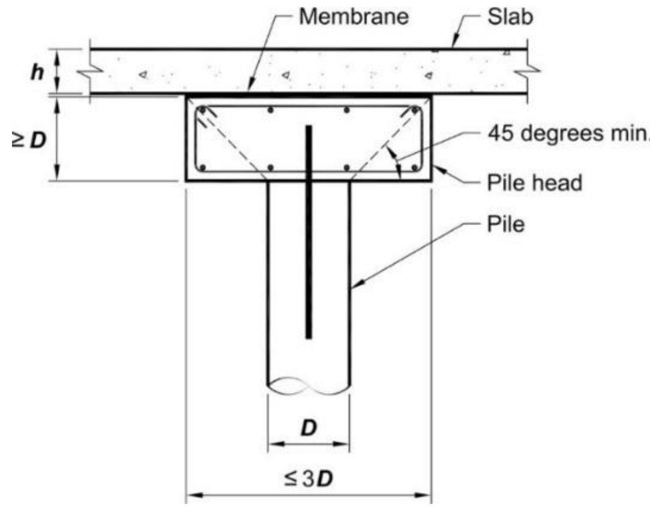
Slabs supported on piles are designed as reinforced structural slabs per ACI 318 or the yield line method disregarding ground support. Steel fibers are usually added to improve impact resistance and to better control cracks (Section 6-10). The recommended dosage of deformed steel fibers for such slabs/mats is 0.5 to 0.63% by volume (66 to 83 lb/yd^3 (40 to 50 kg/m^3)) that will permit workability and pumping ability (Destrée 2001). These slabs/mats are isolated from the rest of the building and do not support loads from columns or walls. For slabs/mats supporting racking, the design of the joint layout arrangement should take into account both the piling grid and the racking grid; refer to ACI 544.6R.

Concrete piling should be designed, constructed, and installed in accordance with the recommendations of ACI 543R. It is preferable to construct the piles with enlarged pile heads for the following reasons:

- Increased two-way shear resistance against punching shear
- Reduced effective span length of the slab/mat
- Reduce restraint due to larger and smoother bearing surface area

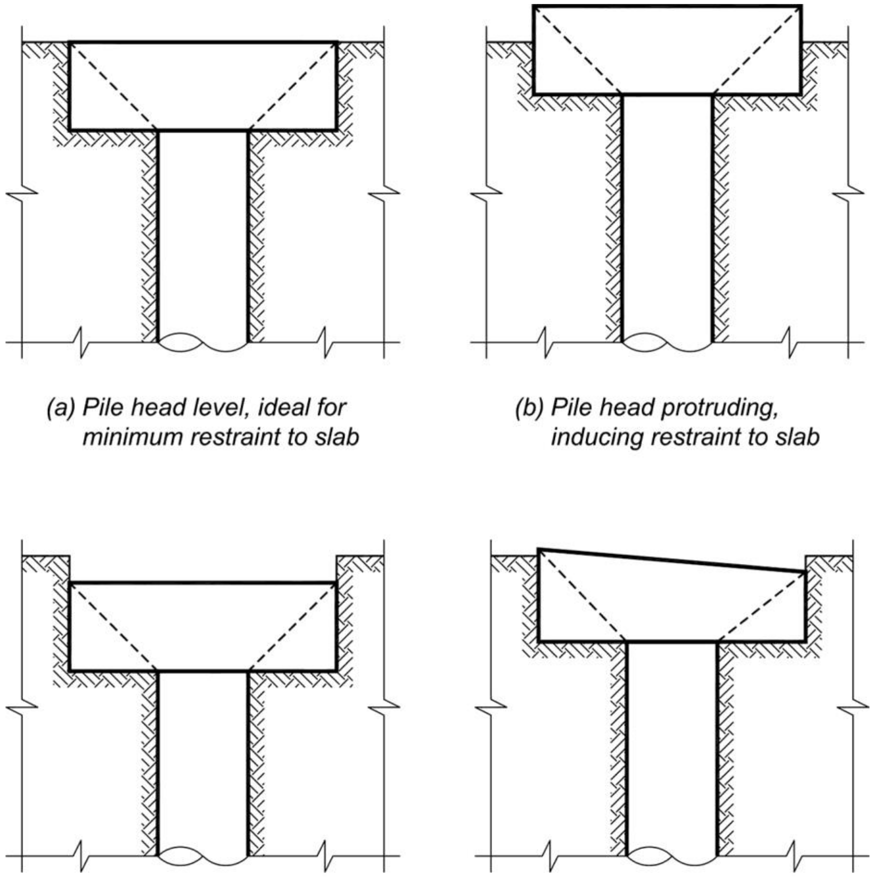
Concrete pile heads, preferred over cone-shaped heads, should include a reinforcement cage and starter bars passing down into the pile shaft. The distance between vertical faces of pile head should not exceed three times the pile diameter and the depth should be at least equal to the pile diameter; refer to Figure 5-22. Provide a slip membrane between the pile head and the underside of the slab/mat so that the pile head is not tied to the slab/mat; refer to Figure 5-22 (TR34).

Figure 5-22 **Pile and Pile Head Supporting Slab-on-Ground**



The contract document should direct the contractor to build the pile heads level and should have a smooth, troweled finish to reduce restraint. They should be constructed flush with the subgrade/subbase top level, as shown in Figure 5-23(a). The level tolerance should be no greater than +0, –1.0 inch (+0, –25 millimeter) with respect to the slab soffit and with a slope not greater than 3/16 inch (5 millimeters) over its width. However, it is possible that, as a result of construction inaccuracies, the pile head may in fact be constructed as shown in Figure 5-23(b) to 5-23(d), which would not be acceptable. If pile heads are damaged during construction, then they should be repaired. Because these slabs/mats are considered structural slabs/mats, contraction joints are not provided. Construction joints are placed at pile centers, or within *L*/3 from pile center, where *L* is the span from centerline of pile to centerline of adjacent pile; refer to Figure 5-24 and 5-25.

Figure 5-23 **Pile Head Construction**



(a) *Pile head level, ideal for minimum restraint to slab*

(b) *Pile head protruding, inducing restraint to slab*

(c) *Pile head indented, inducing restraint to slab*

(d) *Pile head inclined or dished, inducing restraint to slab*

Figure 5-24 **Joint Located at Centerline of Pile**

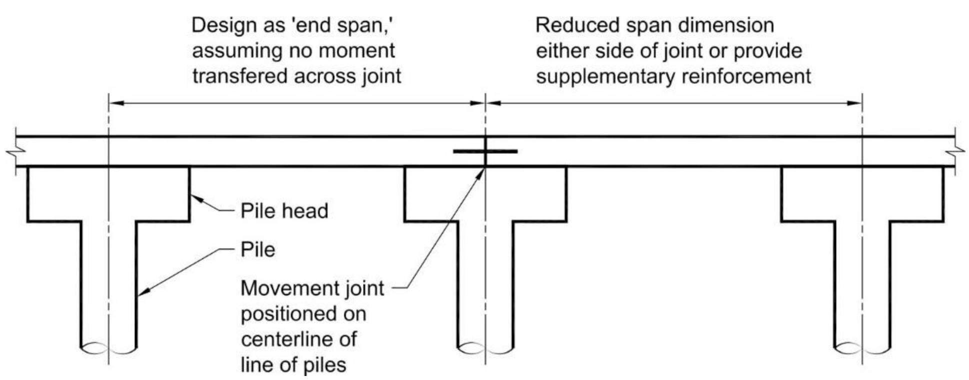
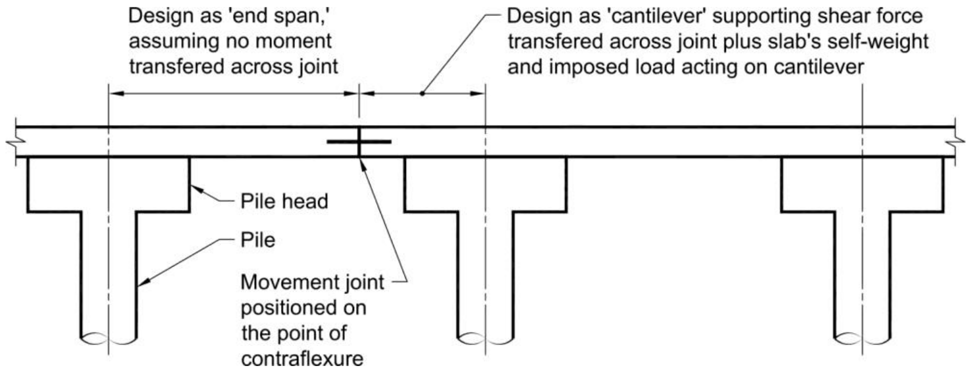


Figure 5-25 **Joint Offset from Centerline of Pile within 1/6-1/3 Slab Span**



5-14 ACI 318 DESIGN LIMITATIONS.

ACI 318 Section 1.4.8 specifically excludes the design of slabs-on-ground unless the slab transmits vertical, lateral forces, or both from portions of the structure to the soil. When analyzing slabs-on-ground using finite element method as presented in Section 5-12, ACI 318's strength design method is used for the design of slabs-on-ground; see Example 5-14. Joint spacing and dowels are designed and detailed per Chapter 6 of this manual.

The SER can use the load factors for dead and live loads as presented in ACI 318 Chapter 5. However, it is recommended to use one common load factor for both dead and live loads. The load factor is affected by the magnitude and frequency of the traveling load and life expectancy of slab-on-ground. Therefore, it should not be less than 1.8. A preferred load factor to use is 2.

For two-layer reinforced slabs-on-ground, the minimum thickness should not be less than 8 inches (200 millimeter). The minimum cover to bottom reinforcement must satisfy ACI 318 Table 20.5.1.3.1—3 inches (75 millimeter); recommended cover to top reinforcement is 1.5 inches (38 millimeters) to reduce bar shadowing and subsidence cracking. The maximum steel bar yield strength used in the design should not exceed 60,000 pounds per square inch (420 megapascal).

Although smaller bar diameters and closer spacings are preferred to control crack widths, the recommended maximum bar diameter to slab thickness are presented in Table 5-9. The minimum bar spacing should not be less than 4 inches (100 millimeters).

Table 5-9 Recommended Maximum Bar Diameter per Slab-on-Ground Thickness

Slab thickness, inch (millimeter)	Recommended maximum bar diameter, inch (millimeter)
≤ 9 (230)	#6 (No. 19)
10 (250)	#7 (No. 22)
≥ 12 (300)	#8 (No.25)

Example 5-14

The finite element analysis of an 8 inch (200 millimeter) thick slab resulted in a maximum allowable moment of M_u = 5300-foot pound per foot (23,576 Newton meter per 300 millimeter) of slab width. Design the required bar size and spacing to resist the applied moment with a factor of safety of 2 for one- and two-layers reinforced concrete slab-on-ground.

Solution:

Concrete compressive strength = 4000 psi (28 MPa)

Modulus of rupture = $7.5\sqrt{4000} = 474$ psi $(0.63\sqrt{28} = 3.3$ MPa)

Cracking moment:

$$M_{cr} = \frac{bd^2}{6} MOR = \frac{(12)(8^2)}{6}\frac{474}{12} = 5056 \text{ ft-lb/ft of slab width}$$

$$\left(M_{cr} = \frac{bd^2}{6} MOR = \frac{(300)(200^2)}{6}(3.3)/0.3048 = 21{,}653 \text{ Nm}/300 \text{ mm of slab width} \right)$$

$M_u > M_{cr}$, therefore, slab-on-ground is cracked and reinforcement is provided.

Apply a load factor of 2 to the applied loads:

M_u = 5300 x 2 = 10,600 ft-lb/ft (47,150 N·m/300 mm) of slab width.

Two tables are included in Appendix C that provide the flexural strength capacity of slabs-on-ground with thicknesses varying from 8 inch (200 millimeter) to 14 inch (350 millimeter) and reinforced with one- and two-layers of bars. Below are numerical calculations for an 8 inch (200 millimeter) slab-on-ground resisting the applied factored moment of M_u = 10,600 ft-lb/ft (47,150 N·m/300 mm).

Note: ϕM_n is calculated using the following equation: $\phi A_s f_y(0.9d)$ and compared to M_u

8 inch (200 millimeter) slab-on-ground reinforced with one-layer of reinforcement:

For one-layer reinforcement, assume bars are placed at slab-on-ground mid-depth; d = 4 inch (100 millimeter) satisfying ACI 318 cover requirements.

Assume slab is reinforced with one-layer of #8 (No. 25)—refer to Appendix C

Slab-on-ground capacity reinforced with one-layer of bars.

$\phi M_n = 0.9(60{,}000)(0.79)(0.9)(4)/12 = 12{,}800$ ft-lb/ft $> M_u$ = 10,600 ft-lb/ft

($\phi M_n = 0.9(420)(510)(0.9)(100)/305 = 56{,}920$ N·m/300 mm > (47,150 N·m/300 mm))

spacing, s = (12,800 ft-lb/ft)/(10,600 ft-lb/ft) x 12 inch = 14.5 inch say 14 inch

(s = (56,920 N·m/300 mm)/(47,150 N·m/300 mm) x 300 millimeter = 362 millimeter, say, 350 millimeter).

Reinforcement #8 at 14 inch (No. 25 at 350 millimeter) on center is required, or alternatively, the SER may use #6 at 8 inch (No. 19 at 200 millimeter) on center;

No. 6 (No. 19) bar has a capacity of 7130 ft-lb/ft (31,700 N·m/300 mm) with d = 4 inch (100 millimeter); bar spacing is calculated below:

s = (7130 ft-lb/ft)/(10,600 ft-lb/ft) x 12 inch = 8.07 inch, say, 8 inch

s = (31,700 N·m/300 mm)/(47,150 N·m/300 mm) x 300 millimeter = 202 millimeter, say, 200 millimeter.

8 inch (200 millimeter) slab-on-ground reinforced with two-layers of reinforcement:

For two-layers, bottom reinforcement is placed with 3 inch (75 millimeter) cover and top reinforcement with 1.5 inch (38 millimeter) cover to the top surface.
Moment arm of top bars:

$d_{top} = t_{slab}$ – cover – $d_b/2$ = 8 in. – 1.5 in. – $d_t/2$ = 6.5 in. – $d_b/2$ (162 mm – $d_b/2$)

Moment arm to bottom bars:

$d_{bot} = t_{slab}$ – cover – $d_b/2$ = 8 in. -3.0 in. – $d_b/2$ = 5.0 in. – $d_b/2$ (125 mm – $d_b/2$)

where d_t is the bar diameter.

If the applied factored moment, M_u = 10,600 ft-lb/ft (47,150 N·m/300 mm), to be resisted is positive (bottom bars) and d = 4.56 inch (114 millimeter) and assume slab-on-ground is reinforced with #7 (No. 22) bars.

From the Appendix C table, the slab-on-ground capacity reinforced with two-layers of bars using #7 at 12 inch (No. 22 at 300 millimeter) on center is ϕM_n = 11,080 ft-lb/ft (49,240 Newton meter per 300 millimeter)

s = (11,080 ft-lb/ft)/(10,600 ft-lb/ft) x 12 inch = 12.5 inch, say, 12 inch

(s = (49,240 N·m/300 mm)/(47,150 N·m/300 mm) x 300 millimeter = 313 millimeter, say, 300 millimeter).

or alternatively, the SER may use #6 @ 9 inch (No. 19 @ 230 millimeter) on center, where ϕM_n = 8240 ft-lb/ft (36,450 Newton meter per 300 millimeter):

s = (8240 ft-lb/ft)/(10,600 ft-lb/ft) x 12 inch = 9.3 inch, say, 9 inch

(s = (36,450 N·m/300 mm)/(47,150 N·m/300 mm) x 300 millimeter = 232 millimeter, say, 230 millimeter).

If the applied factored moment, M_u = 10,600 ft-lb/ft (47,150 N·m/300 mm), to be resisted is negative (top bars) and d = 6.125 inch (152 millimeter), then use #6 @ 12 inch (No. 19 @ 300 millimeter) on center—refer to Appendix C table for two layer of bar reinforcement:

s = (10,910 ft-lb/ft)/(10,600 ft-lb/ft) x 12 inch = 12.35 inch, say, 12 inch

(s = (48,180 N·m/300 mm)/(47,150 N·m/300 mm) x 300 millimeter = 306 millimeter, say, 300 millimeter).

Or the SER may use #5 @ 8 inch (No. 16 @ 200 millimeter) on center:

s = (7770 ft-lb/ft)/(10,600 ft-lb/ft) x 12 inch = 8.8 inch, say, 8 inch

(s = (34,240 N·m/300 mm)/(47,150 N·m/300 mm) x 300 millimeter = 218 millimeter, say, 200 millimeter).

Notes:

It is common practice to use same bar size and spacing for both top and bottom reinforcement for ease of construction and minimizing construction errors. For this example, the SER may:

Use #6 @ 9 inch on center (No. 19 @ 230 millimeter) top and bottom.

If a more rigorous quality control and assurance program is implemented, the SER may consider varying top and bottom bar sizes and spacing:

Use #6 @ 12 inch (No. 19 @ 300 millimeter) on center top reinforcement, and

#6 @ 9 inch (No. 19 @ 230 millimeter) on center bottom reinforcement.

5-15 SUMMARY.

1. The classical methods—COE, PCA, and WRI—assume continuous support to the slab-on-ground and uniform modulus of subgrade strength.
2. Slab-on-ground thickness calculation is related to the concrete compressive strength, while insensitive to minor changes in the modulus of subgrade, *k*, values.
3. The COE method is based on loads applied at the edges, joints, of slabs-on-ground, while PCA and WRI methods assume loads applied away from the edges, joints, of slabs-on-ground. This will result in slightly thicker slab-on-ground when using the COE method.
4. COE and PCA methods allow plain concrete slab-on-ground designs. Consideration should be given to add reinforcement for reasons stated in Section 5.9.
5. Steel fibers can be used to improve resistance to fatigue and impact loading of the slab-on-ground. It also improves its serviceability and durability but not its strength.
6. RP bars may be used to reinforce a slab-on-ground to control crack widths and spacing, but more research is required to validate the approach.
7. The FE method is flexible and can analyze loads such as moving and stationary (line, distributed, or concentrated loads) applied individually or combined anywhere on a slab-on-ground.
8. When using the FE method, apply the modulus of subgrade given in the geotechnical report to the center of the slab-on-ground and increase the value to twice the recommended values at the edges. This will result in a more realistic behavior of the slab-on-ground.
9. When using the FE method in the analysis, use ACI 318 for the slab-on-ground design and apply a recommended load factor of 2 to the applied loads.
10. The SER should exercise engineering judgment and consider type of loading applied, frequency of travel, whether the slab-on-ground is subjected to impact loading, and environmental conditions, when choosing

a factor of safety. For normal conditions use a recommended factor of safety of 2 for the classical design methods, COE, PCA, and WRI.

11. The most effective way to improve a slab-on-ground performance is to increase its thickness, which will increase its load-carrying capacity, decrease deformation, reduce warping, improve aggregate interlock load transfer, and decrease potential random cracking by maintaining maximum contraction joint spacing of 15 feet (4.5 meters); Chapter 6.

CHAPTER 6 JOINTS AND DOWELS

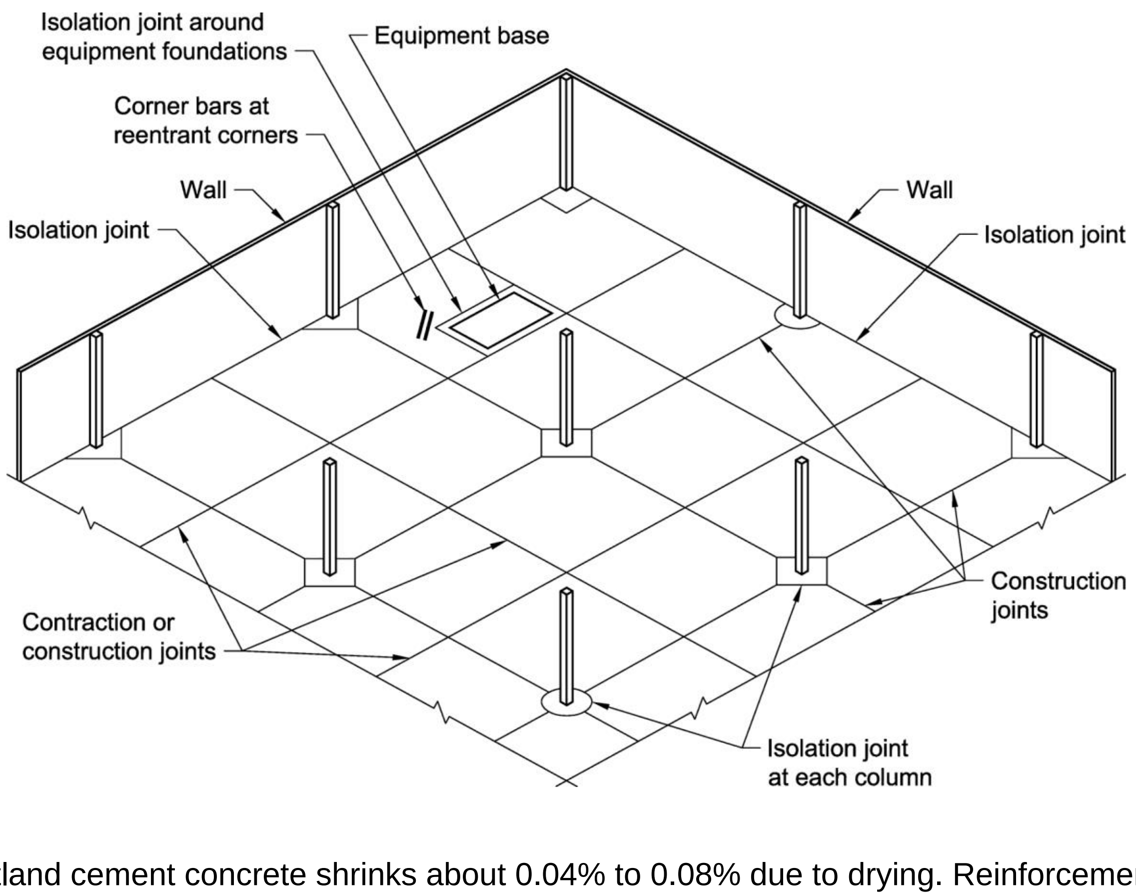
6-1 JOINT TYPES AND USAGE.

Joints are provided in slabs-on-ground to allow for contraction and expansion of the concrete panels, to limit the frequency and width of random cracks, and to relieve curling and warping stresses due to temperature and moisture differentials. Determining joint types and spacings are part of the SER's design responsibilities that must be performed and conveyed to the contractor through the construction documents. The three general types of joints are:

1. Sawcut contraction joints
2. Construction joints
3. Isolation joints

A typical floor-slab joint layout is shown in Figure 6-1. Load transfer across contraction joints can be achieved by aggregate interlock or steel dowels and across construction joints by steel dowels and less effectively by keyways.

Figure 6-1 **Typical Joints in Slabs-on-Ground**



Portland cement concrete shrinks about 0.04% to 0.08% due to drying. Reinforcement reduces drying shrinkage by about one-half. However, as a general rule, in slabs-on-ground with large percentages of deformed reinforcement, the reinforcement should not be continued across sawcut contraction joints because it restrains the joints from opening as the slab shrinks during drying and this increases the probability of out-of-joint random cracking.

6-2 SAWCUT CONTRACTION JOINTS.

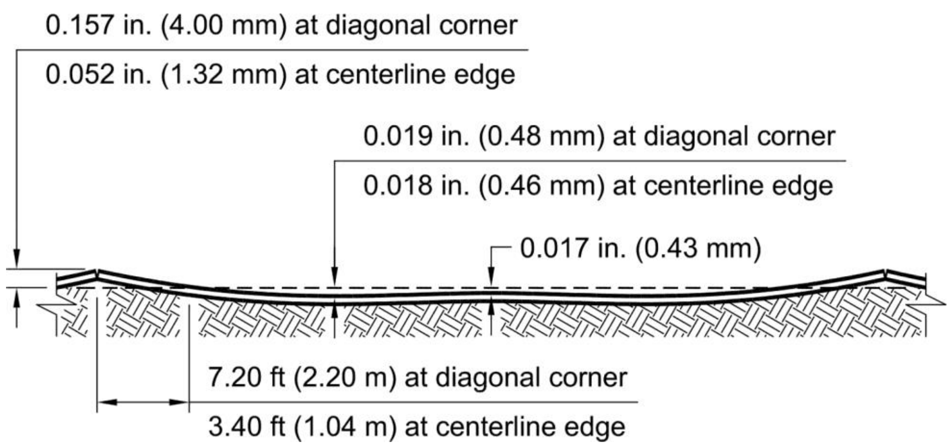
Weakened-plane contraction joints are provided to control cracking in the concrete and to limit curling and warping stresses resulting from drying shrinkage and contraction and from temperature and moisture gradients in the slab-on-ground, respectively. Contraction joints are usually positioned at column lines, with intermediate joints, if required, located at equal spaces between column lines (Figure 6-1). Shrinkage and contraction of the concrete causes slight cracking and separation of the slabs at the weakened planes, which should provide some relief from tensile forces resulting from foundation restraint and compressive forces caused by subsequent expansion.

The SER should determine the slab-on-ground thickness and reinforcement requirements and consider the following when selecting spacing of sawcut contraction joints:

- Slab design method: Chapter 5
- Slab thickness: Chapter 5
- Type, amount, and location of reinforcement: Chapter 5
- Shrinkage potential of the concrete, including cement type and quantity; aggregate type, size, gradation, quantity, and quality; water-cementitious material ratio (*w*/*cm*); type of admixtures; and concrete temperature: Chapter 3
- Dowel requirements: Chapter 6
- Base friction
- Floor slab restraints
- Layout of foundations, racks, pits, equipment pads, trenches, and similar floor discontinuities
- Environmental factors such as temperature, wind, and humidity.

The recommended contraction joint spacing is based on experience and semi-rational approach; refer to Section 6-2.3. Studies have shown that slab thickness and joint spacing does affect warping (Walker and Holland 1999). In general, more closely spaced joints are preferred over joints spaced farther away. Other factors affecting warping stresses are modulus of subgrade strength reaction and specified concrete compressive strength. Increasing the modulus of subgrade reaction should increase warping stresses, especially for shorter joint spacings. As the modulus of subgrade strength increases, the subgrade soil supporting the slab-on-ground deformation decreases under applied loads, not pressing into the subgrade as much, resulting in longer cantilevers due to warping; refer to Figure 6-2. Therefore, increasing the stiffness of the subgrade may sometimes not be beneficial. Also, higher-strength concrete should result in higher warping stresses due to the increase in concrete shrinkage and stiffness (Walker and Holland 1999). A reinforcement ratio of 1.0% in the direction perpendicular to the slab edge would decrease slab-on-ground warping deflection with 1-1/2 to 2 in. (38 to 51 mm) of concrete cover (Abdul-Wahab and Jaffar 1983). Reinforcement in the lower part of the slab may increase upward slab curling for slabs under roof and not subject to surface heating by the sun.

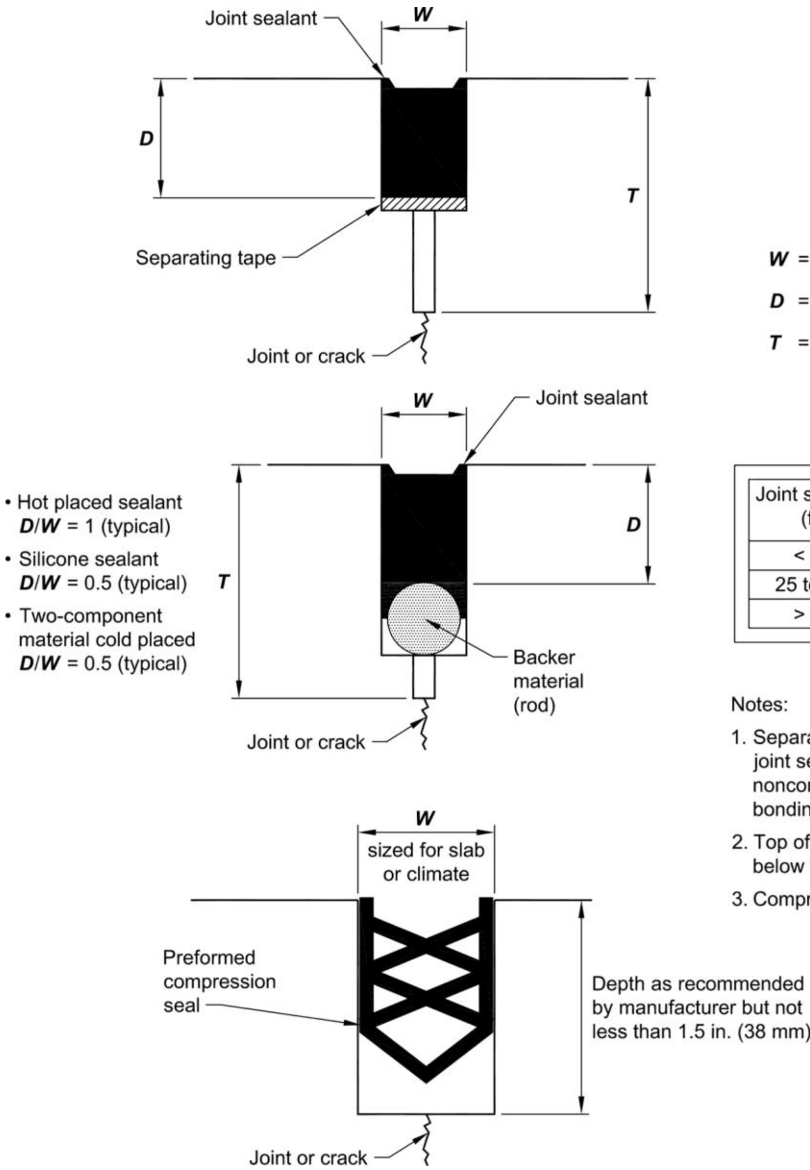
Figure 6-2 **Slab Curled Shape (Walker and Holland 1999)**



6-2.1 Width and Depth of Weakened Plane Groove.

The width of the weakened plane groove should be a minimum of 1/8 inch (3 millimeters) and a maximum equal to the width of the filler or sealant reservoir contained in Section 6-2.2. The depth of the weakened plane groove must be great enough to cause the concrete to crack under the tensile stresses resulting from the shrinkage and contraction of the concrete as it cures. Experience, supported by analyses, indicates that this depth should be at least one-fourth of the slab thickness for slabs-on-ground 12 inches (300 millimeters) or less, 3 inches (75 millimeters) for slabs-on-ground greater than 12 inches (300 millimeters) and less than 18 inches (450 millimeters) in thickness, and one-sixth of the slab thickness for slabs-on-ground greater than 18 inches (450 millimeters) in thickness. In no case should the depth of the groove be less than the maximum nominal size of aggregate used (Figure 6-3).

Figure 6-3 **Joint Sealant Details**



W = width of sealant reservoir (see Table)

D = depth of sealant; 1.0 to 1.5 times ***W***

T = depth of initial sawcut, 1/4 of the slab thickness for slabs less than 12 in. (300 mm); 3 in. (75 mm) for slabs 12-18 in. (300-450 mm); or 1/6 of the slab thickness for slabs over 18 in. (450 mm)

Table

Joint spacing (ft)	***W*** (in.)	
	Min.	Max.
< 25	1/2	5/8
25 to 50	3/4	7/8
> 50	1	1-1/8

Joint spacing (m)	***W*** (mm)	
	Min.	Max.
< 7.6	12	16
7.6 to 15.2	19	22
> 15.2	25	29

Notes:

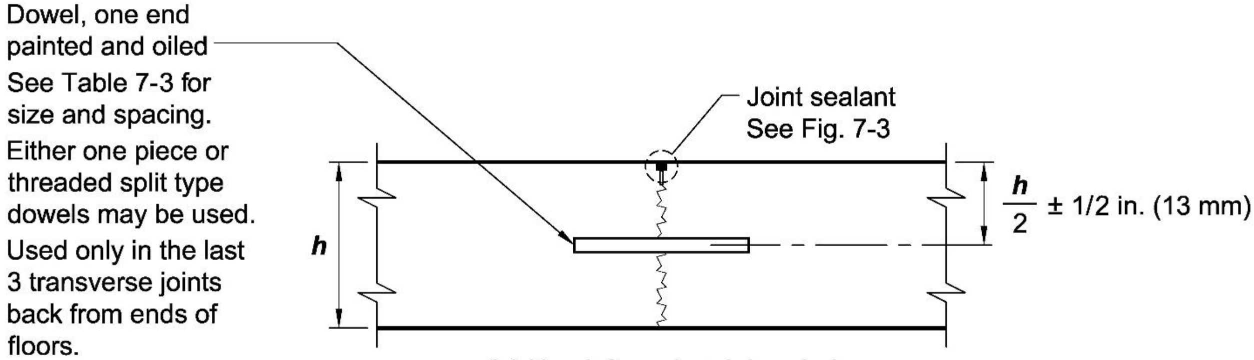
1. Separating tape or backer material required to prevent joint sealant from flowing into sawcut, to separate noncompatible materials, and to prevent sealant from bonding to bottom of reservoir.
2. Top of sealant will be 1/8 in. (3 mm) to 1/4 in. (6 mm) below top of pavement.
3. Compression seal must be in compression at all times.

There will be a marked loss of effectiveness of aggregate interlock at sawcut contraction joints when the joints are too far apart (Spears and Panarese 1983). Positive load transfer using dowels or plates should be provided where joints are expected to open more than 0.025 to 0.035 in. (0.6 to 0.9 mm) for slabs subjected to wheel traffic; refer to Section 6-6.

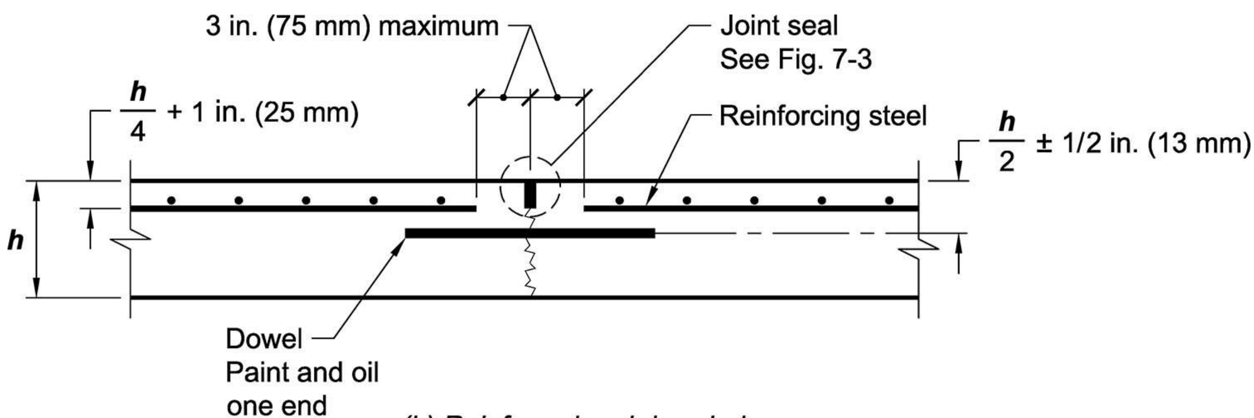
Slabs may be more economical when sawcut contraction joint spacing is increased beyond lengths noted previously by using distributed reinforcement designed for crack-width control, but not less than 0.50% of the cross-sectional area. Floor and lift truck maintenance cost may be lower with the least number and length of joints, as long as curling/warping is not sufficient to cause cracking or joint spalling. Increased joint spacings larger than the critical slab length will not increase warping stresses.

Figures 6-4(a) and 6-4(b) present contraction joints for reinforced and unreinforced slabs-on-ground, respectively.

Figure 6-4 **Contraction Joints for Unreinforced and Reinforced Concrete Slabs-on-Ground**



(a) Unreinforced and doweled



(b) Reinforced and doweled

Cracking of concrete may be influenced by the concrete placement conditions, which may dictate the depth of the grove required. For example, concrete placed early in the day, when the air temperature is rising, may experience expansion rather than contraction during the early life of the concrete with subsequent contraction occurring several hours later as the air temperature drops. By then, the concrete may have attained sufficient strength before the contraction occurs so that adjacent weakened planes do not result in cracking. However, excessive opening may result where cracking does occur. To prevent this, the depth of the groove should be increased to ensure the cracking and proper functions of each of the scheduled joints.

6-2.2 Width and Depth of Contraction Joint.

The width and depth of the contraction joint for the weakened plane groove should conform to dimensions shown in Figure 6-4. The dimensions of the sealant reservoir are critical to satisfactory performance of the joint sealing materials.

Contraction joints could be either filled, sealed, or left open. Contraction joints are filled when hard-wheeled traffic is expected; for pneumatic traffic, contraction joints can be sealed; for pedestrian traffic and office areas that receive floor covering, contraction joints could remain open. The difference between fillers and sealers is the hardness of the material. Fillers, because of their rigidity, provide compressive lateral support to the concrete edges of contraction joints. Table 6-1 provides the type of joint filler for different type of traffic.

