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Concrete Slabs-on-Grade:
Warehouses III
High Performance Slabs

by

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Course 416
4 PDH (4 Hours)

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Concrete Slabs-on-Grade: Warehouses III - High Performance Slabs

Course Outline:

Introduction

High Performance Slabs

Topic #1 – Shrinkage Compensating Concrete Slabs

Topic #2 – Slabs with fibers:

a) Synthetic fibers (Macrofiber)

b) Steel fibers

Topic #3 – Slabs designed with continuous reinforcing

Topic #4 – Post-tensioned slabs-on-grade

Topic #5 – Cold Storage Warehouses

Topic #6 –Automated Racking Systems

Topic #7 – Superflat Floors

References

Examination

Fig. 1 - Computer rendering and progress photo of a refrigerated food warehouse

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Note prior to beginning the course:
This course is a continuation of the first two warehouse courses, which are:
Concrete Slabs-on-Grade: Warehouses I – Background & Loading and
Concrete Slabs-on-Grade: Warehouses II – Slab Design

Introduction

Prior courses address common slab behavior and design methods. Normal loading and temperature conditions were generally assumed. This course aims to expand on that knowledge by exploring more specialized design methods, loading and temperature extremes, and more strict design criteria such as flatness. Time-tested slab design innovations used to mitigate issues with slabs will be presented. Situations where warehouse floors will be subjected to high demand loading and extreme low temperature conditions will be studied. Building slabs that require unusual flatness and levelness are examined.

There are many instances in this course where slab-on-grade and concrete behavior is noted. Most of this information can be found in previous courses on slabs, where access to the knowledge is assumed, and can always be found in a review of the text of those courses. If the information is new, of course, it is explained in the present course. However, most of the topics covered here are done so with a broad brush. There is much more knowledge for the reader to uncover and understand independently before the use of these specialty slabs.
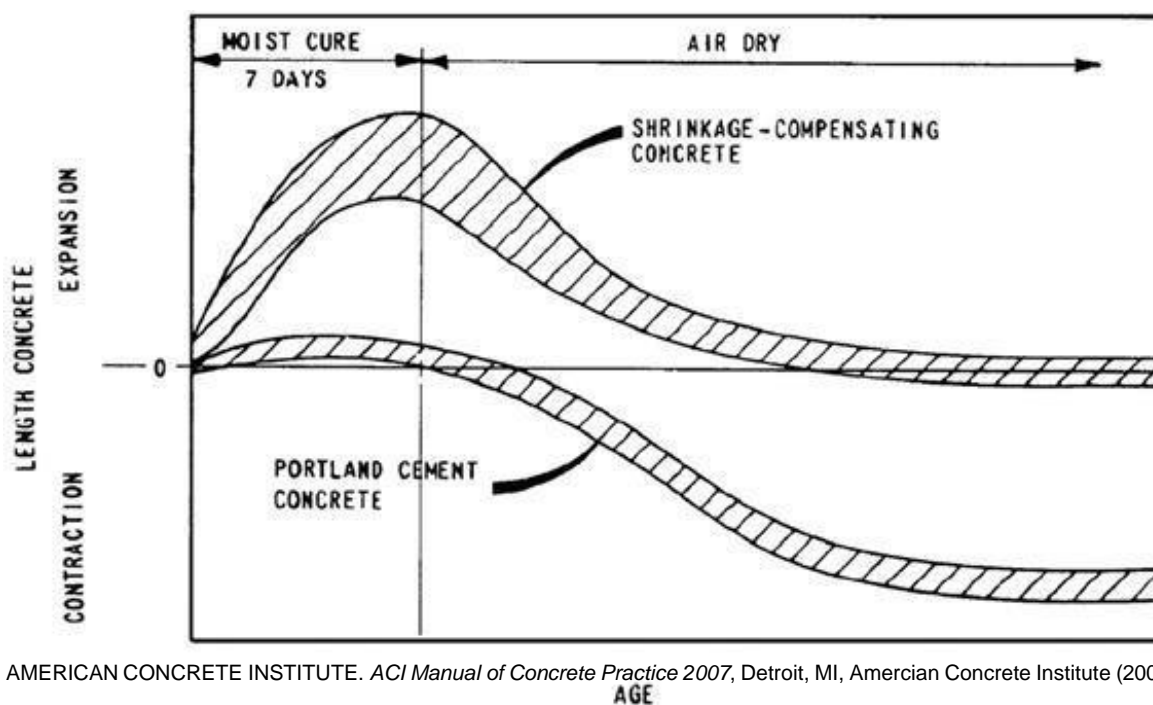
High Performance Slabs

The main issues with warehouse slabs-on-grade are slab curling and cracking, and general degradation of slab joints. By limiting the number of joints, and decreasing the amount of meaningful cracking and curling, the owner will have less maintenance and operational headaches to address for the life of the facility. Over the years, there are many reliable slab construction methods that have been developed to eliminate the number of slab joints and reduce the common durability issues with slabs. Some of the common ones are described below, as well as some other specialty areas that an engineer might run into in at some point in their career.

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1) High Performance Slab Topic #1
Shrinkage Compensating Concrete

Normally, an increase in cement content in a concrete mix will lead to increased shrinkage of concrete slabs. However, **some cements actually promote the expansion of concrete. These cements, Type K, M, or S, are used in shrinkage compensating concrete, or shrink-comp concrete**. When included in a concrete mix, and when restrained by ground friction and embedded reinforcing, the tendency of these cements to expand puts the concrete in a state of compression before the onset of drying shrinkage. When a sufficient portion of expansive cement is used in a concrete mix, shrinkage concerns can be eliminated. As shown in Fig. 2, the expansion generally occurs in the first seven days. Fig. 3 shows the "basic concept".

AMERICAN CONCRETE INSTITUTE. *ACI Manual of Concrete Practice 2007*, Detroit, MI, Amercian Concrete Institute (2007).

Fig. 2, Expansion behavior of shrink comp concrete with age (ACI 223)

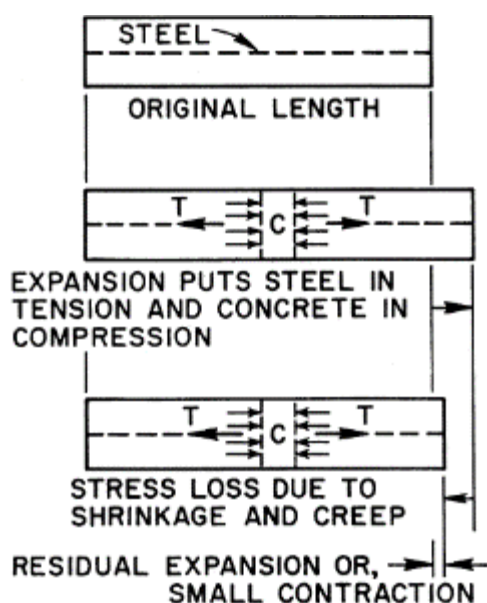Concrete Slabs-on-Grade: Warehouses III - High Performance Slabs

Fig. 3.10—Basic concept of shrinkage-compensating concrete.

Fig. 3, Concept of shrink comp concrete expansion and shrinkage (ACI 224) Expansive cements are used as replacement of ASTM C150 portland cement in quantities that are determined through testing. Sulfates in the cement are required in carefully calibrated amounts to allow for **the formation of ettringite, which is a mineral produced to cause expansion**. Like the process involved in normal portland cement, the formation of ettringite only occurs in the manner desired under the right conditions, with sufficient water and the right blend of cements, happening at the right time, where concrete has set enough to expand against itself, and without the expansive cement being used up early in the curing while the concrete is plastic. Expansive cement includes its consituent compounds SO_3 and Al_2O_3, which are essential for expansion. These are available only in measured and predictable amounts necessary for adequate ettringite formation. Overmixing may cause a significant portion of ettringite to be activated too early before it can be placed, and the concrete needs to expand when it is intended, which is when the concrete is in place, is passing beyond the plastic stage, and into the curing stage.

