Portland Cement Association

pca CONCRETE INFORMATION

Slab Thickness Design for Industrial Concrete Floors on Grade

by Robert G. Packard*

This publication presents guidelines for the thickness design of concrete floors on grade subject to loadings that may occur in factories and warehouses. The guidelines apply only to the design of plain slabs (unreinforced slabs or slabs with only distributed steel, sometimes termed "shrinkage and temperature steel"); however, the charts included may be used to determine bending moments for the design of structurally reinforced slabs.

Existing design information[1,2]** covers only a limited range of slab thicknesses and load magnitudes and configurations. For today's heavy industrial floors, design guidelines for plain slabs need to be extended.

The design procedures presented for loading conditions on factory and warehouse floors are also applicable to the design of slabs for outdoor storage and material handling areas. The three types of loading discussed are:

(1) Wheel loads of industrial vehicles such as lift trucks and straddle carriers.
(2) Concentrated static loads such as those exerted by posts of storage racks.
(3) Distributed loads due to material stacked on the floor in storage bays.

While this discussion is confined to the methods of determining an adequate slab thickness, other considerations equally important to the long-term serviceability of the floor include adequate subgrade-subbase preparation and compaction to achieve reasonable uniformity in the foundation, proper design and spacing of joints, quality concrete, good workmanship in construction, and a durable surface to withstand the surface wear to which the floor may be subjected.

Plain nonstructurally reinforced slabs can be economically and successfully used for a wide variety of load and site conditions. However, soils with very low bearing capacity, high compressibility, or that are highly expansive may require remedial treatment or special slabs (structurally reinforced slab, possibly with stiffening beams, or slab not directly supported by the soil). These special problems, discussed elsewhere† in texts on soil foundation engineering and literature on design of structurally reinforced floors, require the analysis of specialists in these fields.

The design procedures presented here are derived principally from highway and airport pavement design practice because of the large amount of applicable research and performance experience in these fields. As in pavement design, the design factors involved in determining the required floor slab thickness are:

- strength of the subgrade-subbase
- strength of the concrete
- nature and frequency of imposed loads

These design factors are discussed in detail in the following sections.

SUBGRADE-SUBBASE STRENGTH

A soils investigation of the site should be conducted to determine the strength of the subgrade soil and if there are adverse soils conditions that would preclude the use of a simple slab-on-grade. If heavy loads will be applied to the floor slab, the soils investigation should provide estimates of the allowable soil-bearing value and the potential soil settlement.

Soil bearing capacity, soil compressibility, and soil reaction modulus are properties that need to be considered in a design problem. It is important to consider how these different measures of strength-deformation properties apply to the design of floor slabs.

The bearing capacity of the soil is the pressure which, if exceeded, will result in a soil shear failure, which is an abrupt break-through of the load into the soil. The allowable soil pressure to protect against a shear failure may be

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** Superscript numbers in parentheses in the text and tables designate refrences at the end of this publication and at the bottom of tables, respectively.

† Refrences 3, 4, and 5 specifically discuss the design of floor slabs on expansive and compressible soils.

based either on a verbal description of soil consistency or degree of soil compaction, unconfined compressive strength tests, triaxial or direct shear tests, or standard field penetration tests.

Another soil characteristic, compressibility of cohesive soils, determines the amount of long-term settlement under load. The usual method for predicting settlement is based on conducting soil consolidation tests and determining the compression index for use in the settlement computations. The compression index may be estimated by correlation to the liquid limit of the soil.

A third measure of soil strength, Westergaard's modulus of subgrade reaction, k, is commonly used in design procedures for concrete pavements and floors-on-grade that are not structural elements in the building (floors not supporting columns and load-bearing walls).

There is no reliable correlation between the three measures of soil properties: subgrade modulus, soil-bearing capacity, and soil compressibility. This is because they are measurements of entirely different characteristics of a soil. Whereas the k value used for floor-slab design reflects the response of the subgrade under primarily elastic conditions and small deflections—usually 0.05 in. or less—considerations of soil compressibility and load-bearing capacity values, normally applied so that differential settlements between footings or parts of a raft foundation are not excessive, reflect total permanent (inelastic) subgrade deformations that may be 20 to 40 (or more) times greater.

A substantial amount of pavement research shows that elastic deflections and stresses of the slab are predicted reasonably well when the k value is used to represent the subgrade response and that control of slab stresses computed based on the subgrade k-value is a valid design procedure.

Although the k value does not reflect the effect of compressible soil layers at some depth in the subgrade, it is the correct factor to use in design for wheel loads and other concentrated loads because soil pressures under a slab of adequate thickness are not excessive. However, if heavy distributed loads will be applied to the floor, the allowable soil-bearing capacity and the amount of settlement should be computed to determine if excessive settlement may be expected.

If there are no unusually adverse soil conditions, the design analysis requires only the determination of the strength of the subgrade in terms of k. The k-value is measured by plate-loading tests on top of the compacted subgrade or, if a subbase is used, on top of the subbase. A 30-in.-diameter plate is loaded to a deflection not greater than 0.05 in. and the k-value is computed by dividing the unit load by the deflection obtained. The units of k are given in pounds per square inch per inch (psi per in.) or, as commonly expressed, pounds per cubic inch (pci).

A detailed description of the load test is given in ASTM D1196, Non-Repetitive Static Plate Load Tests of Soils and Flexible Pavement Components for Use in Evaluation and Design of Airport and Highway Pavements. When it is not feasible to perform plate-bearing tests at the jobsite, the k value can be estimated from correlations such as shown in Table 1.

If a high-quality, well-compacted granular subbase is used under the floor slab, the k value will increase. On large projects it may be feasible to construct a test section and perform plate-load tests on top of the subbase. If this is not practical, the k value on top of the subbase can be estimated from Fig. 1.

Table 1. Relationships Between Soil Type and Bearing Values

Type of soil	Subgrade strength	CBR,[2] percent	Design k-value, pci
Silts and clays of high compressibility[1] at natural density	Low	2 or less	50
Silts and clays of high compressibility[1] at compacted density Silts and clays of low compressibility[1] Sandy silts and clays, gravelly silts and clays Poorly graded sands	Average	3	100
Gravelly soils, well-graded sands, and sand-gravel mixtures relatively free of plastic fines	High	10	200

[1] *High compressibility, liquid limit equal to or greater than 50.* Low compressibility, liquid limit less than 50. (Liquid limit by ASTM D423, Standard Method of Test for Liquid Limit of Soils.)
[2] California Bearing Ratio, ASTM D1883, Standard Method of Test for Bearing Ratio of Laboratory-Compacted Soils.

CONCRETE PROPERTIES

When a load is applied to a floor on grade, it causes slab bending and produces both compressive and flexural (tensile) stresses in the concrete slab. Of the two, flexural stress is the more critical because the flexural strength of concrete is much less than the compressive strength. Consequently, the flexural stress and the flexural strength of the concrete are used in floor-slab design for the determination of thickness.

Flexural strength is determined by modulus of rupture, MR, tests using ASTM C78, Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading). Usually the 28-day strength is selected as the design strength for floors. This is conservative since the concrete continues to gain strength after 28 days.

Where the size of the job does not warrant the extra cost of making flexural-strength tests, compressive-strength test results can be used to estimate the flexural strength by the formula (computed values are shown in Table 2):

$$MR = 9\sqrt{f'_c}$$

where MR = flexural strength (modulus of rupture), psi
f'_c = compressive strength, psi

The selection of concrete quality also must be governed by the requirements of durability and wear resistance,

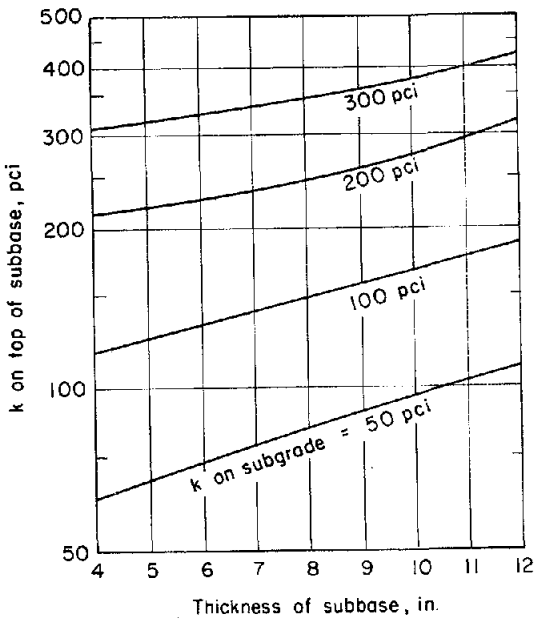

Fig. 1. Effect of granular subbase thickness on k-value.