Table 6-1 Joint Filler Types Based on Different Categories of Traffic

Traffic	Pressure	Filler type
Hard wheel such as solid rubber and steel wheels	1000 psi (7 MPa)	Semi-rigid epoxy resin or polyurea
Pneumatic traffic	90 to 120 psi (0.6 to 0.9 MPa)	Flexible joint sealer over backer rod
Foot traffic	low	No fill*

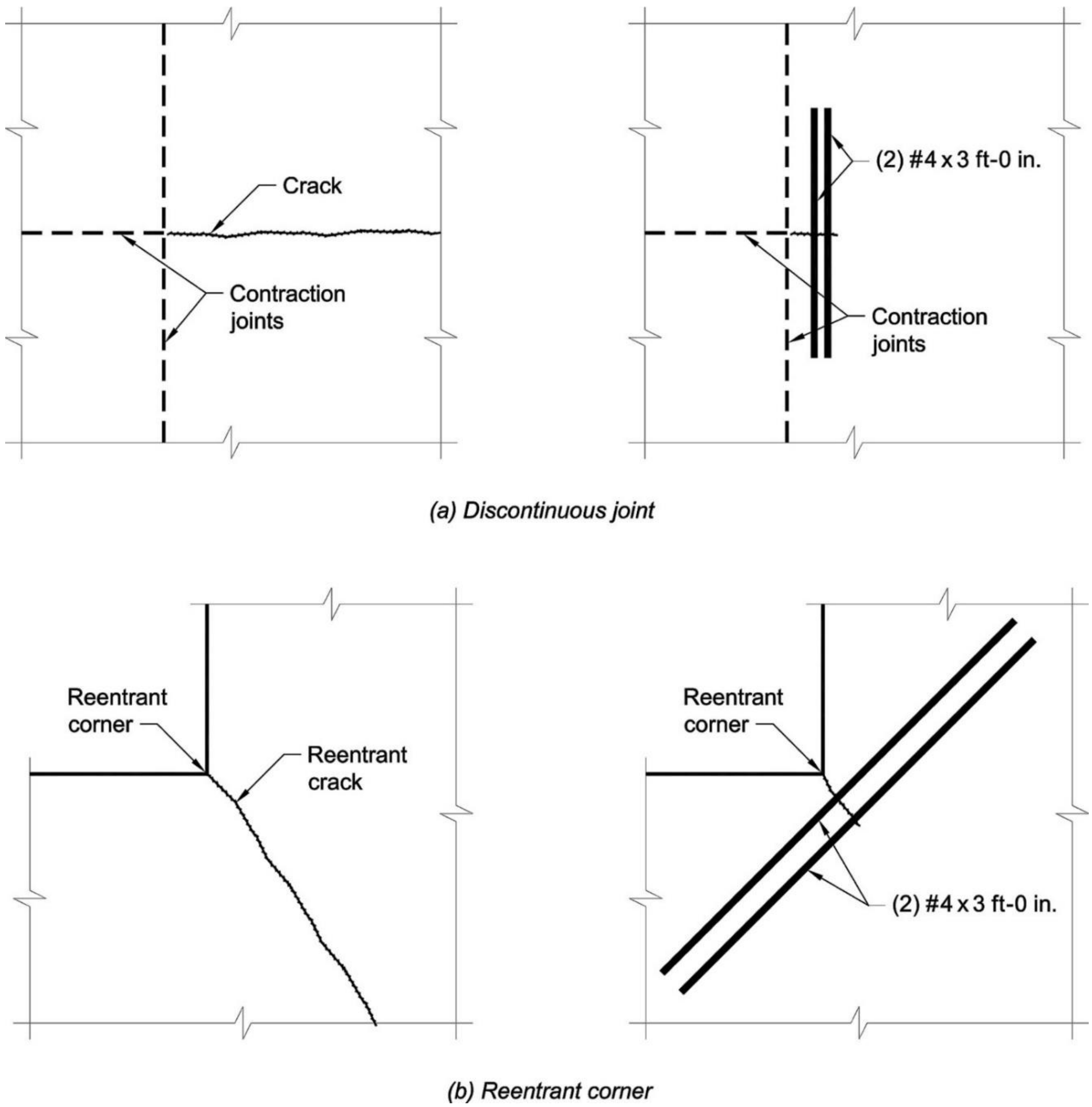
*If there is a concern that joint may be filled with dirt or insects, then joint can be filled with a flexible sealer.

ACI 302.1R recommends using two-component fillers because their curing is independent of job-site conditions. The materials should be 100% solids and have a minimum Shore A hardness of 80 when measured in accordance with ASTM D2240. It should be installed full-depth in a sawcut joint without a backer rod and flush with the slab-on-ground surface.

6-2.3 Spacing of Contraction Joints.

Contraction joints should be constructed across each concrete panel perpendicular and parallel to construction joints. The joint spacing should be uniform throughout the slab-on-ground area, and each joint should be straight and continuous between concrete construction joints. Staggering of joints in adjacent placed concrete panels can lead to undesirable cracking and should not be permitted unless reinforcement is used to intercept the crack (Figure 6-5(a)). Additionally, reinforcement should be provided at re-entrant corners to intercept cracks initiating from corners (Figure 6-5(b)). The maximum spacing of contraction joints that should effectively control cracking will vary appreciably depending on slab-on-ground thickness, thermal coefficient, and other characteristics of the aggregate and concrete; climatic conditions; and foundation restraint. For best slab performance, the number of joints should be kept to a minimum by using the greatest joint spacing that should satisfactorily control cracking.

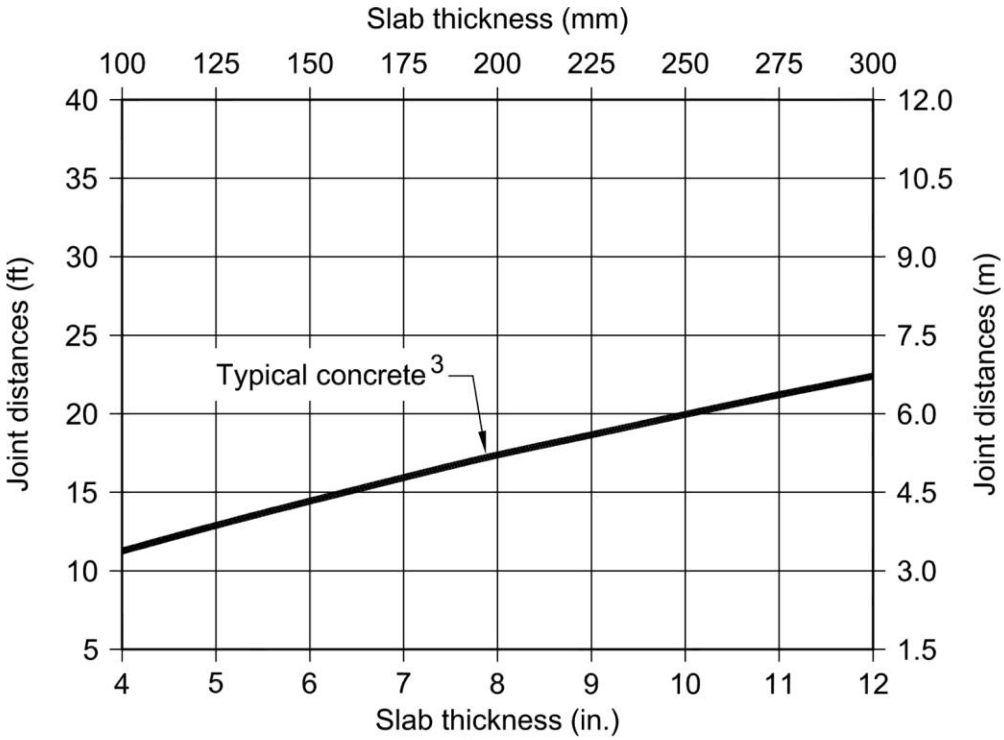
Figure 6-5 **Avoid Discontinuous Joints and Reentrant Corners**



6-2.3.2 Plain and unreinforced slabs-on-ground joint spacings.

Joints are typically spaced uniform throughout the slab-on-ground, and each joint will be straight and continuous from edge to edge of the slab-on-ground. Contraction joints are sawcut at intervals of not less than 12.5 feet (3.8 meters) and generally not more than 20 feet (6 meters). Recommended joint spacings for plain and unreinforced concrete slab-on-ground to control crack width are approximated from Figure 6-6 (ACI 360R Figure 6.6). The maximum allowed joint spacings obtained from Figure 6-6, are an idealization of the historical rule of thumb of using two to three times the slab-on-ground thickness. If those recommendations are followed, lower stresses within the slab-on-ground are produced. In thick slabs-on-ground, 8 inch (200 millimeter) and thicker, contraction joints can be spaced farther apart. However, regardless of slab-on-ground thickness, experience dictates that the preferred contraction joints spacing should remain at 15 foot (4.5 meters), which provides improved control of random cracking and maintains adequate load transfer across the contraction joint by aggregate interlock.

Figure 6-6 **Recommended Joint Spacing for Unreinforced Slabs (ACI 360R Figure 6.6)**



Notes:

1. Joint spacing recommendations based on reducing the curling stresses to minimize mid-panel cracking (Walker-Holland 2001).
2. Joint spacing criteria of 36 and 24 times the slab thickness has been utilized in the past.
3. Concrete with an ultimate dry shrinkage strain of 520 to 780 millionths placed on a dry base material.

Slabs-on-ground with concrete mixture including pea gravel or river gravel should experience higher shrinkage than concrete mixture with crushed limestone aggregate (Chapter 4 Section 4-3). Therefore, tighter joint spacing is recommended not to exceed twice (twenty-four times) the slab-on-ground thickness in feet (meters) or 15 feet (4.5 meters).

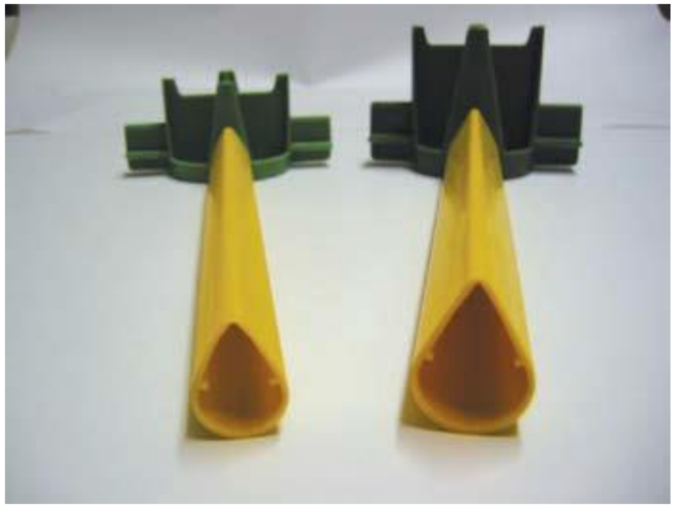
Oblong slabs, especially in thin slabs-on-ground, tend to crack into smaller slabs of nearly equal dimensions under traffic. Therefore, it is desirable, insofar as practicable, to keep the length and width dimensions as nearly equal as possible. The preferred aspect ratio of plain or unreinforced for crack-control slab panels is 1-to-1. In no case should the length dimension (in the direction of placement) exceed the width dimension by more than 25%. L- and T-shaped panels should be avoided. Under certain climatic conditions, joint spacings different from those estimated in Figure 6-6 may be satisfactory.

An alternate method to slabs-on-ground with contraction joints on the visible face, is the joint-free slab-on-ground construction. This is accomplished by positioning crack-inducer tubes on a 3.25 foot (1-meter)-square grid on the subbase before placing the concrete; refer to Figures 6-7 and 6-8. Closely spaced fine cracks are formed above the grid as slab-on-ground concrete hardens and shrinks, thus eliminating the need for joints.

Note that contraction joints made by such inserts forced into the plastic concrete or by manually grooving the plastic concrete surface are unacceptable for military airfields (UFC 3-260-02).

Figure 6-7 **Crack-Inducer Grid Installed Prior to Concrete Placement.**

Figure 6-8 **Crack-Inducer Tubes**



6-2.3.3 Reinforced Slab-on-Ground Subgrade Drag.

This method is commonly used to determine the required area of reinforcement to control cracking due to shrinkage effect within the recommended joint spacing; refer to Example 6-2.3.2. It provides sufficient steel area to resist tensile stresses carried by the steel across cracks that develop as a result of subgrade restraint to slab-on-ground movement (Equation 6-1):

Equation 6-1. [Reinforced Slab-on-Ground Subgrade Drag]

$$A_s = \frac{\mu L w}{2 f_s}$$

FRP reinforcement has a lower modulus of elasticity than steel bars; therefore, the subgrade drag equation should be modified to be strain based rather than stress based—it is not a one for one replacement for steel reinforcement. At the allowable stress of $2/3f_y$, the strain in steel reinforcement is assumed 0.0012; applying the same strain for FRP bars and substituting for the steel stress, f_s, with $0.0012E_f$, should result in the following subgrade drag equation for FRP bars (Equation 6-2):

Equation 6-2. [Subgrade Drag for FRP Bars]

$$A_s = \frac{\mu L w}{2(0.0012 E_f)}$$

The equation should determine the required amount of FRP reinforcement area for a given joint spacing, L.

Example 6-2.3.2

Design an 8 inch (200 millimeter) slab-on-ground for 24 foot (7300 millimeter) contraction joint spacing reinforced with: 1) bars (ASTM A615 or A706) and 2) welded wire fabric (ASM A184) using the subgrade drag equation (Equation 6-1):

1. Assume a contraction joint spacing of 24 foot (7300 millimeter)

Grade 60 (420) bars ASTM A615 or A706:

$$A_s = \frac{\mu L w}{2 f_s}$$

where μ = 1.5, L = 24 ft (7300 m), w = 100 pounds per square foot (4788 pascal [488 kilogram per square meter]) 8 inch (200 millimeter) slab-on-ground self-weight, and f_s = 2/3f_y = 2/3 (60,000) = 40,000 pounds per square inch (275 megapascal).

$A_s = \frac{(1.5)(24\text{ ft})(100\text{ psf})}{2(40{,}000\text{ psi})} = 0.045$ square inch/ft (29 square millimeter per 300 millimeter) required each way.

Use #3 at 29 inch (No. 10 at 740 millimeter) on center. ACI's structural slab limitation of 5h or 18 inch (450 millimeter), whichever is less. Therefore, use #3 at 18 inch (No. 10 at 450 millimeter) on center, $A_{s,prov.}$ = 0.073 square inch per foot (47 square millimeter per 300 millimeter).

For plain welded wire fabric, ASTM A184:

Use the same subgrade drag equation except that f_y = 65,000 psi (450 megapascal).

$A_s = \frac{(1.5)(24\text{ ft})(100\text{ psf})}{2(2/3)(65{,}000\text{ psi})} = 0.042$ square inch/ft (27 square millimeter per 300 millimeter) required each way.

Use W4.5 wire at 12 inch (MW30 wire at 300 millimeter) spacings in each direction:

12 x 12 – W4.5 x W4.5 (300 x 300 – MW30 x MW30).

Use #3 at 29 inch (No. 10 at 740 millimeter) on center. ACI's structural slab limitation of 5h or 18 inch (450 millimeter), whichever is less. Therefore, use #3 at 18 inch (No.10 at 450 millimeter) on center, $A_{s,prov.}$ = 0.073 square inch per foot (47 square millimeter per 300 millimeter).

For plain welded wire fabric, ASTM A184:

Use the same subgrade drag equation except that f_y = 65,000 psi (450 megapascal).

$$A_s = \frac{(1.5)(24\text{ ft})(100\text{ psf})}{2(2/3)(65{,}000\text{ psi})} = 0.042$$ square inch/ft (27 square millimeter per 300 millimeter) required each way.

Use W4.5 wire at 12 inch (MW30 wire at 300 millimeter) spacings in each direction:

12 x 12 – W4.5 x W4.5 (300 x 300 – MW30 x MW30).

2. Assume a contraction joint spacing of 48 foot (14,600 millimeter)

Grade 60 (420) ASTM A615 or A706:

Use L = 48 feet (14,600 millimeter) in Equation 6-1

$$A_s = \frac{(1.5)(48\text{ ft})(100\text{ psf})}{2(40{,}000\text{ psi})} = 0.09$$ square inch/ft (58 square millimeter per 300 millimeter) required each way.

Use #4 at 25 inch (No. 12 at 630 millimeter) on center. ACI's structural slab limitation of 5*h* or 18 inch (450 millimeter), whichever is less. Then, use #4 at 18 inch (No.12 at 450 millimeter) on center, $A_{s,prov.}$ = 0.133 square inch per foot (86 square millimeter per 300 millimeter).

For deformed welded wire reinforcement, ASTM A1064:

Use the same subgrade drag equation except that f_y = 70,000 psi (480 megapascal).

$$A_s = \frac{(1.5)(48\text{ ft})(100\text{ psf})}{2(2/3)(70{,}000\text{ psi})} = 0.077$$ square inch/ft (27 square millimeter per 300 millimeter) required each way.

Use D8 wire at 12 inch (MD50 wire at 300 millimeter) spacings in each direction:

12 x 12 – D8 x D8 (300 x 300 – MD50 x MD50).

Note:

The steel areas selected using the subgrade drag equation are for shrinkage and temperature effects only.

The required steel area increase is proportional to the joint spacing.

6-2.3.4 Reinforced Slabs.

If reinforcement is greater than 0.05% and less than 0.5%, then contraction joints in reinforced concrete slabs should not be constructed at intervals of less than 25 feet (7.6 meters). A recommended maximum spacing of 75 feet (23 meters) is suggested by the COE method. It can be extended to the other classical and FEM methods. Maximum allowable slab width or length may be determined from:

Equation 6-3. [Maximum Allowable Slab Width or Length]

$$L = \sqrt[3]{0.00047 h_r (f_y \rho)^2} \ \leq \ 75 \text{ feet} \qquad \text{(in.-lb)}$$

$$L = \sqrt[3]{0.0109 h_r (f_y \rho)^2} \ \leq \ 23 \text{ meters} \quad \text{(SI)}$$

The equation has been expressed on the nomograph in Chapter 5 Figure 5-14, where the allowable slab thickness, h_r, is obtained from the figure for a yield strength of 60,000 pounds per square inch (420 megapascal). Selection of final spacing should be based on local conditions. Where only a portion of the slabs-on-ground are reinforced, joint spacing should be a maximum commensurate with the unreinforced slab configurations.

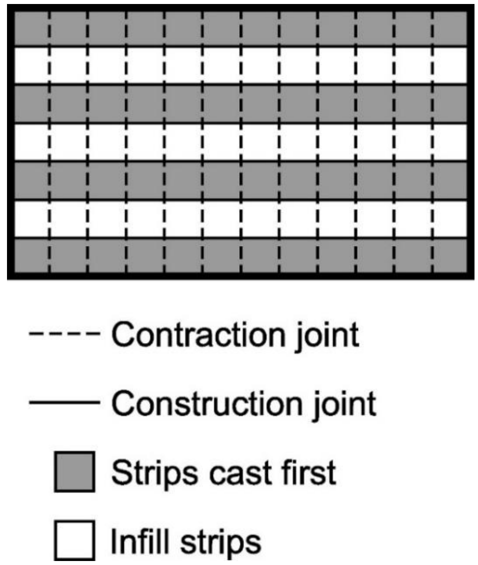
6-2.3.5 Contraction Joint Free Slabs.

Slab-on-ground with reinforcement ratio greater than 0.5% in both directions do not require contraction joints for the methods including the FEM. The slabs-on-ground are then designed per ACI 318.

6-3 CONSTRUCTION JOINTS.

Construction joints are used where there is a physical limit on the concrete placement such as the beginning or end of a concrete placement, at the edges of the concrete placement, or to conform to a predetermined joint layout provided by the SER (Figure 6-1). The construction joint spacings depend primarily on the size and shape of the slab-on-ground that is being placed and the equipment used to place it. Column spacings and bay sizes also have an effect on construction joint spacing. Construction joints, placed in strips (refer to Figure 6-9) are generally spaced at 20 to 25 feet (6 to 7.6 meters) apart but may reach 50 feet (15.2 meters), depending on construction equipment capability. Construction joints should be located in place of other regularly spaced joints (contraction or isolation types). Unplanned construction joints are also formed when concrete placement is interrupted and placed concrete hardens. Therefore, construction documents should provide a detail to address this issue and it should be discussed in the slab preconstruction meeting; refer to Chapter 7 Section 7-2.

Figure 6-9 **Placing Sequence: Long-Strip Construction**



Different construction joint types are shown in Figure 6-10 and 6-11 and as described below. The selection of the type of construction joint should depend on such factors as the concrete placement procedure (formed or slipformed) and foundation conditions.

Figure 6-10 **Doweled Construction Butt Joints for Concrete Floor Slabs**

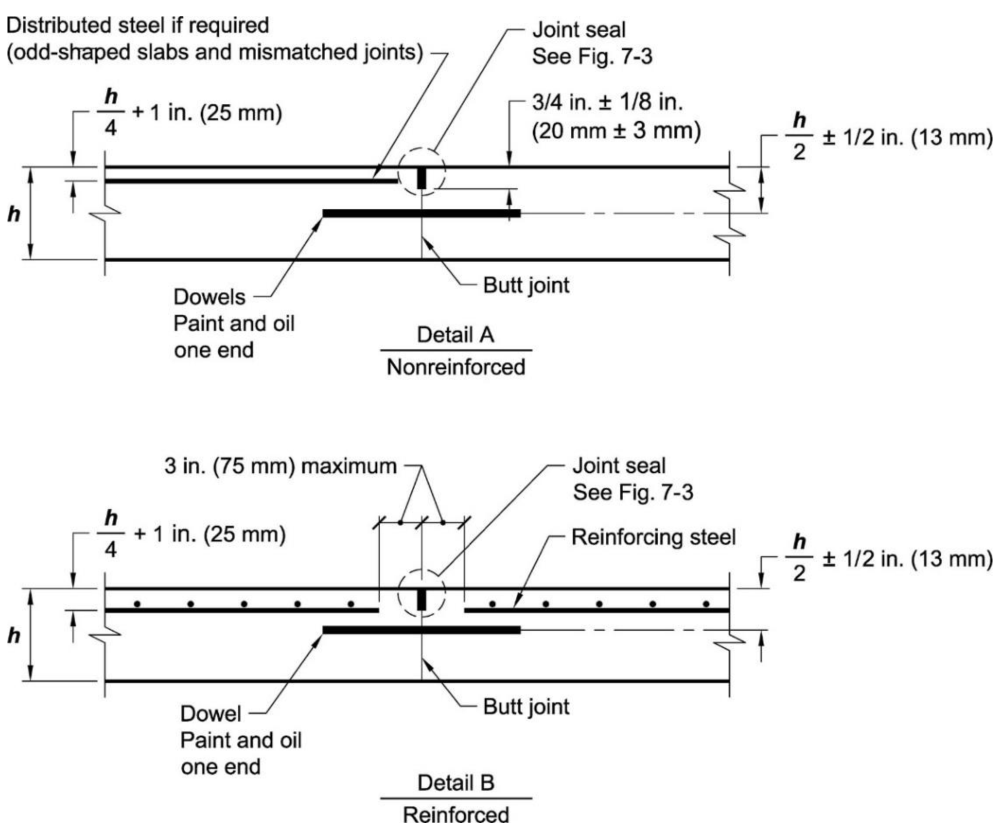
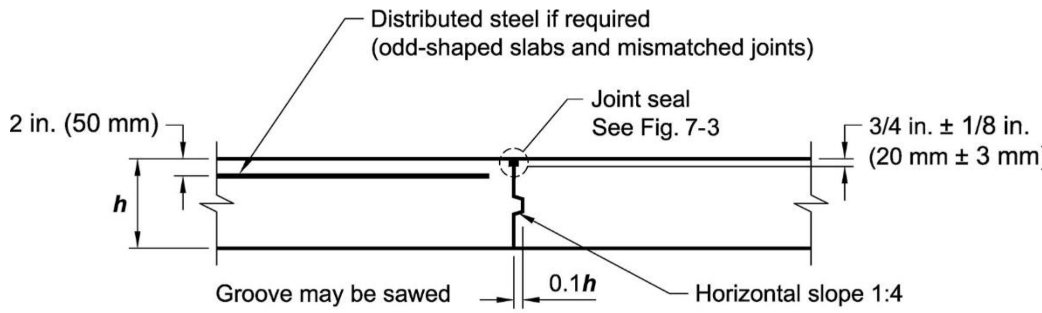
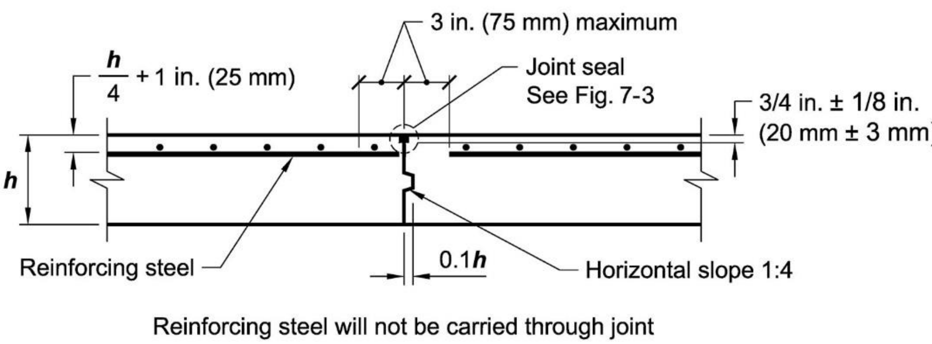


Figure 6-11 **Keyed Construction Joints for Concrete Floor Slabs**



Detail A
Nonreinforced



Detail B
Reinforced

A slab design that uses a small amount of deformed reinforcement to enhance aggregate interlock at joints should conform to the following:

- Estimate contraction joint spacing from Figure 6-6
- Place reinforcement above mid-depth but low enough that the sawcut will not cut the reinforcement
- Place a construction or sawcut contraction joint with a load-transfer device at a maximum of 125 ft (38 m). This forces activation at these joints when the other joints with the deformed reinforcement do not activate
- Use the early-entry sawcut method to create the contraction joints.

A small percentage of deformed reinforcement (0.1%) of the slab-on-ground cross-sectional area, extended through sawcut contraction joints in combination with recommended joint spacings, has provided effective load-transfer capability without using dowels; refer to Section 6-6.2.1 for steel dowel at construction and contraction joints.

As a general rule, the continuation of larger percentages of deformed reinforcing bars should not be used across sawcut contraction joints or construction joints because they restrain joints from opening as the slab shrinks during drying, and this increases the probability of out-of-joint random cracking.

6-3.1 Doweled Butt Joint.

The doweled butt joint is considered the best joint for providing transfer and maintaining slab alignment. It is a desirable joint for the adverse conditions such as heavy loading, high traffic intensity, and lower strength foundations. However, because the alignment and placement of the dowel bars are critical to satisfactory performance, this type of joint is difficult to construct, especially for slipformed concrete. However, the doweled butt joint is required for the construction joints in unreinforced slabs-on-ground. Doweled construction joints are shown in Figure 6-4b. Also refer to Section 6-6 for the design of transfer mechanisms and to Section 7-5.4 for transfer mechanism construction recommendation.

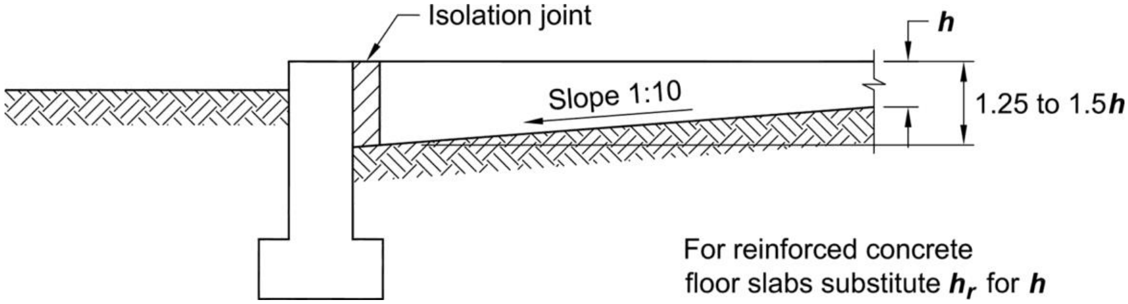
6-3.2 Keyed Joint.

The keyed joint is an economical method, from a construction standpoint, of providing load transfer in a construction joint. It has been demonstrated that the key or keyway can be satisfactorily constructed using either formed or slipformed methods. The dimensions and location of the key are critical to its performance (Figure 6-11). The structural adequacy of keyed end construction joints in rigid slabs-on-ground, however, can be impaired by small changes in the dimensions of the key and positioning the key other than at the mid-depth of the slab-on-ground. Exceeding the design values for the key dimensions produces an oversize key, which can result in failure of either the top or bottom edge of the female side or the joint. Similarly, construction of an undersized key can result in shearing off the key. Keyed joints should not be used in slabs-on-ground 8 inches (200 millimeter) or less in thickness. In general, keyed joints are not recommended for load transfer in areas subjected to wheel traffic due to the shortcomings mentioned above. Also, the two sides of the keyway would lose contact when the construction joint opens due to drying shrinkage.

6-3.3 Thickened-Edge Joint.

Thickened-edge-type joints may be used instead of other types of load joints employing load-transfer devices. Experience has shown that thickening free edges reduces edge warping and slab stress due to increased edge loads. For satisfactory functional performance, the subgrade should be smooth with a low coefficient of friction. ACI 360R recommends thickening the free slab-on-ground edges 50% with a gradual 1-in-10 slope from the free-edge thickness to the design thickness (Figure 6-12). The thickened-edge butt joint is considered adequate for the load-induced concrete stresses. However, inclusion of a key in a thickened-edge joint provides some degree of load transfer in the joint and helps maintain slab alignment; although not required, it is recommended for slab-on-ground constructed on low- to medium-strength subgrade. The thickened-edge joint can be used at free edges of slab-on-ground areas to accommodate future expansion of the facility or where wheel loadings may track the edge of the slab-on-ground. Slabs-on-ground accommodating vehicular traffic should be thickened at doorways to have an edge thickness of 1.25 to 1.5 times the design thickness, h, as shown in Figure 6-12. The use of this type of joint is contingent upon adequate base-course drainage. Note that thickened-edge construction joint is recommended where load transfer cannot be provided by dowels and aircraft traffic will cross or be adjacent to the joint.

Figure 6-12 **Doorway Slab Design for Vehicular Traffic**

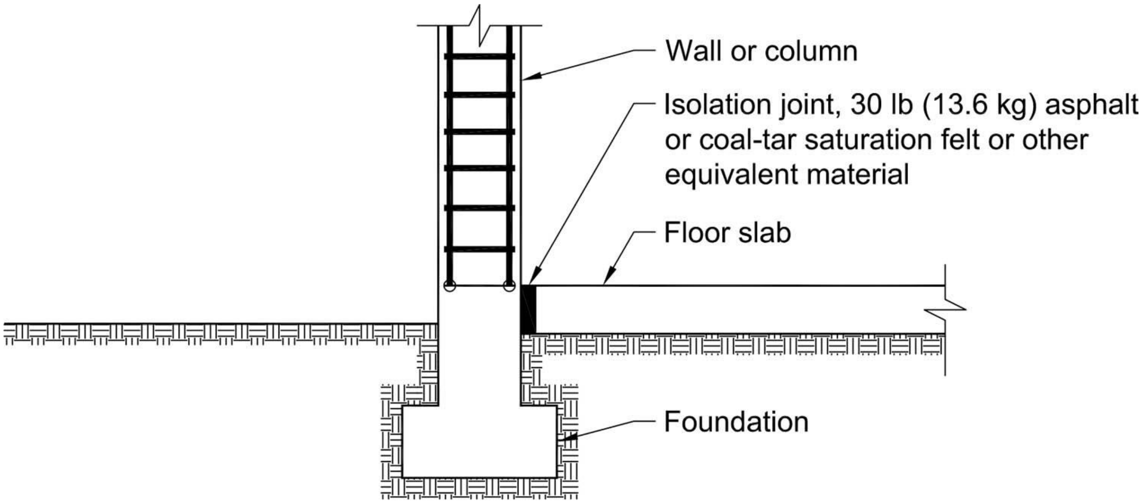


ACI 360R suggests constructing free attached slab-on-ground edges between the slab-on-ground and the equipment foundation or other free edges at isolation joints where positive load-transfer devices, such as dowels, cannot be used.

6-4 ISOLATION JOINTS.

Isolation joints are usually the source of maintenance challenges, so they are used only when concrete movement has to be isolated. They are provided to prevent load transfer and permit horizontal and vertical movement between the slab-on-ground and other building components (refer to Figure 6-1). Isolation joints should be placed at locations where slabs abut walls or their foundations and around columns, column foundations, and other foundations that carry permanent dead load other than stored material. They are provided by placing preformed joint filler such as 30 pound (13.6 kilogram) asphalt, coal-tar saturated felt, or equivalent compressible material between the slab-on-ground and the building's structural components before the floor is placed. Such sheets should be placed or fastened to the building's components to prevent bonding or direct contact between the slab-on-ground and the building component. This requires that the sheets have a height equal to the slab-on-ground thickness and be placed at the same elevation as the slab-on-ground, as shown in Figure 6-13.

Figure 6-13 **Isolation Joints**



Isolation joints must have a height equal to floor slab thickness

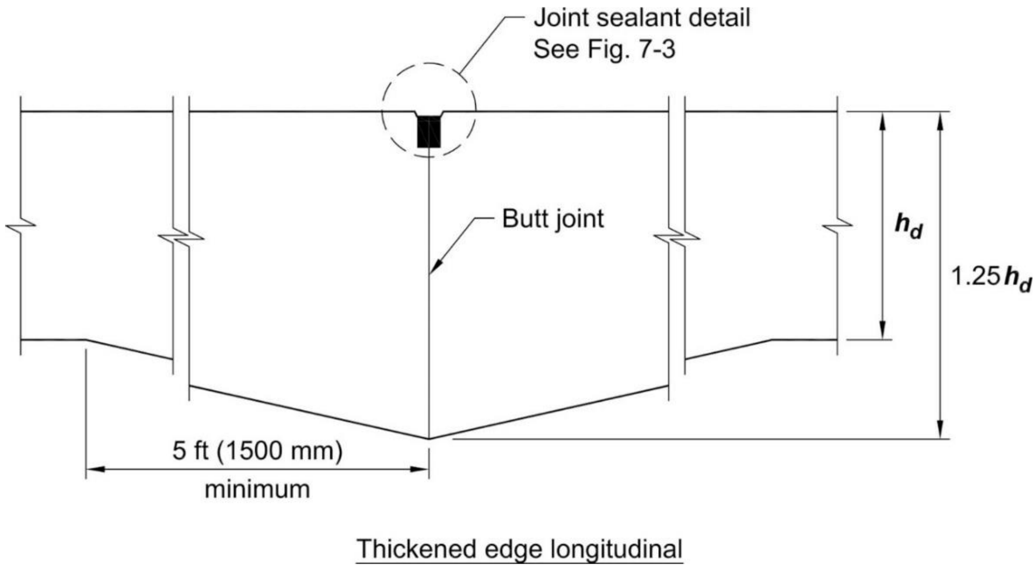
6-5 SPECIAL JOINTS AND JUNCTURES.

Situations could develop where special joints or variations of the more standard type joints should be needed to accommodate the movements that should occur and to provide a satisfactory operational surface. Some of these special joints or junctures are discussed below.

6-5.1 Slip-Type Joints.

At the juncture of two slab-on-ground facilities, expansion and contraction of the concrete slab-on-ground can result in movements that occur in different directions. Such movements may create detrimental stresses within the concrete unless provisions are made to allow the movements to occur. At such junctures, a thickened-edge slip joint shall be used to permit the horizontal slippage to occur (Figure 6-14).

Figure 6-14 **Thickened Edge Longitudinal**



The design of the thickened-edge slip joint should be similar to the thickened-edge construction joint discussed in Section 6-3.3. The bond-breaking medium should be either a heavy coating of bituminous material not less than 1/16 inch (1.5 millimeter) thick when joints match or a normal non-extruding-type expansion joint material not less than 1/4 inch (6 millimeter) thick when joints do not match. The 1/16 inch (1.5 millimeter) bituminous coating may be either a low penetration (60 to 70 Grade asphalt) or a clay-type asphalt-base emulsion similar to that used for roof coating (Military Specification MIL-R-3472) and should be applied to the face of the joint by hand brushing or spraying.

6-5.2 Special joint between new and existing floors.

A special, thickened-edge joint design may be used at the juncture of new and existing floors for the following conditions (Figure 6-15):

a. When load-transfer devices (keyways or dowels) or a thickened edge was not provided at the free edge of the existing floor

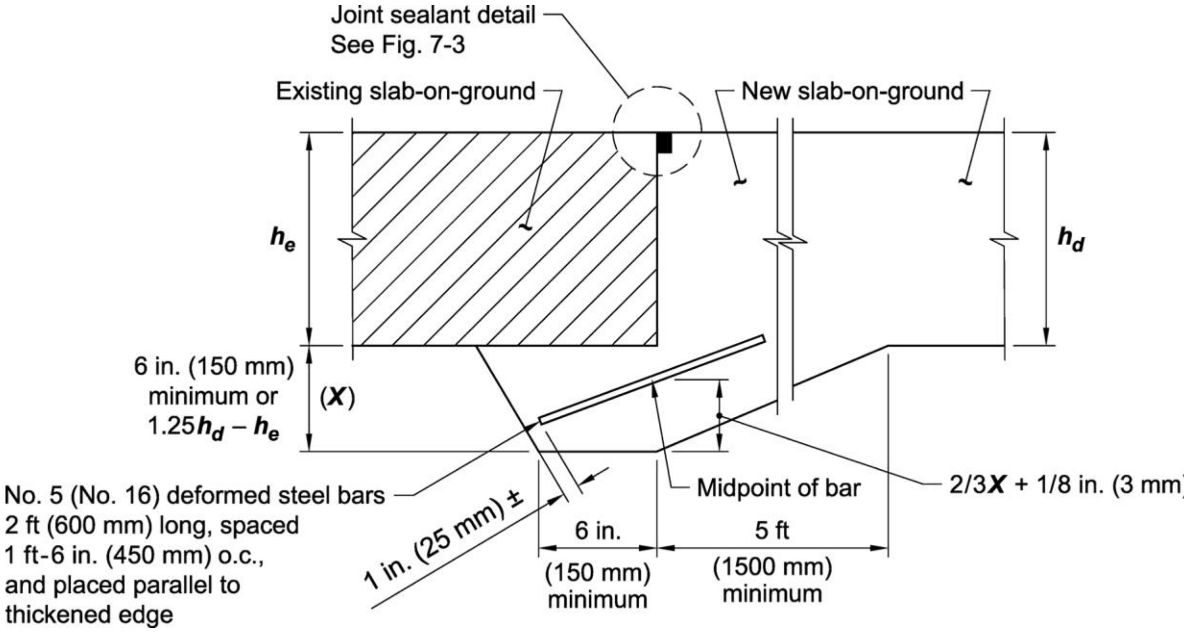
b. When load-transfer devices or a thickened edge was provided at the free edge of the existing floor, but neither met the design requirements for the new floor

c. For contraction joints when removing and replacing slabs in an existing floor

d. For construction joints when removing and replacing an existing slab-on-ground and the existing load-transfer devices are damaged during the existing slab-on-ground removal

e. Other locations where it is necessary to provide load transfer for the existing slab-on-ground

Figure 6-15 **Special Joint between New and Existing Slab-on-Ground**



The special joint design may not be required if a new slab-on-ground joins an existing slab-on-ground that is grossly inadequate to carry the design load of the new slab-on-ground, or if the existing slab-on-ground is in poor structural condition. If the existing slab-on-ground can carry a load that is 75% or less of the new slab-on-ground design load, special efforts to provide edge support for the existing slab-on-ground may be omitted; however, if omitted, accelerated failures in the existing slab-on-ground may be experienced. Load-transfer devices in the existing slab-on-ground should be used at the juncture to provide as much support as possible to the existing slab-on-ground. The new slab-on-ground should simply be designed with a thickened edge at the juncture. Drilling and grouting dowels in the existing slab-on-ground for edge support may be considered an alternate to the special joint; however, a thickened-edge design should be used for the new slab-on-ground at the juncture.

