DESIGN OF SLABS ON GRADE

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How thick should I pour my floor? Do I need reinforcing? Which type of reinforcement is best? How much load can I put on it? Will my fork truck crack it? Do I really need joints in my floor? Should I install a polyethylene vapor barrier or vapor retarder underneath the whole slab? And how much do all these things matter?

Have you ever been asked those questions? Do you have answers to them? If not, where do you turn? This article aims to inform the building designer, contractor and owner about many important issues in the design of a concrete slab on grade.

DETERMINING THE PURPOSE OF THE SLAB

Sound design of a slab on grade begins with determining the intended use and performance criteria. How will the slab be used? What are the types and magnitude of the loads? Are there aesthetic requirements (e.g., is it acceptable to have random cracks or joints)? For example, one might be designing a building slab that is subjected to vehicle traffic such as skid steer loaders, forklifts, trucks or tractors or some combination of these. In this case the ability to handle repetitive loads and to transfer those loads across joints is a critical design criterion. Alternatively, a slab may not have vehicle traffic but instead needs to be impermeable. Such is the case with the base of a storage tank for liquid manure. In some other slab uses (e.g., some farm shops or garages) the slab will receive limited vehicle traffic, or the repetitions are likely not sufficient to control the slab thickness design, but other things—in-floor heat, surface finish including coatings, the slab slope or levelness—significantly influence the design.

Stresses in concrete slabs come from volume changes in the concrete from shrinkage and temperature changes or from imposed loads. The magnitudes of stresses are significantly influenced by the type, strength and uniformity of the subgrade or subbase. Numerous other factors, such as the volume of shrinkage, temperature range exposure, joints, and magnitude of imposed loads, may play a role. Prudent design and development of plans and specifications will focus on controlling or minimizing the stresses. Subsequently, adherence to the project plans and specifications during construction will help provide a slab that will perform for the intended use.

PROPER PREPARATION

Providing an adequate subgrade for your planned slab on grade is one of the main keys to long-term performance. Subgrade for concrete slabs is the natural ground, which is typically prepared by grading and compaction. For more critical slabs, evaluation may involve a site-specific evaluation by a professional engineer. Special considerations are required for problem soil such as highly expansive or compressive soils. Uniform soils that will provide reasonable support are desired. Except for highly organic soils and high-plasticity silts and clays such as those labeled CH or MH according to the Unified Soil Classification System, most soil types will provide a modulus of subgrade reaction, *k*, of at least 100 pounds per cubic inch when compacted and passing a proof roll test with a loaded tandem. Determining the California bearing ratio will help estimate the subgrade modulus. Although many concrete slabs can satisfactorily be cast directly on a soil subgrade, some slab-on-grade systems can be significantly improved by the addition of a good subbase such as a compacted aggregate as shown in **Figure 1**.

A layer of aggregate subbase will also help provide a more uniform base for the slab when it is placed across the entire subgrade, providing more uniform support and helping to minimize thickness variation in the slab. Good subgrade drainage is also important to reduce risk of frost heave on exterior slabs as well as swelling and shrinking. Areas of fill should be avoided or limited as much as possible.

Figure 1. Aggregate subbase prepared for reinforced slab on grade

Compaction of fills should specify a maximum lift thickness, along with requirements for moisture and density based on the fill material. Larger fills will add a surcharge load to the subsurface soils, which may cause differential settlement. Settlement risks should be evaluated by a qualified engineer to control settlement within acceptable limits based on the use of the slab. Grading adequate to drain surface water away from and around the slab is important in most projects. Slabs with coatings or coverings require vapor barriers or retarders in order to limit the water vapor entering the building from the soil below the slab. A vapor barrier will keep the building drier and protect the slab coating coverings from premature deterioration. A sacrificial geotextile will help protect the vapor barrier and reduce subgrade friction and related stress during slab shrinkage or movement due to temperature change.

DETERMINATION OF SLAB THICKNESS

No single design method covers every type or use of slab, so the designer should consider the use and design criteria in order to select an appropriate method. This section outlines a typical method for thickness design, often referred to as the Portland Cement Association method (Farny, 2001), that can be used for a variety of applications (but not all). The PCA method determines slab thickness based on the modulus of rupture of the concrete without counting on any flexural strength improvement from temperature and shrinkage reinforcement. Several additional slab-on-grade design methods are outlined in the American Concrete Institute Committee 360's *Guide to Design of Slabs-on-Ground* (2010).