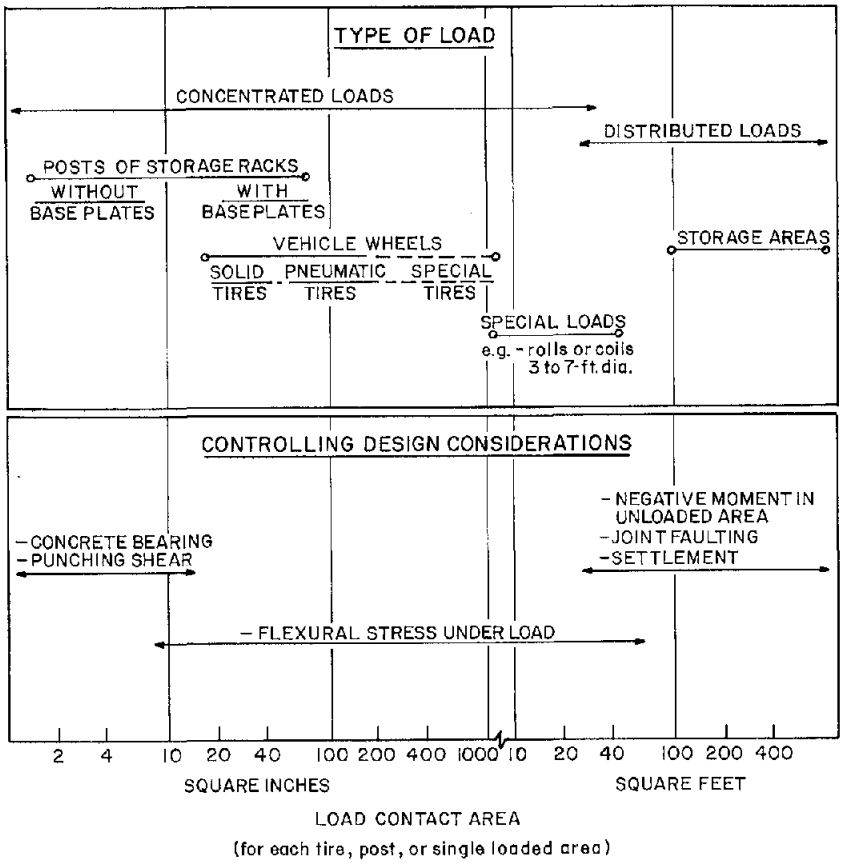

Fig. 2. Controlling design consideration depends on size of load contact area.

Table 2. Approximate Relationship Between Compressive and Flexural Strength of Concrete

Compressive strength, psi	Flexural strength MR, psi
4,000	569
4,500	604
5,000	636
5,500	667
6,000	697
6,500	726
7,000	753

sometimes under severe conditions. ACI Standard 302(1) recommends a 28-day compressive strength of 4,000 psi for Class 4 floors (light industrial/commercial) and 4,500 psi for Class 5 (single-course industrial). These values should be considered as minimums. In addition, compressive strength at 3 days should be at least 1,800 psi in order to avoid damage from subsequent construction traffic.

Generally, it is the best practice to use the highest-strength concrete that can be reasonably obtained with available aggregates. Strengths greater than the minimums indicated above, obtained at higher cement contents, not only permit a design slab-thickness reduction but provide other benefits in concrete properties such as improved wear resistance.

Variations in modulus of elasticity, E, and Poisson's ratio, μ, have only a slight effect on thickness design. The values used to develop the design charts in this publication are $E = 4{,}000{,}000$ psi and $\mu = 0.15$.

DESIGN OBJECTIVES

Several types of slab distress due to excessive loads can occur—cracking due to excessive flexural stress; excessive deflections; settlement due to excessive soil pressures; and, for very concentrated loads, excessive concrete bearing or shear stresses.

The strategy of design of the floor slab is to keep all these responses within safe limits. The most critical of these responses—the controlling design consideration—is different for different sizes of load contact area, as indicated in Fig. 2. For example, flexural stress is the controlling design consideration for lift trucks that normally have wheel contact areas (each wheel) in the range shown. An adequate slab thickness that keeps flexural stress due to wheel loads within a specified limit of safety will keep the other load responses shown in Fig. 2 within an even greater degree of safety.

For distributed loads covering large areas in storage bays, flexural stress under the load is not as critical as other responses. Negative moments* away from the load may cause

*Here, *negative moment* refers to tensile stresses in the top of the slab.

a crack in the aisleway, or the load may cause faulted joints due to differential settlements. Also, excessive soil pressures due to distributed loads may result in objectionable total settlement of some soils.

A third example of the effect of the size of loaded area is provided by a heavy load on the leg or post of a storage rack. If a base plate of adequate size is not provided, slab distress due to excessive bearing or punching shear is of more concern than the other responses. When the base plate is of adequate size to prevent a bearing or shear failure, flexural stress becomes the controlling design consideration.

It should be noted that Fig. 2 is presented as a guide only. Obviously, boundaries between different controlling design considerations are not exact and will vary somewhat depending on many factors, including slab thickness, concrete strength, and subgrade strength and compressibility. Thus, for values of contact areas between or near the limits shown, the other appropriate responses should be considered in the design.

The load effects and the controlling design considerations are also discussed in the following pages under Vehicle Loads, Post Loads, and Distributed Loads.

FLEXURAL STRESSES AND SAFETY FACTORS

When design procedure is based on flexure, the allowable working stress is determined by dividing the concrete flexural strength by an appropriate safety factor. The safety factors for vehicle loads have been established based on experience gained in pavement performance and take into account several influences, including number of load repetitions, shrinkage stresses,* and impact.**

Appropriate safety factors for concentrated, static loads and distributed loads are not well established by experience and research. The designer is advised to give careful consideration to specific design conditions and performance requirements and to seek out performance characteristics of slabs under similar loading conditions.

The flexural stresses indicated in the design charts† are those at the interior of a slab, assuming that the load is applied at some distance from any free edge. When the slab edges at all joints are provided with adequate load transfer (dowels, keyways, or aggregate interlock under saw cuts), it has been found that the area acts as a continuous large slab.

*Except for long, continuously reinforced slabs, shrinkage stresses are not considered significant. For example, a shrinkage stress of 23 psi is computed for an 8-in. slab jointed at 20 ft. using the commonly accepted subgrade friction factor of 1.5. Pavement research[6,7] shows that the actual stress developed will be only a third or half of that computed.

**In some procedures for industrial floor design, the loads are increased by a factor for the effect of wheel impact. However, pavement research[8,9] shows that slab stresses are less for moving loads than for static loads. Therefore, a load impact factor is not used in this procedure.

†Slab stresses for vehicle and post loads were determined by the use of the computer program described in Reference 10, with appropriate modifications in load contact area.

At free edges without adequate load transfer, load stresses are somewhat greater than those for the interior load condition. Because of this, the slab thickness at undoweled butt joints (for example, where floor meets driveway at truck door) should be increased* to compensate for the absence of load transfer, thus keeping the load stresses at these slab edges within safe limits.

The assumption of interior load stresses must be combined with the selection of appropriate safety factors and appropriate concrete design strength to give a reasonable basis for floor design.

In any design procedure, the selection of values to use as safety factor and concrete design strength depends on other design assumptions. For pavement design, several different design procedures have been developed by various agencies. One agency may use a different set of design assumptions than another. The design assumptions cover the following ranges:

load position (for computing stress)	interior or edge
safety factor	1.4 to 2.0
concrete strength	28 or 90 days

In comparing pavement design procedures of different agencies, it has been noted that where a particular procedure makes a more conservative assumption in one aspect of design, this is balanced by a less conservative assumption in another aspect of design. For example, where edge load stresses are used (higher than interior load stresses), this is balanced by the use of lower safety factors plus an allowance for load transfer. The result is that the different procedures give quite similar slab-thickness requirements** because each method is coupled with design adjustments that reflect performance experience. Thus, for any design procedure, it is important to select the proper "set" of design assumptions so that results are reasonably conservative but not excessively so. Assumptions taken out of context with the total design procedure can lead to overdesign or underdesign.

VEHICLE LOADS

The design procedure for vehicle loads involves determination of several specific design factors:

maximum axle load
number of load repetitions
tire contact area
spacing between wheels on heaviest axle
subgrade-subbase strength
flexural strength of concrete

* ACI 302.1R-89 recommends that the slab be thickened by approximately 25% at a taper not to exceed the slope of 1 in 10. In pavement design, thickness at a free edge is increased 20% to 25% at a slope not greater than 1 in 5.

**For a complete discussion of comparative design procedures and results, see Reference 11.

Estimating the traffic is an important factor in floor design. The required traffic information includes the load magnitudes, wheel configurations, and frequencies of loading for the heaviest vehicles that will use the floor. Traffic and load data for past and future plant or warehouse operating conditions can be gathered from several sources, including plant maintenance and engineering departments, planning and operations departments, and manufacturers' data for lift trucks and other vehicles. Based on this information, an adequate safety factor can be selected and used to determine an allowable working stress.

The safety factor (ratio of design flexural strength to working stress) depends on the expected frequency of loadings of the heaviest vehicles. For industrial floor design, safety factors in the range of 1.7 to 2.0 are suggested.* The higher end of this range should be used where heavy load traffic is frequent and channelized, as in aisleways and staging areas.