6-6 LOAD TRANSVERSE MECHANISMS.

One of the key design assumptions is to provide adequate load transfer at the joints such that stresses at the joints are not significantly higher than the stresses at the interior of the slab. Load transfer at contraction joints can be achieved by aggregate interlock or steel dowels, and by keyways, thickened edge joints, or steel dowels at construction joints. In Section 6-3.2, keyways were discussed and it was concluded that such a system has shortcomings and is not recommended for slabs-on-ground subjected to heavy, frequent moving traffic, or both. Thickened edge joints are a construction challenge and are infrequently used in the industry.

6-6.1 Aggregate Interlock.

Aggregate interlock can provide adequate load transfer across joints when the slab-on-ground is originally constructed. However, as joints move due to shrinkage, temperature variation, and load applications, aggregate interlock diminishes and load transfer across contraction joints is greatly reduced. Therefore, the effectiveness of aggregate interlock is dependent on (Tarr and Farny 2008):

a. Joint opening—Joint openings in the range from 0.015 to 0.085 inch (0.4 to 2.2 millimeter) are effective load transfer. The load transfer effectiveness decreases with larger joint openings. To limit joint openings and maintain effective aggregate interlock for load transfer, the concrete mixture must be designed for controlled shrinkage.

b. Slab-on-ground thickness—An increase in the slab-on-ground thickness will increase the number of aggregates straddling a contraction joint and accordingly the load transfer across a joint becomes more effective.

c. Strength of subgrade support—A strong subgrade is not required for a concrete slab-on-ground to support the design loads successfully; refer to Chapter 2. However, joint effectiveness is increased with stronger subgrades (higher *k*-values).

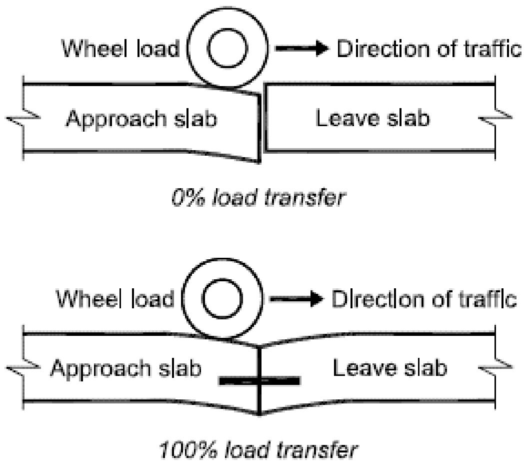
d. Load magnitude and frequency of travel—It is expected that the increase in number and magnitude of repetitive loads may decrease the aggregate interlock effectiveness. Weak aggregate may be ineffective in transferring loads across cracks as they may fracture compared to harder aggregate that is more resistant to joint breakdown.

e. Aggregate shape and size—Natural gravel is less effective in load transfer across joints than crushed and angular shaped aggregates. Also, larger aggregates will provide more effective aggregate interlock and load transfer.

6-6.2 Steel Dowels.

Steel dowels come in different shapes: round and square bars or plates; diagonal; square; or tapered. They are mainly used to transfer loads between two adjacent concrete panels at construction joints and at contraction joints when aggregate interlock effectiveness is reduced, heavy loading is anticipated, or both. Steel dowels maintain vertical alignment of adjacent slab-on-ground panels; refer to Figure 6-16.

Figure 6-16 **Transfer Mechanism Dowel between Two Adjacent Concrete Panels.**



Dowels are required at construction joints in slabs-on-ground subjected to heavy traffic loads and in slabs-on-ground that are 8 inches (200 millimeter) or greater in thickness. Typically, 3/4x13 and 1x16 (19x330 and 25x410) at 12 inch (300 millimeter) on center smooth dowels are placed in 5 to 6 inch (125 to 150 millimeter) and 7 to 8 inch (180 to 200 millimeter) thick slabs-on-ground, respectively (ACI 302.1R). Bar dowels allow for horizontal movement in one direction only, the direction of the dowel's axis. Plate dowels, also frequently used in the industry, provide better load transfer and allow for horizontal movement in two directions of the slab-on-ground compared to dowel bars. Plate dowels decrease bearing stresses because of the larger contact area between the plate and concrete and provide better joint deflection control; refer to Section 6-6.2.2. For military facilities, slabs-on-ground that can receive steel dowels at contraction and construction joints are presented in Table 6-2.

6-6.2.1 Dowel Bars.

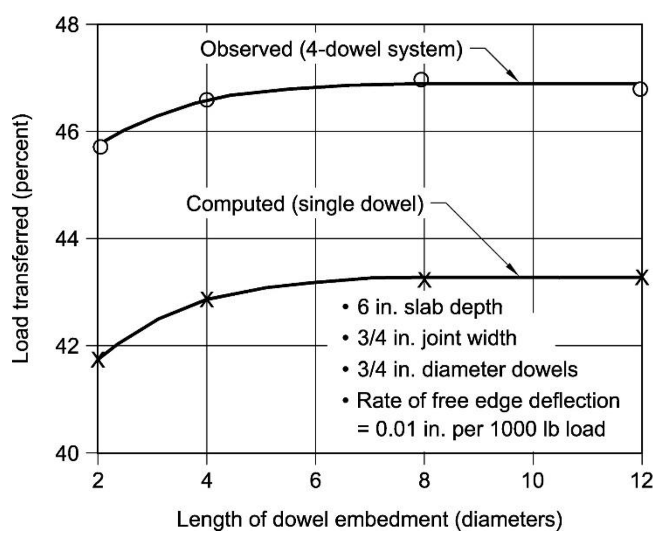
The behavior and performance of slabs-on-ground transfer mechanisms is affected by the dowel bar cross section, stiffness, and proper consolidation within the concrete. Concrete consolidation is important to provide adequate bearing to transfer load across a construction joint as it is the only transfer mechanism. The engineer must consider the maximum aggregate size and half slab-on-ground thickness to ensure that no voids are created below the dowel.

Increasing the dowel stiffness improves load transfer and reduces differential deflections between the two adjacent panels and reduces bearing stresses. The load per dowel bar can be calculated by determining the length of relative stiffness (Equation 5-2), which is used to determine the number of dowels engaged in transferring the applied load between adjacent concrete panels; refer to Example 6-6.2.1. Load transfer effectiveness increases with the increase in the dowel embedment length. There is, however, a limit beyond which an increase in embedment length would not result in increased load transfer percentage. A 3/4-inch (19 millimeter) dowel bar with an embedment length of 8 times the bar diameter or 7 inches (150 millimeters) is sufficient to achieve the desired behavior (Figure 6-17). For 1 inch and 1-1/4 inch (25 millimeters and 32 millimeters), the required effective embedment length is six times the bar diameter or 6 inch and 7-1/2 inch (150 and 190 millimeter), respectively (Snyder 2011).

Table 6-2 Dowels for military facilities slabs-on-ground

Facility	Minimum slab-on-ground thickness, inch (millimeter)	Recommended steel dowels	
		Contraction joint	Construction joint
Office	4 (100)	No	No
Heavy forklift traffic	6 (150)	Yes	Yes
Airplane hangars (maintenance)	8 (200)	No	Yes

Figure 6-17 **Load Transfer versus Dowel Embedment (Observed and Computed), after Teller and Cashell (1958)**



Example 6-6.2.1a provides a step-by-step on how to calculate the force resisted by a dowel.

Example 6-6.2.1a:

Wheel load, P = 8000 pounds (37,800 Newton)

Assume load transfer efficiency is 75%
P_1 = 8000 x 0.75 = 6000 pounds (26,700 Newton)

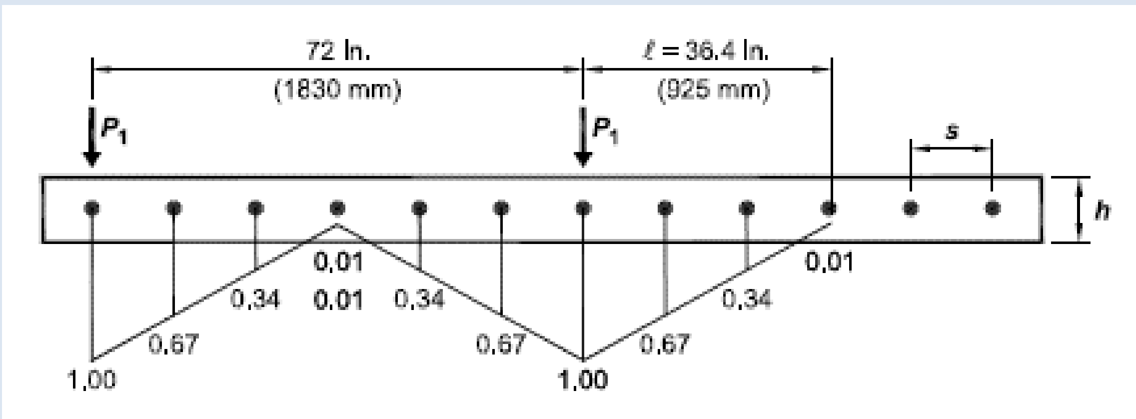
Assume wheel spacing = 72 inches (1830 millimeters)
Dowel spacing, s = 12 inches (300 millimeters)
Slab thickness, h = 8 inches (200 millimeters)
Effective modulus of subgrade support = 100 pounds per square inch per inch (27.1 megapascal per meter)

Concrete modulus of elasticity, E = 4,000,000 pounds per square inch (27,600 megapascal)
Poisson's ratio = 0.15

Solve:

Calculate radius of relative stiffness (Equation 5-2):

$$\ell = \sqrt[4]{\frac{Eh^3}{12(1-\mu^2)k}} = \sqrt[4]{\frac{(4{,}000{,}000)(8^3)}{12(100)(1-0.15^2)}} = 36.4 \text{ inch (925 millimeter)}$$



Calculation of effective dowels:

Dowel directly beneath load: 1.0 effective dowel
Dowels 12 inch (300 millimeter) from load: 24.4/36.4 = 0.67 effective dowel
Dowels 24 inch (600 millimeter) from load: 12.4/36.4 = 0.34 effective dowel
Dowels 36 inch (900 millimeter) from load: 0.4/36.4 = 0.01 effective dowel

Therefore,
Edge load is carried by: 1.0 + 0.67 + 0.34 + 0.01 = 2.02 effective dowels
Mid-panel load is carried by: 1.0 + 2(0.67 + 0.34 +0.01) = 3.04 effective dowels

Using the edge as the most critical
Critical dowel carries: 6000 (1.00/2.02) = 2970 pounds (13,200 Newtons)
Adjacent dowel carries: 6000 (0.67/2.02) = 1990 pounds (8852 Newton)
Second dowel from critical carries: 6000 (0.34/2.02) = 1010 pounds (4493 Newton)
Furthest affected dowel by load: 6000 (0.01 + 0.01) = 120 pounds (534 Newtons)

A study by Snyder, Iowa State University, 2011, states that the dowel bearing stress is directly proportional to the magnitude of the transferred load, joint width, and modulus of dowel-concrete interaction. In other words, bearing stress increases with decrease in dowel elastic modulus of elasticity and moment of inertia (diameter or cross section for round and square dowels, respectively).

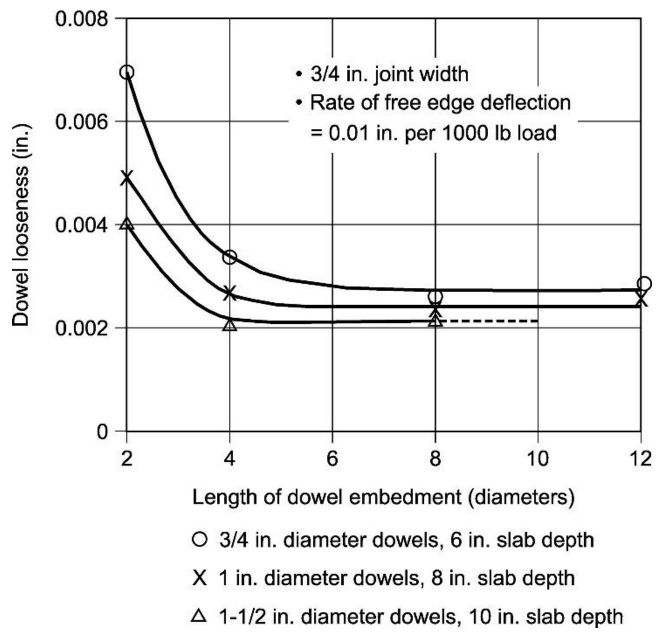
Because the wheel load could be over any bar, the dowels are designed for the largest force:

$A_s = P_1/(0.6f_y)$ = 2970 /(0.6 x 36,000) = 0.14 in.^{2} (90 mm^2)

Therefore, the dowel bar diameter cross-section is not controlled by shear forces or bending.

In Figure 6-18, the term "looseness" refers to the void above and below the dowel at the joint. This looseness occurs from having a small bar diameter or if load is too large and more frequent than assumed in design. The bearing stresses may break down the concrete in time, resulting in void around the dowel bar. When the dowel bar becomes loose, the transfer of loads between slab-on-ground panels becomes less efficient and increases differential movement between the slab panels is observed.

Figure 6-18 **Effects of Dowel Embedment and Diameter on Dowel Looseness after 600,000 Repetitions of a 10,000 lb Load (after Teller and Cashell [1958])**



The nomographs for the PCA and WRI methods were developed for loads applied away from joints or assuming a jointless slab-on-ground. The resulting stresses at a joint, however, can be considerably higher when load is applied at the joint; up to 60% higher than the stresses at mid-panel. Therefore, the calculations performed with the nomographs created for interior loading are modified by an appropriate joint factor (JF). Tarr and Farny (2008) provides the following JF guidelines when aggregate interlock is considered:

JF = 1.1 to 1.2 for low-shrink concrete mixture with joint spacings per Figure 6-6 but not exceeding 15 feet (4.5 meters) and performing early sawcutting.
JF = 1.3 to 1.5 for typical concrete mixtures with joint spacings per Figure 6-6.

JF = 1.6 for high-shrinkage concrete mixture and large contraction joint spacing—no load transfer is anticipated.

For steel dowels when properly spaced and concrete is adequately consolidated around it, a joint factor of 1.0 can be used. Calculations on using the joint factor in the design of a slab-on-ground is presented in Example 6-6.2.1b.

Example 6-6.2.1b; see also Example B-2.1 in Appendix B:

Design a slab-on-ground supporting a 4.5-ton forklift truck. Assume that subbase is 6 inches (150 millimeters) thick and the modulus of subgrade reaction is determined to be 100 pounds per square inch per inch (27.1 megapascal per meter). Concrete compressive strength is specified at 4000 pounds per square inch (28 megapascal). The factor of safety is determined equal to 2.0.

1. Calculate the concrete flexural strength: $9\sqrt{f_c'}$

$$9\sqrt{4000 \text{ psi}} = 570 \text{ psi (3.93 megapascal)}$$

2. Use Joint factor to calculate the concrete working stress:

b. Aggregate interlock: Assuming typical concrete mixture and spacing per Figure 6-6, JF = 1.4. The working stress can be calculated per:

$$WS = \frac{MR}{FS \times JF} = \frac{570 \text{ psi}}{(2)(1.4)} = 203 \text{ psi}$$

c. Steel dowel: Assume a 3/4-inch steel dowel with properly consolidated concrete around it, JF = 1.1:

$$WS = \frac{MR}{FS \times JF} = \frac{570 \text{ psi}}{(2)(1.1)} = 259 \text{ psi}$$

4. Refer to Appendix B, Example B-2.1 for calculating the slab-on-ground thickness.

The conclusions captured from the two examples above (6-6.2.1a and b) are:

1. A typical dowel bar has more capacity than the calculated force due to the applied load.
2. The larger the spacing between the dowel bars, the greater the loads applied to the dowel bars are.
3. For improper consolidation around dowels and for large joint spacings the joint factor increases, the allowable working stress is reduced and consequently the slab-on-ground thickness is increased.

6-6.2.2 Dowel Specifications.

Dowel bar spacings are dependent on the concrete slab-on-ground thickness. As a rule of thumb, a 3/4-inch (20 millimeter) diameter and 12-inch (300 millimeter) dowel spacing is sufficient to transfer load traffic across a joint. If slab-on-ground thickness is reduced or the subgrade conditions are poor, then dowel spacing should be decreased. However, closely spaced dowels can create a weak plane running through the centers of the dowels thus resulting in delamination.

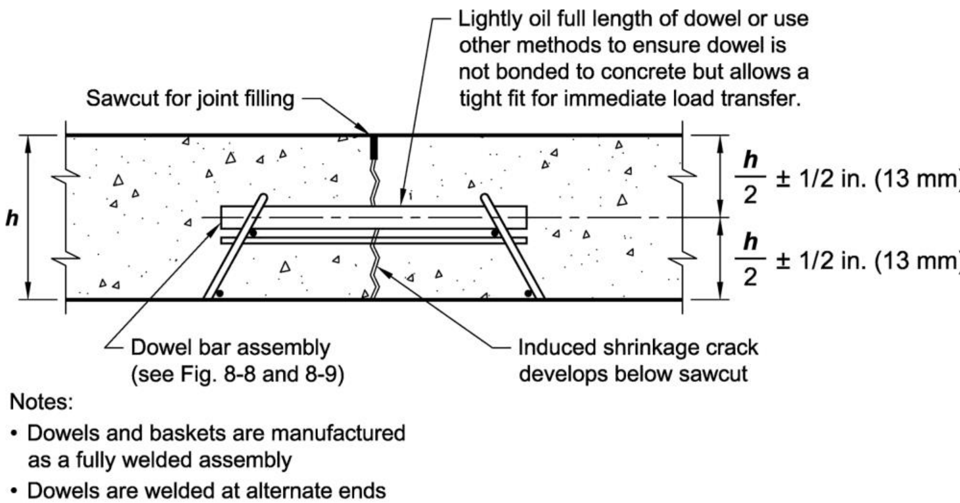
The COE method provides the criteria for dowel diameter, length, and spacing in relation to slab-on-ground thickness (refer to Table 6-3), which is comparable to ACI 360R Table 6.1. The construction documents should direct the contractor to install smooth dowels, aligned with flat, square, and deburred end edges that should allow a joint to open freely, and should not restrain concrete as it shrinks. When dowels larger than 1 inch (25 millimeter) in diameter are required, an extra-strength pipe may be used as an alternate for solid bars. When an extra-strength pipe is used for dowels, however, the SER should require that the pipe be filled with a stiff mixture of sand-asphalt or cement mortar, or the ends of the pipe should be plugged. If the ends of the pipe are plugged, plugs should fit inside the pipe and be cut off flush with the end of the pipe so that there should be no protruding material to bond with the concrete and prevent free movement of the pavement. Dowels should be straight, smooth, and free from burrs at the ends.

Table 6-3 Smooth Dowel Size and Spacing

Slab-on-ground thickness, inches (millimeter)	Minimum dowel length, inches (millimeter)	Maximum dowel spacing, inches (millimeter)	Dowel diameter and type
Less than 8 (200)	16 (400)	12 (300)	3/4-inch (19 millimeter) bar
8 (200 to and including 11.5 (290)	18 (450)	12 (300)	1- to 1-1/4-inch (27- to 32-millimeter) bar check
12 (300) to and including 15.5 (390)	20 (500)	15 (380)	1- to 1-1/4-inch (27- to 32 millimeter) bar, or 1-inch (25 millimeter) extra-strength pipe
16 (400) to and including 20.5 (520)	20 (500)	18 (450)	1- to 1-1/2-inch (27- to 38 millimeter) bar, or 1 to 1-1/2-inch (38-millimeter) extra-strength pipe
21 (530) to and including 25.5 (550)	24 (600)	18 (450)	2-inch bar (50-millimeter), or 2-inch (50-millimeter) extra-strength pipe
Over 26 (660)	30 (760)	18 (450)	3-inch bar (75 millimeter), or 3-inch (77-millimeter) extra-strength pipe.

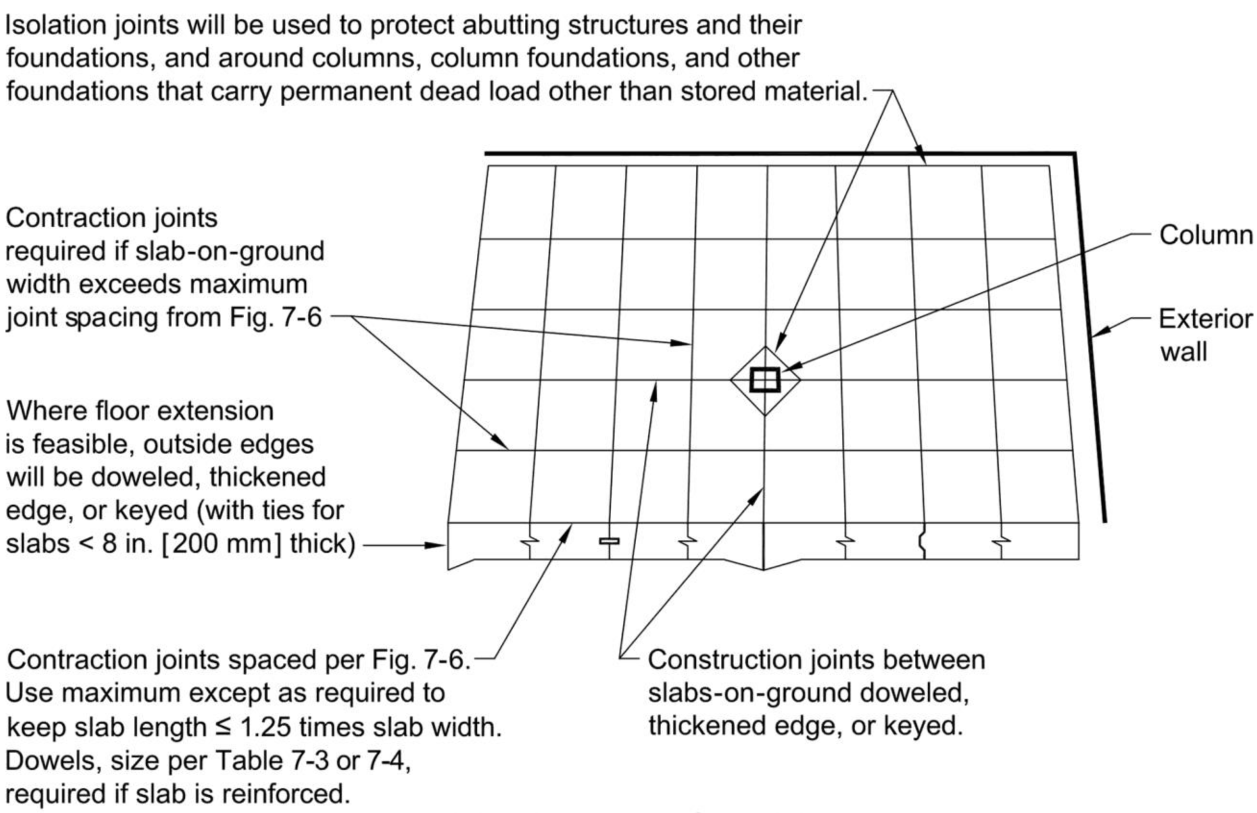
One-half of each dowel should be painted and oiled or otherwise treated to prevent bonding with the concrete, refer to Figure 6-19. A schematic drawing of joint layout showing dowels is given in Figure 6-20.

Figure 6-19 **Typical Doweled Joint**



Typical doweled contraction joint

Figure 6-20 **Joints in Concrete Slabs-on-Ground.**



Joints in concrete floor slab

6-6.3 Dowels Other Than Circular In Shape.

Dowels other than circular that are commonly used in the industry are square dowel bars and plate dowels of various geometries: diamond, rectangular, tapered, and double-tapered plate dowels (refer to Figure 6-21 and 6-22). Plate and square dowels can accommodate horizontal slab-on-ground movements in two directions, parallel and perpendicular to a joint, which results in minimizing shrinkage restraint and significantly reduces the risk of random cracking at joints. Plate dowels have an advantage over round and square dowels—they provide the same vertical load transfer capability at a larger spacing because they have a larger bearing area and considerably shallower embedment depth.

These advantages result in an overall reduction in the steel volume required at each joint. In general, plate dowels are more effective than round or square dowels because plate dowels place more steel closer to the joint where the bearing, shear, and bending stresses caused by vertical loads are highest (Walker and Holland 1998).

Plate dowel dimensions are per manufacturers' recommendations because of the various plate dowel geometries and installation devices available from different manufacturers. ACI 360R provides recommended plate spacing; refer to Table 6-4. Dowels, plates, and square and round smooth bars should satisfy the requirements of ASTM A36/A36M.

Research of oblong or elliptical bars, with the major axis placed parallel to the subgrade, have shown better behavior and load transfer efficiency. Elliptical bars with an 18% increase in cross sectional area over a circular dowel resulted in over a 26% decrease in bearing stress (Porter 2001). The same study revealed that circular or round bars had a slight advantage in stiffness over the elliptical dowels. The difference in stiffness, however, is insignificant based on the slabs-on-ground small variance in deflection. Elliptical bars, however, have not gained acceptance because of placement and availability concerns.

Table 6-4 Square Dowel Sizes and Plate Dowel Spacing

Slab depth, inch (millimeter)	Dowel dimensions, inch (millimeter)			Recommended dowel spacing center-to-center, inch (millimeter)	
	Square dowels*		Plate dowel**	Square dowel*	Plate dowel
	Construction joint	Contraction joint			
5 to 6 (130 to 150)	3/4 x 10 (19 x 250)	3/4 x 13 (19 x 330)	M/R	14 (360)	18 (460)
7 to 8 (180 to 200)	1 x 13 (25 x 390)	1 x 16 (25 x 410)	M/R	14 (360)	18 (460)
9 to 11 (230 to 280)	1-1/4 x 15 (32 x 380)	1-1/4 x 18 (32 x 460)	M/R	12 (300)	18 (460)

*Square dowels should have compressible material securely attached on both vertical faces.
**Manufacturers' recommendations. Because of the various plate dowel geometries and installation devices available from different manufacturers, the manufacturers should be consulted for their recommended plate dowel size.

Figure 6-21 **Plan View Indicating Provisions for Longitudinal Movement at Doweled Construction Joints**

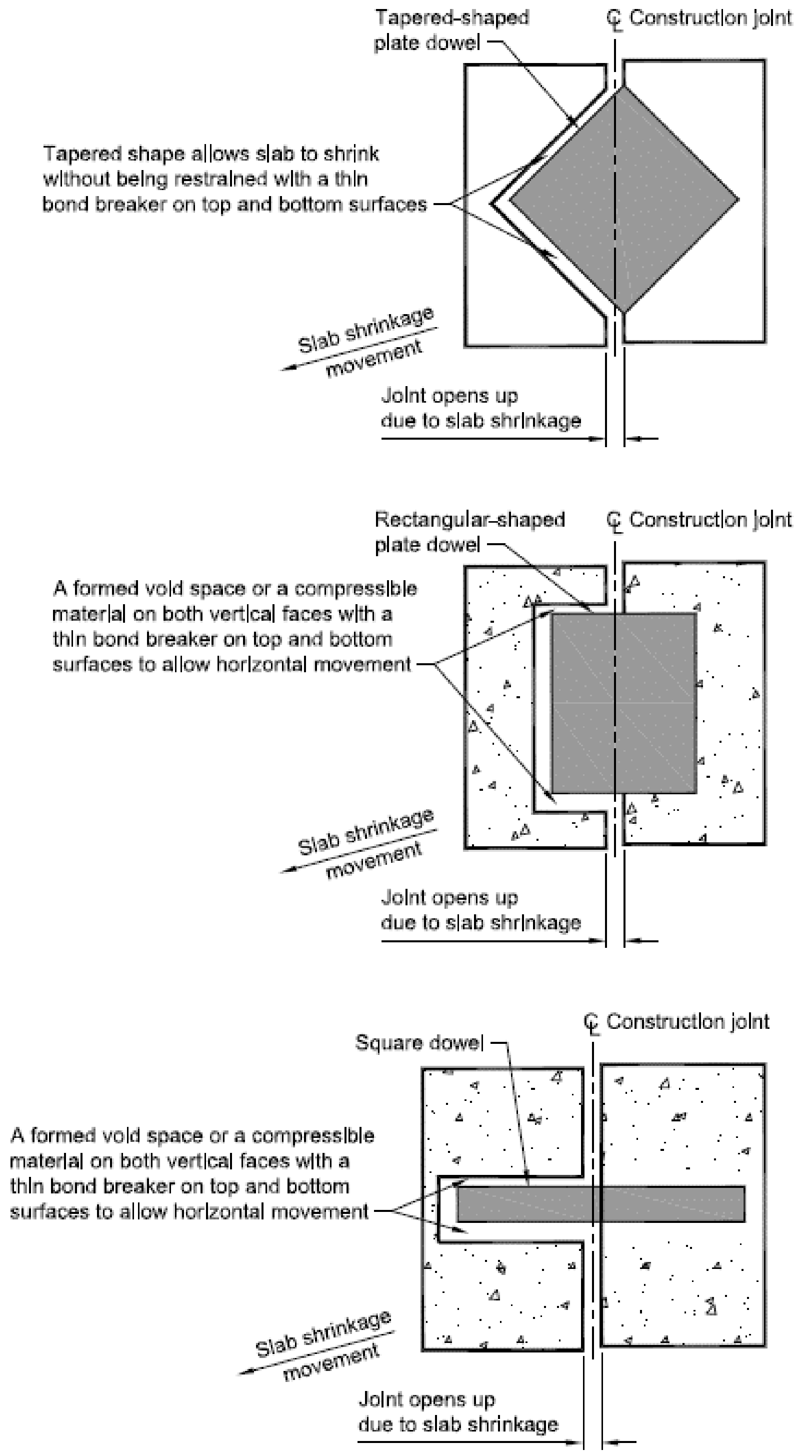
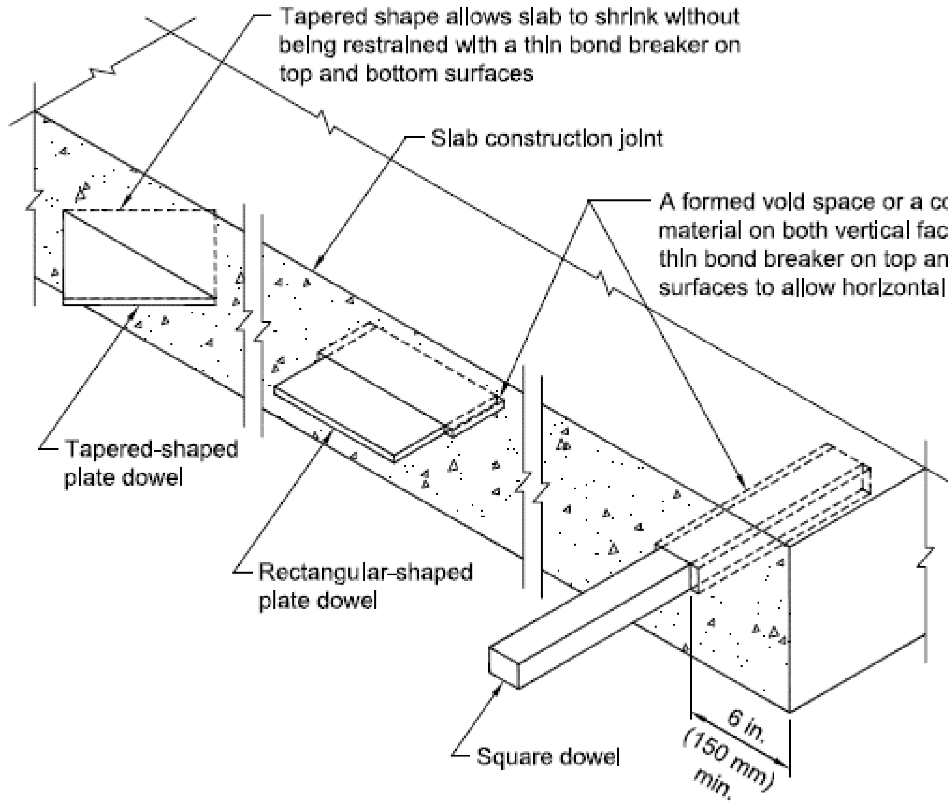


Figure 6-22 **Isometric View Indicating Provisions for Longitudinal Movement at Doweled Construction Joints**



6-6.4 GFRP Dowels.

Since the early 2000s, GFRP bars and dowels have been proposed with limited use in slabs-on-ground and pavements to provide better corrosion resistance. However, because of their low modulus of elasticity and reduced stiffness—approximately 20% of that of steel—will result in higher bearing stresses between concrete and dowels, higher differential joint deflections, and lower load transfer efficiency under repeated loads (Cable and Porter 2003; Shalaby 2001; Corvetti 1999). To compensate for the low modulus of elasticity, larger dowel diameters, closer spacings, or both are implemented to produce the same behavior as in steel dowels (Figure 6-23). It is recommended that a dowel system with less than 12 inch (300 millimeter) spacing be analyzed to ensure proper performance and should not result in the formation of a failure plane running parallel to the subgrade at the dowels level thus resulting in delamination. Because of the load shear modulus, FRP bars have an advantage when demolition of the slab-on-ground is required.

Figure 6-23 **Glass Fiber-Reinforced Polymer Dowels**

6-7 SUMMARY.

1. Minimum and maximum contraction joint width is 1/8 inch (3 millimeters) and equal to the width of the sealant reservoir, respectively.
2. Provide contraction joint depth for sealant reservoir between 1.0 and 1.5 times the joint width; refer to Figure 6-3.
3. Contraction joint spacing for plain and unreinforced concrete slab-on-ground should be limited; refer to Figure 6-6.
4. The effectiveness of aggregate interlock may be improved by increasing base strength, coarse aggregate size and angularity, and shorter spacing of joints.
5. Dowels are required for slabs-on-ground supporting traffic loading and for slabs-on-ground with minimum 8 inch (200 millimeter) thickness.
6. Dowel embedment depth should not be less than 6 inches (150 millimeter) for 3/4- and 1-inch (20 and 25 millimeter) diameter dowels and 7-1/2 inch (190 millimeter) for 1-1/4-inch (32 millimeter) diameter dowel.
7. Dowels placed close to each other, less than 12 inches (300 millimeters), can result in a weak plane and accordingly delamination.
8. Dowel transfer is improved by increasing dowel diameter or plate thickness.
9. Load transfer effectiveness by aggregate interlock is improved by using low-shrinkage concrete mixture and joint spacing not exceeding 15 feet (4.5 meters).
10. Load transfer effectiveness by steel dowel is improved by proper concrete consolidation around dowel bars.
11. Use FRP dowels with caution as they have lower load transfer efficiency due to lower modulus of elasticity.

CHAPTER 7 CONSTRUCTION CONSIDERATION

7-1 CONSTRUCTION DOCUMENT INFORMATION.

For a successful project, the construction documents, prepared by the SER, should include information that record the design assumptions and provide directions to the contractor on the joint locations, finishing, curing, and other construction requirements. ACI 360R lists information that should be as a minimum addressed in the construction documents. These items are:

- Slab-on-ground design criteria (see list below) (Chapter 5)
- Base and subbase materials, preparation requirements, and vapor retarder, when required (Chapters 2 and 7)
- Concrete thickness (Chapter 5)
- Concrete compressive strength, flexural strength, or both (Chapter 5)
- Concrete mixture proportion requirements
- Joint locations and details (Chapters 6 and 7)
- Reinforcement (type, size, and location), when required (Chapter 5)
- Surface treatment, when required
- Surface finish
- Tolerances (base, subbase, slab thickness, and floor flatness and levelness) (Chapter 7)
- Concrete curing
- Joint filling material and installation
- Special embedments
- Testing requirements
- Preconstruction meeting, quality assurance, and quality control. (Chapter 7)

The slab-on-ground design criteria should include some of the following:

- Geotechnical soil properties used for the different loading types (Chapters 2 and 4)
- Uniform storage loading (Chapter 4)
- Forklift and other moving vehicular loadings (Airplanes) (Chapter 4)
- Frequency of travel of moving loads (Chapter 4)
- Rack loadings
- Line loads (Chapter 4)

- Equipment loads
- When the slab is used to resist wind or seismic foundation uplift forces
- When the slab is used as a horizontal diaphragm to resist horizontal forces due to tilt-walls, masonry walls, tops of retaining walls, and metal building system columns.

7-2 PRECONSTRUCTION MEETING AGENDA.