The other ingredients in shrink comp concrete are similar to those found in normal mixes with portland cement. However, the specialty contractor in charge of the shrink comp concrete is expertly informed about the optimal ingredients for the mix, and knows what will be detrimental to the mix or cause uncertainty in performance.

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In practice, past experience and best practices dictate many prescriptive measures to promote effective use of shrink comp concrete. ACI 223 explains these in greater detail, but they are summarized here. Also, the use of shrink comp concrete in other applications (structural slabs) merits consideration, but the discussion here will focus on slabs on grade. See Figs. 4a & 4b.

Figs. 4a & 4b, Shrink comp concrete pour and fininshed slab

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Shrinkage compensating concrete will expand during the initial cure. If no special preparations are made and the slab is unreinforced, ground friction would restrain the growth, but not in a predictable manner. Upon subsequent shrinkage, the concrete would shrink as it normally does, with potentially the same shrinkage issues on a mass of concrete that is merely larger in volume (due to joints spaced further). The key to effectively leveraging the expansive nature of shrink comp concrete is to restrain the concrete with reinforcing as it cures and expands. Reinforcing bonds to the concrete paste in the slab at its surface deformations, and tends to stretch in tension when the concrete expands, while the response of the concrete to this restraint is to go into a simultaneous state of compression. When the concrete undergoes subsequent drying shrinkage, the reinforcing will relax, the compression in the concrete will decrease, and ideally the slab will experience no net shrinkage under static temperatures. **When the amount of expansion equals or exceeds the amount of drying shrinkage, this is known as full shrinkage compensation.**

The amount of reinforcing and its location within the slab are important considerations. ACI 223 has recommendations for estimating reinforcing amounts See Fig 5. One of the examples from ACI 223, Appendix A1, notes point A in Fig. 5 This relates to a 6-inch thick slab with 0.15% reinforcing drying from one face only. If values of shrinkage for a mix are not known, the radial lines in Fig. 5 can be used to determine a lower bound for restrained prism expansion (by ASTM C878 lab testing, see below) required for full shrinkage compensation. So, enter the figure at V/SA = 6.0 inches and ρ = 0.15%, Point A. Note that the ratio V/SA will have units of inches. This gives a lower bound of restrained prism expansion of 0.0305%, a value that could be used as a guide for thr proposed slab for working with shrink comp suppliers.

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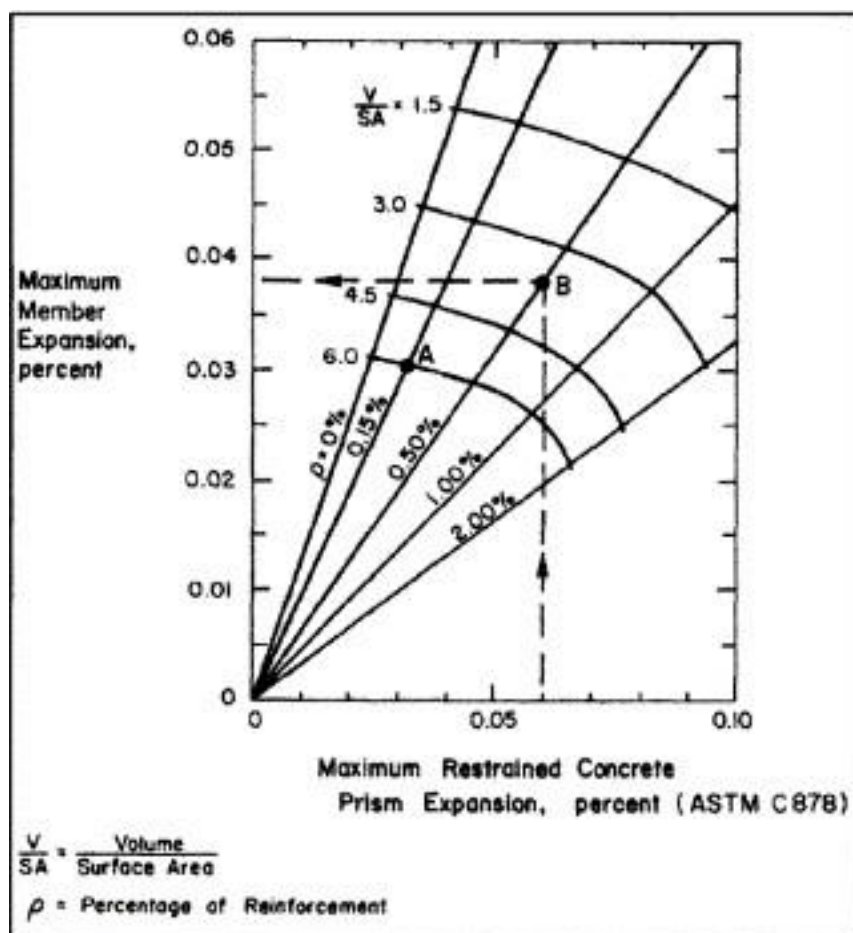

Fig. A.1—Slab expansion versus concrete prism expansion.

Fig. 5, Shrink comp slab expansion (ACI 223); **NOTE: The ratio V/SA will have units of INCHES**

ASTM C878 is the test used to establish the expansive characteristics of a shrink comp concrete mix. This test must be conducted well in advance of concrete placement, with ample time for review by the engineer and architect of record. The expected expansion of the concrete mix needs to be greater than the expected long term shrinkage. Typically, restrained expansion test results are measured at 1, 3, 7, and 28 days. The magnitude of both expansion and shrinkage can be estimated based on these lab tests. A range of values for expansion is generally targeted to cover for marginally controlled variables. ACI 223 recommends that concrete mixes in general should be in range of 0.03% to 0.10% expansion when measured by ASTM C878.

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Generally speaking, the amount of cement in shrink comp mixes should be similar to that for mixes with Portland cement alone. However, due to the early formation of ettringite, and the water consumed in the process, an increase in water content (about 10% per ACI 223) should be expected. At the point of placement, if distances from the concrete batch plant to the job site dictate a long mix and delivery time, the early activation of ettringite may result in loss of slump due to stiffening. Added water and plasticizers may be suggested, but care should be taken not to disturb the predicted expansive process of the concrete and its timing. Any admixtures desired should be included in the mix that receives ASTM C878 testing to understand any impact on volume changes and timing.

Once the lab testing is complete, guidance on reinforcing from ACI 223 can be used. The default minimum reinforcement ratio for slabs-on-grade is 0.0015, or a 0.15% ratio of steel reinforcing area to gross concrete area. This amounts to roughly #4@16"oc in an 8" slab or #4@22"oc in a 6" slab. This amount can be decreased if the shrinkage values are low enough, and if the procedures of ACI 223, Section 3.2.3 are used. ACI 223 reports that the use of shrink comp cements in concrete slabs that have significant reinforcing (more than the minimums) are certainly effective, but that effectiveness diminshes as the reinforcing ratio proportionally increases.

Reinforcing should be chaired or placed on concrete blocks. ACI 223 and ACI 360 recommended placement in the upper half, and preferably 1/3 of the depth of slab from the top. If used, welded wire fabric should not be of the rolled variety, but should arrive on site in flat sheets. The performance of the reinforcing is much more critical than that of shrinkage and temperature steel, so proper reinforcing laps should be used. Minor deviations from the overall plan can result in cracks that an owner paid additional money to avoid.