Because of the large variety of sizes, axle loads, and wheel spacings of industrial trucks, it is not practical to provide separate design charts for each vehicle. Consequently, two design charts, Figs. 3 and 4, have been prepared that can be used for the axle loads and axle-wheel configurations of most industrial trucks affecting floor design.

Fig. 3 is used for industrial trucks with axles equipped with single wheels. The chart is entered with an allowable working stress per 1,000 lb. of axle load. This allowable stress is computed by dividing the concrete flexural

*The fatigue criteria described in Reference 12 gives a more quantitative procedure for selecting safety factors and determining the allowable number of load repetitions. However, in most cases the projected traffic data are only an estimate that does not warrant a more precise analysis.

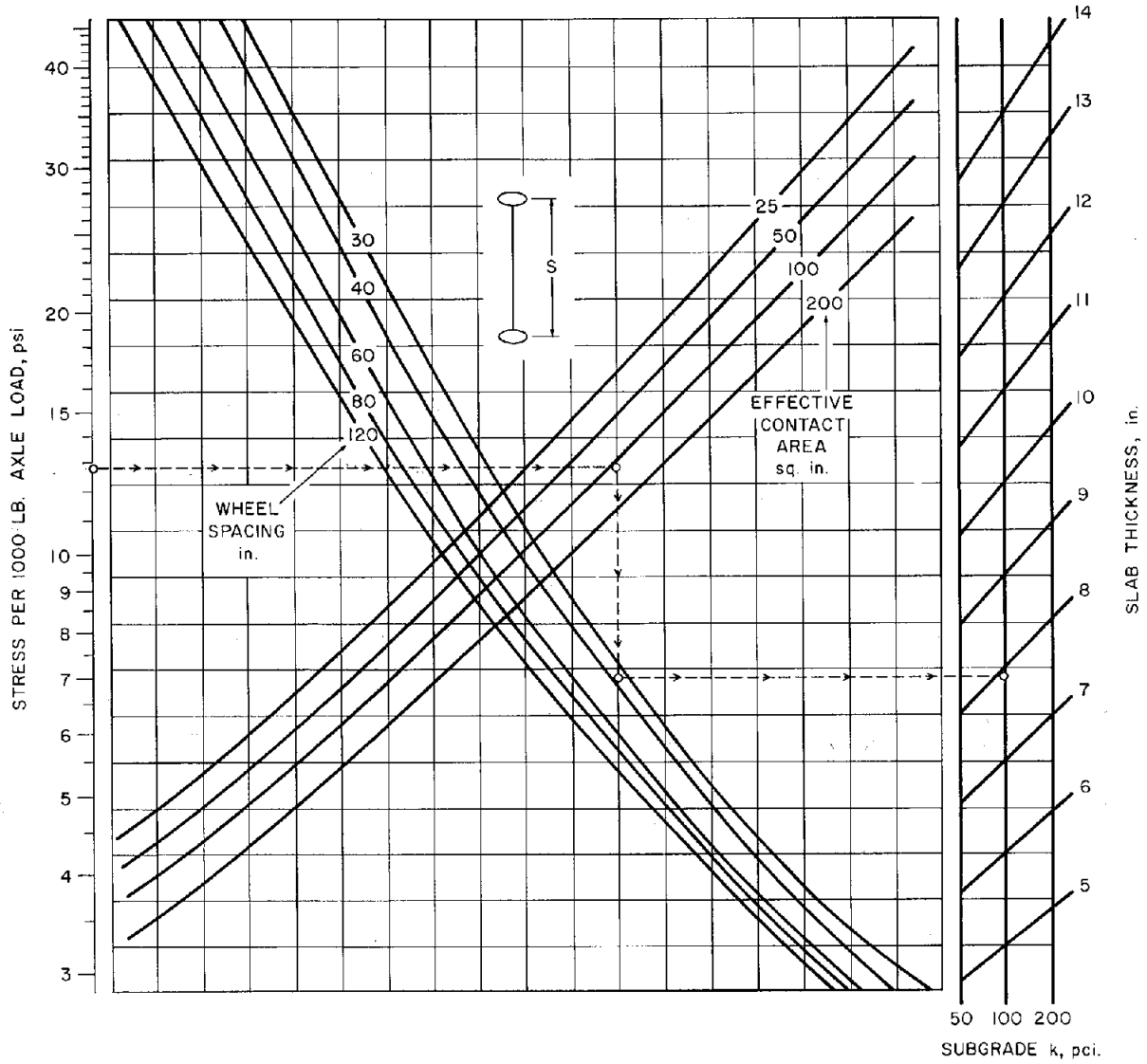

Fig. 3. Design chart for axles with single wheels.

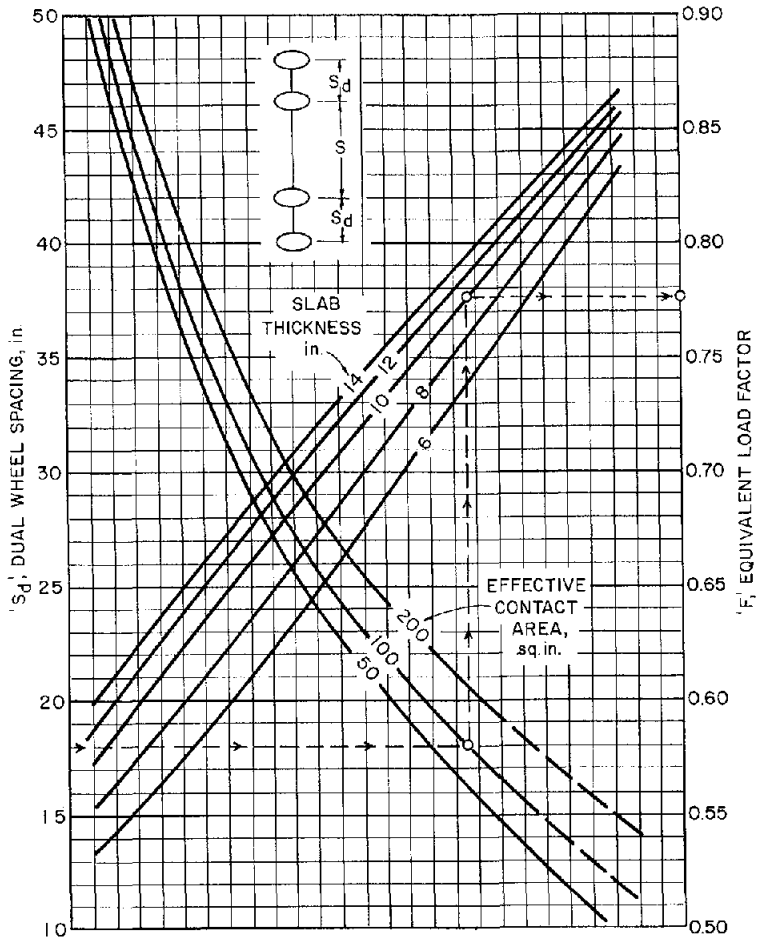

Fig. 4. Design chart for axles with dual wheels.

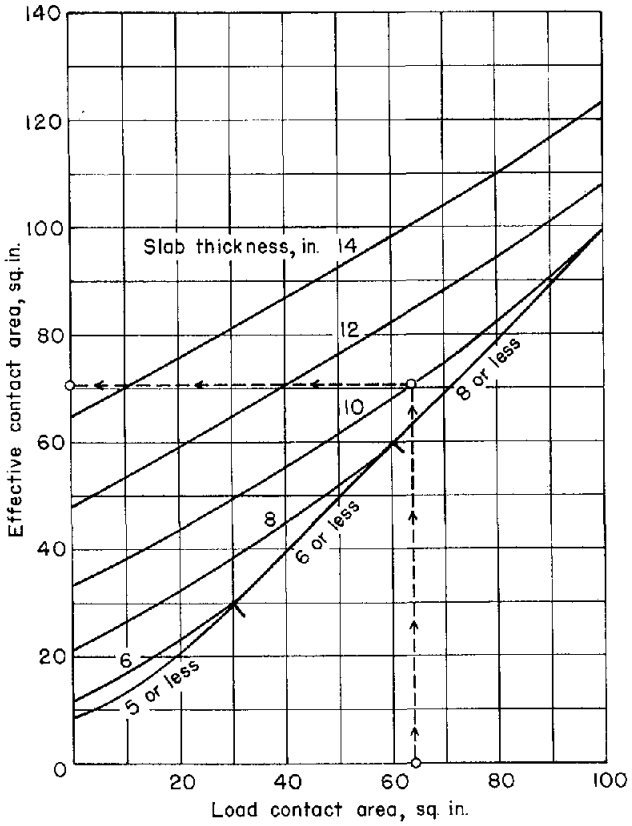

Fig. 5. Effective load contact area depends on slab thickness.

strength by the safety factor and then dividing this result by the axle load in kips (1 kip = 1,000 lb.).

For axles equipped with dual wheels, Figs. 3 and 4 are used together to determine floor slab thickness. First, Fig. 4 is used to convert the dual-wheel axle load to an equivalent single-wheel axle load (the axle load is multiplied by the factor, F). Then, with the equivalent load, Fig. 3 is used to determine the flexural stress in the slab.