A successfully completed slab-on-ground is dependent not only on a detailed design, quality of materials used, and the experience of the workers on the project, but also on open communication between the parties involved (contracting officer, SER, contractor, and specialty contractors). Therefore, to ensure that the involved parties develop a common understanding of the project, the SER should hold a preconstruction meeting before construction commences. The following individuals should attend:

- Contracting officer
- Licensed design professional (SER)
- General contractor/construction manager
- Concrete contractor and finisher foreman
- Concrete producer
- Testing agency
- Pumping contractor
- Other trades that directly affect production and working environment

The SER should distribute the agenda at least 10 days before the meeting to the attendees (Figure 7-1). Some of the items on the agenda that should be addressed at the preconstruction meeting are listed below. The SER should modify the list below to suit the project:

- Project information and schedule
- Construction sequence and processes (Chapter 7)
- Base and sub-base composition, preparation, compaction, testing, and tolerances (Chapter 2)
- Subgrade proof-roll and inspection (Chapter 2)
- Vapor retarder requirement (Chapter 7)
- Concrete mixture design (Chapter 3)
- Mixture design submittal form
- Window of finishability
- Flexural strength requirements (Chapter 5)

- Climatic conditions and concrete needs
- Placement condition and weather protection
- Placement methods and procedures, including needed mixture design changes (Chapter 5)
- Maximum joint spacing and the type of joints to be used (Chapter 6)
- Type of dowels, installation, and spacing (Chapter 6)
- Curing methods
- Testing procedures (specimen storage, transportation, and testing) and frequency
- Joint filler (Chapters 6 and 7)
- F_F/F_L specification and repair guideline (Chapter 7)
- Protection of concrete
- Mitigation of cracking and curling (Appendix D)
- Special materials
- Owner expectations
- Dispute resolution
- Report distribution
- Corrective actions
- Job site safety

Figure 7-1 **Preconstruction Meeting Agenda Example**

A/E Logo
Street, City, State
Phone:
Email:

PRE-CONSTRUCTION MEETING AGENDA **DATE: MM/DD/YEAR**

ADMINISTRATIVE
Construction Meeting No.: **1**
Project Name: **Any project**
Meeting Location: Job site **1:30 P.M.**

List of Attendees
Name 1, Contractor's Project Manager
Name 2, Contractor's Superintendent
Name 3, Concrete Subcontractor
Name 4, Inspectors
Name 5, Safety Supervisor
Name 6, A/E
Name 7, Vapor retarder (if required)

1. General Introduction and distribution of the Attendance Sign-In Form
2. Construction contract overview
3. Construction plans review
    a. Clarifications to Contractor's questions provided by A/E
    b. Construction sequence
4. Working area limits
5. Project site access and requirements
6. Requirements and responsibilities for project site sampling
7. Requirements and responsibilities for sample storage and security
8. Safety—Provide a safety plane following OSHA guidelines
9. Plans and Addendum Submittals
10. Permits process and issuance
11. Discuss Construction Schedule
12. Submittal process and turnaround
13. RFI process and turnaround
14. Communication protocol for inspection and testing nonconformance
15. Requirements, authority, and responsibility for acceptance or rejection of fresh concrete on site
16. Quality control and quality assurance plans
17. Change Orders
18. Site cleanup/closeout
19. Report distribution and transmission method
20. As-built drawings
21. Next Meeting Confirmation

Adjourn

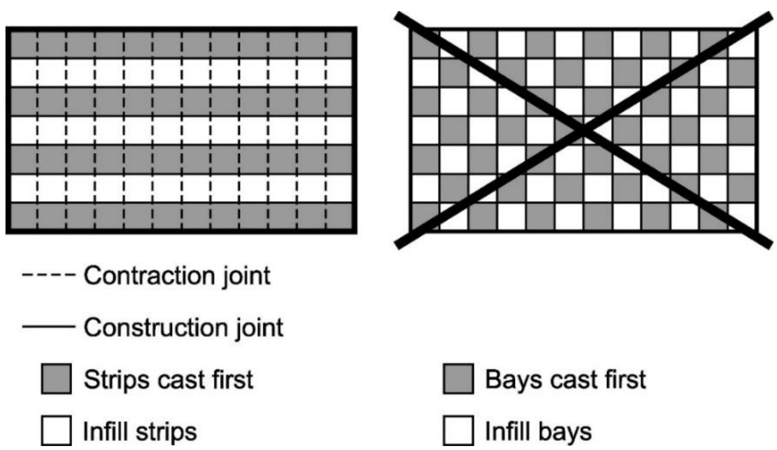
7-3 PLACING SEQUENCE.

Place slab-on-ground, if practical, in large panels with laser guided, wheel-mounted screed, equipment. There are no limits to slab-on-ground placements. Placements of 30,000 to 40,000 square feet (2800 to 3700 square meters) have been completed (Shashaani 2000). Allow maximum time possible for the slab-on-ground to freely move at the edges before placing an adjacent placement.

Long, alternating strip placements are an acceptable alternative to large panel placements if access to the job site is limited, inadequate, or a laser screed is not available. Long, alternating strips allow access to the sections being placed and are recommended for slabs-on-ground requiring high tolerance.

A checkerboard sequence of placement with side dimensions of 50 feet (17 meters) or less has been used in the past to allow earlier placements to shrink and to obtain minimum joint width. However, experience has shown that shrinkage of the earlier placements occurs too slowly for this method to be effective. Also, access is more difficult, expensive, and joints may not be as smooth. Therefore, checkerboard placement is not recommended; refer to Figure 7-2 (ACI 360R).

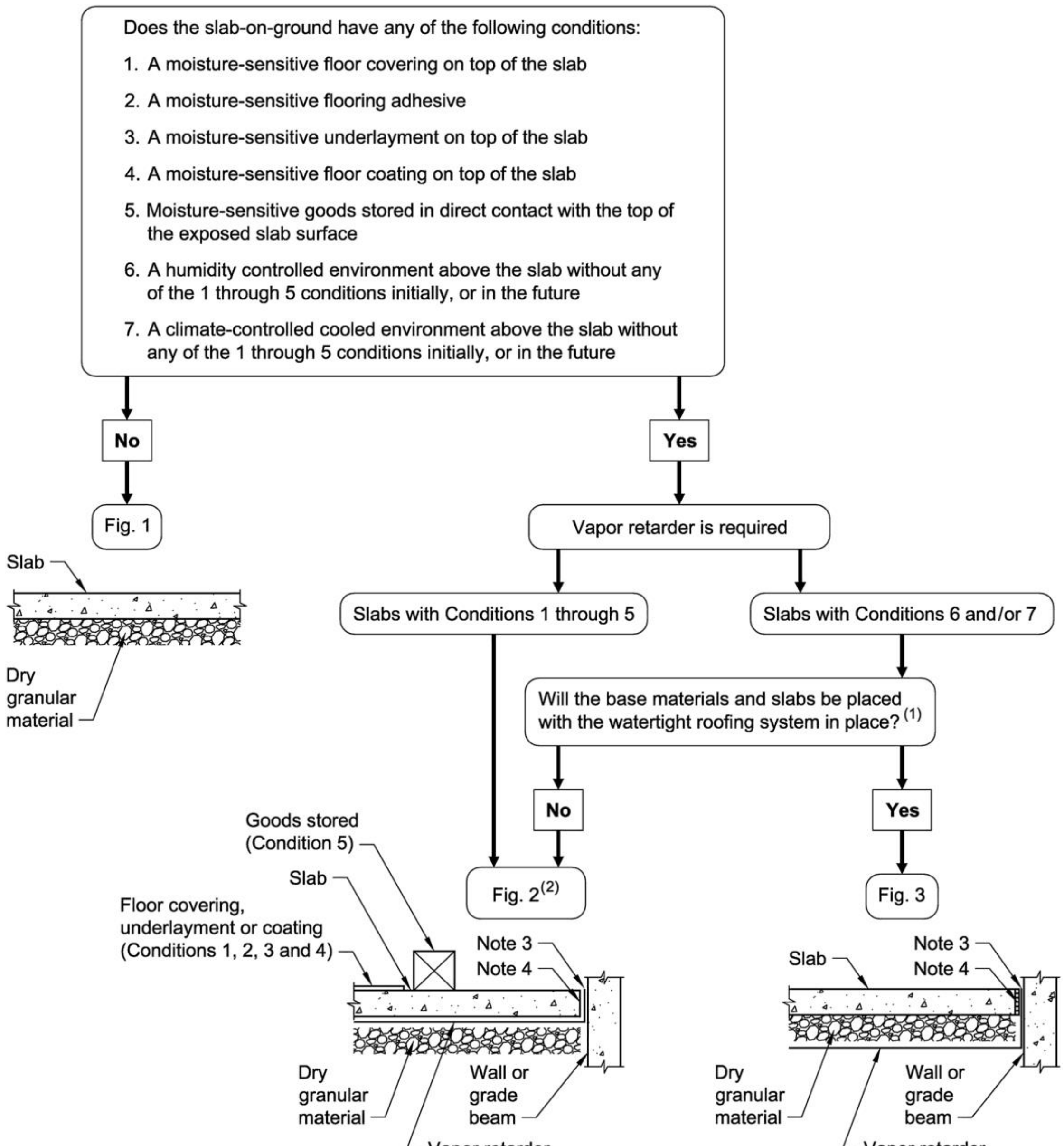
Figure 7-2 **Placing Sequence Long-Strip Construction (left) is Recommended; Checkerboard Construction (right) is Not Recommended**



7-4 VAPOR RETARDER

Vapor retarders are placed where required to control moisture transmission through the floor system. Its function is to keep moisture from getting into the concrete and to keep the enclosed structure drier to avoid flooring problems. This is especially critical where the slab-on-ground receives floor covering, underlayment on top of the slab, floor coating, goods stored in direct contact with concrete and are moisture sensitive, or the space above slab-on-ground is climate-controlled. The proposed installation should be evaluated and approaches for moisture sensitivity should be addressed. If moisture transmission is not an issue, then vapor retarder should not be used. Refer to Figure 7-3 for conditions to determine the recommended location of a vapor retarder. The anticipated benefits and risks associated with the specified location of the vapor retarder should be reviewed with the parties during the preconstruction meeting. Placing a concrete slab-on-ground on an impervious base can experience serious shrinkage cracking and warping (Nicholson 1981).

Figure 7-3 **Flowchart to Determine When and Where a Vapor Retarder Should be Used**



Notes:

(1) If granular material is subject to future moisture infiltration from wet-curing, wash-down areas sloped to drainage, or other liquids that can pond on top of the slab and seep through joints, cracks or other openings, use Fig. 2.

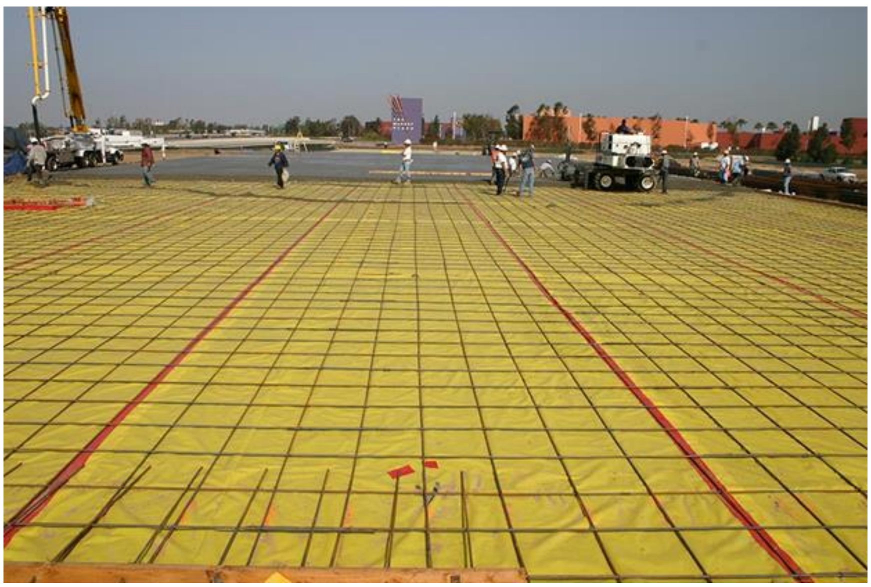
(2) If Fig. 2 is used, measures to minimize slab curling, dominant joints, delaminations, blistering, crusting, plastic shrinkage cracking, bar shadowing and subsidence cracking longitudinally over the reinforcement, reduction in surface flatness, and finishing time will likely be required.

(3) At the perimeter, vapor retarder should be turned up and sealed to wall, grade beam or slab.

(4) Flexible closed cell foam plank full depth of slab (where required) with elastomeric joint sealant (where required). (Note: Foam plank is not shown in Fig. 2 but can be used as shown in Fig. 3).

The specified vapor retarder used on a job site should be in compliance with ASTM E1745 and its thickness and permeance are based on the durability of the system during and after installation. The SER should specify a vapor retarder with a permeance level, also known as the water vapor transmission rate, not exceeding 0.1 perms (0.0659 metric perms = 5.72 $ng/s^{-1} m^{-2} Pa^{-1}$) as determined by ASTM E96/E96M or ASTM F1249. However, a permeance level well below 0.1 perms (0.0659 metric perms = 5.72 $ng/s^{-1} m^{-2} Pa^{-1}$) is recommended for the majority of flooring installations. To prevent water or moisture from penetrating at laps, overlap seams or laps of a vapor retarder a minimum of 6 inches (150 millimeters) (ASTM E1643) or as recommended by the manufacturer. Joints and penetrations should be sealed with the manufacturer's recommended adhesive, pressure-sensitive tape, or both (Figure 7-4).

Figure 7-4 **Vapor Retarder Placed before Slab-on-Ground Concrete Placement (Source: CTI)**



7-4.1 Vapor Retarder In Direct Contact with Slab-on-Ground.

When slab-on-ground is placed directly over a vapor retarder, it should not lose moisture to the subbase, and bleed water should evaporate through the top surface of the slab-on-ground. This, however, may delay the finishing time by about two hours. Also, if potential water from rain, saw-cutting, curing, cleaning, compaction, or other sources become trapped within the fill, then vapor retarder is placed in contact with the slab-on-ground. As a consequence, potential effects of slab warping, cracking, and crusting may occur. Therefore, the SER should consider implementing design and construction measures to offset or to reduce these effects. ACI Committee 302 recommends that slabs-on-ground covered with moisture-sensitive coverings should have the vapor retarder placed on top of dry granular fill and directly beneath the slab-on-ground.

7-4.2 Vapor Retarder Not In Direct Contact with Slab-on-Ground.

This condition is applied when the space above the slab-on-ground is humidity- or climate-controlled. A fill layer of reasonably dry, trimmable, compactible granular material is placed between the vapor retarder and the concrete slab-on-ground. It is approximately 4 inches (100 millimeters) thick and provides a permeable, absorptive base directly under the slab-on-ground. It may, however, also serve as an avenue for moisture to enter and travel freely beneath the slab-on-ground and can lead to an increase in moisture within the slab once it is covered. Moisture can also enter the fill layer through voids, tears, or punctures in the vapor retarder.

When the base is kept moist by groundwater or when the slab-on-ground is placed on a wet base, this increases the moisture gradient in the slab-on-ground and increases warping.

Irrespective where the vapor retarder is placed, it should be protected from damage during construction, as it may influence its effectiveness by increasing finishing time, promoting cracking, increasing slab curling, and reducing strength. The different settings must be communicated and clarified during the preconstruction meeting among the parties involved. These challenges, however, may be less costly than performance failures related to excessive moisture transmission through the slab. For further discussion on the effect of vapor retarder on slab-on-ground, refer to ACI 302.1R.

7-4.3 Polyethylene Sheets as Slip Sheets.

When using crushed stone as a base material, the upper surface of the crushed stone should be choked off with fine aggregate material to provide a smooth surface that allows the slab-on-ground to shrink with minimum restraint. Otherwise, polyethylene sheets are provided without stone cover to serve as a slip sheet to reduce friction between slab-on-ground and base with the base remaining dry. The sheet should be drilled with holes at approximately 12 in. (300 mm) centers when still folded or on a roll to allow water to leave the slab bottom before the concrete sets.

7-5 JOINT CONSTRUCTION AND DOWEL PLACEMENT.

Slabs-on-ground are exposed to wear and tear throughout their service life. Therefore, the design of construction and contraction joints is important for the longevity of slabs-on-ground. Additionally, transfer mechanisms help in the stabilization of the joints and are an important consideration for the serviceability of a slab-on-ground subjected to moving loads; refer to Chapter 6 for joint and dowel design.

7-5.1 Sawcut Contraction Joints.

In slabs-on-ground, random cracking is primarily controlled by saw cutting joints. The reduced cross section—weakened plane—increases the likelihood that cracking occurs in a controlled manner at specific locations. Refer to Chapter 6 Section 6-2 for recommended width and depth of sawcut contraction joint dimensions.

ACI 301 requires cutting begin as soon as concrete has gained enough strength to prevent dislodgement of coarse aggregate particles. Table 7-1 presents three types of sawcut methods that are commonly used in the industry including proposed times when to perform sawcut of contraction joint for each method.

Table 7-1 Slab-on-Ground Sawcut Methods

Sawcut type	Equipment	Maximum cutting depth	Timing of sawcut	Minimum sawcut depth
Conventional wet-cut saw	Gasoline-powered	Capable of cutting joints up to 12 inches (300 millimeters) depth or more	Four to 12 hours after the slab has been finished in an area. Four hours in hot weather, and 12 hours in cold weather	The greater of at least 1/4 slab depth or 1 inch (25 millimeters)
Conventional dry-cut saw	Electrical or gasoline power	Varies depends on the equipment	Four to 12 hours after the slab has been finished in an area. Four hours in hot weather, and 12 hours in cold weather	Same as conventional wet-cut-saw
Early-entry dry-cut saw	Electrical or gasoline power	Cut to a maximum depth of 1-1/4 inches (32 millimeters), but some cut to a maximum depth of 4 inches (100 millimeters).	Sawcut before significant concrete tensile stresses develop. Approximately 1 hour in hot weather, and 4 hours in cold weather after completing the finishing of the slab in that joint location	1 inch (25 millimeters) for slabs up to 9 inches (230 millimeters).

For slab-on-ground with steel fibers added, it is important to sawcut the slab-on-ground per the early-entry dry-cut saw timing before concrete starts forming random drying-shrinkage cracks and as soon as the concrete surface is firm enough not to pull up the steel fibers. The depth of the weakened plane groove using wet conventional sawcut must be a minimum of one-third of the slab thickness. For slab-on-ground with low concentration of steel fibers and using an early-entry sawcutting, the depth can be the same as for unreinforced and lightly reinforced concrete slabs-on-ground. For higher fiber concentrations and a slab-on-ground thickness of up to 9 inches (230 millimeters), early-entry sawcut should be preferably 1-1/4 inches (32 millimeters) minimum (ACI 360R). It is recommended that the contractor uses new, clean saw blades for crisp sawcuts.

7-5.2 Joint Sealing.

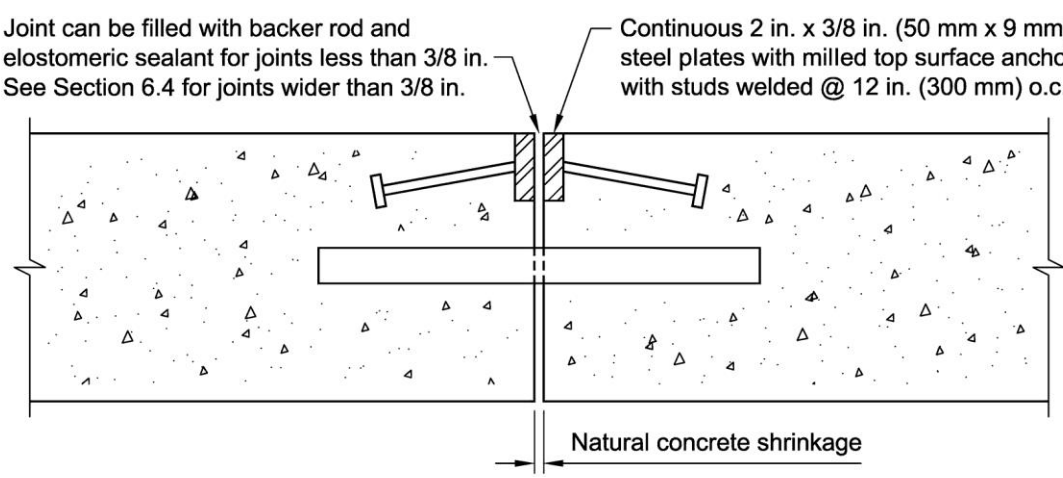
Joints should be sealed with a suitable sealant to prevent infiltration of surface water and solid substances. A jet-fuel-resistant (JFR) sealant should be used in the joints of floors where diesel fuel or other lubricants may be spilled during the maintenance and servicing of vehicles. Sealants that are not fuel-resistant should be used in joints of other slabs-on-ground. SFRC sealants should conform to Federal Specifications SS-S-200 and SS-S-1614, and non-SFRC sealants should conform to Federal Specifications SS-S-1401. Preformed sealants must have an uncompressed width of not less than twice the width of the joint sealant reservoir. The selection of a pourable or preformed sealant should be based upon the economics involved. Compression-type preformed sealants are recommended when the joint spacings exceed 25 feet (7.6 meters) and are required when joint spacings exceed 50 feet (15.2 meters); refer to Figure 6-3.

The majority of shrinkage in a slab-on-ground occurs within the first year, but it continues for years. Therefore, joints subjected to wheel traffic should be protected by either filling the joint with semi-rigid epoxy or polyurea that provide sufficient shoulder support to the edges of the concrete and prevent joint breakdown that restores surface continuity (refer to Figure 6-3). Construction documents should direct the contractor to apply joint fillers when construction becomes stable to reduce the effects of shrinkage-related joint opening on the filler of sealant. Provide provisions in the contract documents for the contractor to return between 6 months and 1 year to repair the joint filler separations using the same manufacturer’s product when schedule dictates for early joint filling. Load transfer elements at joints increase protection of the joint edges by limiting vertical movement and reducing fatigue.

When the building is equipped with an HVAC system, run it for approximately 2 weeks before joint filling, especially where joint fillers are used in traffic-bearing joints because such materials have minimal extensibility. Otherwise, separation between the joint edge and the joint filler or within the joint filler itself is expected. These slight openings can subsequently be filled with a low-viscosity compatible material. The SER should specify for the contractor to remove dirt, debris, saw cuttings, curing compounds, and sealers before applying a joint sealant. Vacuuming is recommended over blowing the joint cut with compressed air.

For heavy wheel loads or hard wheels, armor the edges by providing steel plates to protect the edges; refer to Figure 7-5. Steel angles should not be used to protect the joint edges because they exhibited limited success in practice. The top surface of the armored plates must be level with the top of the slab. Otherwise, milling may be required to produce a flat surface. When steel-armored joints are less than 3/8 inch (9.5 millimeters) wide, then they should be sealed with an elastomeric sealant.

Figure 7-5 **Typical Armored Construction Joint Detail**



When steel armored joints are equal or greater than 3/8 inch (9.5 millimeters) wide, they should be filled with semi-rigid epoxy or polyurea joint filler or joint filler that contains an integral sand extender for the full depth. This is critical to provide a smooth transition for wheel traffic and reduce damage to the tire tread.

7-5.2.1 Joint Sealing In Cold Rooms.

In cold or freezer rooms, joints will open wider than in a typical slab-on-ground because of the thermal contraction of the concrete and the placement of the slab-on-ground on the insulation layer that has a reduced coefficient of friction. The anticipated thermal contraction due to the difference in temperature between placement and operation is about three to four times greater in cold or freezer rooms slabs-on-ground than the typical slab-on-ground. Therefore, the contractor should delay the joint filling for as long as practically possible to allow the concrete to shrink and joints to open. The SER should specify joint fillers that are specifically developed for cold temperature applications. The contract document should direct the contractor to hold room temperature at its planned operating temperature for at least 48 hours. For freezer rooms with operating temperatures below 0°F (–18°C), maintain the operating room temperature for 14 days before starting filling joints.

7-5.3 Special Provisions for Slipform Slab-on-Ground.

Provisions must be made for slipform slab-on-ground when there is a change in joint configuration. The thickness can be varied without stopping the concrete placement train, but the joint configuration cannot be varied without modifying the side forms, which should normally require stopping the slab-on-ground concrete placement and installing a header. The following requirements shall apply:

a. The header may be set on either side of the transition slab with the transverse construction joint doweled as required. The dowel size and location in the construction joint should be proportionate with the thickness of the slab-on-ground at the header.

b. When there is a transition between a doweled construction joint and a keyed construction joint, the construction joint in the transition slab can be either keyed or doweled. The size and location of the dowels or keys in the transition slabs should be the same as those in the slab-on-ground with the doweled or keyed joint, respectively.

c. When there is a transition between two keyed joints with different dimensions, the size and location of the key in the transition slab should be based on the thickness of the thinner slab-on-ground.

7-5.4 Dowel Placements.

Normally, dowels should be located at mid-depth of a slab-on-ground (Figure 7-6 and 7-7). However, a tolerance of one-half of the dowel diameter, above or below mid-depth of the slab, is allowed in locating the dowels in contraction and construction joints where the allowance of such a tolerance should expedite construction. ACI 117 provides tolerances for the installation of slab-on-ground round dowels (Table 7-2).

Figure 7-6 **Installation of (a) Diamond Plate Form and (b) Rectangular Plate Form**

(a) Diamond plate form

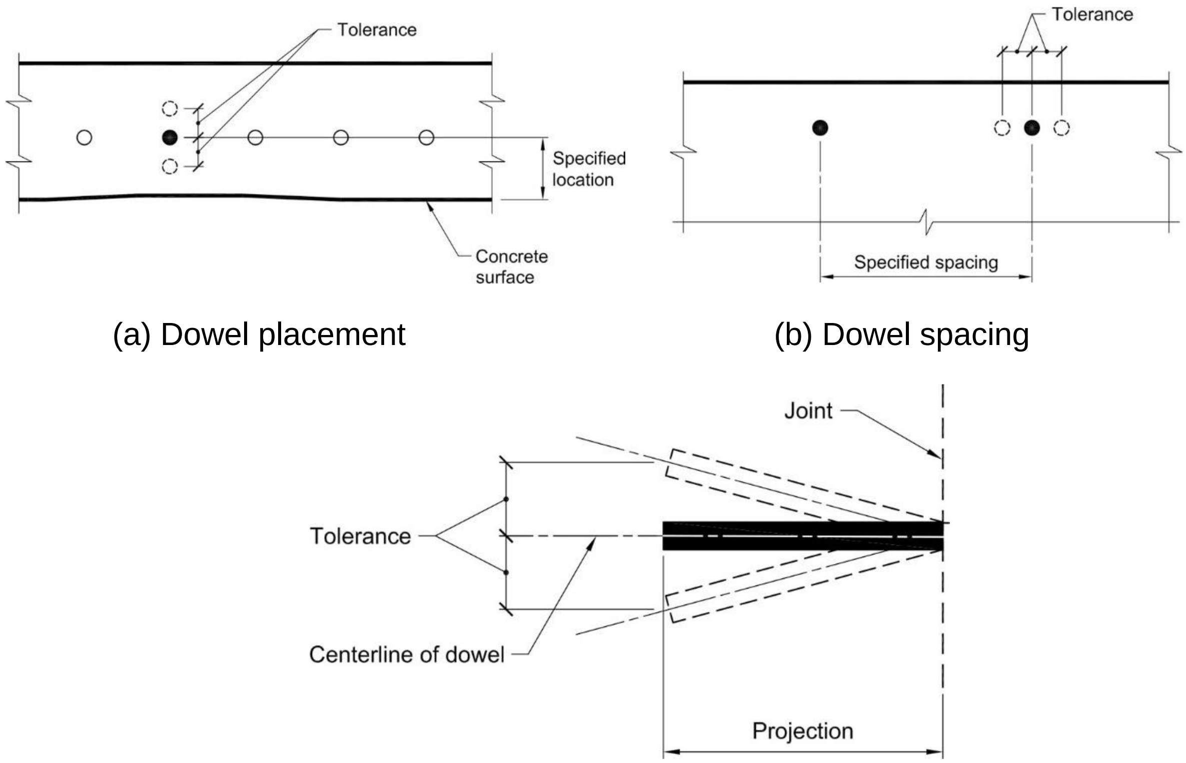
(b) Rectangular plate form

(c) Round smooth bar

Table 7-2 Slab-on-Ground and Bar Dowel Tolerances

Condition	Requirement	Tolerance	Figure
Centerline of dowel, vertical deviation measured from bottom of concrete slab at the joint for slab thickness	≤ 8 inch (≤ 200 millimeter)	±1/2 inch (±13 millimeter)	7-7(a)
	> 8 inch (> 200 millimeter)	±1 inch (±25 millimeter)	
Spacing of dowels, measured along a line parallel to the specified spacing	For all slab thicknesses`	±3 inch (±75 millimeter)	7-7(b)
Centerline of dowel with respect to a horizontal line that is perpendicular to the plane established by the joint	Horizontal deviation	±1/2 inch (±13 millimeter)	7-7(c)
	Vertical deviation	±1/2 inch (±13 millimeter)	

Figure 7-7 **Dowel Bar Tolerances**



(a) Dowel placement (b) Dowel spacing

(c) Dowel deviation from line

To ensure that dowels meet the tolerance requirements, contractors should place dowels on supports—dowel baskets (Figure 7-8 and 7-9)—so they may remain parallel in both the horizontal and vertical planes during the placing and finishing operations and to maintain alignment of dowels in sawcut contraction joints. Plate dowels in contraction joint basket assemblies with the compressible material or tapered shape allow for some horizontal misalignment with the sawcut contraction joint. Because plate and square dowel systems provide minimal horizontal restraint, they can be placed as close as 8 inches (150 millimeters) to the intersection of joints. Round or bar dowels should be placed at a minimum 12 inches (300 millimeters) from the intersection of joints because the maximum movement caused by horizontal dry shrinkage occurs at this point, and the corner of the slab may consequently crack.

Figure 7-8 **Round Dowel Basket Assembly**

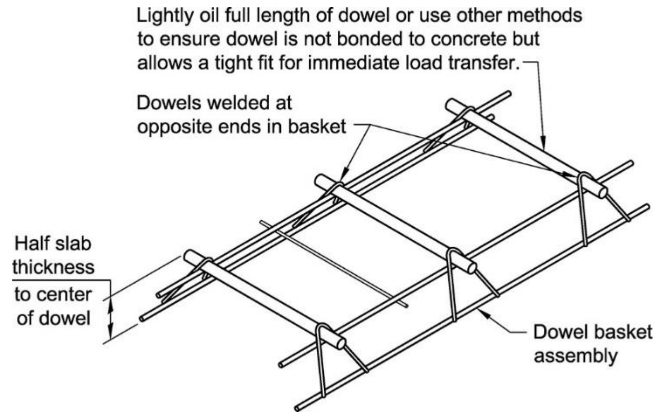
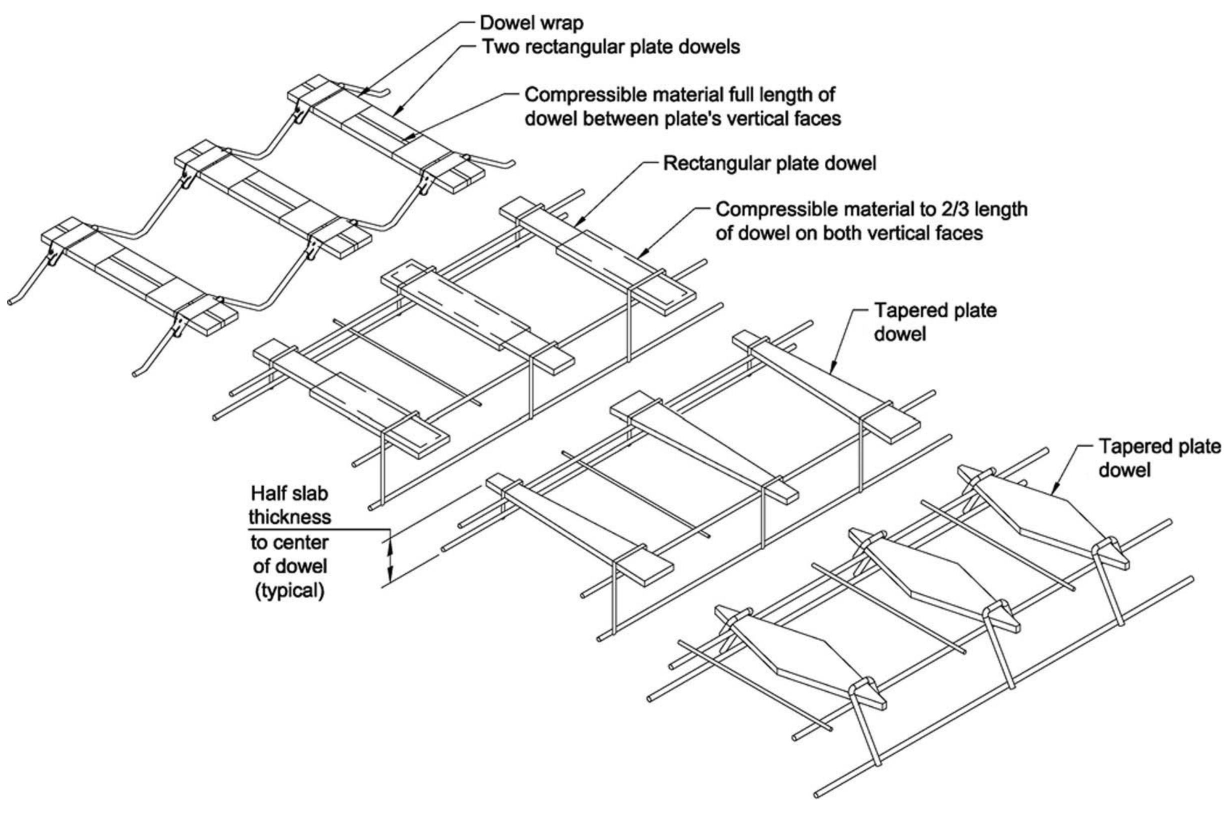


Figure 7-9 **Different Plate Dowel Basket Assemblies**



7-6 CONCRETE OVERLAY.

Concrete overlays are used to increase slab-on-ground thickness during initial construction or as a remedial measure. For bonded and unbonded overlay the minimum thickness must not be less than 3/4 inch (19 millimeter) and 4 inch (100 millimeters), respectively. Joints in concrete overlay slabs should be located directly over joints in the base slab and, when the concrete overlay is bonded, no additional joints are required. The bonded concrete overlay slab should be designed for the shrinkage restraint due to the bond to the existing slab, and the bond should be sufficient to resist the upward tension force due to curling/warping. With the designer’s approval, construction joint details and sawcut contraction joint details can be interchanged. The concrete overlay slab can have high curling/warping stresses due to the bottom slab being a hard base for the concrete overlay slab. Therefore, for a thin, unreinforced, unbonded concrete overlay slab, consider additional joints between the existing joints in the bottom slab to help reduce the curling stress in the concrete overlay slab. Also, cracks in the base slab that are not stable should be repaired to ensure they should not reflect through into the concrete overlay slab.

7-7 SLAB TOLERANCES.

Floor surface tolerances should conform to ACI 117. The face floor profile numbers or shortly referred to as F-numbers include two numbers floor flatness, F_F, and floor levelness, F_L. The SER provides these two numbers based on the operational performance needs in the construction documents. Floor flatness is related to variations or bumpiness over 24 inches (600 millimeters) and floor levelness controls local conformance to design grade by limiting differences in inclination from design grade over 120 inches (3 meters) distance when measured along sample measurement lines in accordance with ASTM E1155 (Figure 7-10(a) and 7-10(b)). Floor flatness and levelness must be controlled from a theoretical flat plane, which must be within 3/4 inches (19 millimeters) of design elevation. Floor surfaces are measured within 24 hours after placement but no later than 72 hours after installation.

Figure 7-10 **Floor Flatness and Levelness Measurements.**

(a) Floor flatness is calculated from elevation readings over 24 inch (600 millimeter) meter) increments

(b) Floor levelness is calculated from elevation readings over 10 foot (3 increments

The SER should specify two numbers only if traffic/movement is random on the slab-on-ground—the specified overall floor flatness (SOF_F) and specified overall floor levelness (SOF_L) (Table 7-3). ACI 117 allows a minimum local value for F_F and F_L of 3/5 of the SOF_F and SOF_L, unless noted otherwise. However, minimum local values should never be less than F_F13/F_L10. Whereas in manufacturing or warehouses where defined traffic is planned, such as narrow aisles with high-lift materials handling equipment between racks, it requires tighter control on surface regularity than in typical warehouse or industrial facility. The SER should be cognizant that inadequate surface regularity increases the risk of collision between the high-lift trucks and racks, resulting in adverse effects on the operations (refer to Figure 7-11). ACI 360R provides typical defined traffic values for different rack heights that have been used successfully (Table 7-4).

Table 7-3 ASTM E1155 Method

Floor surface classification	Specified overall flatness SOF_F	Specified overall levelness SOF_L
Conventional	20	15
Moderately flat	25	20
Flat	35	25
Very flat	45	35
Super flat	60	40

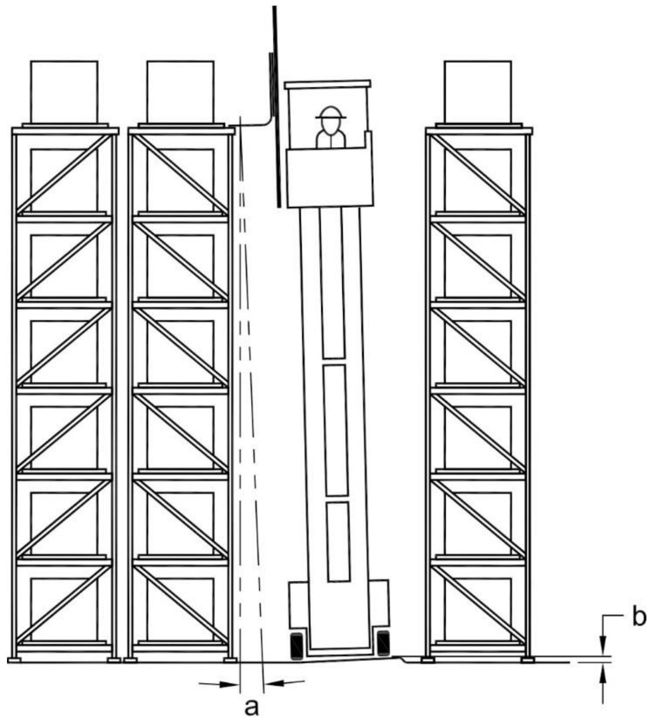
Table 7-4 Defined Traffic Values

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 to65 (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.

Figure 7-11 **Improper Slab-on-Ground Tolerances may Result in Obstruction to Operations**



a = static lean
b = variation in floor level

Floor flatness and floor levelness are affected by placement methods and finishing procedures during construction. Table 7-5 summarizes the construction procedures to obtain the minimum flatness and levelness F-numbers that are expected to be achieved by competent and knowledgeable finishers.

If slab-on-ground is out of tolerance, then remedial measures must be performed including grinding, planning, surface repair, concrete overlay, and removal and replacement of the entire slab-on-ground. Contract documents should clearly identify the acceptable corrective method(s) to be used.