If the concrete slab is truly shrinkage compensated, there will be no net shrinkage in concrete volume from time of placement. **This means that the normal use of control joints to introduce controlled straightline cracks to relieve tension is no longer necessary.** Construction joints are the only joints required, so the spacing of joints that an owner is required to maintain is increased much more. The author was the engineer of record on a project where areas up to 115'-0"x106'-0" were poured joint-free. The main benefit of expansive cement in slab design is the addition of compression to the tension forces due to bending in slabs. Over-simplfying this within a portion of the

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slab, we can write the basic equation for stress due to bending and axial load on a section:

$$f = \frac{M}{S} + \frac{P}{A}$$

f = normal stress
M = Bending moment in slab
S = Section modulus of the slab cross section
P = Normal force
A = Cross-sectional area of slab

Tensile stresses will control the choice of slab thickness for slabs.The more the tensile stresses can be controlled, the thinner the slab can be. Whereas normal slabs undergo both tension due to bending and tension due to drying shrinkage, a shrink comp slab is designed so the tension due to drying shrinkage is negated.

Shrink comp concrete is especially effective in slabs on grade in industrial applications where hard–wheeled lift traffic is used, and where the elimination of joints and shrinkage cracking is very desirable. Also, slab design for pallet racking is simplified. By designing the sparse joints to handle larger loads (foregoing discussion on armored joints), joints can by and large be ignored in slab design.

Besides giving owners an extremely low maintenance floor slab, the owner will have a more efficiently designed slab section because:
a) shrinkage and curling stresses do not need to be considered (the final cured slab ends up as just as flat as it was initially poured and finished),
b) joint design does not need to be considered, and
c) there may be a residual compression stress in the unloaded condition.

For example, in the PCA methods of design (chapter 5 of Tarr(2008)), a joint factor of 1.1 to 1.6 is normally used when determining allowable stresses. This is effectively a factor of safety to cover for the effects of shrinkage. If the joint factor is reduced to 1.0, it will often allow for a thinner slab to be selected. Here it is assumed that the slab is not relying on steel reinforcing for the strength of a slab. The heavier and more concentrated the design loads, the more benefit that shrink comp concrete can have on the choice of slab thickness.

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Armored assemblies are recommended at the construction joints, complete with 3/8"x2" continuous plates and load transfer dowels. (See Fig. 6) The combination of large joint spacing and joint treatment will limit the number of future repairs. This is especially desirable if the facility has low operating temperatures, where repairs are more difficult due to freezing conditions.
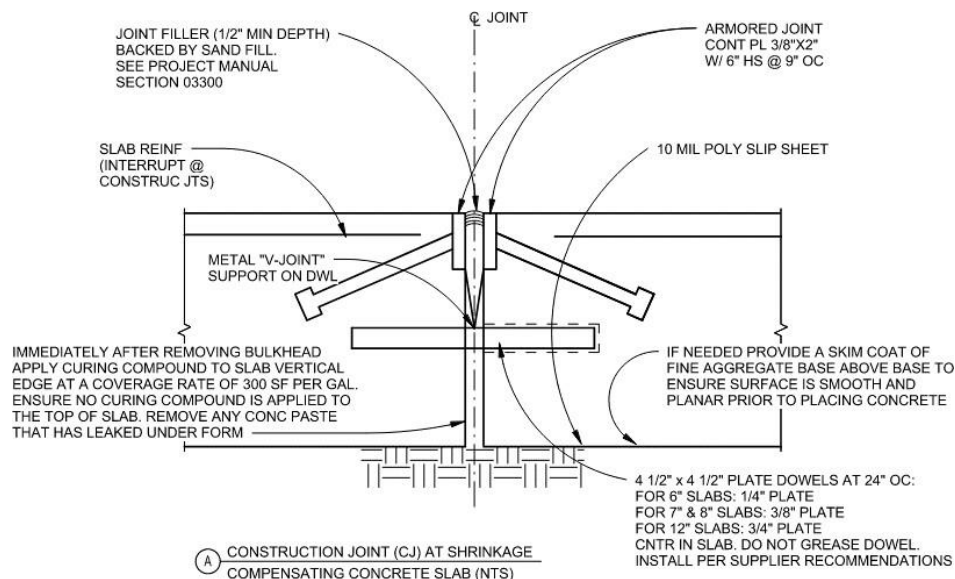

Fig. 6, Armored Joint

Approaches for ground preparation for shrink comp slabs seem to vary. ACI 223 recommends a wetted gravel base, or a minimum 2"-3" wetted gravel base on top of a vapor barrier if a vapor barrier is required. The thought is that more uniform moisture loss occurs from the volume of concrete than that which occurs with a vapor barrier directly below. Many shrink comp suppliers pour directly on a vapor barrier or two sheets of 6 mil polyethylene sheeting (poly) to allow any movement to occur in a manner as predictable as possible while eliminating some of the frictional restraint (in an inexpensive manner). It is best to let suppliers dictate this, but in the author's experience, the use of poly has yielded excellent results.

In general, is extremely important to allow the slab to move while curing. Placement methods per ACI 223 should be followed to allow the slab to expand towards a free edge in both directions. So, individual pours must not be poured against existing opposing restraining slab areas (no checkerboard placements). See Fig 7.

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Fig. 3.4.8(a)—Center adjacent slab placement pattern.   *Fig. 3.4.8(b)—Center rotation slab placement pattern.*

Fig. 3.4.8(c)—Lag slab placement pattern.

Fig. 7, Slab placement patterns for shrink comp concrete (ACI 223)

Also, isolation joints at locations of potential restraint are necessary. This is to make the slab itself behave predictably, promoting the development of tensile forces in the reinforcing, and to protect restraining elements from being disturbed or damaged from expansion forces that can be quite large. For example, columns located in the middle of a pour should be isolated from the slab to allow for contraction without pulling against the column. See Figs. 8a & 8b (joints, etc.). Other detailing is noted in Figs. 9 through 11.

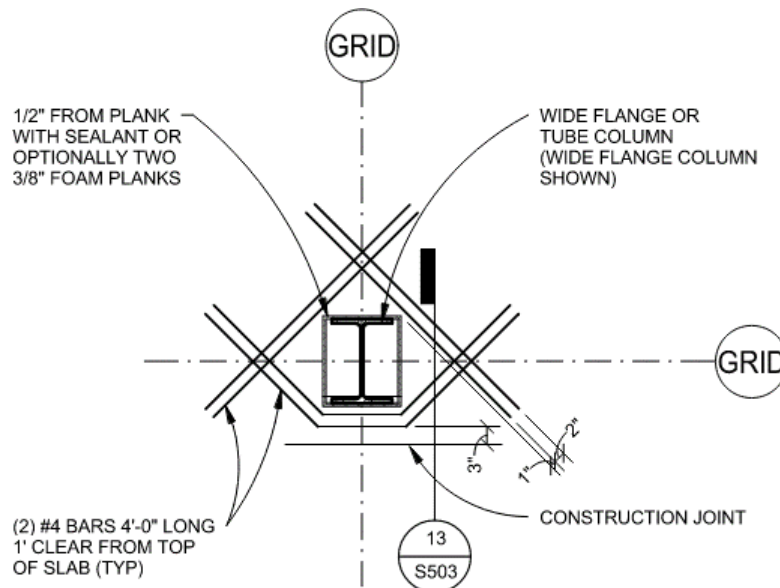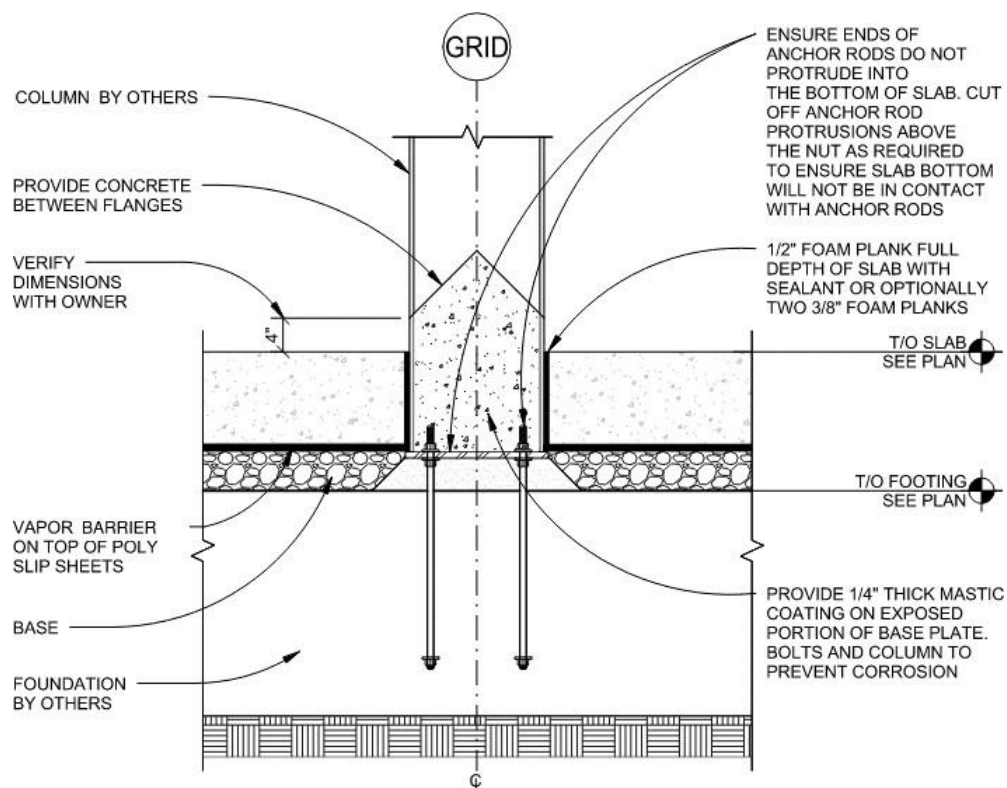Concrete Slabs-on-Grade: Warehouses III - High Performance Slabs