The load contact area is the area of slab contact of one tire.* If tire data are not available, the contact area may be estimated for pneumatic tires by dividing wheel load by inflation pressure and roughly approximated for solid or cushion tires by multiplying tire width by three or four. If the tire size is known, the tire data may be obtained from manufacturers' tables.[14,15]

When the tire contact area has been determined, Fig. 5 is used to find the effective contact area for use in the design charts. The reason for making this correction is that the slab stresses for small load contact areas are overestimated when computed by conventional theory. The basis for this adjustment is given in Reference 13. (This same adjustment is used for post loads discussed in a later section.) In using Fig. 5 it is necessary to assume a slab thickness; this is a trial-and-error process to be checked against the final required design thickness. The degree of correction increases as contact area becomes smaller and slab thickness becomes greater.

The following example problems illustrate the use of Figs. 3 and 4 for slab-thickness design for vehicle loads:

Design Example–Single Wheels

Data for Lift Truck A

Axle load	25 kips
Wheel spacing	37 in.
No. of wheels on axle	2
Tire inflation pressure	110 psi

$$\text{Tire contact area} = \frac{\text{wheel load}}{\text{inflation pressure}}$$

$$= \frac{25{,}000/2}{110} = 114 \text{ sq.in.}$$

Subgrade and Concrete Data

Subgrade modulus, k	100 pci
Concrete flexural strength, MR	640 psi at 28 days

*The contact area to be used is sometimes referred to as the gross contact area, that is, the total area of the contact envelope regardless of the tire tread design.

Design Steps

1. Safety factor, SF:
   For frequent operations of this forklift truck in channelized aisle traffic, select a safety factor of 2.0 (permits unlimited stress repetitions).
2. Concrete working stress, WS:

$$WS = \frac{MR}{SF} = \frac{640}{2.0} = 320 \text{ psi}$$

3. Slab stress per 1,000 lb. of axle load:

$$\frac{WS}{\text{axle load, kips}} = \frac{320}{25} = 12.8 \text{ psi}$$

4. Enter Fig. 3 with stress of 12.8 psi; move right to contact area of 114 sq.in.;* then down to wheel spacing of 37 in.; then right to read a slab thickness of 7.9 in. on the line for subgrade k of 100 pci (use 8-in.-thick slab).

Design Example—Dual Wheels

Data for Lift Truck B

Axle load	50 kips
Wheel spacing	18 X 40 X 18 in.
No. of wheels on axle	4
Tire inflation pressure	125 psi
Tire contact area	$= \frac{\text{wheel load}}{\text{inflation pressure}}$
	$= \frac{50{,}000/4}{125} = 100$ sq.in.*

Subgrade and Concrete Data

Subgrade modulus, k	100 pci
Concrete flexural strength, MR	640 psi at 28 days

Design Steps

1. Safety factor, SF:
   Lift truck B will carry its maximum load inside the warehouse infrequently, only once or twice a week. Therefore, a safety factor near the lower end of the suggested range is selected—1.8.
2. Concrete working stress, WS:

$$WS = \frac{MR}{SF} = \frac{640}{1.8} = 356 \text{ psi}$$

3. Enter Fig. 4 with a dual wheel spacing of 18 in.; move right to a contact area of 100 sq.in.; then up to a trial slab thickness** of 10 in.; then right to an equivalent load factor, F, of 0.775. The equivalent single-wheel axle load is the factor F times the dual-wheel axle load = 0.775 X 50 = 38.8 kips.
4. Slab stress per 1,000 lb. of axle load

$$= \frac{WS}{\text{axle load, kips}} = \frac{356}{38.8} = 9.2 \text{ psi}$$

5. Enter Fig. 3 with stress of 9.2 psi; move right to contact area of 100 sq.in.; then up to wheel spacing of 40 in.; then right to a slab thickness of 9.7 in. on the line for subgrade k of 100 pci (use 10-in.-thick slab).

In preliminary design stages, or when detailed design data are not available, Fig. 6 may be used as a guide to indicate slab thickness based on the rated capacity of the heaviest lift trucks that will use the floor. The figure was prepared for typical lift trucks from manufacturers' data, composites of which are shown in Table 3. The figure would not apply for vehicles with load and wheel-spacing data that differ substantially from the tabulated data.

The conservative assumptions in Fig. 6 regarding the subgrade strength and working stress in the concrete should be noted. The combination of these assumptions results in a greater-than-usual degree of conservatism, which seems necessary when detailed design data are not available. Fig. 6 is intended as a rough guide only; more reliable and usually more economical designs may be obtained using more complete design data and Figs. 3 and 4.

POST LOADS

In some industrial buildings and warehouses, racks are used for storing products or materials. If the rack loads are heavy, significant stresses are induced in the floor slab by the loads on the posts supporting the rack. These concentrated loads can be more severe than the wheel loads of vehicles operating in the building and thus may control the thickness design of the floor slab.

For post loads, the design objective is to keep flexural stresses in the slab within safe limits. Within the range of design variables presented in this section, flexure controls the slab-thickness design. When flexural requirements are satisfied with an adequate slab thickness, soil pressures are not excessive; and when the appropriate size of base plate is used, concrete bearing and shear stresses are not excessive.*

*This contact area is large enough that correction by the use of Fig. 5 is not required.

**In using Fig. 4 it is necessary to assume a trial slab thickness that will later be checked against the design thickness determined from Fig. 3. This trial-and-error process—steps 3 through 5—may have to be repeated.

*For inadequate-size base plates, concrete bearing and shear stresses may be excessive even though flexural stresses are not. The size of the base plate should be large enough so that concrete bearing stress under maximum service load does not exceed 4.2 times the 28-day modulus of rupture, or half of this for loads applied at slab edges or corners. With an adequate-size base plate to control bearing stresses and an adequate slab thickness to control flexural stresses, shear stresses are not excessive for the ranges of design variables indicated in this section. This statement on shear stresses is based on an allowable shear of 0.27 times modulus of rupture and the assumption that the critical section in shear may be taken at a distance of half slab depth from the periphery of loaded area excluding, for loads at slab edge or corner, any section along slab joints. These criteria are a suggested interpretation of how current building code requirements[16] may be applied to the situation of post loads on floor slabs.

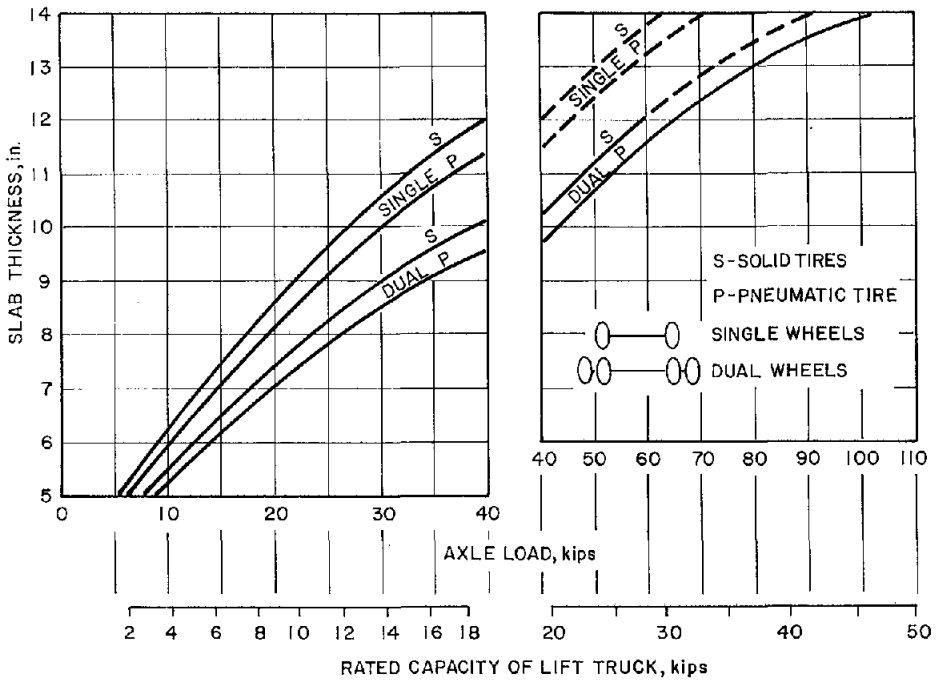

Fig. 6. Estimated slab thickness for lift trucks (based on average truck data shown in Table 3 and conservative design assumptions: k = 50 pci; concrete working stress of 250 psi).