Table 7-5 Slab-on-Ground Flatness/Levelness Construction Guide (ACI 360R)

FLATNESS	
Typical specification requirements	Typical finishing requirements
Specified overall value—20 Minimum local value—15	1. Smooth surface using 4 to 5 ft wide bull float. 2. Wait until bleed water sheen has disappeared. 3. Float surface with one or more passes using a power float (float-shoe blades or pans). 4. Make multiple passes with a power trowel (trowel blades).
Specified overall value—25 Minimum local value—17	1. Smooth and restraighten surface using 8 to 10 ft wide bull float. 2. Wait until bleed water sheen has disappeared. 3. Float surface with one or more passes using a power float (float-shoe blades or pans). 4. Restraighten surface following paste-generating float passes using 10 ft wide highway straightedge. 5. Make multiple passes with a power trowel (trowel blades).
Specified overall value—35 Minimum local value—24	1. Smooth and restraighten surface using 8 to 10 ft wide bull float. Apply in two directions at 45-degree angle to strip. 2. Wait until bleed water sheen has disappeared. 3. Float surface with one or more passes using a power float (float-shoe blades or pans). 4. Restraighten surface following paste-generating float passes using 10 ft wide highway straightedge. Use in two directions. Use supplementary material to fill low spots. 5. Multiple passes with pans. 6. Multiple passes with a power trowel (trowel blades).
Specified overall value—50 Minimum local value—35	1. Smooth and restraighten surface using 8 to 10 ft wide bull float or highway straightedge. Apply in two directions at 45-degree angle to strip. 2. Wait until bleed water sheen has disappeared. 3. Float surface with one or more passes using a power float (float-shoe blades or pans). First float pass should be across width of strip. 4. Restraighten surface following paste-generating float passes using 10 ft wide highway straightedge. Use in two directions. Use supplementary material to fill low spots. 5. Multiple passes with pans. 6. Multiple passes with a power trowel (trowel blades). 7. Restraighten surface after trowel passes using multiple passes with weighted highway straightedge to scrape the high points. No filling of the low spots is done at this stage.
LEVELNESS	
Typical specification requirements	Typical forming and strike-off requirements
Specified overall value—15 Minimum local value—10	1. Set perimeter forms (optical or laser instruments). 2. Use block placements of varying dimensions. Use wet screed strike-off techniques to establish initial grade.
Specified overall value—20 Minimum local value—15	1. Set perimeter forms (optical or laser instruments). 2. Use block placements of varying dimensions. Use wet screed strike-off techniques to establish initial grade. 3. Check grade after strike-off. Repeat strike-off as necessary.
Specified overall value—25 Minimum local value—17	1. Set edge forms using optical or laser instruments. Optical instruments provide more accurate elevation control. 2. Use strip placements with maximum widths of 50 ft. Use edge forms to establish initial grade. 3. Use vibratory screed for initial strike-off. 4. Use a laser screed instead of rigid strike-off guides and vibratory screed to produce this same quality.
Specified overall value—30 Minimum local value—20	1. Set edge forms using optical or laser instruments. Optical instruments provide more accurate elevation control. 2. Use strip placements with maximum widths of 30 ft. Use edge forms to establish initial grade. 3. Use vibratory screed for initial strike-off. 4. Check grade after strike-off. Repeat strike-off as necessary. 5. Use a laser screed instead of rigid strike-off guides and vibratory screed to produce this same quality.
Specified overall value—50 Minimum local value—35	1. Set edge forms using optical instrument to ±1/16 in. in accuracy. Use straightedge to identify form high spots; place top surface to fit inside 1/16 in. envelope. 2. Use strip placements with maximum widths of 20 ft. Use edge forms to establish initial grade. 3. Use vibratory screed for initial strike-off. 4. Check grade after strike-off. Repeat strike-off as necessary. 5. Follow vibratory screed pass with two or three hand straightedge passes along the axis of the strip. 4. Use a laser screed instead of rigid strike-off guides and vibratory screed to produce this same quality.

Notes
a) 1 in. = 25.4 mm
b) These descriptions illustrate typical tolerance levels and construction procedures for floor surfaces in which direction and location of traffic may vary (random-traffic pattern). Most surfaces should accommodate random traffic patterns.
c) The use of F-numbers to specify tolerances allows the specifier and contractor independent control of surface waviness and levelness. The Flatness F-number (F_F) controls waviness; the Levelness F-number (F_L) controls local levelness. Levelness quality is mainly dependent on accuracy of formwork and initial strike-off.
d) The tolerance examples illustrate average to high floor tolerances; specified quality levels should be dictated by facility use.
e) Descriptions of placing and finishing methods are intended to assist the contractor in evaluation and fine-tuning of relative costs associated with producing the various levels of quality in flatness and levelness.
f) Finishing sequences described in this table require a slight modification when a metallic hardener, mineral-aggregate hardener, pigmented hardener, or pigment is to be applied. Refer to 10.6 for detailed discussion of suggested techniques. Proposed techniques for application of hardener and finishing concrete should be confirmed with a successful panel installation.

7-8 SPECIAL CONSIDERATIONS.

For electric-powered forklifts, the SER should specify 1/4 to 1/2 inch per foot, or 10% slope (10 feet (3 meters) vertically for every 100 feet (30.5 meters) horizontally). The abovementioned maximum slopes are based on a coefficient of friction of 0.9 for the operating surface. The use of sealants, waxes, and other similar products to reduce dusting should lower the coefficient of friction considerably. In areas where these compounds are used and a rough broom finish is not practical, reducing the slope of the ramp should be considered. If the slope cannot be reduced, pressure-sensitive abrasive tapes can be installed. The abrasive tapes are of the type used on stairway treads to produce a nonskid surface.

7-9 SUMMARY.

1. Specifications should be complete, including design assumptions and direction to the contractor for subgrade/base preparation.
2. A preconstruction meeting should be held at least two weeks before construction of slab-on-ground commences.
3. Slab-on-ground placement should be in large panels or in alternating longitudinal strips.
4. Vapor barriers/retarders should be used only in certain conditions; refer to Figure 7-3.
5. It is recommended to use early-entry sawcut method for contraction joints; refer to Table 7-1.
6. Delay application of joint sealant as much as possible and provide a provision in the specification for the contractor to return between 6 months and 1 year to repair joint filler separation.
7. Dowels should be used in slabs-on-ground supporting traffic or are more than 8 inches (200 millimeters) thick.
8. Dowels are not bonded to concrete and allow a tight fit for immediate load transfer.
9. Dowel tolerances satisfying ACI 117.
10. Slab levelness and flatness satisfying ACI 117.

This Page Intentionally Left Blank

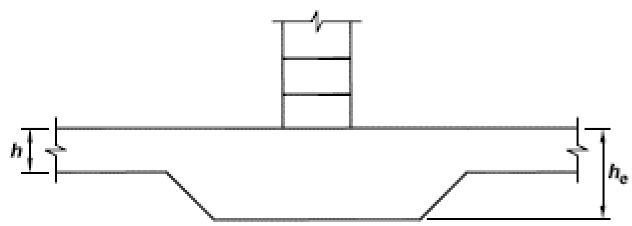
APPENDIX A **EQUATIONS FOR COMPUTING THE ALLOWABLE WALL LOADS NEAR CENTER OF SLAB OR NEAR KEYED OR DOWELED JOINTS**

A-1 LINE LOAD LOCATED NEAR CENTER OF SLAB FAR FROM JOINT.

The allowable wall loads applied within slab-on-ground panel—away from joints:

Allowable load per linear foot can be calculated from Equation A-1.

Equation A-1 **Allowable Load per Linear Foot**



$$p = 4\sigma_t S\lambda$$

where

$\sigma_t = 1.6\sqrt{f_c'}$ (pounds per square inch) [$\sigma_t = 0.13\sqrt{f_c'}$ (megapascal)]

$$S = \frac{bh_e^2}{6}$$

$$\lambda = \sqrt[4]{\frac{12k}{4EI}}$$

$E = 57{,}000\sqrt{f_c'}$ (pounds per square inch) [$E = 4700\sqrt{f_c'}$ (megapascal)]

$$I = \frac{bh_e^3}{12}$$

b = 12 inches (300 millimeters)

Substituting in Equation A-1:

$$p = 4\left(1.6\sqrt{f_c'}\right)\left(\frac{bh_e^2}{6}\right)\sqrt[4]{\frac{12k}{4EI}}$$

$$p = 4(1.6\sqrt{f_c'})\left(\frac{12h_e^2}{6}\right)\sqrt[4]{\frac{3k}{57{,}000\sqrt{f_c'}\left(\frac{12h_e^3}{12}\right)}}$$

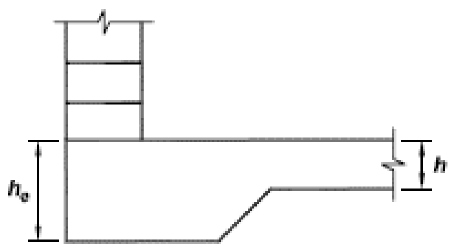
$$p = 12.8(\sqrt{f_c'})h_e^2\sqrt[4]{\frac{k}{19{,}000\sqrt{f_c'}h_e^3}}$$

$p = 1.09(f_c')^{3/8}(h_e)^{5/4}\sqrt[4]{k}$, pounds per foot [$p = 2.45\left(f_c'\right)^{3/8}(h_e)^{5/4}\sqrt[4]{k}$ Newton per meter]

where f_c' = specified compressive strength of concrete, pounds per square inch (megapascal); h_e = slab thickness, inches (millimeter); and k = modulus of subgrade reaction, pounds per cubic inch (megapascal per meter).

A-2 LINE LOAD LOCATED NEAR KEYED OR DOWELED JOINT.

Equation for calculating the allowable wall load near a free edge of a slab-on-ground:



Equation A-2 **Allowable Wall Load**

$$p = \frac{\sigma_t S\lambda}{B_{\lambda x}}$$

$B_{\lambda,x}$ = 0.3224 (point of maximum moment; see table in *Beams on Elastic Foundations* by M. Hetenyi (1946))

$$p = \left(1.6\sqrt{f_c'}\right)\left(\frac{bh_e^2}{6}\right)\frac{\sqrt[4]{\frac{12k}{4EI}}}{0.3224}$$

$$p = \left(1.6\sqrt{f_c'}\right)\left(\frac{bh_e^2}{6}\right)\frac{\sqrt[4]{\frac{3k}{57{,}000\sqrt{f_c'}\left(\frac{12h_e^3}{12}\right)}}}{0.3224}$$

$$p = 9.93\left(\sqrt{f_c'}\right)h_e^2\sqrt[4]{\frac{k}{19{,}000\sqrt{f_c'}h_e^3}} \qquad \left(P = 0.12\left(\sqrt{f_c'}\right)h_e^2\sqrt[4]{\frac{k}{39{,}175\sqrt{f_c'}h_e^3}}\right)$$

$p = 0.85(f_c')^{3/8}\left(h_e\right)^{5/4}\sqrt[4]{k}$ pounds per foot; $\left(p = 1.90\left(f_c'\right)^{3/8}\left(h_e\right)^{5/4}\sqrt[4]{k}\ \text{Newton per meter}\right)$

This Page Intentionally Left Blank

APPENDIX B DESIGN EXAMPLES

B-1 DESIGN EXAMPLES PER CORPS OF ENGINEERS (COE) METHOD.

B-1.1 Example 1: Concrete Slab-on-Ground Thickness for Moving and Stationary Loads

The slab-on-ground for a warehouse will be designed based on the following information:

Traffic

Type of traffic	Average daily volume	Category
5-axle trucks 4 axles, 5 kip (22.2 kN) each 1 axle, 10 kip (44.5 kN)	50	I
15-kip (66.7 kN) forklifts or trucks	15	II
Distributed load	1200 psi (57.5 kPa)	
Interior wall load	1400 lb/linear ft (20.43 kN/m)	

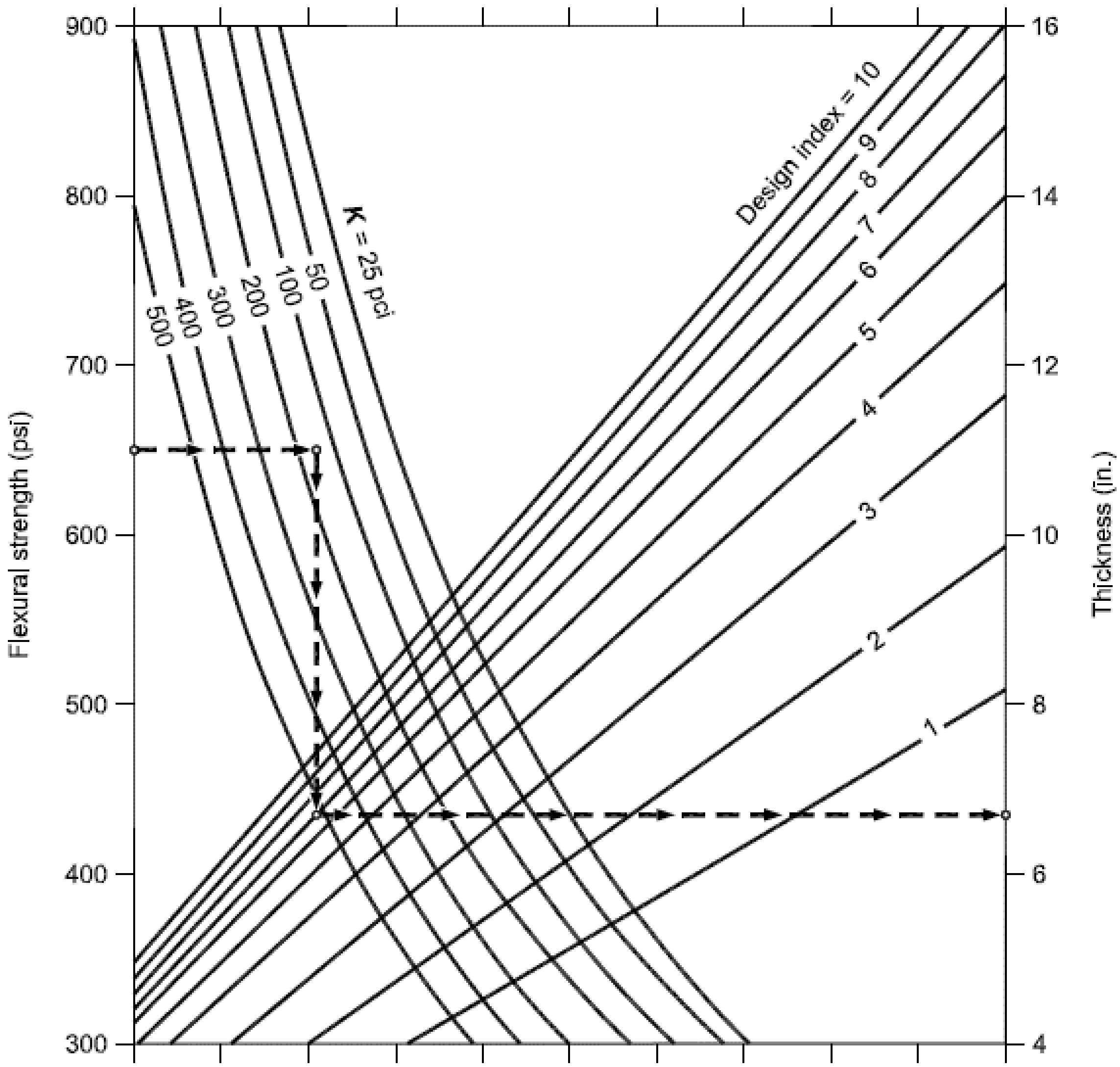
Material properties
Concrete flexural strength = 650 pounds per square inch (4.48 megapascal)
Modulus of subgrade reaction, *k* = 150 pounds per square inch per inch (40.71 megapascal per meter)

Solution
(1) Floor slab thicknesses *h* should be determined by using equivalent forklift truck axle load below.

Equivalent forklift truck axle load, kip	Number of axles	Average daily volume	Maximum operations per day	Design index
5	4	50	200	4
10	1	50	50	4
15	1	15	15	7

Matching the axle loads and maximum operations per day in Table 5-2, the design index for each axle-load group is selected as shown in the far-right column in the above-mentioned table. Design Index 7 is selected for the design. From Figure B-1.1 (Chapter 5, Figure 5-3), using *k* = 150 pounds per square inch per inch (40.71 megapascal per meter) and 650 pounds per square inch (4.48 megapascal) flexural strength, slab thickness is read to be equal to 6.7 inches (170 millimeters). Roundup the slab-on-ground thickness to 7 inches (175 millimeters).

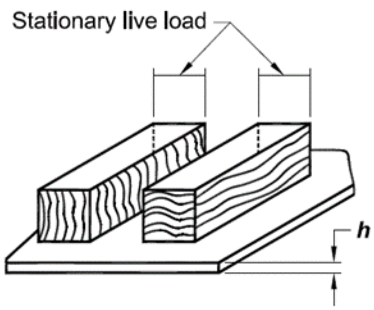
Figure B-1.1 Determine Slab-on-Ground Thickness



(2) One must check for adequacy of 7-inch (175-millimeter) slab for stationary live load, *w* = 1200 pounds per square foot (57.5 kilopascal). Table B-1.1 (Chapter 5 Table 5-3) should be entered using 650 pounds per square inch (4.48 megapascal) flexural strength concrete and 7-inch (175-millimeter) slab thickness; allowable stationary live load is selected, *w* =1109 pounds per square inch (53 kilopascal). The *w* is adjusted based on *k* = 150 pounds per square inch per inch (40.71 megapascal per meter).

Table B-1.1 Maximum Allowable Stationary Live Load (Table 5-3)

Thickness of thickened floor slab, ***h*** (in.)	Flexural strength of concrete (lb/in.^{2})				
	550	600	650	700	Slab line load capacity, ***P*** (lb/lin. ft)
4	425	455	485	510	
5	565	600	640	675	
6	710	755	805	850	
7	860	920	975	1030	
8	1015	1080	1150	1215	
9	1175	1255	1330	1410	
10	1340	1430	1520	1605	



NOTE: Distributed live loads tabulated above are based on a modulus of subgrade reaction (k) of 100 lb/in.^{2}/in. Maximum allowable distributed live loads for other moduli of subgrade reaction will be computed by multiplying the above—tabulated loads by a constant factor. Constants for other subgrade moduli are tabulated below.

Modulus of subgrade reaction	25	50	100	200	300
Constant factor	0.5	0.7	1.0	1.4	1.7

For other modulus of subgrade reaction values, the constant values may be found from the expression $\sqrt{k/100}$.

The values provided in the table are based on 100 lb/in.^{2}/in. (27.1 MPa/m). The existing obtained modulus of subgrade reaction is given as: 150 lb/in.^{2}/in. (40.71 megapascal per meter). Therefore, the allowable distributed load must be recalculated by multiplying the value in Table B-1.1 (Chapter 5, Table 5-3) by $\sqrt{150/100}$

$$w = 1109\sqrt{150/100} = 1358 \text{ lb/ft}^2 > 1200 \text{ lb/ft}^2 \quad \text{(65 kPa > 57.5 kPa)}$$

Therefore, the calculated slab-on-ground thickness is adequate to support the forklift and distributed load.

The SER may also use Equation 5-4 to calculate the allowable distributed load:

$$w = 257.875 \frac{650}{2} \sqrt{\frac{(150)(7)}{4{,}000{,}000}} = 1358 \text{ pounds per square foot}$$

$$w = 57.15 \frac{4.48}{2} \sqrt{\frac{(40.71)(175)}{27{,}600}} = 65 \text{ kilopascal}$$

(3) Thickness h of thickened floor slab supporting interior wall weighing 1400 pounds per linear foot (20.43 kilonewton per meter) should be determined by entering Table B-1.2 (Chapter 5 Table 5-6) using 650 pounds per square inch (4.48 megapascal) flexural strength concrete and wall load p = 1400 pounds per linear foot (20.43 kilonewton per meter). Thus, h equals 10 inches (250 millimeters) and h is adjusted based on k = 150 lb/in.^{2}/in. (40.71 megapascal per meter).

Table B-1.2 (Chapter 5, Table 5-6)

Thickness of thickened floor slab, ***h*** (in.)	Flexural strength of concrete (lb/in.^{2})				
	550	600	650	700	
4	425	455	485	510	Slab line load capacity, ***P*** (lb/lin. ft)
5	565	600	640	675	
6	710	755	805	850	
7	860	920	975	1030	
8	1015	1080	1150	1215	
9	1175	1255	1330	1410	
10	1340	1430	1520	1605	

The value obtained from Table B-1.2 is based on 100 pounds per square inch per inch (40.71 megapascal per meter). Therefore, to convert to an equivalent load per linear length, the value must be multiplied by $\sqrt[5]{100/150}$

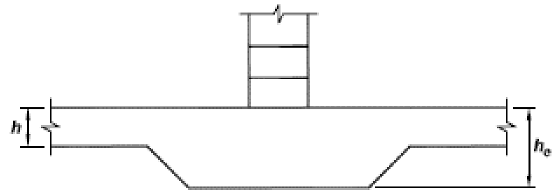
$$h = 10\sqrt[5]{\frac{100}{150}} = 9.22 \text{ inches}$$, say, 10 inches (250 millimeters)

from Figure B-1.1 (Chapter 5 Figure 5-3), minimum $h_{@wall} = h + h_1$; $h_{@wall} = 7 + 3 = 10$ inches (250 millimeters).

The slab thickness could also be calculated from the following equation, Appendix A:

$p = 1.09(f_c')^{3/8}(h_e)^{5/4}\sqrt[4]{k}$, pounds per foot

$\left(p = 2.45(f_c')^{3/8}(h_e)^{5/4}\sqrt[4]{k} \text{ Newton per meter}\right)$



Rearranging the equation to solve for h_e:

$$h_e = \left(\frac{p}{1.09\left(f_c'\right)^{3/8}(k)^{1/4}}\right)^{0.8} = \left(\frac{1400}{1.09(5200)^{3/8}(150)^{0.25}}\right) = 8.6 \text{ inch}, \text{ say, 9 inch}$$

$$h_e = \left(\frac{p}{2.45(f_c')^{0.375}(k)^{0.25}}\right)^{0.8} = \left(\frac{20,431}{2.45(36)^{0.375}(40.7)^{.25}}\right)^{0.8} = 223 \text{ millimeters}$$

Conclusions:

1. The difference in slab-on-ground thickness values obtained from the table versus the one calculated using the equation is due to the approximation when using the table
2. Construct a 7 inch (175 millimeter) thick slab-on-ground that can support the traffic loads. Increase the slab-on-ground thickness to 10 inches (250 millimeters) at wall locations per Figure B-1.1.

B-1.2 Example 2: Thickened Slab-on-Ground Design for Exterior Wall.

The thickened concrete floor slab supporting an 8 inch (200 millimeter) exterior load bearing wall weighing 1000 pounds per linear foot should be designed.

Floor slab data

Thickness = 4 inches (100 millimeters)

Flexural strength = 600 pounds per square inch (4.14 megapascal)

Modulus of subgrade reaction *k* = 200 pounds per inch square per inch (54.28 megapascal per meter)

Solution: Table B-1.3 (Chapter 5 Table 5-7) should be entered using 600 pounds per square inch (4.14 megapascal) and wall load *p* = 1000 pounds per linear foot (14,594 Newton per linear meter). Read required thickness, *h*, of 10 inch (250 millimeter). Adjust thickness based on modulus of subgrade reaction, *k* = 200 pounds per square inch per inch (54.28 megapascal per meter).

$h_e = 10\sqrt[5]{\frac{100}{200}}$ = 8.7 inches (221 millimeters), say, 9 inches (230 millimeters)

For thickened slab configuration, refer to Table B-1.3 (Chapter 5 Table 5-7).

Therefore, the thickened edge of the slab-on-ground needs to be 9 inches (230 millimeters) thick.

Note: For other practical considerations—that is frost line, erosion, etc.—thickness, *h*, may be increased.

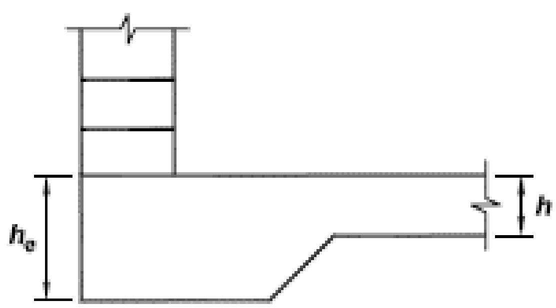


Table B-1.3 (Chapter 5, Table 5-7)

Thickened slab, h_e, in. (mm)	Slab line load capacity P, lb/lin ft (N/lin m)			
	Flexural strength of concrete, psi (MPa)			
	550 (3.79)	**600 (4.14)**	**650 (4.48)**	**700 (4.83)**
4 (100)	330 (4816)	355 (5181)	375 (5473)	395 (5765)
5 (125)	435 (6348)	465 (6786)	495 (7224)	525 (7662)
6 (150)	550 (8027)	585 (8537)	620	660
7 (175)	665 (9705)	710 (10,362)	755	800
8 (200)	785 (11,456)	840 (12,259)	890	945
9 (230)	910 (13,280)	975 (14,229)	1035	1090
10 (250)	1040 (15,178)	1110 (16,199)	1180	1245

B-1.3 Example 3: Reinforced Concrete Slab-on-Ground

It is decided that the 7-inch (175-millimeter) floor slab in Example 1 should be reduced to 6 inches (150 millimeters) by reinforcing the slab using 60,000-pounds per square inch (420 megapascal) yield strength steel reinforcement. The percent reinforcement required for the 6-inch (150-millimeter) slab should be determined.

Solution: From Figure B-1.2 (Chapter 5 Figure 5-14), a straight line should be drawn between h = 7 inches (175 millimeters) and h_t = 6 inches (150 millimeters) and extend line to S. This should read S = 0.12%.

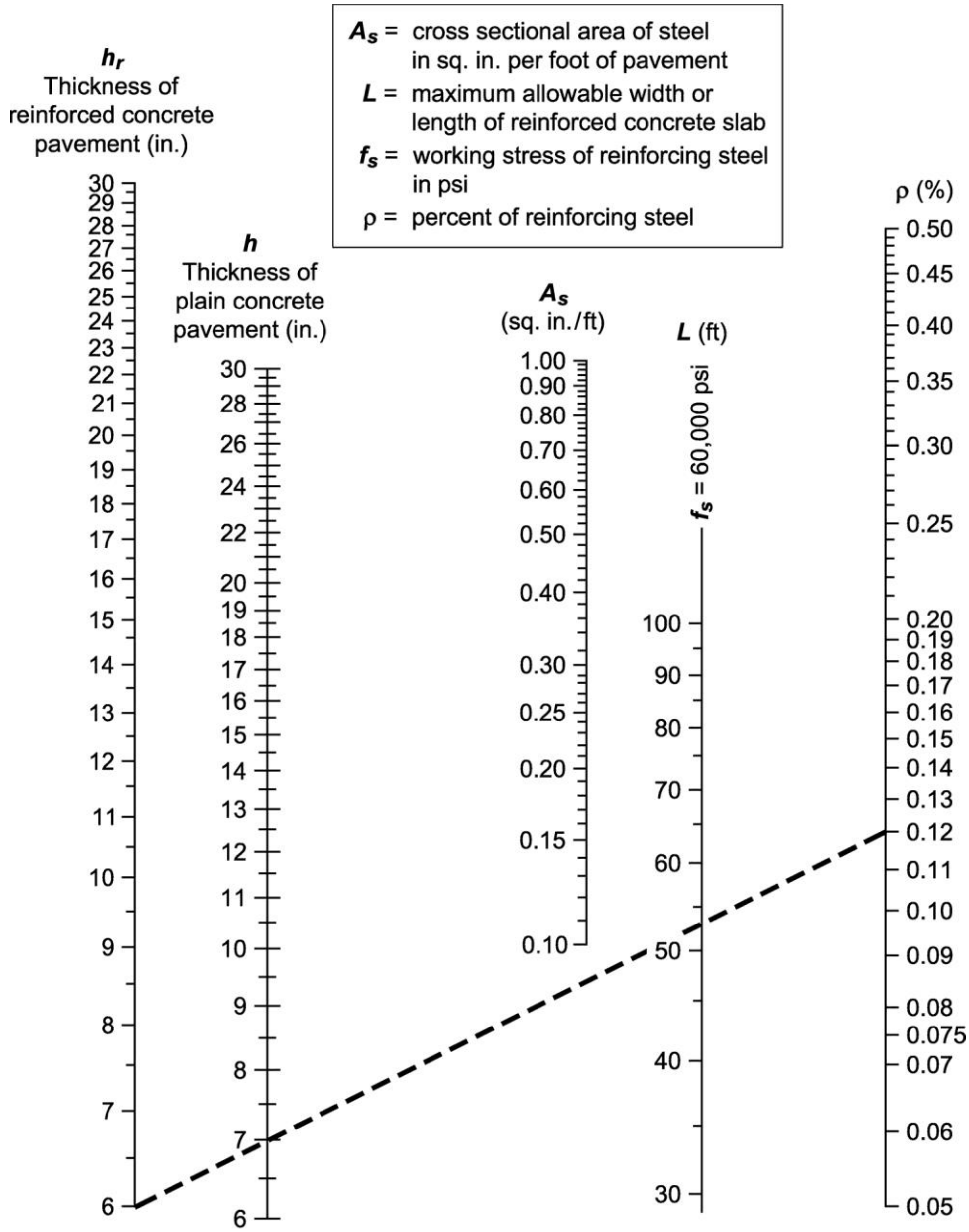
$A_{s,req'd} = 6 \times 12 \times 0.0012 = 0.0864$ square inch (55.7 square millimeter), which is equivalent to No. 4 (No. 13) bars at 24 inch (600 millimeter) on center in both directions.

$A_{s,prov.}$ = 0.1 inch square (65 millimeter square) > $A_{s,req'd}$ = 0.0864 inch square (55.7 millimeter square)

It is preferable to maintain closer bar spacing. Choose No. 4 (No. 13) at 18 inch (450 millimeters) on center, $A_{s,\ recommended}$ = 0.13 square inch (84 square millimeter).

Place bars at slab-on-ground mid-depth, discontinue at joints or cut 1/3 of the bars. Provide dowels per Chapter 5.

Example B-1.3 Determine Slab-on-Ground Required Reinforcement



Reinforced concrete pavement design

Note: Minimum thickness of reinforced concrete floor slabs will be 6 in.

B-1.4 Example 4: Concrete Slab-on-Ground Thickness For Tracked Vehicle.

The floor slab thickness *h* should be determined for a tank repair shop. The largest tank has a gross weight of 60 kip (267 kilonewtons), Traffic is limited to 40 vehicles per day.

Material properties:

Concrete flexural strength = 700 pounds per square inch (4.83 megapascal)

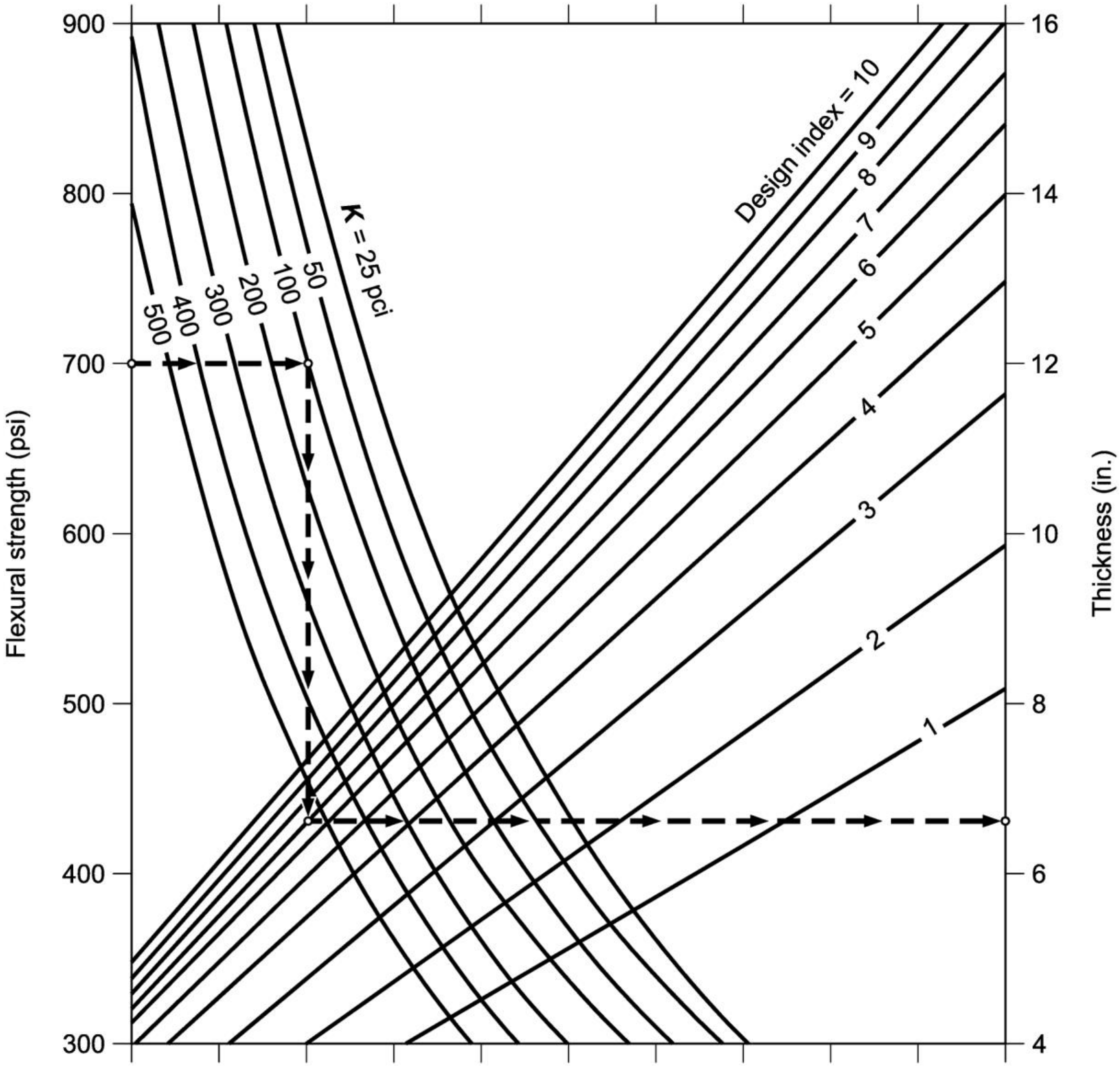
Modulus of subgrade reaction, *k* = 100 pounds per square inch per inch (27.1 megapascal per meter).

Solution: Based on 60 kip (267 kN) gross weight, equivalent forklift category II is selected from second tabulation in Section 5-4.1. From first tabulation in Section 5-4.1 for category II, forklift truck axle load is 10 to 15 kip (44.5 to 66.7 kN). Table B-1.4 is entered using 15 kips (66.7 kN). Loaded at a frequency of 100 operation per day, the design index is 7. Figure B-1.4 (Chapter 5 Figure 5-3) is entered using concrete flexure strength = 700 pounds per square inch (4.83 megapascal), *k* = 100 pounds per square inch per inch (27.1 megapascal per meter) and DI = 7, slab thickness *h* = 6.6 inches (168 millimeters) or rounded to 7 inches (175 millimeters).

Table B-1.4 Traffic Categories for Design Index (Table 5-2)

Maximum operations per day over 25 years	Load	Design Index
50	10-kip (44 kN) axle-load forklift truck	4
250	10-kip (44 kN) axle-load forklift truck	5
10	15-kip (67 kN) axle-load forklift truck	
250	10-kip (44 kN) axle-load forklift truck	7
100	15-kip (67 kN) axle-load forklift truck	
250	15-kip (67 kN) axle-load forklift truck	8
5	25-kip (111 kN) axle-load forklift truck	

Figure B-1.4 Determine Slab-on-Ground Thickness



B-1.5 Example 5: Slab-on-Ground Thickness For 4.5-Ton Forklift Truck.

Design a slab-on-ground supporting a 4.5-ton forklift truck. Assume that the thickness of the subbase is 6 inches (150 millimeters) and the modulus of subgrade reaction is determined to be 100 pounds per square inch per inch (27.14 megapascal per meter). Concrete compressive strength is specified at 4000 pounds per square inch (28 megapascal).

1. Calculate the concrete flexural strength: $7.5\sqrt{f_c'}$

$7.5\sqrt{4000 \text{ psi}}$ = 474 psi (3.27 megapascal)

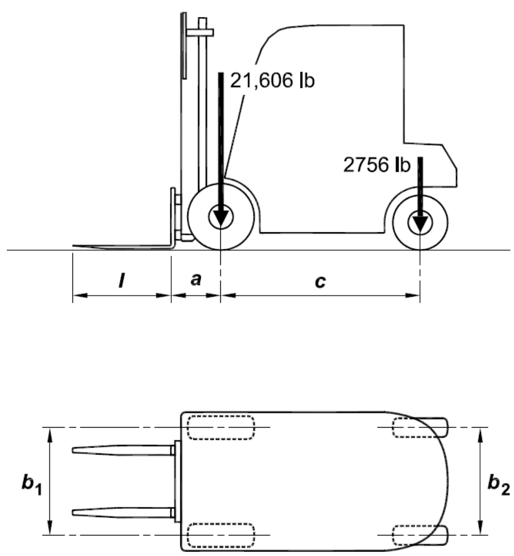
2. Determine forklift's specification from manufacturer's data sheet:

Wheels' axle load

Axle load with load, front/rear: 21,606/2756 pounds (96,108/12,259 Newton).

Therefore, front axle controls: 21,606 pounds (96,108 Newton). The front axle has a single tire; refer to Figure B-1.5a.