1/2" FROM PLANK WITH SEALANT OR OPTIONALLY TWO 3/8" FOAM PLANKS

WIDE FLANGE OR TUBE COLUMN (WIDE FLANGE COLUMN SHOWN)

GRID

GRID

CONSTRUCTION JOINT

(2) #4 BARS 4'-0" LONG 1' CLEAR FROM TOP OF SLAB (TYP)

13 / S503

2"

3"

1"

Fig. 8a, Plan view at column

GRID

COLUMN BY OTHERS

ENSURE ENDS OF ANCHOR RODS DO NOT PROTRUDE INTO THE BOTTOM OF SLAB. CUT OFF ANCHOR ROD PROTRUSIONS ABOVE THE NUT AS REQUIRED TO ENSURE SLAB BOTTOM WILL NOT BE IN CONTACT WITH ANCHOR RODS

PROVIDE CONCRETE BETWEEN FLANGES

VERIFY DIMENSIONS WITH OWNER

1/2" FOAM PLANK FULL DEPTH OF SLAB WITH SEALANT OR OPTIONALLY TWO 3/8" FOAM PLANKS

4"

T/O SLAB SEE PLAN

T/O FOOTING SEE PLAN

VAPOR BARRIER ON TOP OF POLY SLIP SHEETS

PROVIDE 1/4" THICK MASTIC COATING ON EXPOSED PORTION OF BASE PLATE. BOLTS AND COLUMN TO PREVENT CORROSION

BASE

FOUNDATION BY OTHERS

Fig. 8b, Section at column

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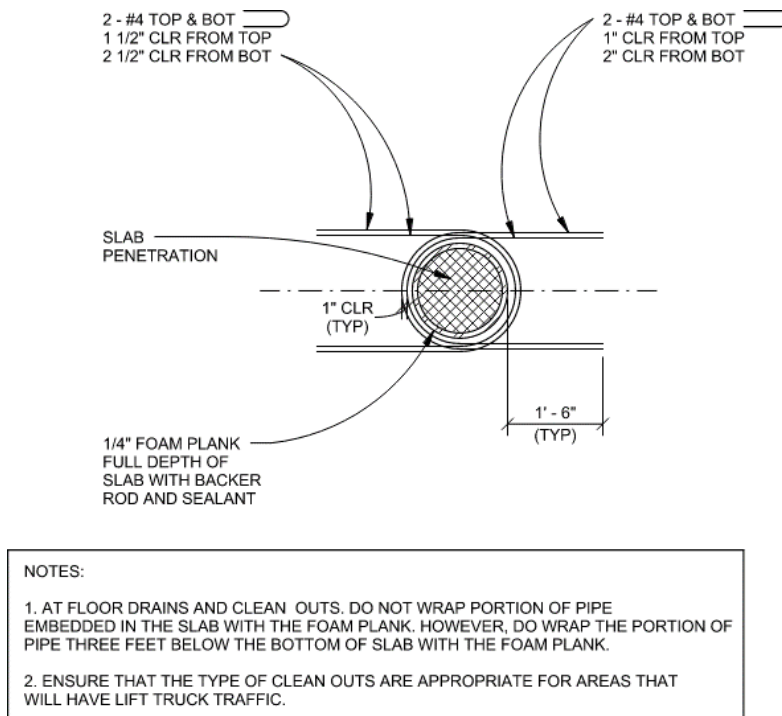
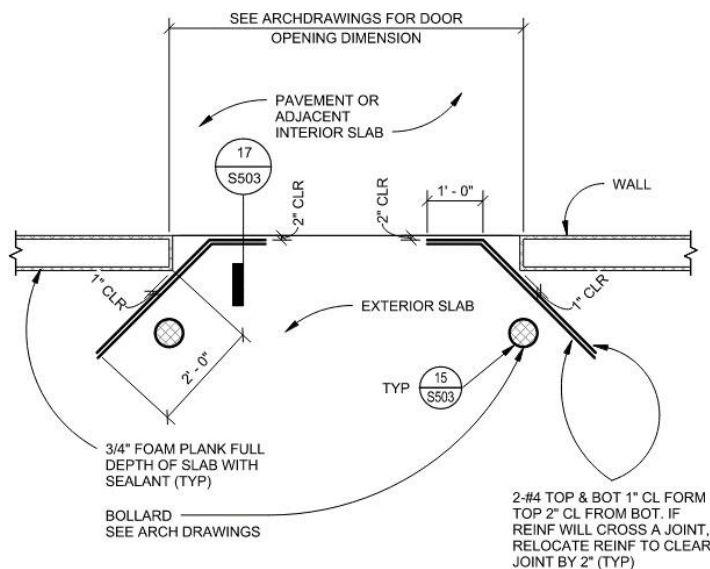
Fig. 9, Bollard detail

Fig. 10, Detail at opening

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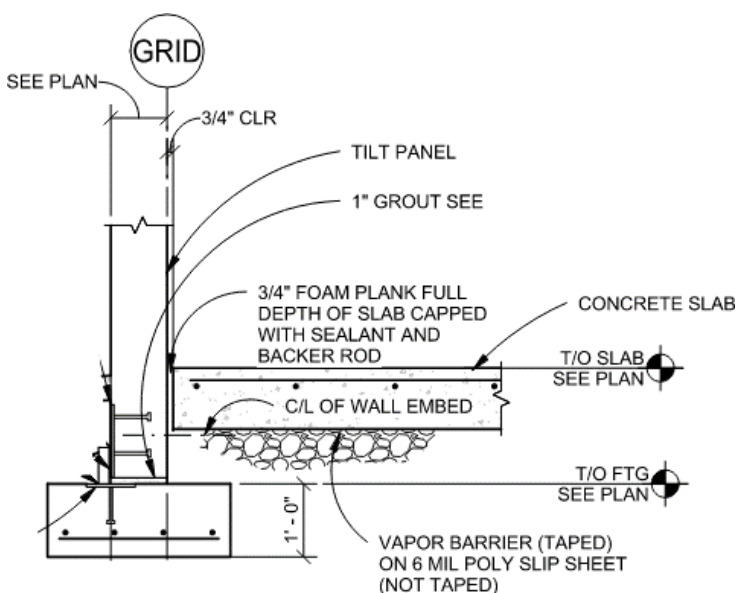

Fig. 11, Section at exterior wall

To test for the expansion of the concrete when placed, various methods may be used. However, a simple method called a jar test is used by some contractors. Fresh concrete samples are drawn from the mix as it is being placed and put in standard one-quart mason or atlas jars to an inch from the top of the jar. The jar is shaken to eliminate voids, then allowed to reach its intitial. Water is filled even with the rim by submerging the jar in a tub, and two lids are used when sealed. If the concrete in the jar expands like it should, it will break the glass jar in a predictable time window, and the test is a success.