Determining slab thickness starts with the purpose of the slab, its use and its loads, in addition to applicable standards. MidWest Plan Service (Koenig & Runestad, 1998, 2005) has used a minimum slab thickness of 4.5 inches for various manure storage facilities, while the minimum required by the U.S. Department of Agriculture's Natural Resources Conservation Service in *Conservation Practice Standard Code 313* (NRCS, 2003) is a 5-inch thickness for applications where liquid-tightness is required, such as in floor slabs of waste storage facilities. The minimum thickness for most slabs for lightweight vehicle traffic is a minimum of 5 inches and is thicker for heavier equipment with repetitive use. A good tool for thickness design with various non-uniform loads is *Concrete Floors on Ground*, published by Portland Cement Association (Farny, 2001). This PCA method covers single- or dual-wheel loads and post loads where the slab is considered an unreinforced spread footing. PCA outlines a procedure for determining slab thickness to control flexural stresses based on the modulus of rupture (*MR*) of plain concrete.

EXAMPLE DESIGN

The following is a vehicle load example with single wheels based on the PCA method. First, a stress ratio is computed based on the number of repetitions in the case of wheel loads (or you can simply use 0.45 for unlimited repetitions). The stress determines your factor of safety (*FS*), which is simply the inverse of the stress ratio, such as 2.2 for unlimited repetitions. A joint factor (*JF*) is determined based on the joint spacing in order to ensure good aggregate interlock. With joints at 20-foot spacing or greater, the joint factor is typically taken as 1.6 unless dowels are used to transfer the load across the joint; in that case the joint factor is taken as 1.0. The allowable slab working stress (*WS*) is calculated by the formula

$$WS = MR/(FS * JF).$$

For this example,

$$WS = 640/(2.2 * 1.6) = 182 \text{ psi}$$

where *MR* is taken as 640 psi for the flexural strength of plain concrete. Then compute the allowable slab stress per 1,000-pound axle load = 182/20 = 9.1 psi for a 20 kip axle load. To determine the load contact area, you can divide the wheel load of 10,000 pounds by the inflation pressure, let's say 100 psi, giving a contact area of 100 square inches. Note that for certain smaller contact areas, the effective contact area may need to be adjusted by the design charts based on the slab thickness. You also need to know the center-to-center wheel spacing, which we will call 80 inches in this example. Using the PCA design chart starting with the slab stress to the contact area, the wheel spacing for our example problem requires a slab thickness of about 9 inches for a subgrade modulus (k) of 100 pci. For k = 50 pci typical of silts and clays with high compressibility or a California bearing ratio of 2 or less, a 9.5-inch-thick slab is needed. For larger slabs with low subgrade modulus, it may be worth adding a well-compacted granular subbase under the slab to increase the k design value.

Load contact area is one of the key factors in determining the adequacy of a proposed floor thickness. Heavier loads with small contact areas may require a footing, which many times can be a thickened slab of 8-inch thickness or more, proportioned to distribute the load sufficiently to resist the stresses, and can require additional reinforcement. The size of tires or column base plates is an important factor because size influences the distribution of the loads. Larger concentrated loads may require thicker slab designs, or a thickened slab footing may be used to control flexural stress or protect against shear failures. Further distribution of concentrated loads may be warranted in some cases such as large point loads.

SLAB REINFORCING AND JOINTS

Reinforcement for slabs varies according to the procedure used and the purpose of the reinforcement. Shrinkage and temperature stresses are the most common tensile stresses that may need reinforcement. For some slabs, frequent joints at less than 15 feet may not require reinforcement. NRCS Code 313 specifies the use of the subgrade drag theory and bases the area of steel on the subgrade friction factor, the distance between joints or free ends of the slab and the weight of the slab. The goal is to hold the shrinkage cracks together tightly and allow the movement at the free ends of the slabs. The subgrade drag formula from ACI Committee 360 (2010) and several PCA publications is

$A_s = F * L * W/2 * f_s$, where

A_s = cross-sectional area of steel in square inches per lineal foot of slab width

F = coefficient of subgrade friction (typically ranging from 0.9 for uniform sand to 2 for soil)

L = slab length (or width) between free ends in feet. A free end is any joint free to move in a horizontal plane such as with a smooth dowel. The 2 in the denominator of the equation relates to two free ends of a slab, such as a con-