Table 3. Lift Truck Characteristics (Composites Averaged from Manufacturers' Data)

Rated capacity,[1] lb.	Load on drive axle,[2] kips	Range of wheel spacings, in. (c. to c.)		
		Single wheels, s[3]	Dual wheels	
			s_d[3]	s[3]
2,000	6.4	26 to 30	–	–
4,000	10.4	31 to 35	–	–
6,000	14.6	32 to 38	–	–
10,000	22.2	37 to 43	10 to 12[4]	41 to 53[4]
15,000	32.5	37 to 45	10 to 12	47 to 60
20,000	42.0	40 to 50	12 to 14	54 to 65
30,000	63.3	–	14	57
45,000	100.6	–	18	73
60,000	132.0	–	21	70

Other Data:
Load Contact Pressure
solid or cushion tires–180 to 250 psi
pneumatic tires–80 to 100 psi (inflation pressure)
Load Contact Area (per tire)
solid or cushion tires–3 or 4 times tire width
pneumatic tires–wheel load divided by contact pressure
Approximately 90% of total weight (truck + load) on drive axle at rated capacity.
Maximum axle load for many lift trucks is slightly greater than twice the rated capacity.

[1] Load center 24 in. from fork face, mast vertical.
[2] Varies by about 10% depending on manufacturer.
[3] See insert drawings on Figs. 3 and 4.
[4] Values shown are for pneumatic tires; limited data for 10,000-lb.-capacity trucks with solid or cushion tires show shorter spacings; for example, 8.5x29 in.

Because flexure controls, the design factors are similar to those used for vehicle loads except that the use of a higher safety factor may be appropriate. The specific design factors are:

maximum post load
load contact area
spacing between posts
subgrade-subbase strength
flexural strength of concrete

Figs. 7a, 7b, and 7c are used to determine the slab thickness requirements for k values of 50, 100, and 200 pci. The charts* were developed to estimate slab stresses for the two equivalent post configurations and load conditions shown in Fig. 8, representing continuous racks. In Figs. 7a, 7b, and 7c, the post spacing, y, is in the longitudinal direction of a continuous rack and x is the transverse spacing.

When using the design charts, the load contact area should be corrected to effective contact area as determined from Fig. 5.

For special post load configurations that deviate substantially from those indicated in Fig. 8, slab stresses may be determined by computer program[10]** or by influence charts.[18]

It should be noted that the design procedure is based on load stresses only; it is not necessary to consider shrinkage stresses (see first footnote on page 4).

*For a structurally reinforced slab, bending moments computed from the flexural stress determined from Figs. 7a, 7b, and 7c may be used to compute the required tensile reinforcement.

**The computer program may be used with appropriate modifications in the shape of the contact area. For the range of contact areas involved, a circular or elliptical area may be used without significant error to approximate a square or rectangular area.

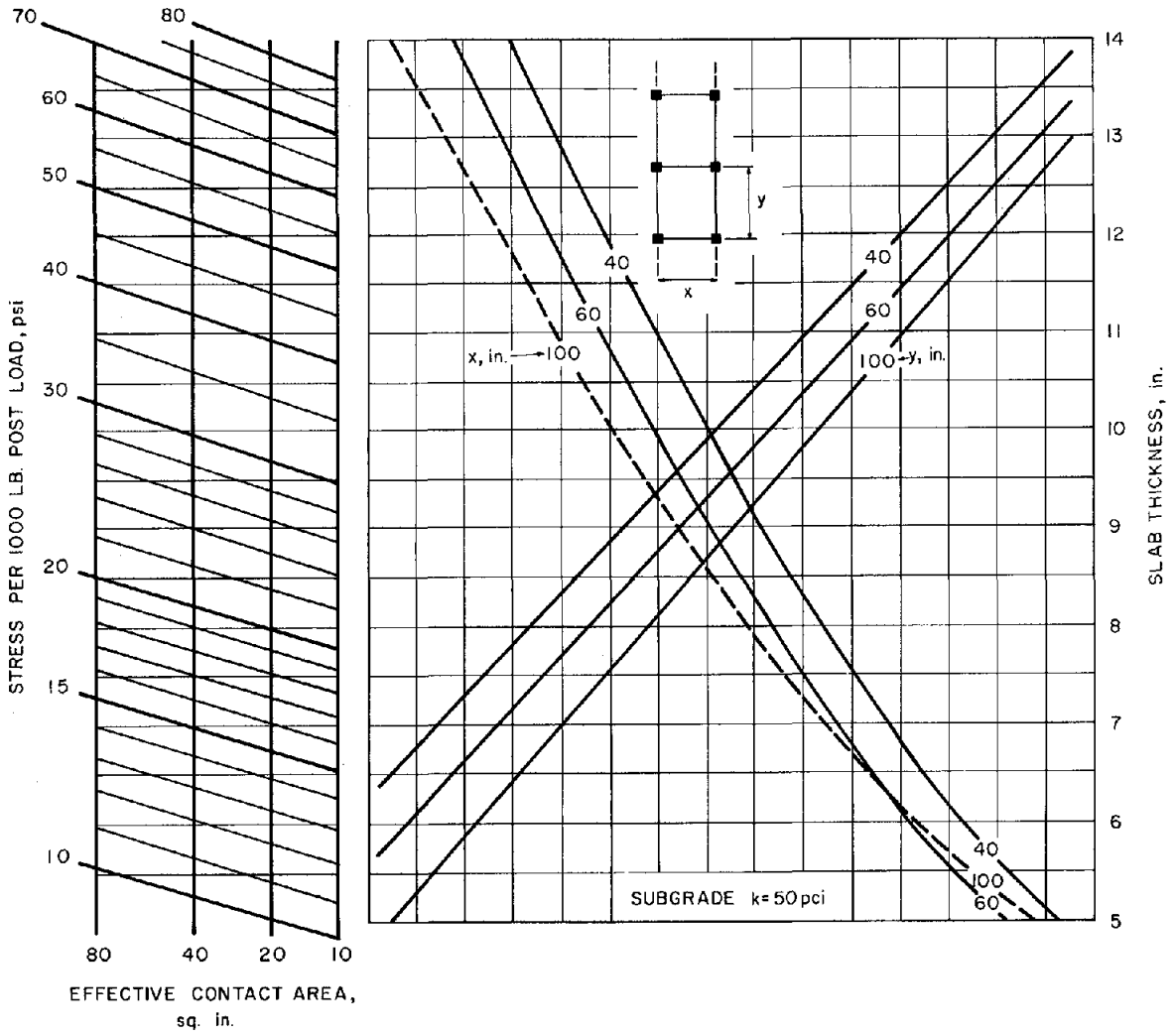

Fig. 7a. Design chart for post loads, subgrade k = 50 pci.

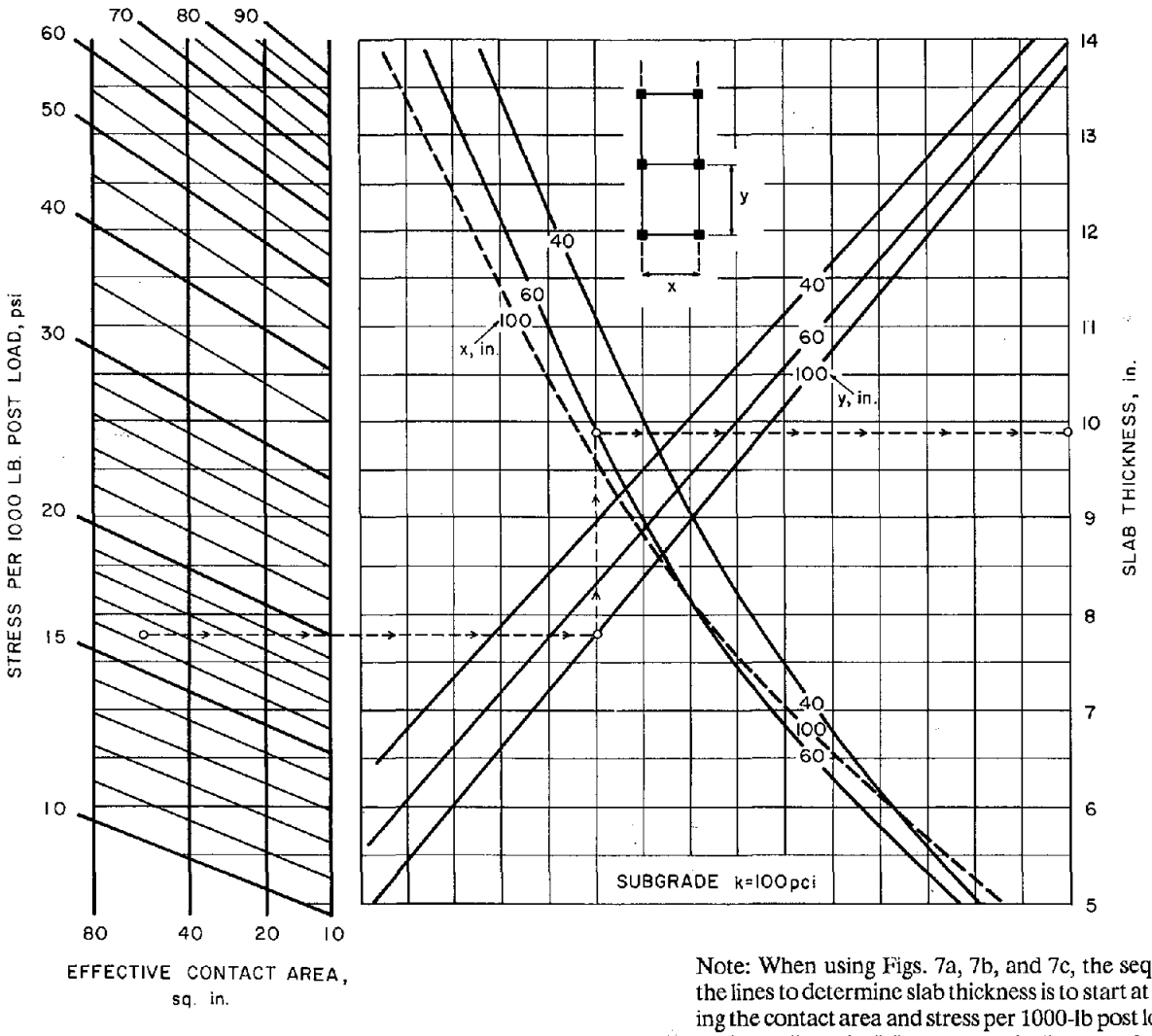

Fig. 7b. Design chart for post loads, subgrade k = 100 pci.