The construction of shrinkage compensating concrete slabs is generally performed by specialty contractors. A contractor with significant experience and skills is necessary to dial in the precise components in the concrete mix, ensure conditions are sufficient for success, and execute the steps necessary for proper placement, finishing, curing, and overall attention to detail. This is very beneficial to an owner that may have little tolerance for poorly performing slabs, or who is new to warehouse construction. Often, shrink comp slabs come with a warranty against undue cracking, so the specialty contractor has incentives to ensure success. In the end, the owner and its operations and maintenance teams have an advocate for the finished product that is just as concerned about its performance as they are, and that contractor generally has the expertise to deliver. With the use of a specialty contractor, the burden

of the designing engineer or architect to deliver a high perfomance slab is significantly decreased.

Because of the enchanced durability of shrink comp concrete, a long maintenance-free life can be expected. Thus, it is also deisrable to use a surface treatment that will also stand the test of time. Often, a monolithic traprock densified topping or dry shake hardener will be blended into the finished surface of slab. Traprock is a flaky rock coated with cement that is applied during finishing, and can be placed with a spreading machine. Some legacy shrink comp companies such as Fricks will broadcast traprock over the slab surface uniformly with manual methods. However, this takes skills developed with care and experience.

2) **High Performance Slab Topic #2:**
Slabs with fibers:
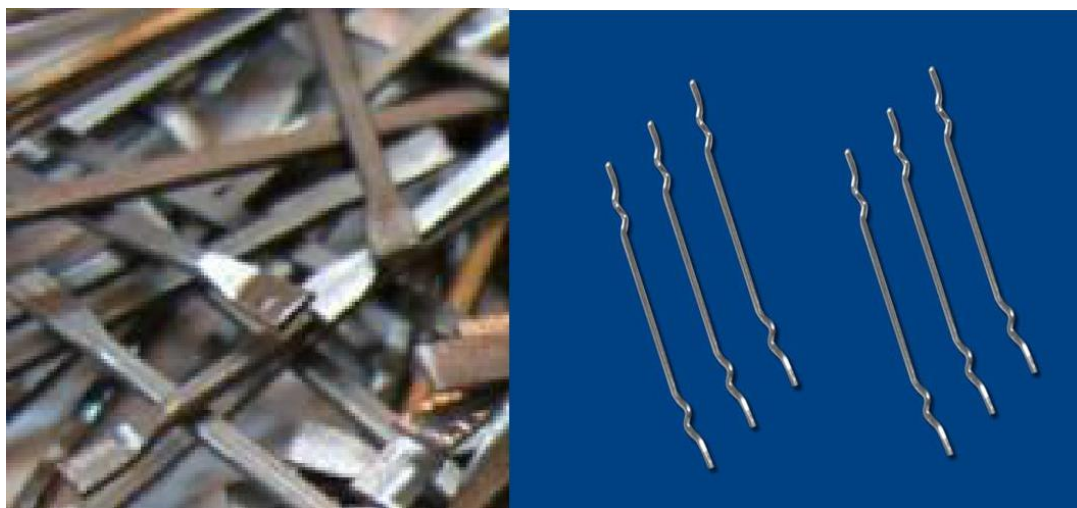## a) **Synthetic fibers (Macrofibers)**
b) **Steel fibers**

The use of fibers in slabs-on-grade was discussed in "Concrete Slabs-on-Grade: From the Ground Up", page 46. **Fibers allow for enhanced post-crack residual strength of the slab.** In other words, if the slab cracks, the cracks remain small enough, and the tensile stresses do not exceed the limits of the fibers, the slab has a way to stay in tension across a crack. Fibers that exhibit ductility, or the ability to stretch, can lend themselves to the use of yield line analyses (see notes on TR34 and ACI 360 below). Impact and fatigue resistance, as well as shrinkage and curling reduction, are common enhancements that depend on the type and dosage of fibers (See Figs. 12a, 12b & 13). ACI 544 is an excellent reference for information on fibers in concrete. Specific strategies depend highly on the behavior of the fibers in concrete slab, and the suppliers should set expectations based on proven performance in tests.

Three additional resources for use in designing slabs with fibers:
1. ACI 360,
2. Tarr: "PCA: Concrete Floors on Ground", 4th Ed or later,
3. TR34 from the British Concrete Society

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https://commons.wikimedia.org/wiki/File:%D0%9F%D0%BB%D1%8E%D1%89%D0%B5%D0%BD%D0%BD%D0%B0%D1%8F.jpg; Iamcasinoroyal, Public domain, via Wikimedia Commons

Fig. 12a, Steel fibers

https://commons.wikimedia.org/wiki/File:Stainless_steel_fiber.jpg; Zs871124, CC BY-SA 3.0 <https://creativecommons.org/licenses/by-sa/3.0>, via Wikimedia Commons

Fig. 12b, Steel fibers

https://www.euclidchemical.com/products/concrete-fibers/synthetic-macrofibers/

Fig. 13, Synthetic fibers – Macrofibers – TufStrand from Euclid

Fig. 14 shows typical concrete beam behavior in bending for applied load versus deflection for beams with increasing amounts of fiber reinforcing. Unreinforced beams have little or no strength after cracking. Beams with a higher amount of fibers have greater strength after initial cracking. This is the post-crack residual strength noted above. Generally, amounts of fiber reinforcing that are used in concrete slabs are limited by up front costs and amounts that allow for sufficient workability of the wet concrete. The lower curve shown below for fiber-reinforced concrete is more typical for practical amounts of fiber. This type of curve would represent a fiber-reinforced concrete

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design that provides enhanced crack control, and is the typical range used for slabs-on-grade. To obtain load deflection curves, tests such as ASTM C1609 are used. See Fig. 15.

Dosage is the weight of fibers per cubic yard of concrete that is uniformly mixed into the concrete. **Typical fiber dosages are as follows for crack control of concrete:**
Synthetic fibers: 3.0 to 7.5 lbs / cu. yd.
Steel fibers: 33 to 125 lbs / cu. yd.
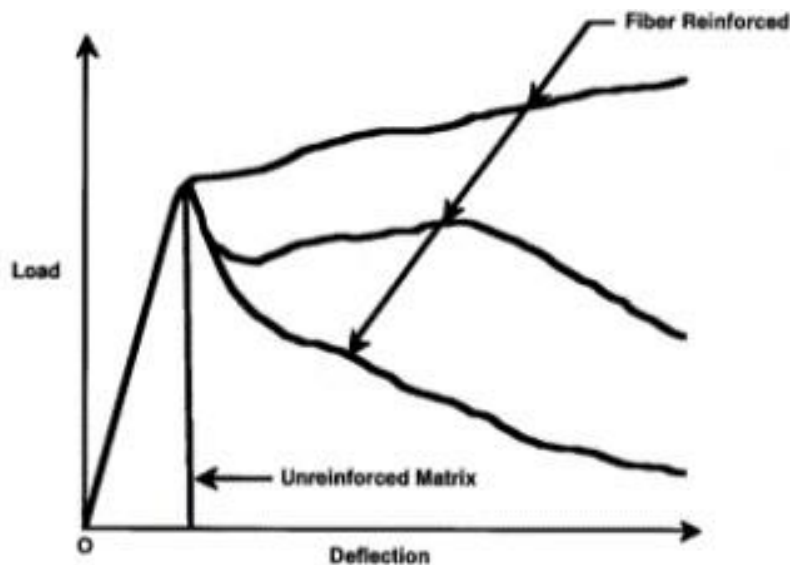
Fig. 1.1—Range of load versus deflection curves for unrein-forced matrix and fiber reinforced concrete