Figure B-1.5a Forklift Loads Applied to Examples B-1.5, B-2.1, B-2.2, B-2.3, and B-3.1

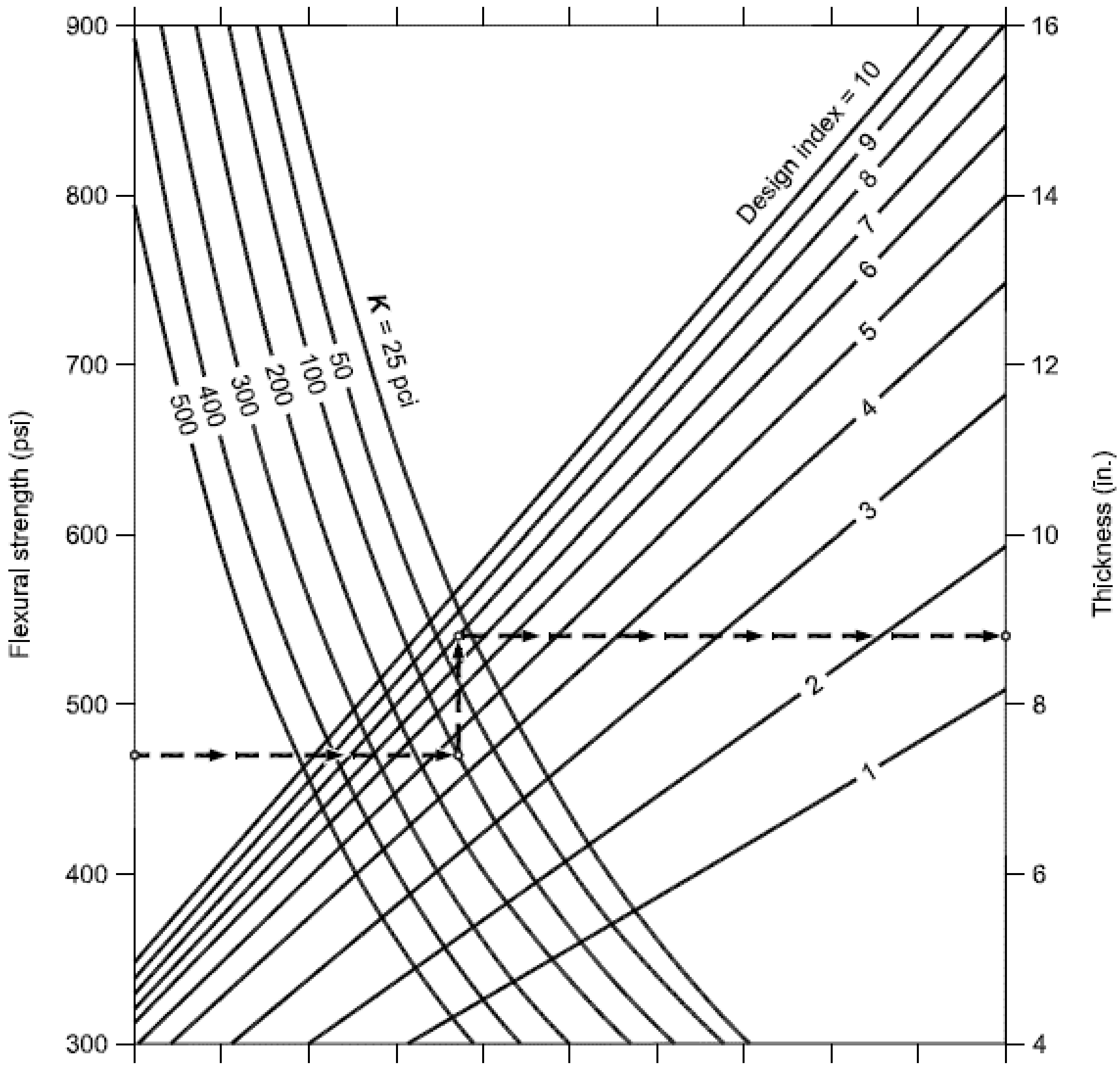


Assume that the person operating the equipment weighs 200 pounds (900 Newton) divided evenly between front and rear axle. The final front axle load is then:

p = 21,606 + 100 = 21,706 pounds (96,553 Newtons)

From Figure B-1.5b (Chapter 5 Figure 5-3), the design index number (DI) = 8

Figure B-1.5b Example B-1.5: Determining Slab-on-Ground Thickness for 4.5-Ton Forklift Truck



Solution: The slab-on-ground thickness is then determined from Figure B-1.5b and is found to be 8.7 inches (221 millimeters).

Use 9-inch (230-millimeter) thick slab-on-ground.

B-2 DESIGN EXAMPLES PER PORTLAND CEMENT ASSOCIATION (PCA) METHOD.

B-2.1 Example 1: Concrete Slab-on-Ground Thickness for Forklift Truck.

Design a slab-on-ground supporting a 4.5-ton forklift truck. Assume that subbase is 6 inches (150 millimeters) thick and the modulus of subgrade reaction is determined to be 100 pounds per square inch per inch (27.1 megapascal per meter). Concrete compressive strength is specified at 4000 pounds per square inch (28 megapascal). The factor of safety is determined equal to 2.0.

1. Calculate the concrete flexural strength: $9\sqrt{f_c'}$

$9\sqrt{4000 \text{ psi}}$ = 570 psi (3.93 megapascal)

2. Determine forklift's specification from manufacturer's data sheet:

Wheels' axle load:

Axle load with load, front/rear: 21,606/2756 pounds (96,108/12,259 Newton).

Therefore, front axle controls: 21,606 pounds (96,108 Newton). The front axle has a single tire-refer to Figure B-1.5a.

Assume that the person operating the equipment weighs 200 pounds (900 Newton) divided evenly between front and rear axle. The final front axle load is then:

p = 21,606 + 100 = 21,706 pounds (96,553 Newtons)

Front track width: 46 inches (1119 millimeters).

Tire pressure: assume 100 pounds per square inch (0.69 megapascal)

3. Calculate wheel contact area:

$$\text{contact area} = \frac{\text{axle load}}{\text{(number of tires)(pressure in tires)}}$$

$$= \frac{\text{21,706 pounds}}{\text{(2 tires)(100 psi)}} = 108 \text{ in.}^2 \ (69{,}677 \text{ mm}^2)$$

4. Choose a factor of safety (SF) = 2.0

5. Calculate working stress:

WS = f_r/ SF = 570/2.0 = 285 psi (1.965 megapascal)

6. Assume a joint factor JF = 1.0, which indicates 100% load transfer at joint or load is calculated within the panel away from the joints. Refer to Example 6-6.2.1b for using a joint factor other than 1.0 in calculating the working stress.

7. Calculate slab stress per 1000 pounds (4448 Newton) of axle load:

$$\text{Axle load}: \left(\frac{21{,}706\ \text{lb}}{1000\ \text{lb/kip}}\right) = 21.7\ \text{kip (96.5 kN)}$$

$$\text{Slab stress: } \sigma = \frac{\text{WS}}{\text{axle load}} = \frac{285\ \text{psi}}{21.7\ \text{kip}} = 13\ \text{psi per 1000 lb (0.09 MPa per 4448 Newtons)}$$

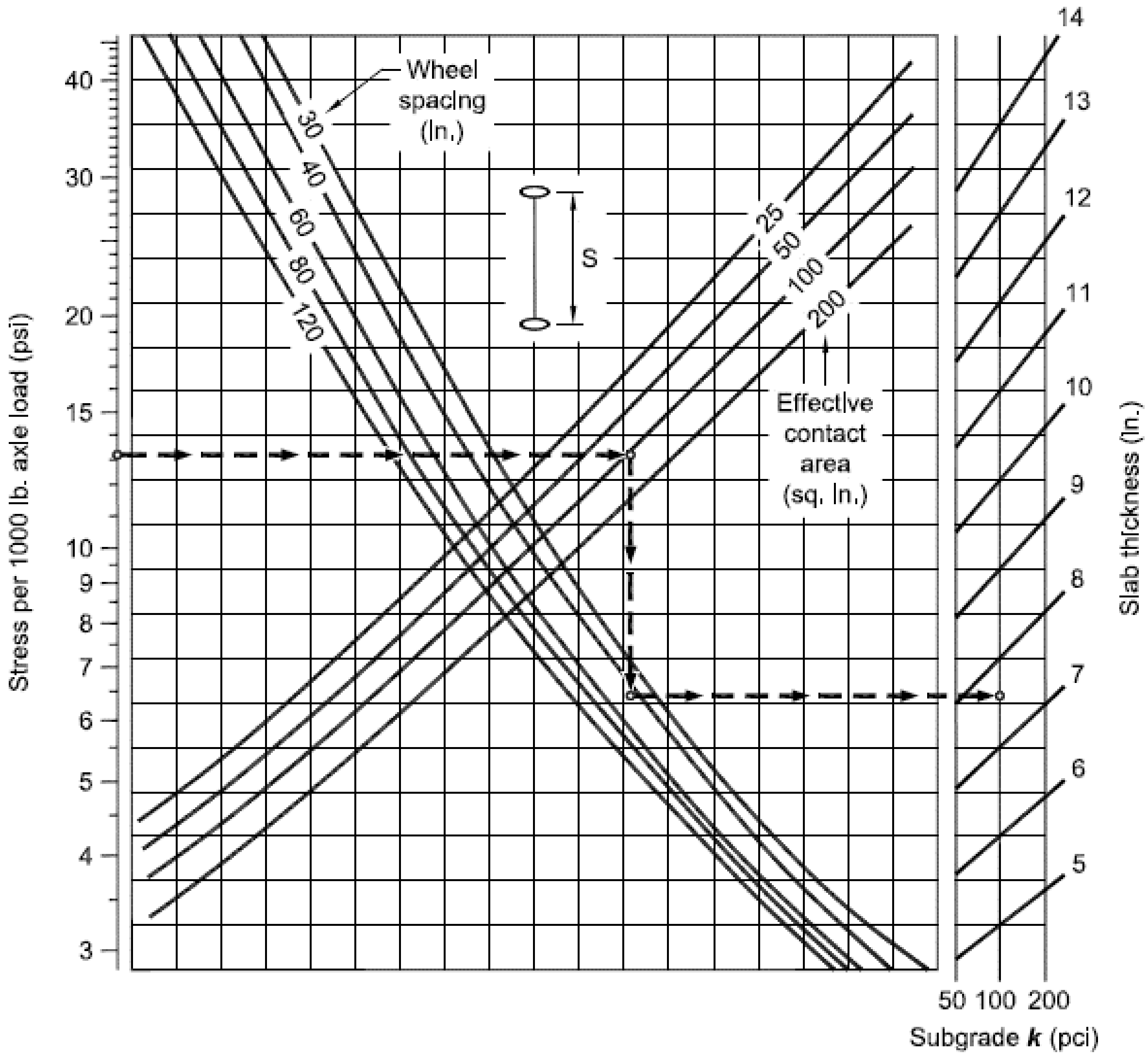
8. From Figure B-2.1:

Starting with a slab stress of 13.2 pounds per square inch (0.09 megapascal), contact area of 108 square inch (69,677 square millimeter) and wheel spacing of 46 inches (1168 millimeters), minimum slab thickness is determined to be 7.5 inches (191 millimeters).

Use minimum slab thickness = 8.0 inches (200 millimeters).

Note: If f_r is taken equal to $7.5\sqrt{f_c'}$, similar to COE and WRI methods, then the WS = 474/2.0 = 237 psi (1.6 MPa). From PCA chart, a required slab-on-ground thickness of 8.5 inch (216 mm) is needed, which the SER would round up to 9 inch (230 mm).

Figure B-2.1 Example B-2.1: Design Chart Axle with Single Wheels (PCA)



B-2.2 Example 2: Concrete Slab-on-Ground Thickness For Forklift.

Repeat Example B-2.1 to determine the required slab-on-ground thickness by choosing a modulus of subgrade *k* = 50 pounds per square inch per inch (13.57 megapascal per meter) and 200 pounds per square inch per inch (54.28 megapascal per meter).

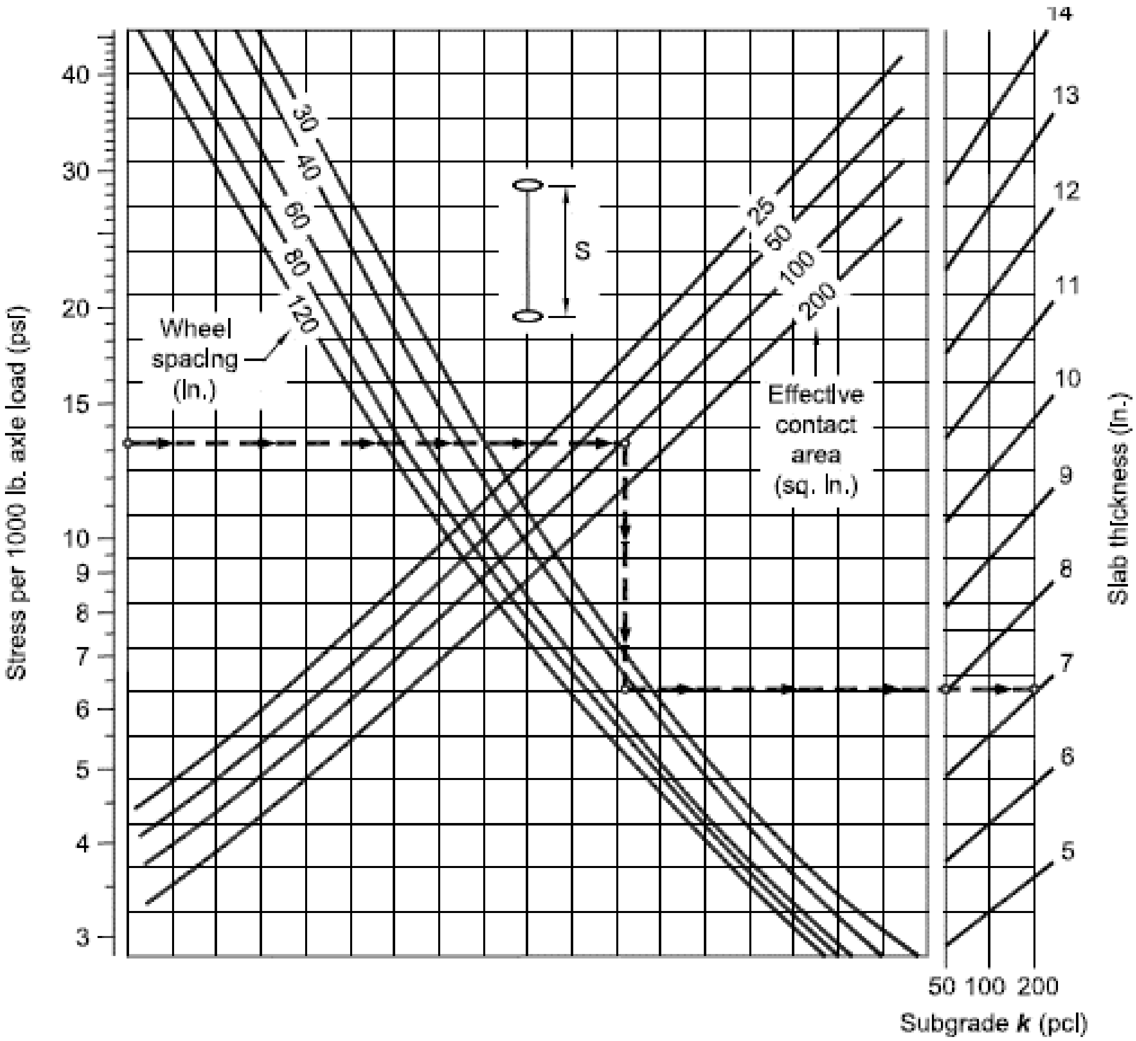
The slab-on-ground thicknesses are obtained from Figure B-2.2 and a summary table is given comparing Example B-2.1 and B-2.2 in Table B-2.1 for summary:

Table B-2.1 Slab-on-Ground Thickness with Varying Modulus of Subgrade, *k*

Modulus of subgrade, *k* lb/in.^{2}/in. (MPa/m)	Slab-on-ground thickness, *t* inch (millimeter)		D% *k* = 100 lb/in.^{2}/in. (27.1 MPa/m) (base)	Example number
	Actual	Rounded up		
50 (13.6)	8 (200)	8 (200)	1.0	C-2.2
100 (27.1)	7.5 (191)	8 (200)	1.0	C-2.1
200 (54.3)	7.0 (180)	7 (180)	0.875	C-2.2

Summary: By varying the modulus of subgrade, *k*, from 50 pounds per square inch per inch (13.57 megapascals per meter) to 200 pounds per square inch per inch (54.3 megapascals per meter), the slab-on-ground thickness decreased by 1 inch (25 millimeters) and there was no difference in slab-on-ground thickness between 100 lb/in.^{2}/in. (27.1 megapascals) and 50 lb/in.^{2}/in. (54.3 megapascals) modulus of subgrade.

Figure B-2.2 Design Chart Axle with Single Wheels (PCA)



B-2.3 Example 3: Concrete Slab-on-Ground Thickness for Forklift with Factor Of Safety; SF = 1.5 and 2.5

Repeat Example B-2.1 to determine the required slab-on-ground thickness by using a modulus of subgrade of 100 pounds per square inch per inch (27.1 megapascals per meter) and factors of safety (SF) equal to 1.5 and 2.5.

1. Calculate the concrete flexural strength: $9\sqrt{f_c'}$

$9\sqrt{4000 \text{ psi}}$ = 570 psi (3.93 megapascal)

2. Determine forklift's specification from manufacturer's data sheet:

Wheels' axle load:

Axle load with load, front/rear: 25,700/3060 pounds (114,300/13,600 Newton).

Therefore, front axle controls: 21,606 pounds (96,108 Newton).

The front axle has a single tire; refer to Figure B-1.5a.

Assume that the person operating the equipment weighs 200 pounds (900 Newtons) divided evenly between front and rear axle. The final front axle load is then:

p = 21,606 + 100 = 21,706 pounds (96,553 Newton)

Front track width: 46 inches (1168 millimeter).

Assume 100 pounds per square inch (0.69 megapascal) tire pressure.

3. Calculate wheel contact area:

$$\text{contact area} = \frac{21{,}706 \text{ pounds}}{(2 \text{ tires})(100 \text{ psi})} = 108 \text{ in.}^2 \ (69{,}677 \text{ mm}^2)$$

4. Choose factor of safety (SF) = 1.5

5. Calculate working stress:

WS = 570/1.5 = 380 psi (2.62 megapascal)

6. Assume a joint factor JF = 1.0, which indicates 100% load transfer at joint or load is calculated within the panel away from the joints. Refer to Example 6-6.2.1b for using a joint factor other than 1.0 in calculating the working stress.

7. Calculate slab stress per 1000 pounds (4448 Newton) of axle load:

$$\text{Axle load}: \left(\frac{21{,}706\ \text{lb}}{1000\ \text{lb/kip}}\right) = 21.7\ \text{kip}\ (96.5\ \text{kN})$$

$$\text{Slab stress: } \sigma = \frac{\text{WS}}{\text{axle load}} = \frac{380\ \text{psi}}{21.7\ \text{kip}} = 17.5\ \text{psi}\ (0.12\ \text{MPa})$$

8. From Figure B-2.3:

Starting with a slab stress of 17.5 pound per square inch (0.12 megapascal), contact area of 108 square inch (69,677 square millimeter) and wheel spacing of 46 inches (1168 millimeters), minimum slab thickness is determined:

Minimum slab thickness = 6.0 inches (150 millimeters).

Factor of Safety (SF = 2.5)

Calculate working stress:

WS = 570/2.5 = 228 psi (1.57 megapascal)

Assume a joint factor JF = 1.0, which indicates 100% load transfer at joint or load is calculated within the panel away from the joints. Refer to Example 6-6.2.1b for using a joint factor other than 1.0 in calculating the working stress.

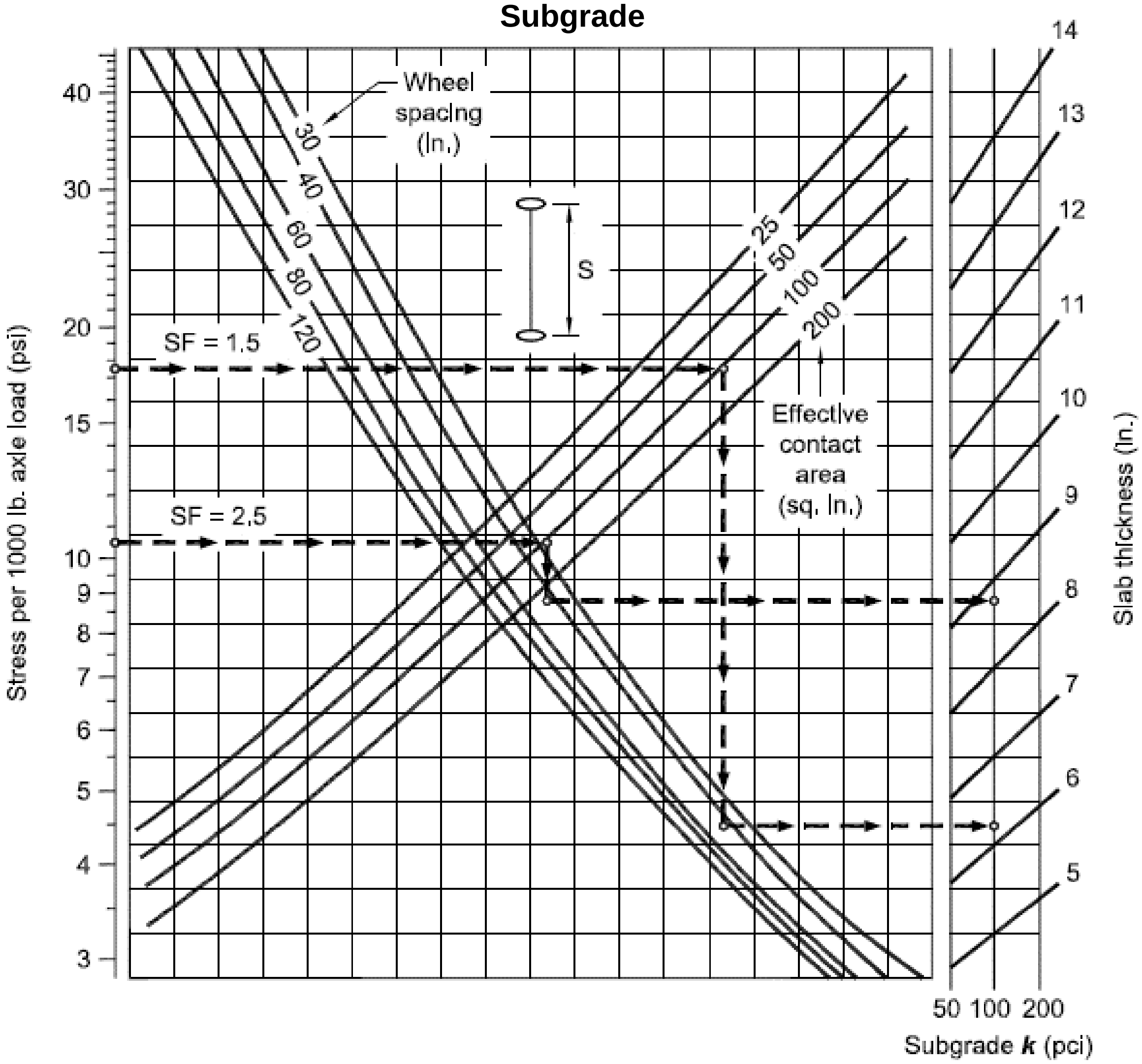
Calculate slab stress per 1000 pounds (4448 Newton) of axle load:

$$\text{Axle load}: \left(\frac{21{,}706\ \text{lb}}{1000\ \text{lb/kip}}\right) = 21.7\ \text{kip}\ (96.5\ \text{kN})$$

$$\text{Slab stress: } \sigma = \frac{\text{WS}}{\text{axle load}} = \frac{228\ \text{psi}}{21.7\ \text{kip}} = 10.5\ \text{psi}\ (0.07\ \text{MPa})$$

From Figure B-2.3, starting at 10.5 pounds per square inch (0.07 megapascal), contact area of 108 square inch (69,677 square millimeter), and wheel spacing of 46 inches (1168 millimeters), the slab-on-ground thickness is determined to be 8.8 inches (224 millimeters).

Figure B-2.3: Determine Slab-on-Ground Thickness with Varying Modulus of Subgrade



From Figure B-2.3, the slab-on-ground thickness obtained for factor of safety (SF) = 1.5 is *h* = 6.0 inches (150 millimeters) and for factor of safety (SF) = 2.5, *h* = 8.7 inches (224 millimeters), say, 9 inches (230 millimeters).

Summary:

Summary of Slab-on-Ground Thickness by Varying the Modulus Of Subgrade.

Factor of safety	Slab-on-ground thickness, *t* Inch (millimeter)	∆% SF = 2.0	Example number
1.5	9 (230)	1.125	B-2.3
2.0	8 (200)	1.0	B-2.1
2.5	6 (150)	0.75	B-2.3

Varying the factor of safety has a higher impact on the slab-on-ground thickness design than varying the modulus of subgrade, *k*.

B-2.4 Example 4: Concrete Slab-on-Ground Thickness for Dual Tire 5-Ton Forklift.

Design slab-on-ground thickness for a dual-wheel 5-Ton forklift.

The modulus of subgrade, k = 100 lb/in.^{2}/in. (27.1 megapascal per meter)

1. Calculate the concrete flexural strength: $9\sqrt{f_c'}$

$$9\sqrt{4000\text{ psi}} = 570\text{ psi (3.93 megapascal)}$$

2. Determine forklift's specification from manufacturer's data sheet:

Wheels' axle load

Axle load with load, front/rear:

25,700/3060 pounds (114,300/13,600 Newton).

Therefore, front axle controls: 25,700 pounds (114,300 Newtons). The front axle has two-dual tires.

Assume that the person operating the equipment weighs 200 pounds (900 Newton) divided evenly between front and rear axle. The final front axle load is then:

p = 25,700 + 100 = 25,800 pounds (114,750 Newtons)

Front track width: 59 inches (1490 millimeters).

Assume 100 pounds per square inch (0.69 megapascal) tire pressure.

3. Calculate wheel contact area:

$$\text{contact area} = \frac{25{,}800\text{ pounds}}{(4\text{ tires})(100\text{ psi})} = 64.5\text{ in.}^2\ (41{,}613\text{ mm}^2)$$

4. Choose factor of safety, SF = 2.0

5. Calculate working stress:

WS = 570/2.0 = 285 psi (1.965 megapascal)

6. Calculate slab stress per 1000 pounds (4448 Newtons) of axle load:

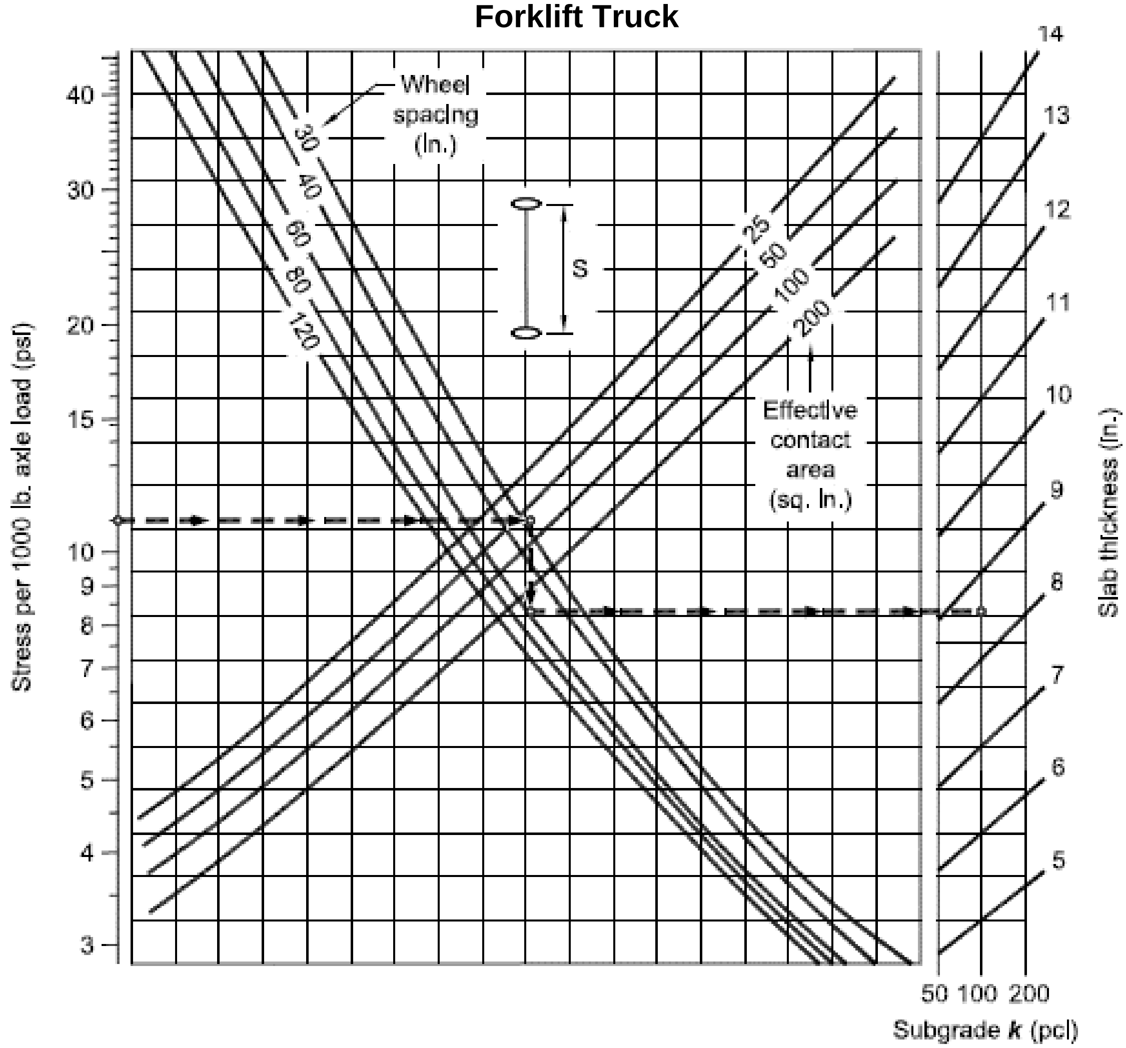
$$\text{Axle load: } \left(\frac{25{,}800\text{ lb}}{1000\text{ lb/kip}}\right) = 25.8\text{ kip (114.75 kN)}$$

Slab stress: $\sigma = \frac{WS}{\text{axle load}} = \frac{285\text{ psi}}{25.8\text{ kip}} = 11\text{ psi (0.08 MPa)}$

6. From Figure B-2.4a:

Starting with a slab stress of 11 pounds per square inch (0.08 megapascal), contact area of 64.5 square inches (41,613 square millimeters) and wheel spacing of 59 inches (1490 millimeters), minimum slab thickness is determined to be: 8.6 inches (218 millimeters), say, 9 inches (230 millimeters).

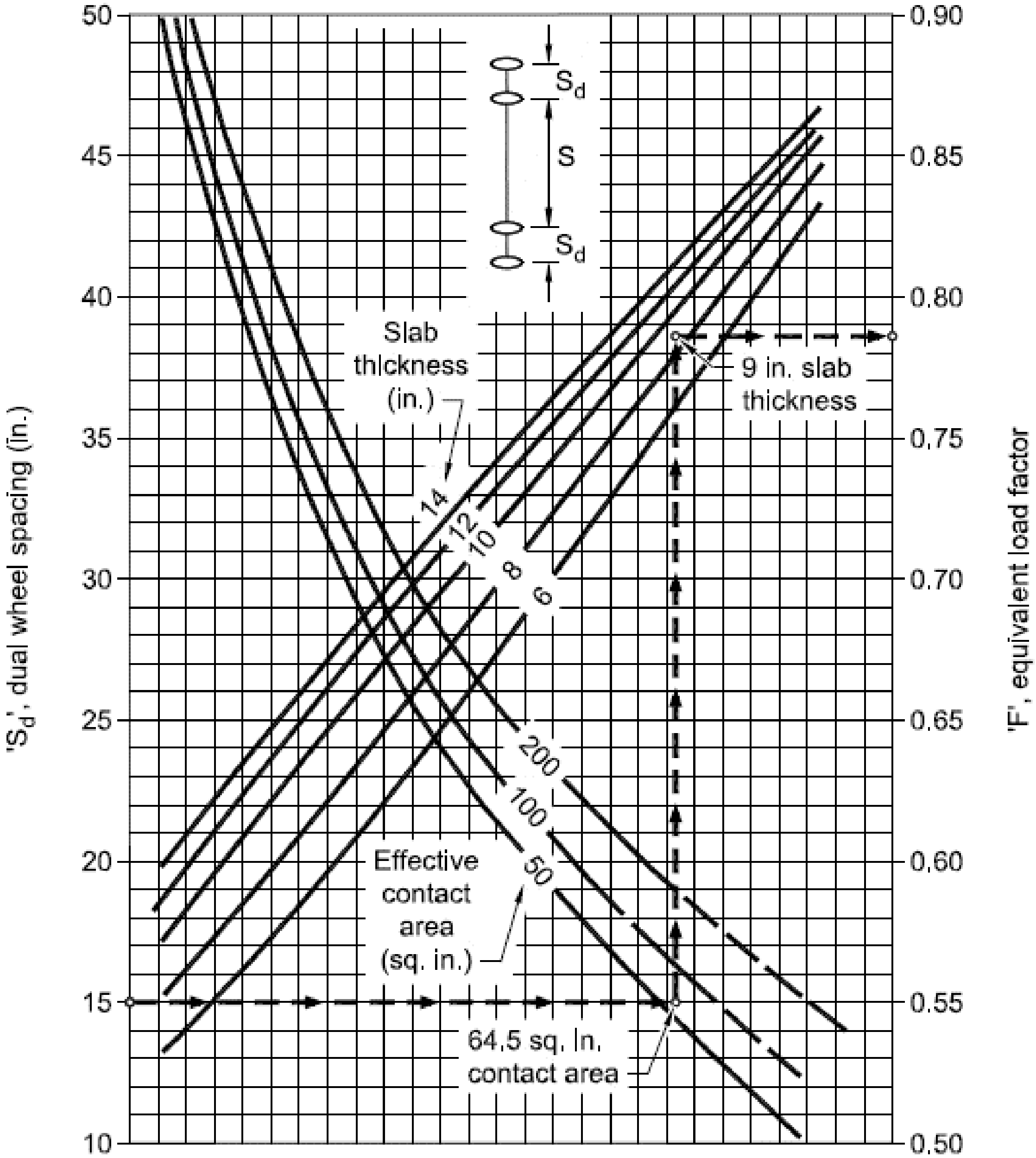
Figure B-2.4a Determine Slab-on-Ground Thickness for the Dual-Wheel Forklift Truck



From Figure B-2.4b, with s_d = 15 inches (380 millimeters) and contact area = 64.5 square inches (41,613 square millimeters), the equivalent load factor (LF) is read to be 0.785.

Therefore, equivalent single wheel axle load is: 25,800 pounds × 0.785 = 20,253 pounds (90,090 Newtons).

Figure B-2.4b Determining the Equivalent Load Factor for Dual-Wheel Forklift Truck

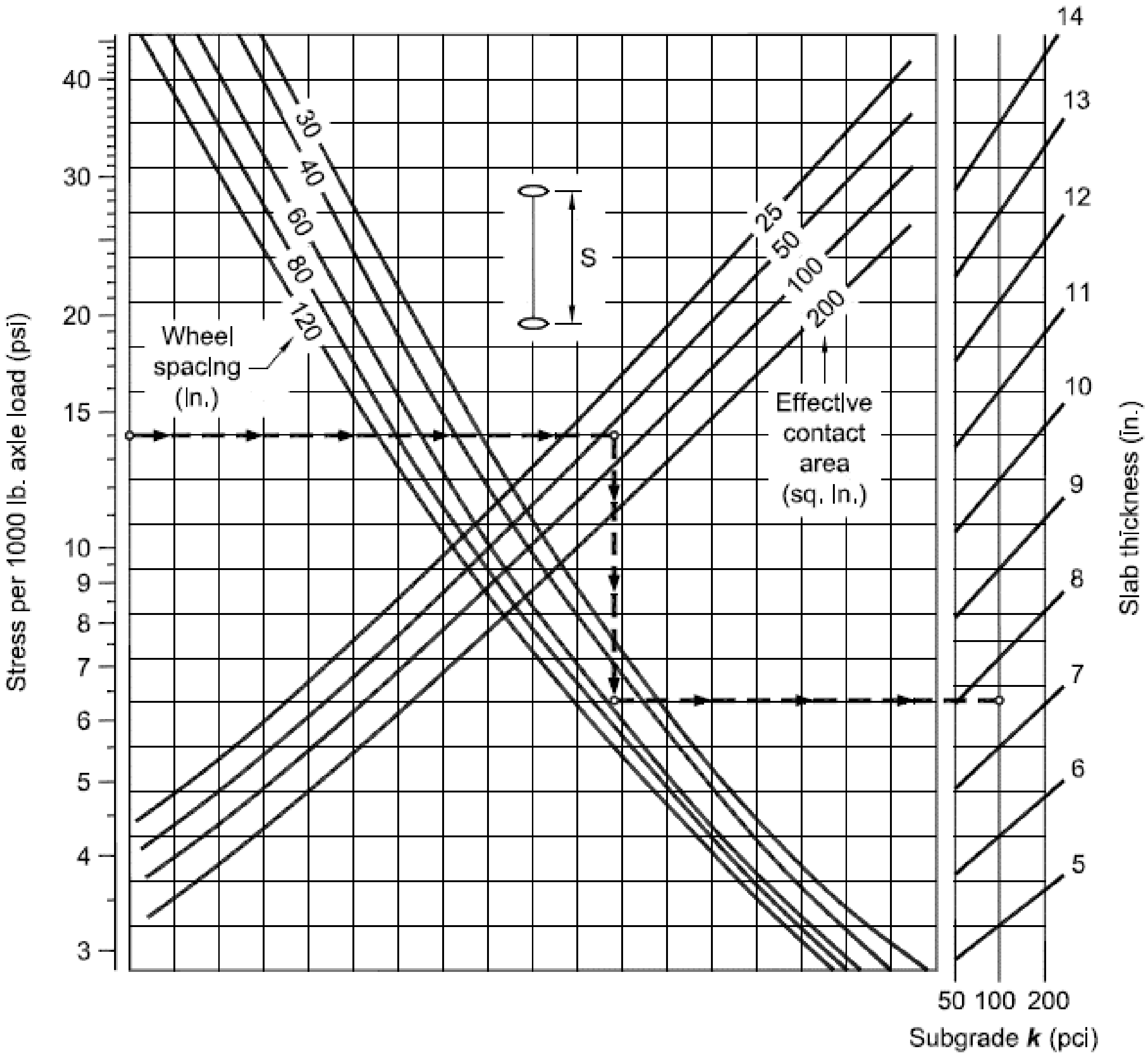


Calculate slab stress:

Slab stress = WS/axle load = 285/20.253 = 14 pounds per square inch (0.097 megapascal).