Note: When using Figs. 7a, 7b, and 7c, the sequence in drawing the lines to determine slab thickness is to start at the point describing the contact area and stress per 1000-lb post load, then proceed horizontally to the "y" curves, vertically, up or down, to the "x" curves, and horizontally to the required slab thickness.

Safety Factors for Post Loads

The specific safety factors to be selected for concentrated static loads are not given here but are left to the judgment of the design engineer. There are two reasons for this:

(1) The range of possible safety factors may be quite wide; the factor may be relatively low–2 or less–under a noncritical loading condition, or quite high –approximately 5–in a situation where consequences of slab failure are quite serious.

(2) Performance experience and experimental data for concentrated static loads are not available.

Some of the factors to be considered in the selection of the safety factor are discussed below.

Static loads on posts have effects different from loads on vehicles in that (1) moving wheel loads produce lower slab stresses than static loads of the same magnitude, and (2) creep effects reduce stress under static load. Information on how these effects may be quantified in design problems is not available.

There may be several reasons to use higher safety factors for loads on high racks than those used for low racks or for vehicle loads or distributed loads. The rack posts are sometimes designed to partially support the roof structure, and effects of differences in deflection between rack posts are magnified with high racks. In addition, if the rack layout and the slab joint layout are not coordinated, it is possible that some rack posts could be located at or near a joint or corner. Unless the slab edges are thickened, this would result in higher stresses* than those shown in Figs. 7a, 7b,

*Edge load stresses are higher than corner load stresses, which are in turn higher than interior load stresses. However, edge and corner stresses are diminished somewhat in the usual situation where load transfer at the joints is provided by dowels, keyways, or aggregate interlock under saw cuts. An analysis using a conservative 25% load transfer and the multiple post configurations indicated in Fig. 8 shows that edge stresses exceed interior stresses by 13% to 50%. Reference 17 gives experimental data on edge and corner stresses and equations for computing these.

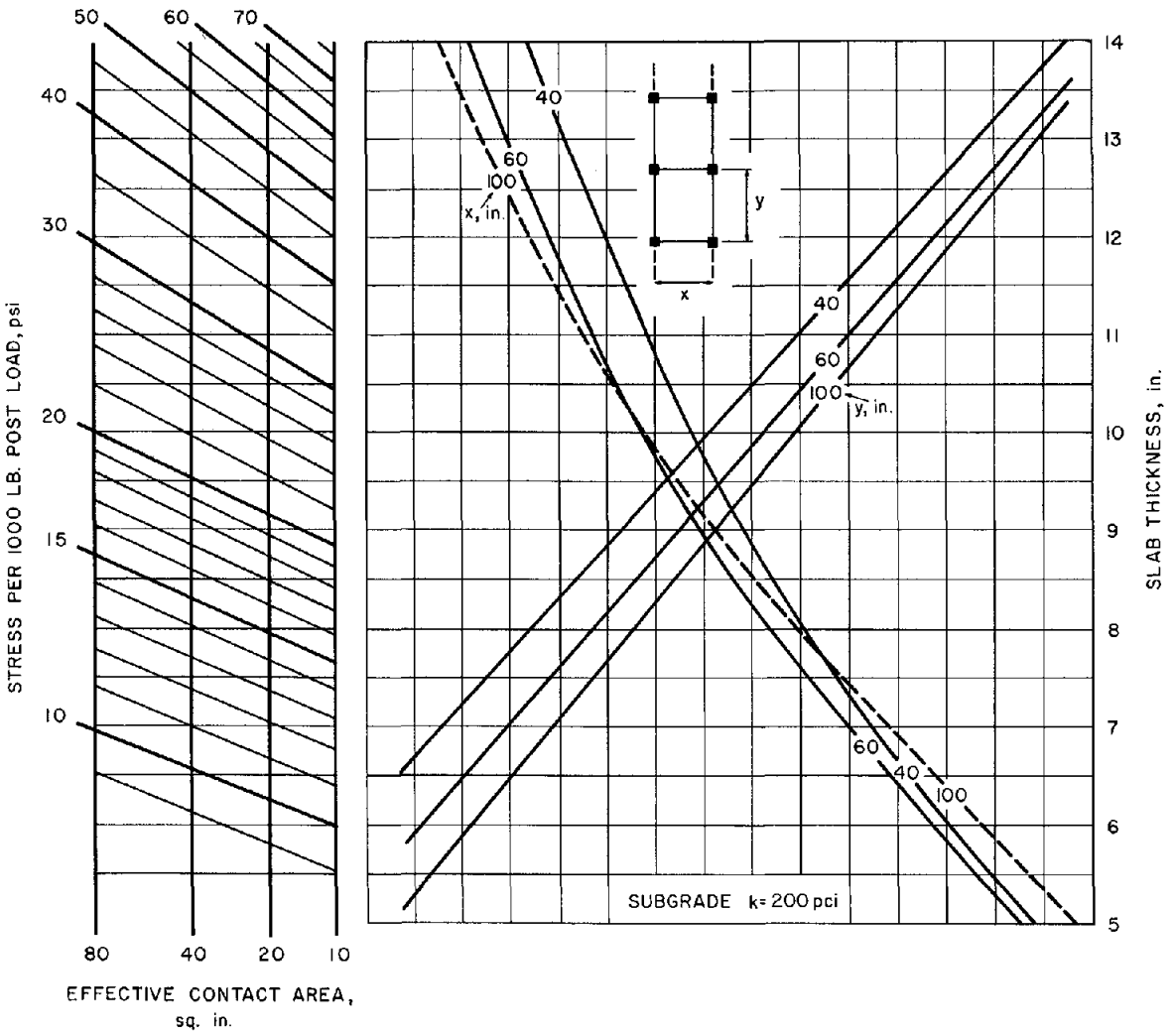

Fig. 7c. Design chart for post loads, subgrade k = 200 pci.

and 7c, which are based on loads at the slab interior. Safety factors should be chosen to account for this possibility of higher stresses due to slab edge or corner loads.

Since there is a lack of published data on performance experience with rack loads on slabs on grade, safety factors cannot be suggested with as much confidence as for vehicle loads. Therefore, it is important to consider carefully the characteristics of this type of loading and the desired performance requirements.

A safety factor of 4.8 can be computed based on building code requirements[16] if the post is considered as a critical structural element—a column—in the building and the slab is considered as an unreinforced spread footing.

This value of 4.8 is considered the upper limit of the safety factor range because the post load situation is usually not as critical as that for columns on footings. The latter are spaced farther apart and each supports a greater proportion of the total structural load. The fundamental difference between the two types of loading lies in the difference in the magnitudes of pressure on the underlying soil. Soil pressures under a footing may be near the limit of allowable soil bearing; if a failure should occur in the footing, the allowable soil pressure would be exceeded and there would be a possibility of intolerable soil penetration, settlement, or complete collapse. On the other hand, soil pressures under a slab of adequate thickness supporting a post load are much lower than those for a footing. This is because the slab distributes the load over a large area of subgrade. Even if a joint or crack, or intersection of these, should occur at a post, deflections and soil pressures will be increased by magnitudes of two or three* but are still not excessive.

After the designer has considered the degree of criticalness of his loading conditions and selected an appropriate safety factor, Fig. 7a, b, or c is used to establish a slab design thickness based on flexure. Shear stress and concrete

*Reference 17 shows experimental data comparing deflections due to loads at slab corners, edges, and interiors from which corresponding soil pressures can be computed.