Fig. 14, Load vs. deflection for increasing fiber amounts

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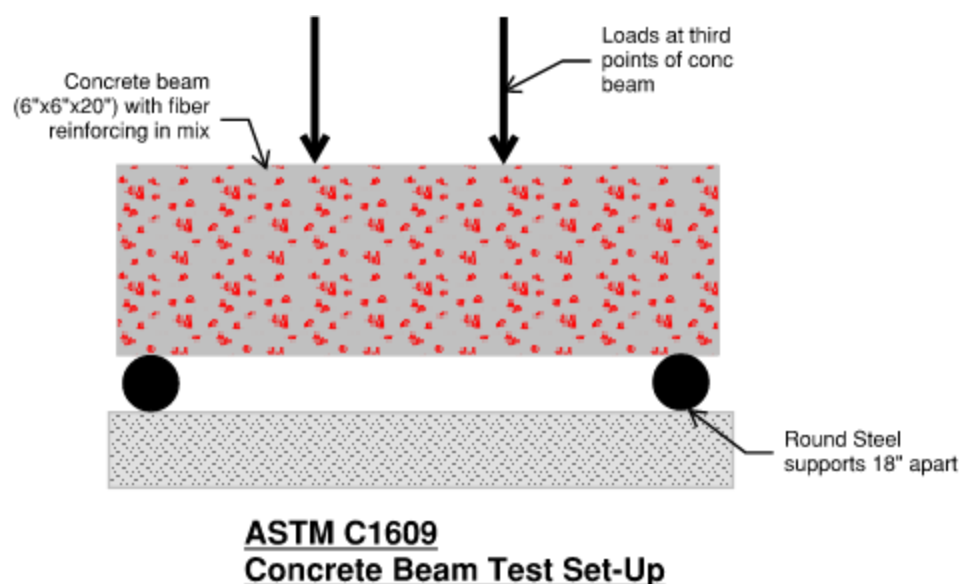
Fig. 15, Beam bending test

An engineer opting for a slab-on-grade strategy that includes the use of fibers will need to lean heavily on the fiber suppliers for information. The performance of the slab will be correlated to the past experience of slabs with specific fibers in them. Questions that an engineer at their desk might be asking fiber suppliers include:

1. What performance data is available related to flexural strength, and are your fibers suitable for use with the design equations in ACI 360 and TR34?

In particular, post-crack residual strength. More specifically, residual strength factor, $R_{e,3}$ per JSCE SF4 and in reference to ACI 360R-06, Chapter 10, as well as Appendix 6, page 73. **If ductility is sufficient, yield line theory (and related equations) would be an advantage in strength checks per those ACI 360 references.** See also TR34, Chapter 9, for alternate equations for yield line theory. This is presented on page 26 of the SunCam course "Concrete Slabs-on-Grade: Warehouses II – Slab Design."

2. What are the recommendations for joint spacing and joint construction (control and construction joints)? Can you spread control joints out? Do you have as-built facilities that can be visited to demonstrate this?

3. How is shrinkage and curling of a concrete slab improved, and how specifically can this be used in design?

4. Do you get improved fatigue performance at joints subject to lift traffic, and how would this improve results from PCA charts for fatigue loading (Chapter 5 of that PCA document)?

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Some suppliers offer recommendations for the use of their fibers. Euclid, for example, has literature available proposing ways to quantify the dosage of fibers in a concrete mix for a slab on grade. The two strategies shown below are common among suppliers.

A. Fibers to enhance crack control
Replace steel reinforcing (rebar) with macrofiber of equivalent performance:
As slabs shrink, they are restrained by friction, which can create tensile stresses. One strategy is to provide reinforcing to handle this tension. It should be noted that ACI Committee 360 has stopped promoting this strategy because curling stresses often far exceed shrinkage stresses due to friction, so results were mixed if friction alone was the focus. In any case, the strategy is to find the area of steel to resist frictional resistance within a sawcut panel, per Tarr(2008):

$$A_s = \frac{LC_f wh}{Kf_s}$$

A_s = area of steel reinforcing for unit width, in^2/ft
C_f =Coefficient of friction with subgrade, say 1.5 for SOG's
w = unit weight of concrete, pcf
h = slab thickness, in
L = Length between control joints, ft
K = 24, conversion factor ft to in and halfing distance to center of mass
f_s = allowable stress in reinforcing, psi, 40,000 psi for 60 ksi steel

Next step: Work with fiber supplier using data from testing to establish amount of fiber required to replace force being resisted by steel reinforcing.

B. Fibers to provide moment strength for bending moments in slab-on-grade:
NOTE: Loading for slab-on-grade in this case would be non-building loads. If building loads were being resisted, ACI 318 would need to be used, and steel reinforcing would be required.
Find bending moments to be resisted in slab on a per foot basis using one of the methods mentioned in previous courses.

Next step: Work with fiber supplier using data from testing to establish amount of fiber required to handle bending stresses. Note that the fiber supplier will have an idea of the concrete stress block that they need to convey. It will look something like the following

Fig. 16 due to the fiber being distributed uniformly in the slab, with uniform post-crack stress with depth at failure for simplicity.

Section through cracked slab

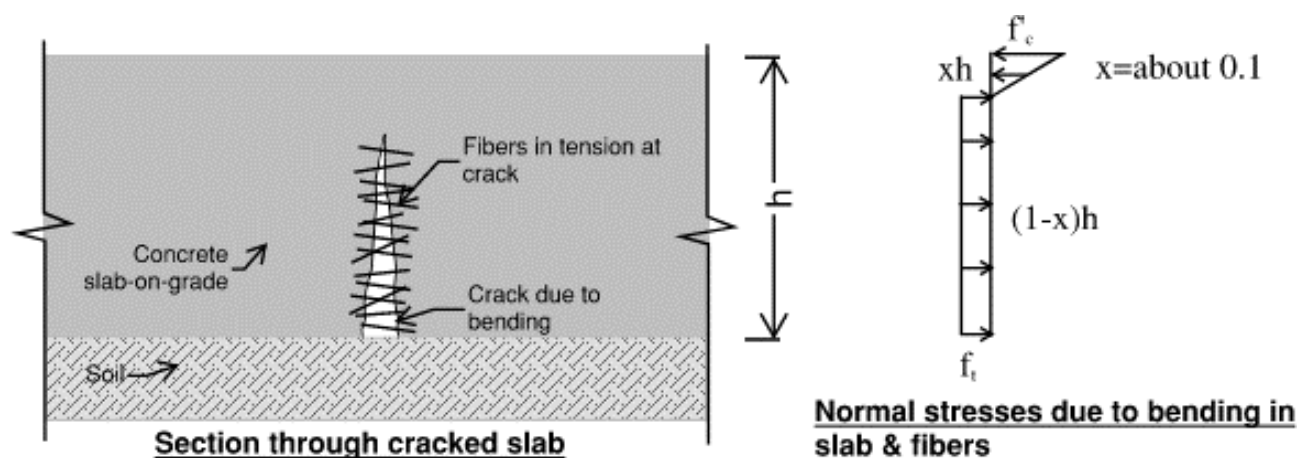**Normal stresses due to bending in slab & fibers**

Fig. 16 (Bonakdar and Mahoney)

The qualitiative benefits of steel fibers and macrofibers for concrete slabs vary with suppliers and types. **For example, macrofibers appear to induce microcracks that are not visible to the naked eye that are spread out over the area of slab, relieving stresses more often, and reducing the chances of random cracking.** Again, the macrofibers provide measurable residual strength at smaller sized cracks.