From Figure B-2.4c, the required slab-on-ground thickness is determined to be 7.4 inches (188 millimeters), say, 8 inches (100 millimeters).

Figure B-2.4c Determining Slab-on-Ground Thickness for the Effective Contact Area of Dual Wheels Forklift Truck



B-3 DESIGN EXAMPLES PER WIRE REINFORCEMENT INSTITUTE (WRI)

B-3.1 Slab-on-Ground Thickness for 4.5-Ton Forklift Truck.

Design a slab-on-ground supporting a 4.5-ton forklift truck using the WRI method. The geotechnical report recommended to provide a 6 inch (150 millimeter) thick subbase and use a modulus of subgrade reaction of 100 pounds per square inch per inch (27.1 megapascals per meter) for the design. Concrete compressive strength is specified at 4000 pounds per square inch (28 megapascals).

The engineer will start by assuming a slab-on-ground thickness and compare it to the end result. If the difference is substantial, then it must be revised until the difference is negligible or small enough.

Data:

4000 pounds per square inch (28 megapascal) specified concrete compressive strength.

E = 3,600,000 pounds per square inch (24,800 megapascals)

Subgrade modulus k =100 pounds per square inch per inch (27.1 megapascals per meter)

Assume a slab-on-ground thickness of 8 inches (200 millimeters)

Figure B-3.1a gives relative stiffness parameter $D/k = 18.0 \times 10^5$ in.^{4} (7.5×10^{11} mm^4). The procedure then uses Figure B-3.1b.

Wheel contact area = 108 inch square (69,677 millimeter square).

Diameter of equivalent circle = $\sqrt{(108 \times 4)/\pi}$ = 11.7 inches (297 millimeters)

Wheel spacing s = 46 inches (1168 millimeters).

This gives the basic bending moment of 235 inch-pound per inch (1045 Newton-meter per meter) of width/1000 pounds (Newton) of wheel load for the wheel load using the larger design chart in Figure B-3.1b. The smaller chart in the figure gives the additional moment due to the other wheel as 37 inch-pound per inch (165 Newton-meter per meter) of width 1000 pounds (Newton) of wheel load.

Moment = 235 + 37 = 272 inch-pound per inch per 1000 pounds (1210 Newton-meter per meter per Newton)

Axle load = 21,706 pounds (96,553 Newton)

Wheel load = 10,853 pounds (48,277 Newton)

Design moment = 272 × 10.853 = 2952 foot-pounds per foot (13,131 Newton-meter per meter) (Note that inch-pound per inch = foot-pounds per foot).

Then, from Figure B-3.1c:

Allowable tensile stress = $7.5\sqrt{4000 \text{ psi}}/2$ = 237 pounds per square inch (1.63 megapascal)

Solution: slab thickness *h* = 8.6 inches (218 millimeters), say, 9 inches (230 millimeters)

This is close enough to the initial assumption of 8 inches (200 millimeters). Therefore, recalculation of the slab-on-ground thickness is not required.

Figure B-3.1a Subgrade and Slab Stiffness Relationship, used with WRI Design Procedure

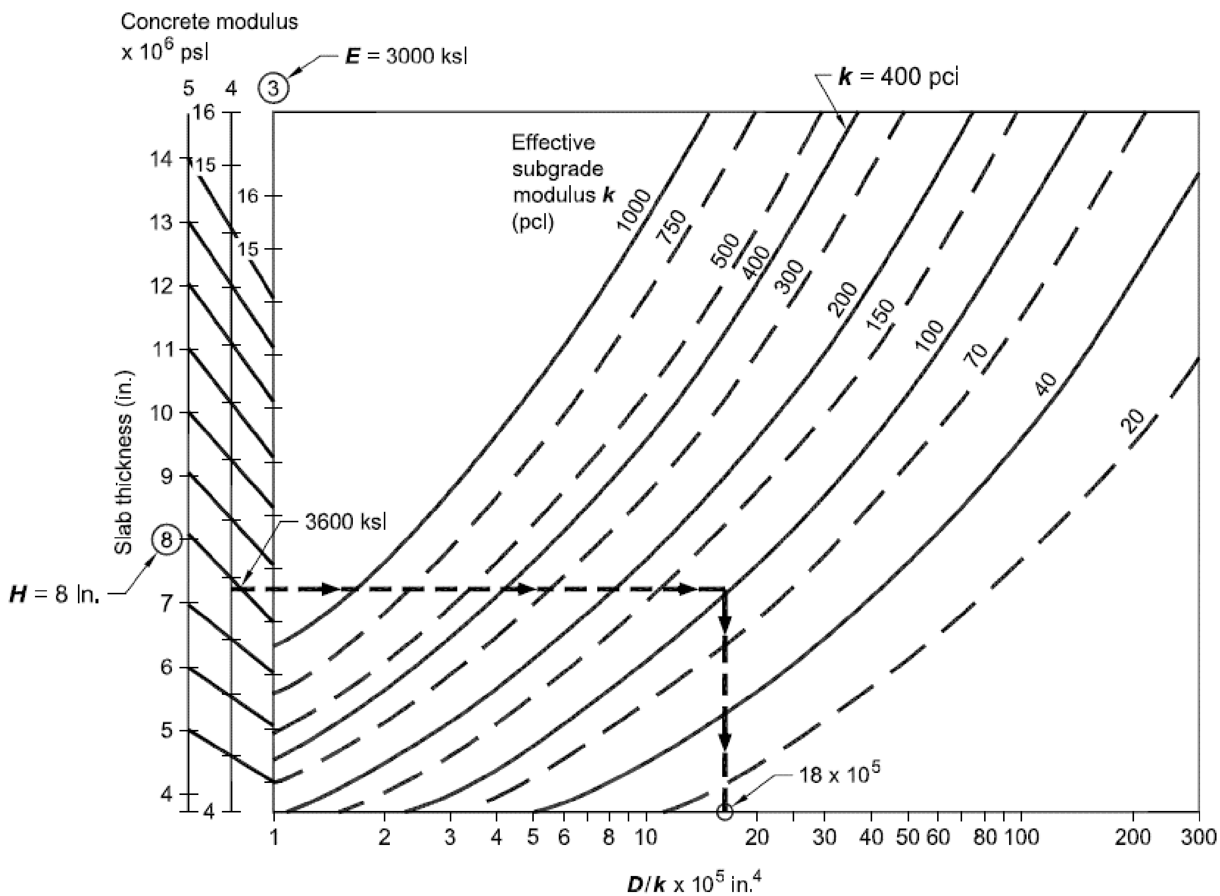


Figure B-3.1b Wheel Loading Design Chart used with WRI Procedure

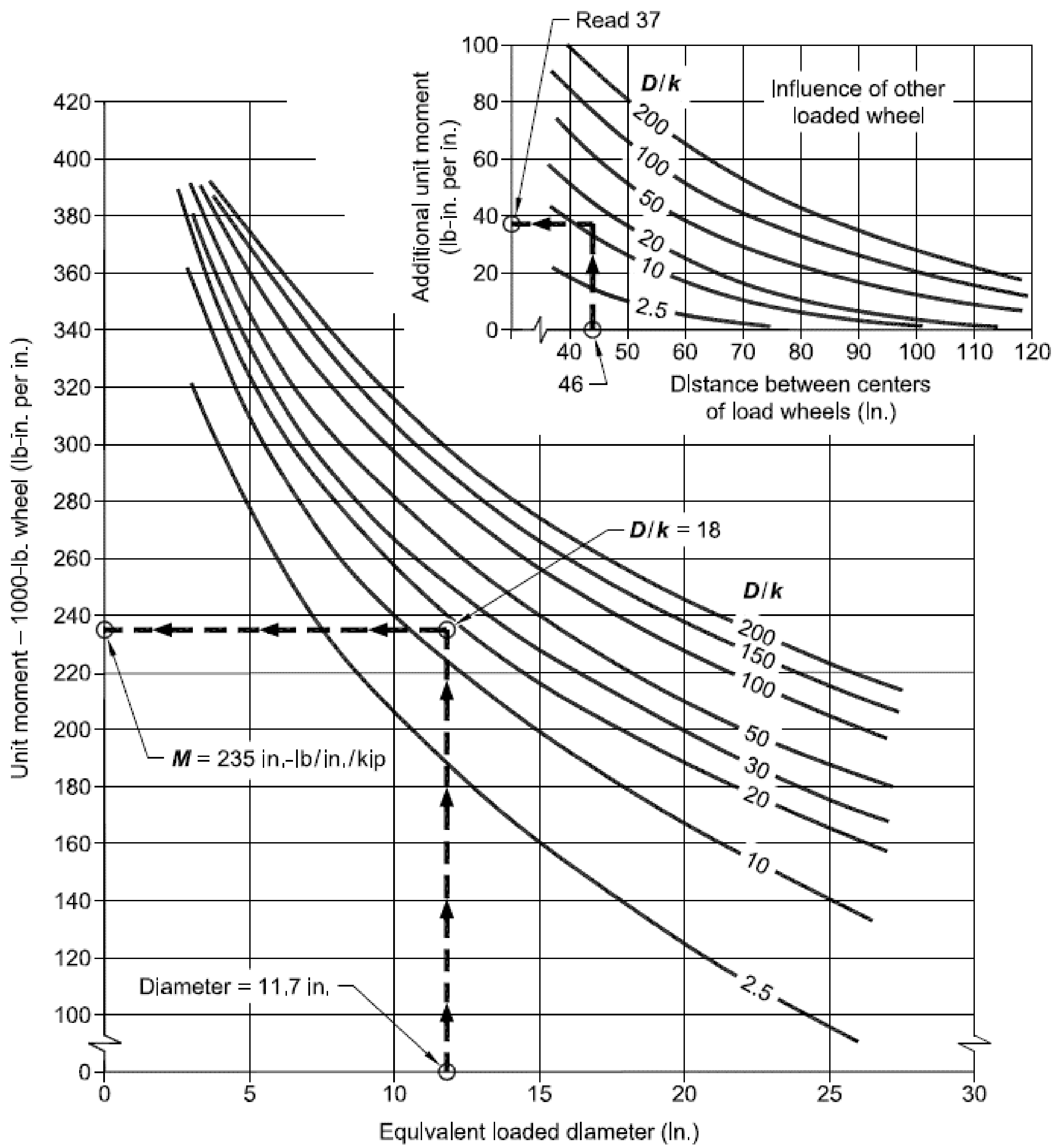
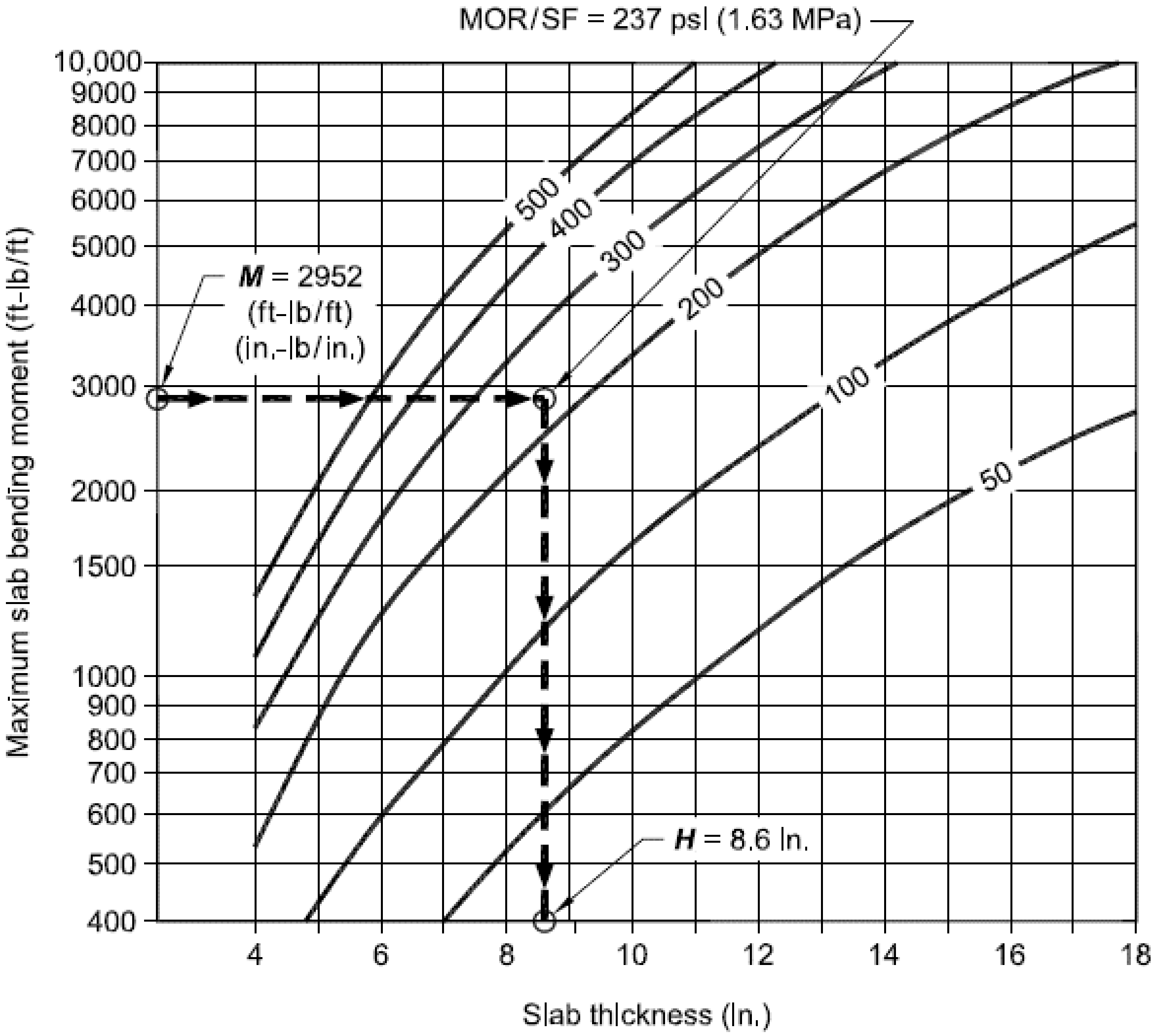


Figure B-3.1c Slab Tensile Stress Charts used with WRI Design Procedure



Summary: In the table below, all three methods are compared for the design of a slab-on-ground supporting a 4.5-ton forklift truck. All three methods yield the same required slab-on-ground design thickness.

Design method		Slab-on-ground thickness, *h*, inch (millimeter) Calculated	Specified
Corps of Engineers		8.7 (221)	9.0 (230)
Portland Cement Association	$9\sqrt{f_c'}$	7.5 (190)	8.0 (200)
	$7.5\sqrt{f_c'}$	8.5 (216)	9.0 (230)
Wire Reinforcement Institute		8.6 (218)	9.0 (230)

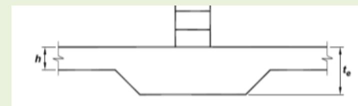
This Page Intentionally Left Blank

APPENDIX C **SLAB-ON-GROUND QUICK REFERENCES**

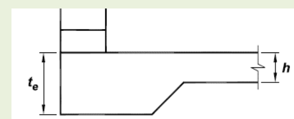
Step 1:	**Step 2:**	**Step 3:**	**Step 4:**	**Step 5:**	**Step 6:**
Determine vehicular/ moving load (forklift, airplane, …) axle load, wheelbase, contact area, pressure	Determine modulus of subgrade reaction, *k*. Use guidelines below or from geotechnical report	Determine concrete compressive strength, assuming concrete not exposed to freeze-thaw	Determine slab-on-ground thickness for 4.5 Ton forklift – see Table below or modify by using charts in Chapter 3.	Determine location of distributed load and thicken slab at those locations if needed from the following equation: $h \ge \left(\frac{w(FS)}{515.75}\right)^2 \frac{E}{k}$ Recommended factor of safety, FS = 2.0, LDP may use other values.	Determine location of line load (wall) and thicken slab where required from the following equations:

Step 6 (continued):

Internal: $$h_e \ge \left(\frac{P\sqrt[4]{\frac{19,000}{k}}}{12.8(f_c')^{3/8}}\right)^{0.8}$$



Edge: $$h_e \ge \left(\frac{P\sqrt[4]{\frac{19,000}{k}}}{9.93(f_c')^{3/8}}\right)^{0.8}$$



Modulus of Subgrade Reactivity

Type of Subgrade Soil	CBR	*k* Value
Fine-grained soils in which silt & clay-sized particles predominate	2.5 - 3.5	75 - 120
Sands & sand-gravel mixtures with moderate amounts of silt & clay	4.5 - 7.5	130 - 170
Sands & sand-gravel mixtures relatively free of plastic fines	8.5 - 12	180 - 220

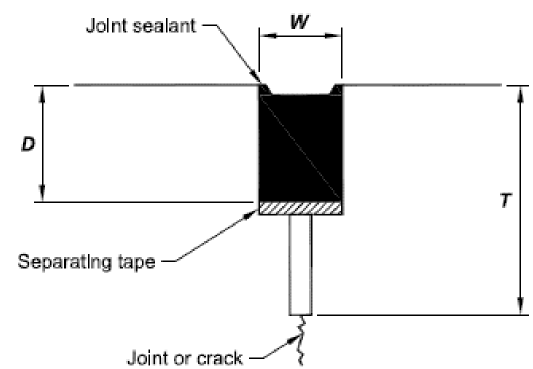
Recommendations for Slab-on-ground thickness for 4.5 Ton Forklift*

	k = 50 lb/in.^{2}/in.				k = 100 lb/in.^{2}/in.			
f_c' (psi)	4000	4500	5000	6000	4000	4500	5000	6000
MOR (psi)	550	600	650	700	550	600	650	700
h (inch)	**9.0**	**8.0**	**8.0**	**7.0**	**8.0**	**8.0**	**8.0**	**7.0**
	k = 200 lb/in.^{2}/in.				k = 400 lb/in.^{2}/in.			
f_c' (psi)	4000	4500	5000	6000	4000	4500	5000	6000
MOR (psi)	550	600	650	700	550	600	650	700
h (inch)	**8.0**	**8.0**	**7.0**	**7.0**	**7.0**	**7.0**	**6.0**	**6.0**

*Note: Design is based on the more conservative slab-on-grade calculated values obtained from the COE and PCA methods

Jointing Guidelines

- It is recommended that you follow these guidelines unless local experience indicates otherwise:
- Joint spacing should not exceed 24 to 30 times the pavement thickness.
- Lay out joints to form square panels. When this is not practical, rectangular panels can be used if the long dimension is no more than 1-1/4 times the dimension.
- The width of the weakened plane groove will be a minimum of 1/8 inch (3 millimeters) and a maximum equal to the width of the sealant reservoir.

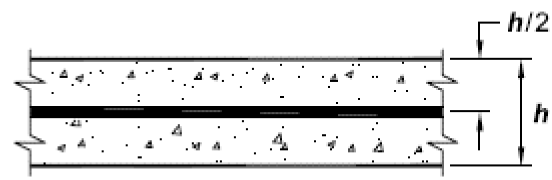


Slab thickness	Contraction joint depth, *T*
$h \le 12$ inch (300 mm)	$h/4$
12 inch (300 mm) < h < 18 inch (450 mm)	3 inch (75 mm)
$h \ge 18$ inch (450 mm)	$h/6$

Slab capacity reinforced with one-layer bars at mid-depth:

h_c, in. (mm)	8 (200)						10 (250)					
Bar sizes	#3 (10)	#4 (13)	#5 (16)	#6 (19)	#7 (22)	#8 (25)	#3 (10)	#4 (13)	#5 (16)	#6 (19)	#7 (22)	#8 (25)
A_s, in.^{2} (mm^2)	0.11 (71)	0.20 (120)	0.31 (199)	0.44 (284)	0.60 (387)	0.79 (510)	0.11 (71)	0.20 (120)	0.31 (199)	0.44 (284)	0.60 (387)	0.79 (510)
d_t, in. (mm)	0.375 (9.5)	0.50 (12.7)	0.625 (15.9)	0.75 (19.1)	0.875 (22.2)	1.0 (25.4)	0.375 (9.5)	0.50 (12.7)	0.625 (15.9)	0.75 (19.1)	0.875 (22.2)	1.0 (25.4)
d, in. (mm)	4 (100)	4 (100)	4 (100)	4 (100)	4 (100)	4 (100)	5 (125)	5 (125)	5 (125)	5 (125)	5 (125)	5 (125)
Cover, in. (mm)	3.63 (90.5)	3.5 (87)	3.38 (84)	3.25 (81)	3.13 (78)	3 (75)	4.63 (92.2)	4.5 (89)	4.38 (85.85)	4.25 (82.55)	4.13 (79.5)	4 (75)
ϕM_n, ft-lb/ft (N.m/300mm)	**1780 (7930)**	**3240 (13,390)**	**5020 (22,210)**	**7130 (31,700)**	**9720 (43,195)**	**12,800 (56,920)**	**2230 (9900)**	**4050 (16,740)**	**6280 (27,760)**	**8910 (39,620)**	**12,150 (53,990)**	**16,000 (71,150)**
h_c, in. (mm)	12 (300)						14 (350)					
Bar sizes	#3 (10)	#4 (13)	#5 (16)	#6 (19)	#7 (22)	#8 (25)	#3 (10)	#4 (13)	#5 (16)	#6 (19)	#7 (22)	#8 (25)
A_s, in.^{2} (mm^2)	6 (150)	6 (150)	6 (150)	6 (150)	6 (150)	6 (150)	0.11 (71)	0.20 (120)	0.31 (199)	0.44 (284)	0.60 (387)	0.79 (510)
d_t, in. (mm)	0.375 (9.5)	0.50 (12.7)	0.625 (15.9)	0.75 (19.1)	0.875 (22.2)	1.0 (25.4)	0.375 (9.5)	0.50 (12.7)	0.625 (15.9)	0.75 (19.1)	0.875 (22.2)	1.0 (25.4)
d, in. (mm)	6 (150)	6 (150)	6 (150)	6 (150)	6 (150)	6 (150)	7 (180)	7 (180)	7 (180)	7 (180)	7 (180)	7 (180)
Cover, in. (mm)	3.63 (90.5)	3.5 (87)	3.38 (84)	3.25 (81)	3.13 (78)	3 (75)	4.63 (92.2)	4.5 (89)	4.38 (85.85)	4.25 (82.55)	4.13 (79.5)	4 (75)
ϕM_n, ft-lb/ft (N.m/300mm)	**2670 (11,890)**	**4860 (20,090)**	**7530 (33,320)**	**10,690 (47,550)**	**14,580 (64,790)**	**19,200 (85,385)**	**3120 (14,260)**	**5670 (24,100)**	**8790 (39,980)**	**12,470 (57,060)**	**17,000 (77,750)**	**22,400 (102,460)**

Note: Calculation assumptions:



Concrete compressive strength, f_c' = 4000 psi (28 MPa)

Reinforcement placed at slab-on-ground mid-depth, $d = h_c/2$

Strip width, b = 12 inch (300 millimeter)

Slab moment capacity; $\phi M_n = \phi f_y A_s(0.9d)$

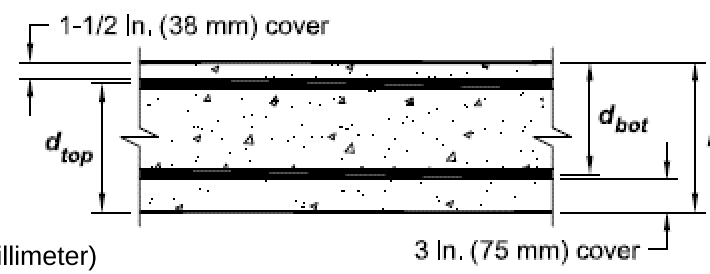
Slab moment capacity is in foot pound per foot of slab width (Newton meter per 300 millimeter)

Slab capacity reinforced with two-layer bars:

h_c, in. (mm)	8 (200)						10 (250)					
	#3 (10)	#4 (13)	#5 (16)	#6 (19)	#7 (22)	#8 (25)	#3 (10)	#4 (13)	#5 (16)	#6 (19)	#7 (22)	#8 (25)
A_s, in.^{2} (mm^2)	0.11 (71)	0.20 (120)	0.31 (199)	0.44 (284)	0.60 (387)	0.79 (510)	0.11 (71)	0.20 (120)	0.31 (199)	0.44 (284)	0.60 (387)	0.79 (510)
d_t, in. (mm)	0.38 (9.5)	0.50 (12.7)	0.625 (15.9)	0.75 (19.1)	0.875 (22.2)	1.0 (25.4)	0.38 (9.5)	0.50 (12.7)	0.625 (15.9)	0.75 (19.1)	0.875 (22.2)	1.0 (25.4)
d_{top}, in. (mm)	6.31 (157)	6.25 (156)	6.19 (154)	6.125 (152)	6.06 (151)	6.0 (149.3)	8.31 (211)	8.25 (210)	8.19 (208)	8.125 (206)	8.06 (205)	8.0 (200)
$\phi M_{n,top}$, ft-lb/ft (N.m/300mm)	**2810 (12,440)**	**5060 (20,890)**	**7770 (34,240)**	**10,910 (48,180)**	**16,360 (72,470)**	**19,197 (84,990)**	**3700 (16,720)**	**6680 (28,130)**	**10,280 (46,200)**	**14,180 (65,300)**	**19,590 (88,550)**	**25,600 113,850)**
d_{bot}, in. (mm)	4.81 (120)	4.75 (118)	4.6875 (117)	4.625 (115)	4.56 (114)	4.5 (112)	6.81 (170)	6.75 (169)	6.6875 (167)	6.625 (165)	6.56 (164)	6.5 (162)
$\phi M_{n,bot}$, ft-lb/ft (N.m/300mm)	**2140 (9510)**	**3850 (15,800)**	**5890 (25,990)**	**8240 (36,450)**	**11,080 (49,240)**	**14,400 (63,750)**	**3030 (13,470)**	**5470 (22,630)**	**8400 (37,090)**	**11,800 (52,300)**	**15,940 (70,840)**	**20,800 (92,220)**
h_c, in. (mm)	12 (300)						14 (350)					
	#3 (10)	#4 (13)	#5 (16)	#6 (19)	#7 (22)	#8 (25)	#3 (10)	#4 (13)	#5 (16)	#6 (19)	#7 (22)	#8 (25)
A_s, in.^{2} (mm^2)	0.11 (71)	0.20 (120)	0.31 (199)	0.44 (284)	0.60 (387)	0.79 (510)	0.11 (71)	0.20 (120)	0.31 (199)	0.44 (284)	0.60 (387)	0.79 (510)
d_t, in. (mm)	0.38 (9.5)	0.50 (12.7)	0.625 (15.9)	0.75 (19.1)	0.875 (22.2)	1.0 (25.4)	0.38 (9.5)	0.50 (12.7)	0.625 (15.9)	0.75 (19.1)	0.875 (22.2)	1.0 (25.4)
d_{top}, in. (mm)	10.31 (157)	10.25 (156)	10.19 (154)	10.125 (152)	10.06 (151)	10.0 (149.3)	12.31 (211)	12.25 (210)	12.19 (208)	12.125 (206)	12.06 (205)	12.0 (200)
$\phi M_{n,top}$, ft-lb/ft (N.m/300mm)	**4600 (12,440)**	**8300 (20,890)**	**12,790 (34,240)**	**18,040 (48,180)**	**24,450 (72,470)**	**32,000 (84,990)**	**5480 (16,720)**	**9920 (28,130)**	**15,300 (46,200)**	**21,600 (65,300)**	**29,300 (88,550)**	**38,390 113,850)**
d_{bot}, in. (mm)	8.81 (120)	8.75 (118)	8.6875 (117)	8.625 (115)	8.56 (114)	8.5 (112)	10.81 (120)	10.75 (118)	10.6875 (117)	10.625 (115)	10.56 (114)	10.5 (112)
$\phi M_{n,bot}$, ft-lb/ft (N.m/300mm)	**3920 (12,440)**	**7090 (20,890)**	**10,900 (34,200)**	**15,370 (48,180)**	**20,800 (65,220)**	**27,200 (84,990)**	**4800 (9500)**	**8700 (15,800)**	**13,400 (25,990)**	**18,930 (36450)**	**25,660 (49,240)**	**33,600 (63,750)**

Note: Calculation assumptions:

- Concrete compressive strength, f_c' = 4000 psi (28 MPa)
- Top reinforcement placed with 1-1/2 inch (38 millimeter) cover, $d_{top} = h_c - 1.5 - d_b/2$,
- Bottom reinforcement placed with 3 inch (75 millimeter) cover, $d_{bot} = h_c - 1.5 - d_b/2$, where d_b is the bar diameter
- Strip width, b = 12 inch (300 millimeter)
- Slab moment capacity: $\phi M_n = \phi f_y A_s(0.9d)$
- Slab moment capacity is in foot pound per foot of slab width (Newton meter per 300 millimeter)



Summary of side effects and interactions of SCMs.

Properties	Supplementary Cementitious Material					
	Fly ash Class F	Fly ash Class C	Slag cement	Silica fume	Metakaolin	Limestone
Workability	Significantly improved	Improved	Neutral/ improved	Improved at low dose (<5%), decreased at high dose	Decreased	Slightly improved
Air void system	May be difficult to entrain air with high LOI*	Neutral	Neutral	May be difficult to entrain air	May be difficult to entrain air	Neutral
Setting	Delayed	Slightly delayed	Slightly delayed	Accelerated	Neutral	Neutral
Incompatibility	Low risk	Some risk	Low risk	Low risk	Low risk	Low risk
Strength gain	Slower but continues longer	Slightly slower but continues longer	Slightly slower but continues longer	Accelerated initially	Accelerated initially	Neutral
Stiffness	Related to strength					
Heat generation	Lower	Slightly lower	Slightly lower	Higher	Slightly higher	Slightly lower
Shrinkage	Neutral	Reduced	Neutral	Increased l	Increased	Neutral
Permeability	Improved over time	Improved over time	Improved over time	Improved	Improved	Neutral
ASR	Improved		Improved at sufficient dosage	Slightly improved	Improved	Neutral
Sulfate attack	Improved	Improved at sufficient dosage	Improved at high dosages	Neutral	Neutral	May be worse at high dosages in very cold environments
Corrosion resistances	Slightly improved	Slightly improved	Improved	Improved	Improved	Neutral

*LOI—Loss of ignition

Preparing the Subgrade for Best Performance.

Proper subgrade preparation will ensure superior performance of your concrete pavement. While no special subbase is required, it is important that the soil type, moisture content, and density of the subgrade be uniform. Replace non-uniform subgrade areas with materials that are similar to the rest of the area. The subgrade must also be reasonably smooth and without tire ruts so that the concrete placed over it will be uniform in thickness.

Smooth dowel bar size and recommended spacing.

Slab-on-ground thickness, inches	Dowel length, inches	Dowel spacing, inches	Dowel diameter and type
Less than 8	16	12	3/4-inch bar
8 to and including 11.5	18	12	To 1-1/4-inch bar
12 to and including 15.5	20	15	1- to 1-1/4-inch bar, or 1-inch extra—strength pipe
16 to and including 20.5	20	18	1- to 1-1/2-inch bar, or 1-1-1/2-inch extra-strength pipe
21 to and including 25.5	24	18	2-inch bar, or 2-inch extra-strength pipe
Over 26	30	18	3-inch bar, or 3-inch extra-strength pipe.

Specified overall floor flatness (SOFF) and specified overall floor levelness (SOFL)

Floor surface classification	Specified overall flatness SOF_F	Specified overall levelness SOF_L
Conventional	20	15
Moderately flat	25	20
Flat	35	25
Very flat	45	35
Super flat	60	40

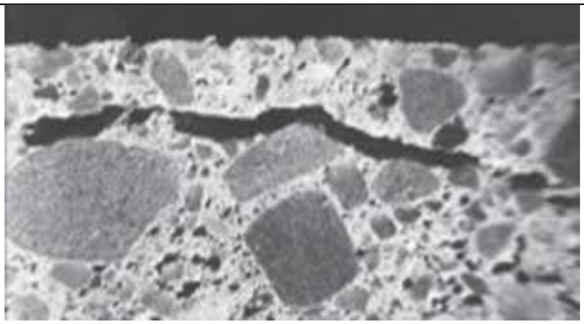
Construction Practices.

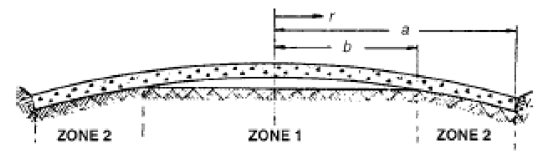
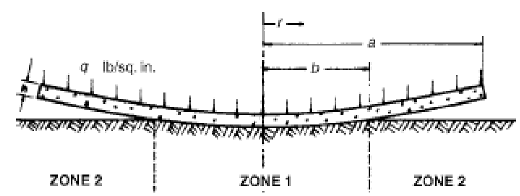
Procedures that ensure a quality job are:

- Slope finish grade away from structure minimum 2% or 1/4 inch per foot for surface drainage.
- Moisten subgrade just prior to placement of concrete.
- Cure fresh concrete. Liquid membrane-forming curing compound is usually recommended as the most cost-effective curing agent.
- Keep light traffic off the slab (less than 1 ton) for three days and heavy traffic off the slab for seven days, unless tests are made to determine that the concrete has gained adequate strength. This is usually 3000 psi.

APPENDIX D **SLAB-ON-GROUND CONSTRUCTION DEFECTS MITIGATION**

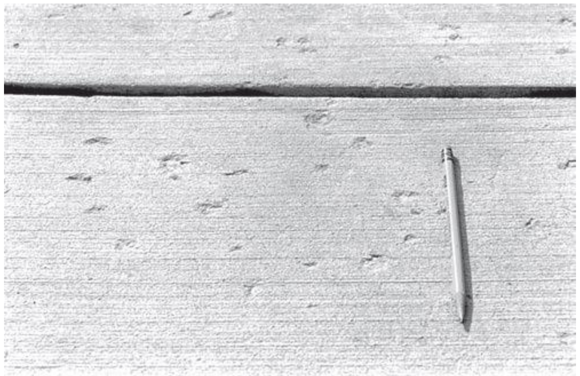
Issues	Factors contributing to shortcoming	Mitigation	Photo
Bleeding, excess	After concrete is placed and before it begins to harden, the aggregate and cement particles tend to sink and bleed water appears on the surface of the concrete, the amount of bleeding is affected by: • High slump concrete caused by excess water • Non-air entrained concrete will bleed more than air-entrained concrete • Mixtures made with gap-graded aggregate or with coarse sands which do not have much material finer than a No. 50 mesh sieve • Too little cementitious material in the mixture • Rate of bleeding influenced by drying conditions	• Reduce amount of water in the mixture • Use air-entrained concrete • Correct any aggregate gradation deficiency problem • Increase the amount of fines in the sand • Select proper admixtures to reduce bleeding • Use cementitious materials with finer particles • Increase the amount of cement resulting in a reduced water-cement ratio • Use or increase the amount of supplementary cementing materials such as fly ash, slag cement, or silica fume • Refer to ACI 302.1R Section 10.16 for additional information	
Blisters and delamination	• Entrapped air or water underneath a sealed, airtight surface due to top slab surface stiffens, dries, or sets faster than the underlying concrete. Blisters are 1/4 to 4 inch (5 to 100 millimeter) with a depth of 1/8 inch (3 millimeter) • Sticky mixtures crust under drying winds • Insufficient vibration during compaction may not adequately release entrapped air • Excessive vibration may leave the surface with excessive fines	• Avoid the use of purposely air-entrained concrete when the surface is finished using power equipment • Avoid the use of concrete mixtures with a high water content, high mortar fraction, or both • Avoid the use of concrete with high slump • Use appropriate cement contents • Warm the base before placing concrete during cool weather • During hot, dry, windy weather, reduce evaporation over the slab by using an evaporation retardant	

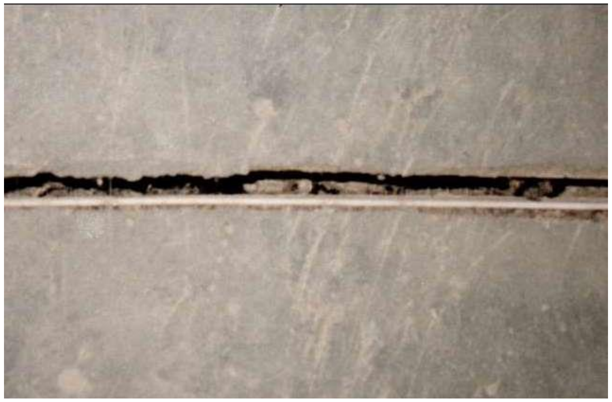
	• Improper finishing, wrong tools are used for floating and troweling • The subgrade is cooler than the concrete. This causes the top surface of the concrete to set faster than the interior and the bottom layer • A sticky concrete mixture; too much cement and not enough aggregate can trap air bubbles before they can escape through the surface • Concrete is placed directly on top of a vapor retarder or impervious base. This prevents bleed water from being absorbed by the subgrade	(monomolecular film), a fog spray, or a slab cover (polyethylene film or wet burlap) • When placing a slab directly on a vapor retarder/barrier, consider the potential for a prolonged bleed period • Avoid overworking the concrete • Do not attempt to seal (finish) the surface too soon • Avoid early sealing during initial surface straightening and floating • Use proper finishing techniques and proper timing during and between finishing operations • Replace about 100 to 200 lb/yd^3 (60 to 120 kg/m^3) of sand with a like-amount of the smallest-size coarse aggregate • Most entrapped air is released by using normal vibration • Avoid placing concrete directly on vapor retarder. Use a 4 inch (100 millimeter) compactible fill • Use fog spray or slab cover to reduce evaporation	 Note: The chain drag method, ASTM D4580, is intended for bridge decks but is also used on concrete slabs-on-ground with delamination issues.
Crazing	Does not penetrate much below the surface. It is an indication of minor surface shrinkage. • Curing with water that is more than 20°F (11°C) cooler than the concrete • Alternate wetting and drying of the concrete surface at early ages • Overuse of jitterbugs, vibrating screeds, and bull floats • Overworking and over-troweling, especially when the surface is too wet • Premature floating and troweling	• If using wet-cure method, water of temperature used fr curing should not be more than 20°F (11°C) to 30°F (17°C) colder than the concrete temperature • Avoid implementing the mentioned shortcomings • Starting curing process immediately after finishing For additional information refer to ACI Practitioner’s Guide to Slabs-on-Ground (PP4)	

	• Dusting dry cement onto a surface to hasten drying before finishing • Too much clay and dirt in aggregates • Sprinkling water onto the surface of a slab during finishing		
Curling/ warping, Slab edge	• The thicker a subbase layer is constructed, the greater the increase in support stiffness • Slabs are built on high moisture content subgrades • Excess water • High water tables • Wet subgrades • Thin slabs will curl more than thicker slabs when joint spacing is 15 to 20 feet (4.6 to 6.1 meters) • Concrete with a low modulus of elasticity curl less than high modulus of elasticity • Presence of vapor barriers/retarders. If required, they should be covered with a layer of compactible fill. 2 to 3 inches (50 to 75 millimeter) is common, others recommend 6 inches (150 millimeters) to protect vapor barrier from concrete truck traffic and to maintain a level subgrade	• Equalizing moisture content and temperature between the top and bottom of a slab • Using a concrete mixture with low-shrinkage characteristics • Using a permeable, or porous, dry or almost-dry base • Using shrinkage-compensating concrete • Placing a minimum amount of 1 percent reinforcement in the top one-third of the slab • Using post-tensioning • Not exceeding the joint spacing recommendations provided in Section 7-2.3.1 • Increase slab thickness • Extend curing with the use of Type II cement and specify concrete strength of 4500 psi at 90-days • Increase edge slab thickness 50 percent with a maximum 1/20 slope; or	 Exterior slab-on-ground edges curl downward at edges during the day when the sun warms the top of the exposed slab.  Interior slab-on-ground warps upward because of the moisture differential between top and bottom of slab-on-ground.