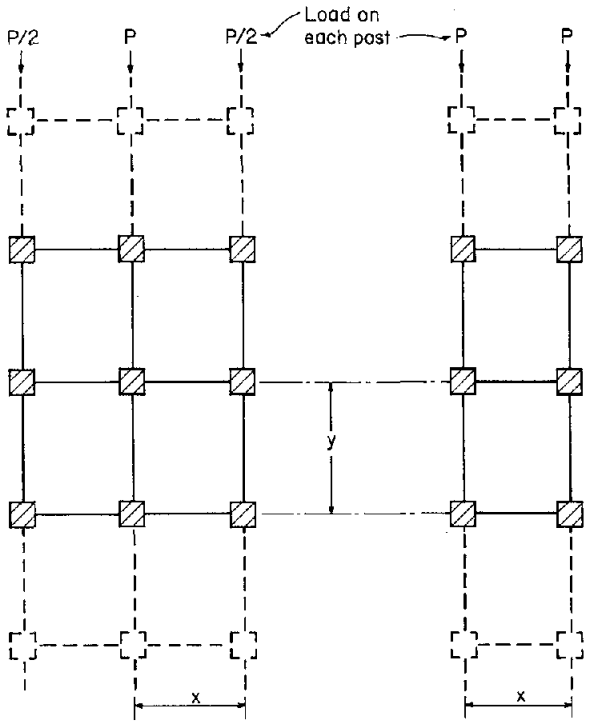

Fig. 8. Post configurations and loads for which Figs. 7a, 7b, and 7c apply.

bearing stress should also be computed to determine if these values are within safe limits. The following example problem illustrates the procedure for determining slab stresses due to post loads.

Design Example–Post Loads

Data for Post Configuration and Load

Post spacings	98 in. longitudinal (y), 66 in. transverse (x)
Post loads	13 kips, each post
Load contact area	8-in.-sq. plate (64 sq.in.)

Subgrade and Concrete Data

Subgrade modulus, k	100 pci
Concrete flexural strength, MR	640 psi at 28 days

Design Steps

1. Safety factor, SF:
   Assume that a factor of 3.0 has been selected.
2. Concrete working stress, WS:

$$WS = \frac{MR}{SF} = \frac{640}{3.0} = 213 \text{ psi}$$

3. Slab stress per 1,000 lb. of post load

$$= \frac{WS}{\text{post load, kips}} = \frac{213}{13} = 16.4 \text{ psi}$$

4. For a subgrade k-value of 100 pci, use Fig. 7b. In the grid at the left of the figure, locate the point corresponding to 16.4 psi stress and 64-sq.in. contact area; then move right to y-post spacing of 98 in.; up to x-post spacing of 66 in.; then right to slab thickness of 9.8 in. (use 10-in.-thick slab).
5. Use Fig. 5 to determine if the effective contact area is significantly larger than the actual contact area. For a 10-in. slab and contact area of 64 sq.in., the effective contact area is 70 sq.in.; this correction does not significantly change the required slab thickness.
6. The following check of concrete bearing and shear stresses indicates that they are within allowable limits (see footnote on page 7, right column).

allowable bearing stress
for interior load $= 4.2MR = 2{,}690$ psi
for edge or corner load $= 2.1MR = 1{,}345$ psi

$$\text{computed bearing stress} = \frac{\text{post load}}{\text{load area}} = \frac{13{,}000}{64}$$

$$= 203 \text{ psi}$$

$$\text{allowable shear stress} = 0.27MR = 173 \text{ psi}$$

$$\text{computed shear stress} = \frac{\text{post load}}{\text{shear area}}$$

computed shear stress for interior load

$$= \frac{\text{post load}}{\text{slab depth [(load periphery)} + 4 \text{ (slab depth)]}}$$

$$= \frac{13{,}000}{10\ [32 + 40]} = 18 \text{ psi}$$

computed shear stress for edge load

$$= \frac{\text{post load}}{\text{slab depth [0.75 (load periphery)} + 2 \text{ (slab depth)]}}$$

$$= \frac{13{,}000}{10\ [24 + 20]} = 30 \text{ psi}$$

computed shear stress for corner load

$$= \frac{\text{post load}}{\text{slab depth [0.5 (load periphery)} + \text{(slab depth)]}}$$

$$= \frac{13{,}000}{10\ [16 + 10]} = 50 \text{ psi}$$

For very heavy post loads, the required thickness of plain concrete slabs may be great enough that alternate designs should be considered, such as:

- integral or separate footings under each post or line of posts (post locations would have to be permanently fixed);
- structurally reinforced slabs with steel designed to take the tensile stresses;
- use of a cement-treated subbase under the concrete slab.

DISTRIBUTED LOADS

Distributed loads are defined as loads covering a large area

due to material placed directly on the floor in storage bays. For most plant and warehouse buildings, concentrated loads are the controlling factor in floor design since distributed loads usually do not produce flexural stresses of the same magnitude. However, after an adequate slab thickness has been selected to support the heaviest vehicle and post loads, the effects of distributed loads should also be examined.

As discussed on pages 3 and 4, the design objectives for distributed loads are (1) to prevent cracks in the aisleways due to excessive negative moment (tension in top of slab), and (2) to avoid objectionable settlement of the slab.

Cracking in an unjointed aisle due to distributed loads can be controlled by selecting an adequate slab thickness. Slab settlement, however, cannot be prevented by making the slab thicker. Usually the magnitude of distributed loads placed on floors with properly prepared and compacted subgrades is not sufficient to cause excessive settlement. However, for very heavy distributed loads on compressible subgrades, the possibility of soil consolidation should be examined by soil foundation engineering techniques.

Allowable Loads to Prevent Cracking in Unjointed Aisleway

In an unjointed aisleway between distributed load areas, the maximum negative bending moment in the slab may be up to twice as great as the moment in the slab beneath the loaded area. As a result, one design objective is to limit these stresses in the aisleway so that a crack will not occur.

Allowable loads based on this design objective are shown in Tables 4 and 5.* The use of these tables is discussed in the following sections. Table 4 is used if the aisle and storage layout may be changed during the service life of the floor. If the layout is permanently fixed, Table 5 is used.

It should be noted that the k-value of the subgrade, rather than the k on top of the subbase (if there is one), is used in Tables 4 and 5. This is appropriate for distributed loads covering large areas, while the use of the k-value on the top of the subbase is appropriate for concentrated loads.

Variable Storage Layout

The magnitudes of flexural stresses and deflections due to distributed loads vary with slab thickness and subgrade strength. They also depend on aisle width, width of loaded area, and whether or not a joint or crack exists in the aisle-

Table 4. Allowable Distributed Loads, Unjointed Aisle (Nonuniform Loading, Variable Layout)

Slab thickness, in.	Subgrade k,[1] pci	Allowable load, psf[2]			
		Concrete flexural strength, psi			
		550	600	650	700
5	50	535	585	635	685
	100	760	830	900	965
	200	1,075	1,175	1,270	1,370
6	50	585	640	695	750
	100	830	905	980	1,055
	200	1,175	1,280	1,390	1,495
8	50	680	740	800	865
	100	960	1,045	1,135	1,220
	200	1,355	1,480	1,603	1,725
10	50	760	830	895	965
	100	1,070	1,170	1,265	1,365
	200	1,515	1,655	1,790	1,930
12	50	830	905	980	1,055
	100	1,175	1,280	1,390	1,495
	200	1,660	1,810	1,965	2,115
14	50	895	980	1,060	1,140
	100	1,270	1,385	1,500	1,615
	200	1,795	1,960	2,120	2,285

[1] k of subgrade; disregard increase in k due to subbase.
[2] For allowable stress equal to ½ flexural strength.
Based on aisle and load widths giving maximum stress.

way. These additional variables are not always constant or predictable during the service life of a floor. Therefore, the allowable loads shown in Table 4, representing the most critical conditions, are suggested for practical design use where the aisle and storage layout is not predictable or permanent.

Since the allowable loads in Table 4 are based on the most critical conditions, there are no restrictions on the load layout configuration or the uniformity of loading. Loads up to these magnitudes may be placed nonuniformly in any configuration and changed during the service life of the floor. (Heavier loads may be allowed, as shown in Table 5, under restricted conditions of load configuration.)

The allowable loads in Table 4 are based on a safety factor of 2.0 (allowable working stress equal to one-half of the concrete's flexural strength). This is conservative. For other safety factors that the designer may wish to use, the allowable working stress is first computed by dividing the 28-day flexural strength, MR, by the safety factor; then the allowable load may be computed as:

$$W = 0.123 f_t \sqrt{hk}$$

where W = allowable load, psf
f_t = allowable working stress, psi
h = slab thickness, in.
k = subgrade modulus, pci

Fixed Storage Layout

As discussed in the previous section, slab stresses under distributed loads vary with aisle width, load width, and joint

* In the preparation of these tables, flexural stresses were computed based on Hetenyi.[21] A similar approach was used by Rice [20] for distributed loads. Although the basic equations are the same, the allowable loads shown in Tables 4 and 5 differ from those of Rice because he made a large allowance for slab shrinkage stresses. In addition, he considered zero uplift of joints in the aisleway as one of the design criteria. As explained in the first footnote on page 4, shrinkage stresses may be disregarded in the design procedure. Also, it can be shown that loads up to the magnitudes shown in Tables 4 and 5 produce only very small joint uplifts that would be completely tolerable for most requirements. Concerning slab stresses due to wheel loads at uplifted joints, experimental data [17] show that these are less than the stresses in slabs that are not uplifted at the joint.