Fibers add initial cost to a slab. However, costs should be explored further. If control joints can be spread out, as many suppliers will recommend, a long-term life cycle cost study can be conducted. Often, when reduced joints and long-term maintenance costs are studied, a fiber-reinforced slab can be less expensive in the long run.

Fiber suppliers should be communicating learnings and also debunking myths with both the design team and construction team. For example, mixes might have less slump when tested, but workability might be similar when the concrete is pushed around. Also, a discussion should be conducted on final finished appearance. A general concern is that fibers will be unsightly and sit proud of the surface, but burnished, steel-troweled floors generally have little fiber visibility.

3) High Performance Slab Topic #3
Slabs designed with continuous reinforcing

With normal a concrete warehouse slab that is not shrink comp or post-tensioned, has no fiber dosage in it, and does not support structural building loads, a slab design engineer will need to decide whether to include steel reinforcing in the slab.

If used, steel reinforcing in the form of deformed bars (rebar) or welded wire fabric or mesh can be installed on the ground prior to concrete placement so it is included in the final slab. There are various reasons to include reinforcing. Tarr (2008) has broken it down to the following:

"Reinforcing not necessarily required, if all of the following are true:
1. **Stable, uniform subgrade;**
2. **Reasonable concrete shrinkage;**
3. **Joint spacing less than 15 feet on center in each direction**

"Reinforcing recommended, if any one of the following are true:
1. **Joint spacing wider than ACI 360 recommendations**
2. **High shrinkage concrete**
3. **When joints are unacceptable in floor use but random cracks that do not widen significantly are acceptable"**

It is common for reinforcing to be included in slabs on grade. However, in previous SunCam slab courses, it has been noted that it is not necessary if the conditions are right. The author has designed vast areas of slab for warehouse use (racking, lift traffic) that are unreinforced. Strategic joint reinforcing was used where degradation of joints was possible and likely, and low shrinkage concrete was used to minimize curling and shrinkage. Regular maintenance and occasional repairs will be necessary for these slabs, but owners generally find maintenance to be standard practice in normal warehouses, and part of the return on investment studies and operating budget.

Small reinforcing amounts: 0.1% or less by area
As described in the Warehouse II course, p.36, some slab designers add a small amount of reinforcing with the intent of keeping joints small enough to enhance aggregate interlock, say 0.1% by area. Also, some engineers may use light reinforcing to control crack sizes should they develop, and perhaps to stretch out the spacing of

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control joints. Again, roughly 0.1% by area. Also noted in the previous courses, 0.2% to 0.4% reinforcing by area tends to induce cracks that are inconsistent in size and spacing. Almost as if the concrete and steel are competing for control, and neither wins. The only winners perhaps are the legal parties in the event of lawsuits. See Figs. 17a & 17b from the highest authorities. The 0.1% reinforcing apporach may be effective for engineers who can control certain variables or have insights into practices that allow for the effective use of this type of reinforcing. The author's experience has been that light reinforcing may be effective for some engineers, but so can slab design strategies invloving: a) controlling joint spacing, b) controlling concrete shrinkage, c) smart joint design and use of stronger joints where it makes sense, d) awareness of soil conditions.
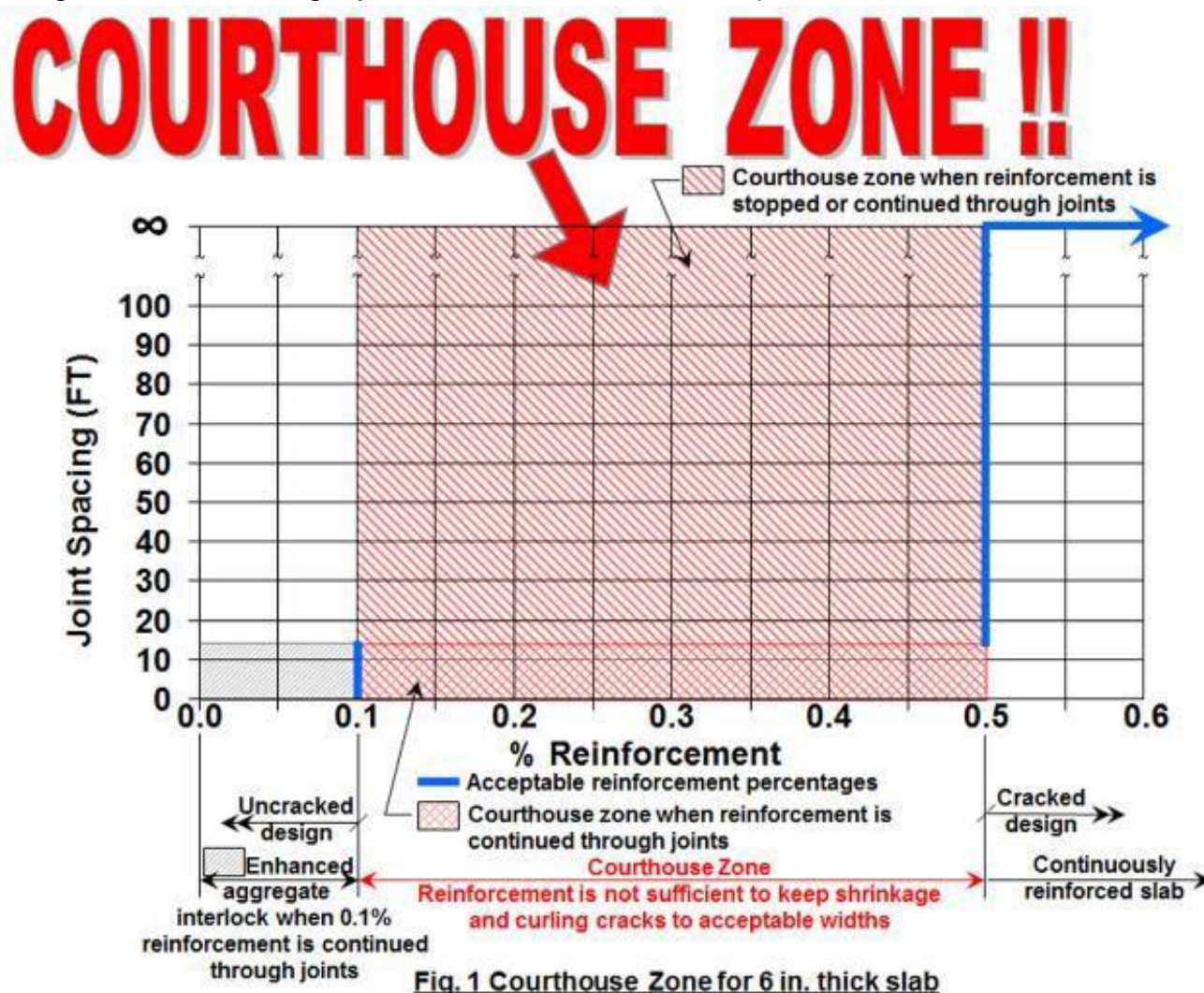

Fig. 17a (Walker and Holland, 2016)

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3.5.2 *Reinforcement*—Properly placed reinforcement, used in adequate amounts, will reduce the number and widths of cracks, reducing unsightly cracking. By distributing the shrinkage strains along the reinforcement through bond stresses, the cracks are distributed so that a larger number of narrow cracks occur instead of a few wide cracks. Although the use of reinforcement to control cracking in a relatively thin concrete section is practical, it is not needed in massive structures, such as dams, due to the low drying shrinkage of these mass concrete structures. The minimum amount and spacing of reinforcement to be used in structural floors, roof slabs, and walls for control of temperature and shrinkage cracking is given in ACI 318 or in ACI 350R. The minimum-reinforcement percentage, which is between 0.18 and 0.20%, does not normally control cracks to within generally acceptable design limits. To control cracks to a more acceptable level, the percentage requirement needs to exceed about 0.60%.