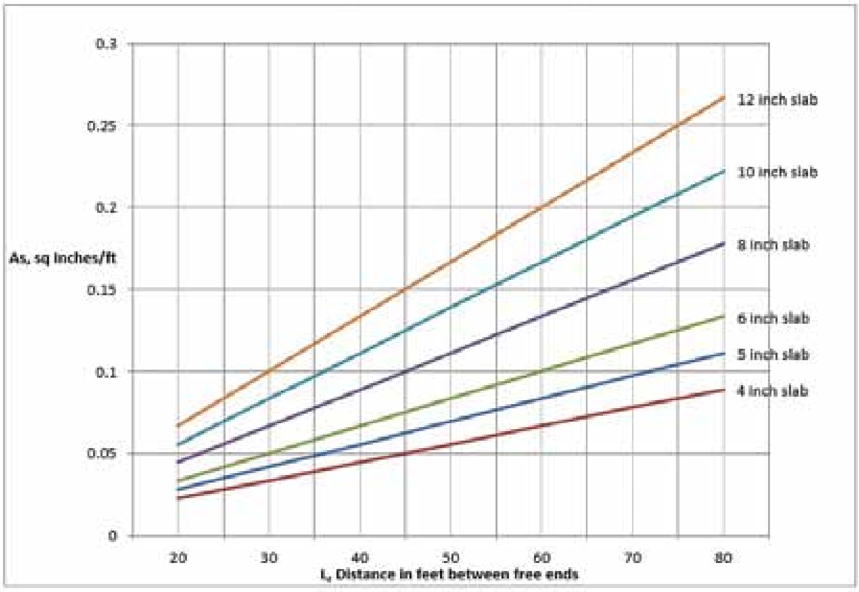

Figure 2. Joint spacing for various slab thicknesses and areas of steel

struction or control joint where the slab reinforcement is interrupted.

W = weight of slab in pounds per square foot

f_s = allowable working stress of reinforcement in pounds per square inch (psi), typically 0.67 or 0.75 times the yield strength of the steel.

Figure 2 shows the required area of steel for various slab thicknesses and various values of *L*. The chart is based on the assumption that $f_s = 45{,}000$ psi and $F = 2$.

Reinforcement for slabs is typically placed in the middle-to-upper third of the slab thickness. Flat sheets of welded wire reinforcement are typical for 4-inch and 5-inch-thick slabs where 1.5-inch cover is recommended from the top of the slab to the WWR. For 6-inch and thicker slabs, deformed bars are more typical, with a placement cover of 2 inches to the top of the slab. Support the slab steel on chairs or concrete blocks as needed to ensure proper position with the slab.

Getting free ends on large slabs requires joints. These can be control (i.e., contraction) joints or construction joints. Control joints can be sawn if this is done within a few hours after the concrete sets up, which is the same day the concrete is placed. Saw depths should be at least 0.25 times the slab thickness. Other control joints may be made with a base seal waterstop that provides a weakened location for the joint to form. The slab steel must be interrupted at the joint if a free end is desired. Smooth dowels or plate dowels can be used across the joint so as to allow horizontal movement at the joint but provide shear transfer across the joint. Shear transfer may not be needed in some cases, such as with a tank that will never see wheel loads. Some projects can use a keyway at construction joints. Use of keyways is typical with unreinforced slabs with construction or control joints spaced at less than 15 feet so that the keyway continues to provide effective shear transfer across the joint. For control-joint spacing of less than 15 feet, aggregate interlock may suffice for shear transfer, but it really depends upon the magnitude of the load and the expected slab contraction. When a joint moves more than 0.035 inches, aggregate interlock effectiveness decreases.

If joints are not desired or are not allowed by the project owner, use of a larger area of steel is required for larger slabs where the distance between free ends is too long. Adding a subbase such as compacted sand, which has a lower subgrade friction factor, will also help. In some projects the control of cracking may not be important, and joints may not be needed.

Waterstops are needed for waste containment and in similar structures where having a watertight structure is necessary. Waterstops should be properly selected for the type of joint and material to be contained (see **Figure 3** and **Figure 4**). Some waterstops are not to be used in moving joints. See the manufacturer's specifications for details.

SLAB CURING

Curing slabs properly is just as important as curing other concrete members, but in many ways it is more important because slabs are generally thinner members. Use of curing compound or coverings such as polyethylene sheeting, burlap or sprinklers is critical, especially for the first several days. As concrete cures, the energy released is tremendous, and much of this energy results in the evaporation of water from the concrete surface, water that is needed for proper hydration and hence curing of the concrete. The rate of concrete curing varies greatly with the temperature. Concrete continues to cure for several months and even longer if it has to cure during cold weather. It's interesting to note that when this moisture is released into a poorly ventilated space, it has the potential to create condensation problems for customers and contractors alike. Remember that condensation is a symptom of a larger problem that will need to be addressed.