Table 5. Allowable Distributed Loads, Unjointed Aisle (Uniform Load, Fixed Layout)

Slab thickness, in.	Working stress, psi	Critical aisle width, ft.[2]	Allowable load, psf					
			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 pci[1]								
5	300	5.6	610	615	670	815	1,050	1,215
	350	5.6	710	715	785	950	1,225	1,420
	400	5.6	815	820	895	1,085	1,400	1,620
6	300	6.4	670	675	695	780	945	1,175
	350	6.4	785	785	810	910	1,100	1,370
	400	6.4	895	895	925	1,040	1,260	1,570
8	300	8.0	770	800	770	800	880	1,010
	350	8.0	900	935	900	935	1,025	1,180
	400	8.0	1,025	1,070	1,025	1,065	1,175	1,350
10	300	9.4	845	930	855	850	885	960
	350	9.4	985	1,085	1,000	990	1,035	1,120
	400	9.4	1,130	1,240	1,145	1,135	1,185	1,285
12	300	10.8	915	1,065	955	915	925	965
	350	10.8	1,065	1,240	1,115	1,070	1,080	1,125
	400	10.8	1,220	1,420	1,270	1,220	1,230	1,290
14	300	12.1	980	1,225	1,070	1,000	980	995
	350	12.1	1,145	1,430	1,245	1,170	1,145	1,160
	400	12.1	1,310	1,630	1,425	1,335	1,310	1,330
Subgrade k = 100 pci[1]								
5	300	4.7	865	900	1,090	1,470	1,745	1,810
	350	4.7	1,010	1,050	1,270	1,715	2,035	2,115
	400	4.7	1,155	1,200	1,455	1,955	2,325	2,415
6	300	5.4	950	955	1,065	1,320	1,700	1,925
	350	5.4	1,105	1,115	1,245	1,540	1,985	2,245
	400	5.4	1,265	1,275	1,420	1,760	2,270	2,565
8	300	6.7	1,095	1,105	1,120	1,240	1,465	1,815
	350	6.7	1,280	1,285	1,305	1,445	1,705	2,120
	400	6.7	1,460	1,470	1,495	1,650	1,950	2,420
10	300	7.9	1,215	1,265	1,215	1,270	1,395	1,610
	350	7.9	1,420	1,475	1,420	1,480	1,630	1,880
	400	7.9	1,625	1,645	1,625	1,690	1,860	2,150
12	300	9.1	1,320	1,425	1,325	1,330	1,400	1,535
	350	9.1	1,540	1,665	1,545	1,550	1,635	1,795
	400	9.1	1,755	1,900	1,770	1,770	1,865	2,050
14	300	10.2	1,405	1,590	1,445	1,405	1,435	1,525
	350	10.2	1,640	1,855	1,685	1,640	1,675	1,775
	400	10.2	1,875	2,120	1,925	1,875	1,915	2,030
Subgrade k = 200 pci[1]								
5	300	4.0	1,225	1,400	1,930	2,450	2,565	2,520
	350	4.0	1,425	1,630	2,255	2,860	2,990	2,940
	400	4.0	1,630	1,865	2,575	3,270	3,420	3,360
6	300	4.5	1,340	1,415	1,755	2,395	2,740	2,810
	350	4.5	1,565	1,650	2,050	2,800	3,200	3,275
	400	4.5	1,785	1,890	2,345	3,190	3,655	3,745
8	300	5.6	1,550	1,550	1,695	2,045	2,635	3,070
	350	5.6	1,810	1,810	1,980	2,385	3,075	3,580
	400	5.6	2,065	2,070	2,615	2,730	3,515	4,095
10	300	6.6	1,730	1,745	1,775	1,965	2,330	2,895
	350	6.6	2,020	2,035	2,070	2,290	2,715	3,300
	400	6.6	2,310	2,325	2,365	2,620	3,105	3,860
12	300	7.6	1,890	1,945	1,895	1,995	2,230	2,610
	350	7.6	2,205	2,270	2,210	2,330	2,600	3,045
	400	7.6	2,520	2,595	2,525	2,660	2,972	3,480
14	300	8.6	2,025	2,150	2,030	2,065	2,210	2,480
	350	8.6	2,360	2,510	2,365	2,405	2,580	2,890
	400	8.6	2,700	2,870	2,705	2,750	2,950	3,305

[1] k of subgrade; disregard increase in k due to subbase.
[2] Critical aisle width equals 2.209 times radius of relative stiffness.

Assumed load width = 300 in.; allowable load varies only slightly for other load widths. Allowable stress = one-half flexural strength. Modulus of elasticity (E) is 4 x 10^6 psi.

location. In a storage area where this layout is known and will remain fixed throughout the service life of the floor, the heavier distributed loads shown in Table 5* may be allowed. These loads are based on limiting the negative moment in an unjointed aisleway so that an aisle crack does not occur.

Allowable Loads to Prevent Slab Settlement

In the previous discussion, the allowable loads were based on preventing a crack in an unjointed aisleway between loaded storage areas. If these cracks can be tolerated or if there are joints in the aisleways, there need be no such restriction on the load magnitude. In this case, the limit of load depends on the tolerable settlement of the slab.

Slab settlement is caused by excessive pressures on the soil below. For concentrated loads, a greater slab thickness reduces the pressure on the soil. However, for distributed loads, slab thickness has virtually no effect on soil pressure—the soil pressure is equal to the distributed load plus the weight of the slab. Therefore, use of a thick slab does not reduce settlement under distributed loads.

An estimate of the minimum settlement that may occur can be made by computing[21] the elastic deflection using the subgrade modulus k. Computing the deflection profile for the entire slab width provides an estimate of the potential slab uplift away from the load as well as downward deflection of the part of the slab that is under the load. These computed elastic deflections may be a fair estimate only if the soil is relatively incompressible.

For slabs on compressible subgrades, settlement under distributed loads may be considerably greater than the computed elastic deflection. If the distributed loads are heavy, the settlement should be estimated by methods used in soils engineering for spread or raft foundations. As described in most texts on soils engineering, data from test footings of different sizes are helpful in estimating the amount of settlement on compressive soils.

The tolerable settlement may be considerably less than that allowed for foundations, depending on the operational requirements of the floor. For example, if a joint or crack exists in the aisle or within certain distances of the edge of the distributed load, the differential settlement between the loaded and unloaded sides of the joint or crack may cause a bump that is objectionable to vehicle traffic.

UNUSUAL LOADS

Special load configurations—unusual wheel or post configurations, tracked vehicles, vehicles with closely spaced axles or with more than 4 wheels per axle, very large wheel contact areas, strip loads—that differ substantially from those indicated in the previous discussions may be analyzed by one of the following methods:

1. For concentrated loads (wheel or post loads), slab stresses, deflections, and soil pressures may be determined with influence charts[18] or a computer program.[10] The influence charts may also be used for strip loads if the length of the load contact area is not great.**
2. When one or both of the dimensions of a load contact area is large† (distributed loads in a storage bay or a strip load), the situation can be considered as a one-dimensional problem and the method of Hetényi[21] may be used.

In either case, the controlling design considerations will be similar to those indicated in Fig. 2 based on the size of the load contact areas. (For strip loads, the controlling design considerations cannot be expressed in terms of contact area; it may be necessary to analyze several of the design considerations indicated in Fig. 2.)

A wide range of design situations can be analyzed with a computer program for foundations mats.[19]

Vibrating loads, such as those caused by heavy generators or compressors, may require a special foundation design and this is beyond the scope of this discussion.

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*What may at first appear to be anomalies in the values shown in Table 5 are explained by the following considerations. For a given slab thickness and subgrade strength there is a critical aisle width for which the slab stress in the aisleway is maximum. As shown in Table 5, the allowable load for the critical aisle width is less than for any other aisle width. The critical aisle width exists when the maximum bending moment in the aisle due to a load on one side of the aisle coincides with the point of maximum moment due to the load on the other side of the aisle. This doubles the negative bending moment (tension in top of slab) at aisle centerline. For aisle widths other than the critical aisle width, the bending moments due to loads on each side of the aisle are not maximum; the load on one side of the aisle may counteract stress caused by a load on the other side.

**Influence charts cover a dimension of either 4ℓ or 6ℓ (see next footnote), depending on the particular chart used.

†The analysis of Hetényi as used for slab design applies to loads of finite width and infinite length; however, the error is not significant if the length exceeds 6ℓ where ℓ is defined by:

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

where ℓ = radius of relative stiffness, in.
E = concrete modulus of elasticity, psi
h = slab thickness, in.
μ = Poisson's ratio
k = modulus of subgrade reaction, pci

For more information on the design, construction, and repair of floors on ground, see *Concrete Floors on Ground*, EB075D.

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Metric Conversions

1 ft = 0.305 m
1 in. = 25.4 mm
1 sq ft = 0.093 m2
1 sq in. = 645 mm2
1 lb = 454 g
1 kip = 454 kg
1 psi = 6.9 kPa
1 psf = 47.9 Pa
100 pci (subgrade k) = 27.15 MPa/m

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