		• Increase reinforcement at slab edges by 1 percent steel at perimeter slab edges, perpendicular to edge, 10 feet (3 meters) into slab For additional information refer to ACI 302.1R and ACI Practitioner's Guide	
Discoloration	The following are causes of dark areas: • Use of calcium chloride in concrete • Low spots where water stands longer before evaporating can cause dark areas • Curing with waterproof paper and plastic sheets can cause a lighter color where the sheet is in contact with the surface and a darker color where the sheet is not in contact with the surface • Insufficient removal of curing compounds and bond-breaking membranes • Changes in the w/cm of concrete mixtures can significantly affect color • Changes in source or type of cement • The uneven application of dry-shake materials • Changes in the amount, source, and chemistry of a mineral admixture	• Reduce or eliminate use of high-alkali content cements • Avoid use of calcium chloride admixtures • Use consistent concrete ingredients from one batch to the other • Use proper and timely placing, finishing, and curing practices	 **Source: Chris Sullivan, Cause and Effect of Curing Differential on Colored Concrete**
Drying shrinkage	• occur as moisture leaves the concrete after the slab has hardened • main cause is concrete that is too wet, referred to as a "high-slump" mix • Difference in shrinkage between top and bottom of slab • use of high-early-strength concrete increases slab shrinkage • slabs are built on high moisture content subgrades	• Reduce total water content of concrete • Use of clean, low shrinkage aggregates • Use largest possible maximum sized coarse aggregate – preferably 1-1/2 inch (38 millimeter) • Coarser sand • Aggregate free of clay and other fine materials • Cement with low C3A content	

		• Shortest travel time from central mix plant to job • Fewest agitating revolutions after complete mixing is achieved • Place slab on ½ inch (13 millimeter) layer of sand on top of a dry subgrade or subbase • If subgrade can become moist because of ground water, provide a minimum of 50 mil (1.3 millimeter) thick vapor retarder covered with 6 inch (150 millimeter) of crushed stone and topped with a ½ inch (13 millimeter) thick layer of sand • Reinforcement, bars or welded wire mesh placed in the middle or upper half of slab-on-ground For additional information refer to ACI 302.1R.	
Dusting	• Concrete mixtures with excessive mixing water • Insufficient cement • Excessive bleeding • Too much entrained air in the surface mortar • Overworking high slump concrete • Finishing the concrete while bleed water is on the surface • Water applied to the surface to facilitate finishing • Early carbonation of the plastic surface during winter concreting (unvented heaters) • Inadequate curing • Early-age freezing • Excessive clay, dirt, and organic materials in the aggregate • Use of dry cement as a blotter to speed up finishing	• Proper concrete mixture • Low slump concrete mixture • Do not start finishing while bleed water is on the surface • Do not use additional water to facilitate finishing • Provide adequate venting when heaters are used • Proper curing • Prevent concrete from early freezing • Do use a concrete curing agent on the fresh concrete to seal the surface to stop moisture leaving the concrete too fast Corrective actions: • Grind off the thin layer of laitance to expose the solid concrete • Apply surface hardeners	

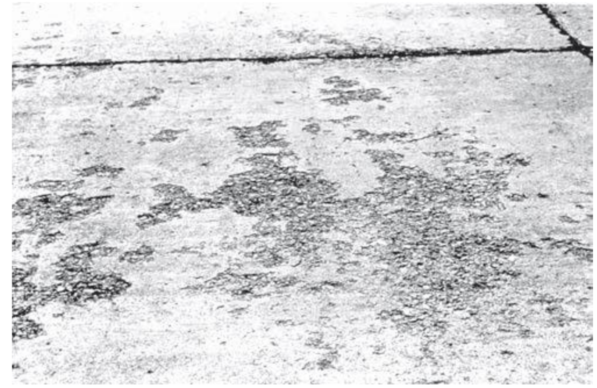
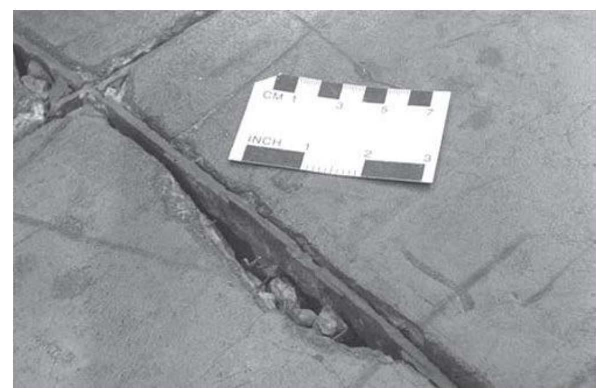
	• Allowing abrasive traffic before concrete has gained adequate strength		
Early cracking	• Restraining shrinkage occurs during the first few days of slab-on-ground related to drying shrinkage and thermal contraction • Cracking of concrete around bars or other embedments • Cracking along edges where forms are not rigid due to insufficient consolidation, or high slump • Rapid cooling of slab surface • Temperature differences of more than 20º F (11º C) (15º F (8º C) is preferred) between concrete and base during placement • Damage from form removal	• sawcut contraction joints are the most common method of controlling early-age cracking. They do not prevent cracking but control the location of the cracking	 Early cracking 
Mortar flaking	Occurs over coarse aggregate particles: • Mostly flat surface aggregates • Placement of concrete on hot, windy days • Excessive and early drying of the surface mortar • Poor finishing practices	• Proper finishing and curing • Aggregate gradation comply with project documents • Do not use dirty unwashed aggregates For more information refer to McKinney (2013)	

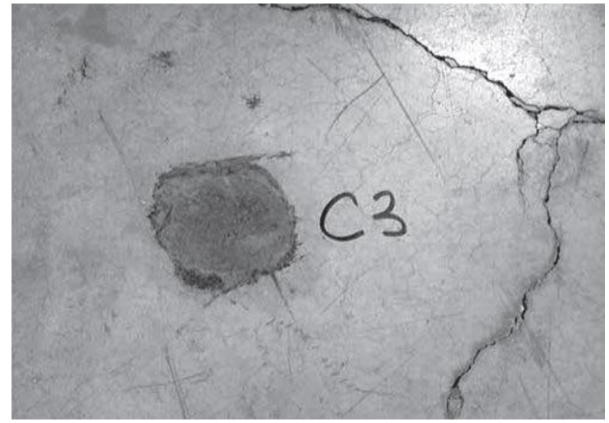
Opening of joints and loss of sealant	• Most shrinkage in slab-on-ground occurs within the first year, but it will continue for years. Therefore, early joint filling will result in contraction joints not retaining any type of joint filler	• Defer joint filling and sealing as long as possible to lessen the effects of shrinkage-related joint opening on the filler or sealant • When the building is equipped with an HVAC system, run it for approximately two weeks before joint filling • Fill slight openings with a low-viscosity compatible material	 Source: Inspecpedia.com
Plastic shrinkage cracking	• Rate of water evaporation from the concrete exceeds 0.2 $lb/ft^2/h$ (1.0 $kg/m^2/h$) • Moisture evaporates faster than it can be replaced by bleed water • Vapor retarder immediately under the concrete may aggravate plastic and drying-shrinkage	• Dampen base when no vapor retarder is used • Erect windbreaks • Erect sunshades • Cool aggregates and mixing water before mixing Prevent rapid drying by: • Use moisture-retaining coverings during delay between placing and finishing • Cover with damp burlap or with white polyethylene sheeting immediately after screeding and bull-floating • Use monomolecular films • Use a fog spray • Postpone each step of finishing and its inherent reworking of the surface • Avoid the use of vapor retarder/barrier where not needed • Use microsynthetic fibers in concrete	 What You Need to Know About Plastic Shrinkage Cracking by Kim Basham 

		For more information on rate of water evaporation and plastic shrinkage mitigation refer to ACI 305 and ACI 302.1R	
Popouts	• Expansion of a piece of chert, soft fine-grained limestone, hard-burned lime, hard-burned dolomite, pyrite, or coal or lignite • Freezing or absorption of moisture • Chemical change, i.e., reaction between alkalies in concrete and reactive siliceous aggregates	• Switching to a non-offending source of aggregate for floors and slabs, if possible • Using two-course construction with selected or imported aggregate without popout potential for the topping course • Using aggregates from which the offending particles have been removed by heavy-media separation, if available and economically feasible • Using wet-curing methods such as continuous fogging or covering with wet burlap immediately after final finishing • Using the lowest practical slump possible to prevent potential popout-causing particles from floating to the surface Refer to ACI 302.1R	
Restraint of volume changes	Slab-on-ground is restraint by: • Aggregate of poor inherent quality with respect to shrinkage • Excessive dirt or fines due to insufficient washing of aggregates • Restrained drying shrinkage occurs during the first few days of slab-on-ground related to drying shrinkage	• Properly spaced contraction joints • Proper timing of contraction joint saw-cutting • Avoidance of elongated panels with large aspect ratios <1.5 to 1.0 (preferably keep below 1.25 to 1.0) and use of T-joint intersections • Discontinued or minimal reinforcement through joints	

		• Slabs not restrained by a rutted or uneven base • Avoid changes in slab thickness • Compressible isolation joints provided around columns and other penetrations • Slabs not restrained at their perimeter by bond of floor or slab concrete to foundation walls or other construction, or tying-in reinforcement to other members • Ultimate drying shrinkages of proposed concrete mixtures compared using ASTM C157/C157M and ACI 209R • Concrete mixtures that do not include high shrinkage components • Proper and timely curing procedures • Sufficiently deep contraction joints • Proper jointing and additional reinforcement placed diagonally or perpendicular to reentrant corners • Slabs cast on a base that has a low coefficient of friction	 Source: Don Marks, What lies beneath the concrete slab 
Removing restraints to shrinkage	designers use the floor slab as an anchor by detailing reinforcing bars from foundation walls, exterior walls, and pit walls to the floor slab. Result in cracks in slab-on-ground	• When there is no other way to anchor these walls except by tying them into the floor, then unreinforced slabs should be jointed at half the recommended joint spacing from the wall • Isolate slab from guard posts (bollards) that penetrate the floor • Specify compressible material full slab depth around all restraints to allow the slab to shrink and move relative to the fixed items • Burry electrical conduit and storm drain lines in the subgrade so they	

		do not reduce the slab thickness or restrain drying shrinkage • Replace conventional round dowels that provide restraint parallel to the joint with square, tapered-plate, or rectangular-plate dowel systems with formed voids or compressible isolation material on the bar or plate sides	
Other causes for concrete cracking – random cracking	• Variable support by a poorly prepared subgrade, subbase, or base; poor drainage; resulting in settlement • Expansive clay in the subgrade • Sulfates in subgrade soil or groundwater • Placing concrete over preformed joint filler when placing adjacent concrete • Improper jointing (joint too far apart) and sealing • Sawed or grooved joints not installed soon enough , deep enough, or both • No contraction joints at re-entrant corners • Structural overloading • Impact loads • Disruption from expansive alkali-silica reaction • Disruption from corrosion of reinforcing steel • Disruption from freezing and thawing along edges and at corners • Earth movements from contiguous construction; i.e., pile driving • Thermal contraction • Early or excessive construction traffic • Improper design	• Avoid implementing the mentioned shortcomings	

Scaling	• Two major causes of surface scaling of concrete slabs: ○ Freezing of moisture in aggregate fissures and dirty aggregates ○ Finishing of concrete slabs while there is bleed water on the surface, or finishing before bleeding has stopped • Permeable and poor-quality concrete • Altered air-void system parameters • Inadequate thermal protection—freezing of surface at early age • Blistering • Improper water drain from the slab • Loss of surface mortar and mortar surrounding aggregate particles • entrained air voids are not properly spaced within the near-surface region of the slab	• Use of air-entrained concrete • Do not start finishing while there is bleed water or bleeding has not stopped • Use of good quality concrete which does not bleed excessively • Avoid placing warm concrete on a cold subgrade • Follow proper curing practices For additional information refer to ACI 302.1R Section 13.5	
Spalling, joint	• Insufficient concrete cover over bars • Concrete over embedded bars fails to provide corrosion protection due to: i. Overworking still-plastic concrete during finishing ii. Serious loss of entrained air during such wet-finishing operations iii. Problems with excessive bleeding during finishing, especially in cold weather iv. Inadequate or delayed curing v. Severe cracking that permits water and salts to attack the steel vi. Loss of bond between concrete and reinforcement caused by placement of concrete on top of excessively hot steel during hot-weather concreting	• Use semi-rigid epoxy joint filler to provide lateral support to the joint For additional information refer to ACI 302.1R and ACI Practitioner's Guide to Slabs-on-Ground	

	• Joint edge spalls caused by small hard-wheeled vehicles traveling across improperly installed or filled joints • Poor bonding of topping to base course in two-course floors due to: i. Inferior quality of surface concrete in the base course ii. Unremoved contamination in, or poor preparation of, the surface of the base course iii. Differences in shrinkage between topping and base courses iv. Drying of the bonding grout before the topping concrete is placed v. Excessive pressure developed at joints, where preformed joint material was topped by continuous concrete vi. Restraint of movement of deck slabs on supporting walls and piers due to inadequate provision for such movement		

This Page Intentionally Left Blank

APPENDIX E GLOSSARY

E-1 NOTATIONS.

A_{cont} = wheel contact area, square inch (square millimeter)

A_s = cross-sectional area of reinforcement, square inch per linear foot of slab width (square millimeter per meter of slab width)

a = equivalent radius of contact area, inch (millimeter)

b_f = thickened slab-on-ground width, inch (millimeter)

c = half-aisle width, inch (meter)

D/k = slab-on-ground stiffness factor, in.^{4}, (mm^4)

E_c = modulus of elasticity of concrete, pound per square inch (megapascal)

E_f = modulus of elasticity of fiber reinforced polymers, pounds per square inch (megapascal)

E_{fs} = flexural modulus of elasticity of steel fiber reinforced concrete, pounds per square inch (megapascal).

E_s = modulus of elasticity of steel, pounds per square inch (megapascal)

e = base of natural logarithms.

f_b = allowable tensile stress, pounds per square inch (megapascal)

f_c' = specified concrete compressive strength, pounds per square inch (megapascal)

f_r = flexural strength (modulus of rupture) as determined by ASTM C78, pounds per square inch (megapascal)

f_s = allowable steel stress, pounds per square inch (megapascal)–usually 0.67 or 0.75 of the yield strength of the steel, recommend the use of 0.67

f_y = steel yield strength, pounds per square inch (megapascal)

h = slab-on-ground thickness, inch (millimeter)

h_o = thickness of rigid slabs-on-ground overlay required over the stabilized layer, inches (millimeters)

h_1 = thickened slab-on-ground, inch (millimeter)

h_r = reinforced concrete slab-on-ground thickness, inch (millimeter)

h_s = thickness of stabilized layer, inches (millimeters)

I = moment of inertia, in.^{4} (m^4)

k = modulus of subgrade reaction, pound per square inch per inch (meganewton per meter)

ℓ = radius of relative stiffness, inch (millimeter)

L = slab length between free ends in the direction of analysis, feet (meter)

M_c = slab-on-ground moment at the center of the aisle, inch-pound per inch (Newton millimeter per millimeter)

q = soil pressure pounds per square foot (kilopascal)

P = moving—vehicle, forklift, or airplane—axle load, pounds (Newton)

$R_{e,3}$ = residual strength factor determined using JSCE SF4, percent

SF = factor of safety

s = moving load wheel spacing, inch (millimeter)

w = uniform allowable (unfactored) distributed load, pound per square foot (Newton per square meter)

y = slab-on-ground vertical deflection or settlement, inch (millimeter)

α = an empirical factor to convert concrete compressive strength to modulus of rupture

μ = coefficient of subgrade friction, usually taken equal to 1.5

ν = Poisson's ratio, 0.15-0.2 for concrete

δ = deflection inch (millimeter)

ρ = steel reinforcing ratio, percentage of the required steel area

E-2 DEFINITIONS.

The following definitions have been adopted for this manual:

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

allowable soil bearing capacity—the maximum pressure to which a soil should be subjected to guard against shear failure or excessive settlement.

base—a layer, usually granular or stabilized material, on which a concrete slab-on-ground is placed.

California bearing ratio (CBR)—the load required to force a standard piston into a prepared sample of soil divided by the load required to force the standard piston into a well-graded crushed stone in accordance with ASTM D1883 and D1429, usually expressed as 100 times the result.

continuously reinforced slab-on-ground—concrete slab containing reinforcement ratios greater than 0.5% ($\rho > 0.5\%$) in both directions for the purpose of eliminating contraction joints.

contraction joint—formed, sawed, or tooled groove in a concrete structure to create a weakened plane to regulate the location of cracking resulting from the dimensional change of different parts of the structure. (See also **isolation joint** and **expansion joint**.)

curling—out-of-plane deformation of the corners, edges, and surface of a slab-on-ground from its original shape usually caused by temperature differentials within the slab. (Tarr, 2004)

dead load—all the materials comprising the permanent structure, including permanent wall loads and all equipment that is fixed in position.

design load—the effects of stationary live, dead, and wall loads, and moving live loads. Dead loads of slabs-on-ground are ignored.

dowel—a steel element, commonly a plain or coated round steel bar, steel plate, or square bar that extends into adjoining portions of a concrete construction, as at an expansion or contraction joint in a pavement slab, to transfer shear loads.

dry-shake—a dry mixture of hydraulic cement and fine aggregate (either mineral or metallic) that is distributed evenly over the surface of concrete flatwork and worked into the surface before time of final setting and then floated and troweled to desired finish.

flatness—deviation of a surface from a plane.

heavy loads——loads that consist of any one of the following: 1) moving live loads exceeding a forklift axle load of 5000 pounds (22,200 Newton); 2) stationary live loads exceeding 400 pounds per square foot (0.019 megapascal), and concentrated wall loads exceeding 600 pounds per linear foot (8760 Newton per linear meter).

isolation joint—a separation between adjacent sections of a concrete structure to allow relative movement in three directions and through which all the reinforcement is interrupted.

joint—a physical separation in a concrete system, whether precast or cast-in-place, including cracks if intentionally made to occur as specified.

joint filler—compressible material used to fill a joint to prevent the infiltration of debris and provide support for sealants applied to the joint.

joint sealant—compressible material used to exclude water and solid foreign materials from joints.

levelness—deviation of a line or surface from a horizontal line or surface.

light loads—loads that consist of (comparable) forklift axle load of 5000 pounds (22,200 Newton) or less and stationary live loads less than 400 pounds per square foot (0.019 megapascal).

lightly reinforced slab-on-ground—concrete slab containing reinforcement ratios less than 0.05% ($\rho \le 0.05\%$) for the purpose of limiting crack width caused by the restraint of movement due to shrinkage and temperature.

live load—load imposed by the use and occupancy of the structure

modulus of subgrade reaction—ratio of the load per unit area of soil to the corresponding settlement of the soil, typically evaluated in place per ASTM D1196.

moving live load—loads imposed by vehicular traffic such as forklift.

panel—a concrete element that is thin with respect to other dimensions (approximately 1:20 to 1:25) and is bordered by joints or edges.

placement—(1) the process of placing and consolidating concrete; (2) a quantity of concrete placed and finished during a continuous operation (often inappropriately referred to as ”pouring”).

plain concrete slab-on-ground— concrete slab with no reinforcement.

reinforced slab-on-ground—concrete slab containing reinforcement ratios between $0.05 \le \rho \le 0.5\%$ for the purpose of increasing joint spacing or reducing slab thickness compared to plain concrete slabs-on-ground.

screed—(1) to strike off a cementitious mixture lying beyond the desired plane or shape; (2) a tool for striking off the cementitious mixture surface, sometimes referred to as a “strikeoff”; (3) a ribbon or pad of a cementitious mixture that is preplaced to act as a guide for maintaining the desired level as more material is placed.

slab-on-ground—slab, supported by ground, whose main purpose is to support the applied loads by bearing on the ground. Slab cast directly on the ground (also called “slab-on-grade”).

soil bearing capacity—the vertical load is increased to a point where the load exceeds the soil strength.

special soils (problematic soils)—soils that do not fit conventional theory of soil mechanics or that may require extensive improvement for slab on ground support.

stationary live load—loads imposed by movable items such as stored materials.

structural slab-on-ground—slab designed according to ACI 318 for the purpose of designing slabs directly supported by the ground or spanning between supports for the calculated stresses using factored loads.

subbase—a layer of selected or engineered material placed on top of subgrade and provides support to the concrete slab-on-ground.

subgrade—natural ground graded and compacted that supports concrete slab-on-ground.

wall load—line loads imposed by walls or partitions.

warping—out-of-plane deformation of the corners, edges, and surface of a slab-on-ground from its original shape usually caused by moisture differentials within the slab. (Tarr, 2004)

This Page Intentionally Left Blank

APPENDIX F **REFERENCES**

F-1 GOVERNMENT PUBLICATIONS

FEDERAL SPECIFICATIONS

SS-S-200E *Sealants, Joint, Two-Component, Jet-Blast-Resistant, Cold-Applied, for Portland Cement Concrete Pavement*

SS-S-1401C *Sealant, Joint, Non-Jet-Fuel-Resistant, Hot-Applied, for Portland Cement Concrete and Asphalt Concrete Pavements*

SS-S-1614P *Sealants, Joint, Jet-Fuel-Resistant, Hot-Applied, for Portland Cement and Tar Concrete Payments*

U.S. ARMY CORPS OF ENGINEERS

CRD-C653-95 *Standard Test Method for Determination of Moisture-Density Relation of Soils*
https://www.wbdg.org/ffc/army-coe/standards/crd-c653

DEPARTMENTS OF THE ARMY AND THE AIR FORCE.

TM 5-825-3/AFM 88-6, Chap. 3 *Rigid Pavements for Airfields*

UNIFIED FACILITIES CRITERIA

https://www.wbdg.org/ffc/dod/unified-facilities-criteria-ufc

UFC 3-130-01 *General Provisions--Arctic and Subarctic Construction*

UFC 3-130-04 *Foundation for Structures – Arctic and Subarctic Construction*

UFC 3-130-06 *Calculation Methods for Determination of Depths of Freeze and Thaw in Soil – Arctic and Subarctic Construction*

UFC 3-220-01 *Geotechnical Engineering*

UFC 3-250-01 *Pavement Design for Roads and Parking Areas*

UFC 3-250-11 *Soil Stabilization and Modification for Pavements*

UFC 3-260-02 *Pavement Design for Airfields*

UFC 3-301-01 *Structural Engineering*

F-2 NON-GOVERNMENT PUBLICATIONS

AMERICAN ASSOCIATION OF STATE HIGHWAY & TRANSPORTATION OFFICIALS (AASHTO)

https://transportation.org/

GDPS-4-M *Guide for the Design of Pavement Structures*

T 307 *Determining the Resilient Modulus of Soils and Aggregate Materials*

AMERICAN CONCRETE INSTITUTE (ACI)

https://www.concrete.org/

ACI 117 *Specification for Tolerances for Concrete Construction and Materials and Commentary*

ACI 209R *Prediction of Creep, Shrinkage, and Temperature Effects in Concrete Structures*

ACI 212.3R *Report on Admixtures for Concrete*

ACI 223 *Shrinkage-Compensating Concrete - Guide*

ACI 301 *Specifications for Concrete Construction*

ACI 302.1R *Guide to Concrete Floor and Slab Construction*

ACI 305 *Guide to Hot Weather Concreting*

ACI 318 *Building Code Requirements for Structural Concrete and Commentary*

ACI 360R *Guide to Design of Slabs-on-Ground*

ACI 440.1R *Guide for the Design and Construction of Structural Concrete Reinforced with Fiber-Reinforced Polymer Bars*

ACI 515.2R *Guide to Selecting Protective Treatments for Concrete*

ACI 515.3R *Guide to Selecting Protective Treatments for Concrete*

ACI 543R *Guide to Design, Manufacture, and Installation of Concrete Piles*

ACI 544.1R *Report on Reinforced Concrete*

ACI 544.6R *Report on Design and Construction of Steel Fiber-Reinforced Concrete Elevated Slabs*

ACI PP4 *Practitioner’s Guide to Slabs-on-Ground*

AMERICAN SOCIETY OF HEATING, REFRIGERATING, AND AIR CONDITIONING ENGINEERS (ASHRAE)

https://www.ashrae.org

ASHRAE Handbook and Product Directory, 1982, *Equipment*, 1979, and *Applications*, 1982.

ASTM INTERNATIONAL

https://www.astm.org/

ASTM A36/A36M *Standard Specification for Carbon Structural Steel*

ASTM A184/A184M *Standard Specification for Welded Deformed Steel Bar Mats for Concrete Reinforcement*

ASTM A370 *Standard Test Methods and Definitions for Mechanical Testing of Steel Products*

ASTM A615/A615M *Standard Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement*

ASTM A706/A706M *Standard Specification for Deformed and Plain Low-Alloy-Steel Bars for Concrete Reinforcement*

ASTM A820/A820M *Standard Specification for Steel Fibers for Fiber-Reinforced Concrete*

ASTM A1064/A1064M *Standard Specification for Carbon-Steel Wire and Welded Wire Reinforcement, Plain and Deformed, for Concrete*

ASTM C33/C33M *Standard Specification for Concrete Aggregates*

ASTM C78/C78M *Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)*

ASTM C109/C109M *Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 4-in. or [50 mm] Cube Specimens)*

ASTM C150/C150M *Standard Specification for Portland Cement*

ASTM C157/C157M Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete

ASTM C260/C260M *Standard Specification for Air-Entraining Admixtures for Concrete*

ASTM C330/C330M *Standard Specification for Lightweight Aggregates for Structural Concrete*

ASTM C387/C387M *Standard Specification for Packaged, Dry, Combined Materials for Concrete and High Strength Mortar*

ASTM C494/C494M *Standard Specification for Chemical Admixtures for Concrete*

ASTM C595/C595M Standard Specification for Blended Hydraulic Cements

ASTM C618 Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete

ASTM D698 *Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft-lbf/ft3 (600 kN-m/m3))*

ASTM D854 Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer

ASTM D1196/D1196M *Standard Test Method for Nonrepetitive Static Plate Tests of Soils and Flexible Pavement Components for Use in Evaluation and Design of Airport and Highway Pavements*

ASTM D1556 *Standard Test Method for Density and Unit Weight of Soil in Place by Sand-Cone Method*

ASTM D1557 *Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft3 (2,700 kN-m/m3))*

ASTM D1671 *Method of Test for Absorbed Gamma Radiation Dose in the Fricke Dosimeter* (withdrawn 1983)

ASTM D1883 *Standard Test Method for California Bearing Ratio (CBR) of Laboratory-Compacted Soils*

ASTM D2166/D2166 *Standard Test Method for Unconfined Compressive Strength of Cohesive Soil*

ASTM D2167 *Standard Test Method for Density and Unit Weight of Soil in Place by the Rubber Balloon Method*

ASTM D2216 *Standard Test Method for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass*

ASTM D2240 *Standard Test Method for Rubber Property—Durometer Hardness*

ASTM D2487 *Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)*

ASTM D2488 *Standard Practice for Description and Identification of Soils (Visual-Manual Procedures)*

ASTM D2850 *Standard Test Method for Unconsolidated-Undrained Triaxial Compression Test on Cohesive Soils*

ASTM D2937 *Standard Test Method for Density of Soil in Place by the Drive-Cylinder Method*

ASTM D3017 *Standard Test Method for Water Content of Soil and Rock in Place by Nuclear Methods (Shallow Depth)* (withdrawn 2017)

ASTM D3441 *Standard Test Method for Mechanical Cone Penetration Testing of Soils*

ASTM D4083 *Standard Practice for Description of Frozen Soils (Visual-Manual Procedure)*

ASTM D4253 *Standard Test Methods for Maximum Index Density and Unit Weight of Soils Using a Vibratory Table*

ASTM D4254 *Standard Test Methods for Minimum Index Density and Unit Weight of Soils and Calculation of Relative Density*

ASTM D4318 *Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils*

ASTM D4546 *Standard Test Methods for One-Dimensional Swell or Collapse of Soils*

ASTM D4580/D4580M *Standard Practice for Measuring Delaminations in Concrete Bridge Decks by Sounding*

ASTM D4829 *Standard Test Method for Expansion Index of Soils*

ASTM D6913/D6913M *Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis*

ASTM D6938 *Standard Test Methods for In-Place Density of Soil and Soil-Aggregate in Place by Nuclear Methods (Shallow Depth)*

ASTM E96/E96M *Standard Test Methods for Water Vapor Transmission of Materials*

ASTM E1155 *Standard Test Method for Determining FF Floor Flatness and FL Floor Levelness Numbers*

ASTM E1643 *Standard Practice for Selection, Design, Installation, and Inspection of Water Vapor Retarders Used in Contact with Earth or Granular Fill Under Concrete Slabs*

ASTM E1745 *Standard Specification for Plastic Water Vapor Retarders Used in Contact with Soil or Granular Fill under Concrete Slabs*

ASTM F1249 *Standard Test Method for Water Vapor Transmission Rate Through Plastic Film and Sheeting Using a Modulated Infrared Sensor*

F-3 ADDITIONAL REFERENCES

Abdul-Wahab, H. M. S., and Jaffar, A. S., 1983, “Warping of Reinforced Concrete Slabs Due to Shrinkage,” *ACI Journal Proceedings*, V. 80, No. 4, pp. 109-118.

Cable, J. K., and Porter, M. L., 2003. “Demonstration and Field Evaluation of Alternative Portland Cement Concrete Pavement Reinforcement Materials,” Final Report, Iowa DOT Project HR-1069, Iowa Department of Transportation. Ames, IA.

Corvetti, J. A., and Owusu-Ababio, S., 1999, “Investigation of Feasible Pavement Design Alternatives for WISDOT,” *Report* No. WI/SPR 15-99, Madison, WI.

Destrée, X., 2001, “Steel Fiber Reinforcement for Suspended Slabs,” *Concrete (London)*, Sept, pp. 58-59.

Geopier, 2016, “Structural Design Considerations for Uniformly-Loaded Floor Slabs Supported by Rammed Aggregate Pier Elements,” Technical Bulletin 10, Davidson, NC, 12 pp.

Grieb, W. W., and Werner, G., 1962, “Comparison of Splitting Tensile Strength of Concrete with Flexural and Compressive Strength,” *ASTM Proceedings*, V. 62, pp. 972-995.

Grosek, J.; Zuzulova, A.; and Brezina, I., 2019, “Effectiveness of Dowels in Concrete Pavements,” *Materials*, V. 12, No. 10, doi: 10.3390/ma12101669.

Hammitt II, G. M., 1974, “Concrete Strength Relationships,” Miscellaneous Paper S-74-30, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Hansen, W.; Jensen, E. A.; and Mohr, P., 2001, “The Effects of Higher Strength and Associated Concrete Properties on Pavement Performance,” FHWA-RD-00-161, Federal Highway Administration, June, 238 pp.

Harrison, P., 2004, “For the Ideal Slab on Ground Mixture,” *Concrete International*, V. 26, No. 3, Mar., pp. 49-55.

Hetenyi, M., 1946, *Beams on Elastic Foundations*, The University of Michigan Press, Ann Arbor, MI.

Heukelom, W., and Klomp, A. J. G., 1962, “Dynamic Testing as a Means of Controlling Pavements During and After Construction,” *Proceedings of the 1st International Conference on the Structural Design of Asphalt Pavements*, pp. 667-685.

Lösberg, A., 1961, “Design Methods for Structurally Reinforced Concrete Pavements,” Chalmers Tekniska Hogskolas Handlingar, Transactions of Chalmers University of Technology, Sweden.

McKinney, A., and Neuber Jr., J., 2015, “Industrial Slab-on-Ground Surface Defects,” *Concrete International*, V. 35, No. 7, July, pp. 29-34.

Meyerhof, G. G., 1962, "Load-Carrying Capacity of Concrete Pavements," *Journal of the Soil Mechanics and Foundations Division*, June, pp. 89-117.

Nicholson, L. P., 1981, "How to Minimize Cracking and Increase Strength of Slabs-on-Ground," *Concrete Construction*, V. 26, No. 9, Sept., pp. 739-741.

Packard, R., 1996, "Slab Thickness Design for Industrial Concrete Floors on Grade," Portland Cement Association, Skokie, IL, 18 pp.

Panak, J. J.; McCullough F. B.; and Treybig, H. J., 1973, "Design Procedure for Industrial Slabs Reinforced with Welded Wire Fabric," Interim Report prepared for the Wire Reinforcement Institute by Austin Research Engineers, Inc., Mar.

Panak, J. J., and Rauhut, J. B., 1975, "Behavior and Design of Industrial Slabs on Grade," *ACI Journal Proceedings*, V. 72, No. 5, May, pp. 219-224.

Pickett, G., 1951, "A Study of Stresses in the Corner Region of Concrete Pavement Slabs Under Large Corner Loads," *Concrete Pavement Design*, Portland Cement Association, Skokie, IL, pp. 77-86.

Porter, M., 2001, "Dowel Bar Optimization: Phase I and II, Final Report," Iowa State University, Center for Transportation Research and Education, Ames, IA, 32 pp.

Rettberg, W. A., 1986, "Steel-Reinforced Concrete Makes Older Dam Safer, More Reliable," *Hydro Review*, Spring, pp. 18-22.

Rice, P. F., 1957, "Design of Concrete Floors on Ground for Warehouse Loadings," *ACI Journal Proceedings*, V. 54, No. 8, Aug., pp. 106-113.

Shalaby, A., and Scott, M., 2001, "Using Fiber-Reinforced Polymer Load Transfer Devices in Jointed Concrete Pavement," Seventh International Conference on Concrete Pavements: The Use of Concrete in Developing Long-Lasting Pavement Solutions for the 21st Century, Orlando, FL 2001, pp. 607-621.

Shashaani, G. R.; Vahman, J.; and Valdez, E., 2000, "24 Steps to Successful Floor Slabs," *Concrete International*, V. 22, No. 1, Jan., pp. 45-50.

Snyder, M., 2011, "Guide to Dowel Load Transfer Systems for Jointed Concrete Roadway Pavements," Iowa State University, Ames, IA, 28 pp.

Spears, R. and Panarese, W., 1983, "Concrete Floors on Ground," EB075.02D, Portland Cement Association, Skokie, IL, second edition, 1983; revised 1990.

Staab, E., 1980, "Partition Loads on Slabs-on-Grade," U.S. Army Engineer Missouri River Division.

Tarr, S. M., 2004, "Interior Cement Floors Don't Curl: But Concrete Floors Do Warp and Joints Suffer!" *L&M Concrete News*, V. 5, No. 2, pp. 1-5.

Tarr, S., and Farny, J., 2008, “Concrete Floors on Ground,” fourth edition, EB075, Portland Cement Association, Skokie, IL, 256 pp.

Taylor, P., 2014, “The Use of Ternary Mixtures in Concrete,” National Concrete Pavement Technology Center, Iowa State University, Ames, IA, 33 pp.

Teller, L. W. and Cashell, H. D., 1958, “Performance of Doweled Joints Under Repetitive Loading,” *Public Roads*, V. 30, No. 1, Apr.

The Concrete Society, 2013, “Concrete Industrial Ground Floors, a guide to design and Construction,” *Technical Report 34*, fourth ddition, Camberley, Surrey, England, 104 pp.

Tribedi, A., 2018, “Variable Modulus of Subgrade Reaction,” *Structural Magazine*, Dec., pp. 31-33.

Waddell, J. W., 1968, *Concrete Construction Handbook*, McGraw-Hill, New York, pp. 6-12.

Walker, W., and Holland, J., 1998, “Plate Dowels for Slabs on Ground,” *Concrete International*, V. 20, No. 7, July, pp. 32-38.

Walker, W. W., and Holland, J. A., 1999, “The First Commandment for Floor Slabs: Thou Shalt not Curl nor Crack… (Hopefully),” *Concrete International*, V. 21, No. 1, Jan., pp. 47-53.

Westergaard, H. M., 1925a, “Theory of Stresses in Road Slabs,” Proceedings, fourth Annual Meeting, Highway Research Board, Washington DC.

Westergaard, H. M., 1925b, "Computation of Stresses in Concrete Roads," Proceedings, Highway Research Board, V. 5, Part I, pp. 90-112.

Whiting, D., and Dziedzic, W., 1992, “Effects of Conventional and High-Range Water Reducers on Concrete Properties,” *Research and Development Bulletin RD107*, Portland Cement Association, Skokie, IL, 28 pp.

Winkler, E., 1867, “Die Lehre von Elastizitat und Festigkeit,” Prague, The Netherlands, 182 pp.