Figure 3. Reinforced slab preparation with waterstops at control joints

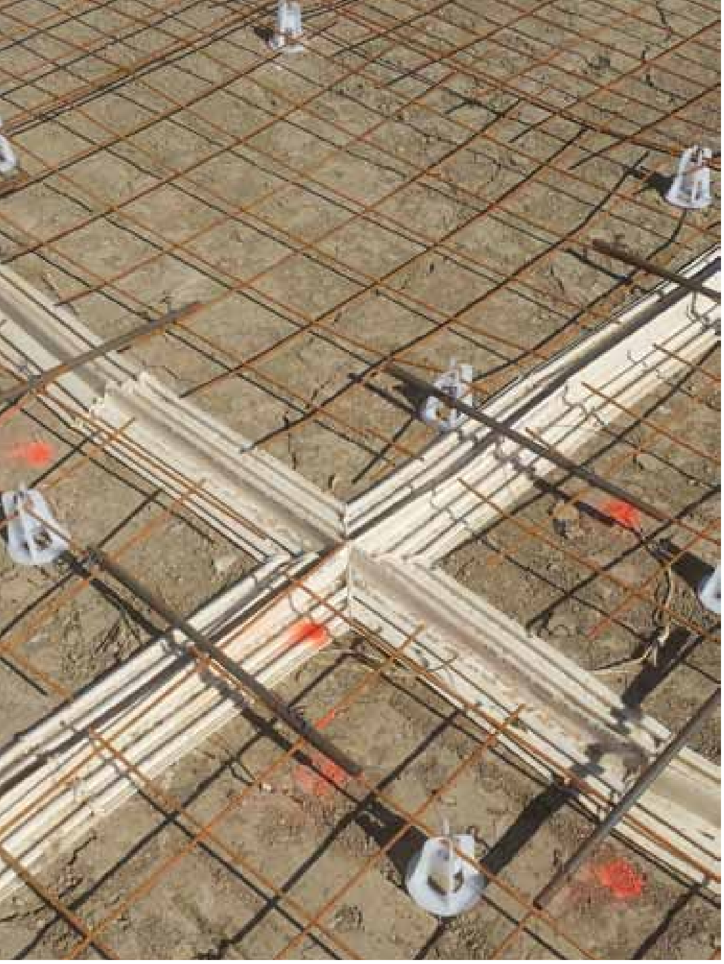

Figure 4. Control-joint intersection using a base seal waterstop and smooth dowels with slab steel interrupted

EDGE CONDITIONS

Where slabs on grade are employed in post-frame buildings, edge conditions vary significantly. For buildings that are set on a properly designed and insulated continuous foundation, the builder does not need to consider the potentially detrimental aspects of having frost get underneath the slab. Bearing the edge of the slab on the foundation may create its own set of issues because that slab now has two sets of bearing conditions. This may lead to cracking around the perimeter of the floor area where the supporting stiffness for the slab varies.

More common in post-frame applications is to have the posts set in the ground and the edge of the slab just "floating" around the perimeter. Frost conditions must also be considered here to prevent undue movement of the slab. The most common practice of insulating the perimeter of a slab is to cover the edge with rigid insulation behind the skirt plank and then lay down the same rigid material underneath the slab for a given distance. Frost may still get under the slab and cause some movement. A surer way of preventing frost from getting under the slab is to use a design from the American Society of Civil Engineers, the *Design and Construction of Frost-Protected Shallow Foundations* (ASCE, 2001).

Generally, it is *not* advisable to physically attach the slab on grade to the building columns. In fact, it is best to provide an expansion joint around the columns so that if the slab moves, the building isn't forced to move in concert with it or vice versa. Often, concrete contractors do not make the effort to provide a bond-break between the edge of the concrete and the skirt-boards or columns, and the fact that the concrete shrinks a bit during the curing process is enough to provide a break in the bond between the concrete and the wood.

SLAB INSULATION

Many theories exist regarding the proper use of insulation in and around a slab on grade. We do not cover that topic in this article, but we do note two points:

- Thermal bridging around the perimeter of a slab is a real phenomenon that the design professional needs to attend to.
- In-floor radiant heating system installers have different theories regarding the amounts and types of insulation that should be used for the best performance of their system.

CONCLUSIONS

The design of a slab on grade—seemingly a simple feature in a building—takes considerable thought and careful attention if the slab is to perform well during the life of the structure.

- The designer and project owner must work together to determine the purpose of the slab, the intended use and important design considerations so that the designer can adequately specify the criteria for obtaining the appropriate slab-on-grade design.
- Evaluating the subgrade and specifying adequate subgrade preparation are important for good long-term slab-on-grade performance.
- Most slabs require the use of control or construction joints to control stresses and cracking. The use of reinforcing steel in the slab will help control cracking and hold tightly together the cracks that do form.
- Engaging the services of a qualified professional engineer will help to ensure that all the appropriate variables and conditions are considered. FBN

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