Fig. 17b (ACI 224)

<u>Reinforcing amounts to control crack size: 0.5% or more by area</u>
The next level of reinforcing to consider is at 0.5% reinforcing by area, or what is known as continuous reinforcing. Continuously reinforced slabs are those with enough reinforcement to provide sufficient reinforcing stiffness and ductile strength to reduce crack sizes to sizes that can be largely ignored, thereby eliminating control joints.

There are defintely some slab areas where owners have determined they want to eliminate joints completely. One of these areas is high speed traffic aisles. In a standard warehouse, this may be where forklfts and pallet jacks are constantly running at maximum speeds to get to and from a dock area. Or, they may be going from an inbound dock area to an outbound dock area as quickly as they can, and the distance could easily be 1,000 feet or more. With joints, the hard wheels of lifts and pallet jacks are hitting them, causing much wear and tear on the equipment and the joints, and the lift/jack operators are being subject to constant fatigue from the bumps on the hard wheels. If the cracks can be held small, and the owner finds small but minor cracks acceptable, this would land on the third criteria above for reinforcing.

The author has designed high speed traffic aisles with no joints, using pours as long as 700 feet without interruption, with most of the credit going to the general contractor and

concrete contractor. Fig. 18 The strategy at these aisles was to provide 0.6% reinforcing by area, and allow the slab to crack, but the reinforcing keeps the cracks small. **The largest cracks for these pours after several years in service is typically about 0.03**", or the thickness of a credit card. See Fig. 19.The facilities have had no reported issues with this type of slab, and the strategy has continued to be used in subsequent projects.
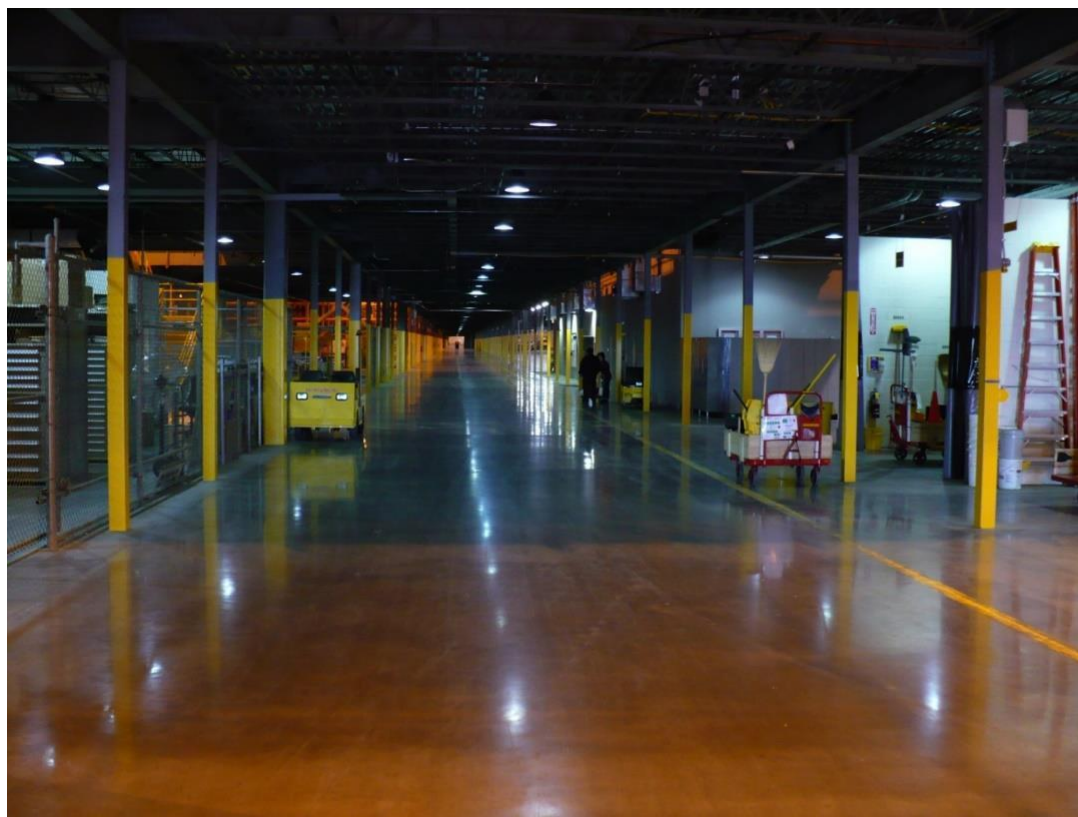

Fig. 18, Continuously reinforced high speed travel aisle

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Fig. 19, Typical largest crack in a continuously reinforced high speed travel aisle

Joints and column leave outs
There are at least two main items to address when it comes to joints for continually reinforced slabs.

1. Joints along adjacent, non-continuous slab areas, or the long joints parallel to the travel aisle. These are essentially standard construction joints, though the best way to control movement parallel to the joint is to use diamond dowels. For more information on dowels, use the "preview course" tool for the Warehouse II course. See Fig. 20 for the recommended joint detail.

2. Buiding columns or other potential rigid inclusions that are tied to footings below the slab: Columns are a good example, as these travel aisles may often have an overhead system of conveyors for automatic materials handling. These are essentially mezzanine structures with columns roughly 20 to 30 feet on center that straddle the travel aisle. The preference would be to have the columns placed far enough outside the travel aisle so the joint around the column can miss the travel aisle. Next best would be to align the face of the column wrap (concrete or sacrifical protective barrier) with the long parallel joint, so the travel aisle pour is not interrupted. See Fig. 21 The last straw would be to use an isolation joint around any incusion. See Fig. 8.

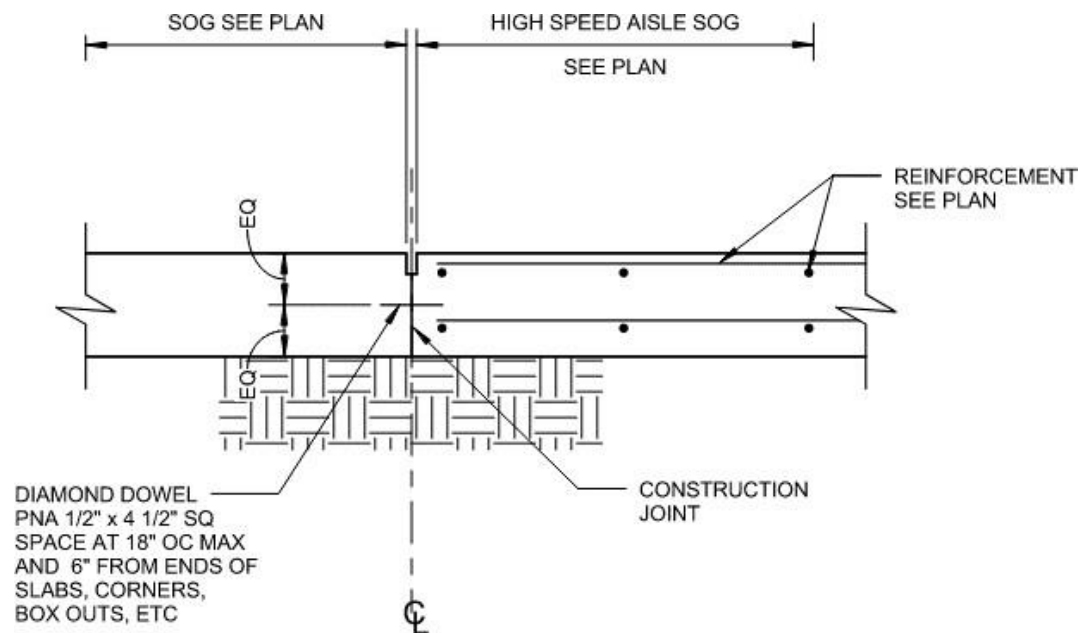## Concrete Slabs-on-Grade: Warehouses III - High Performance Slabs
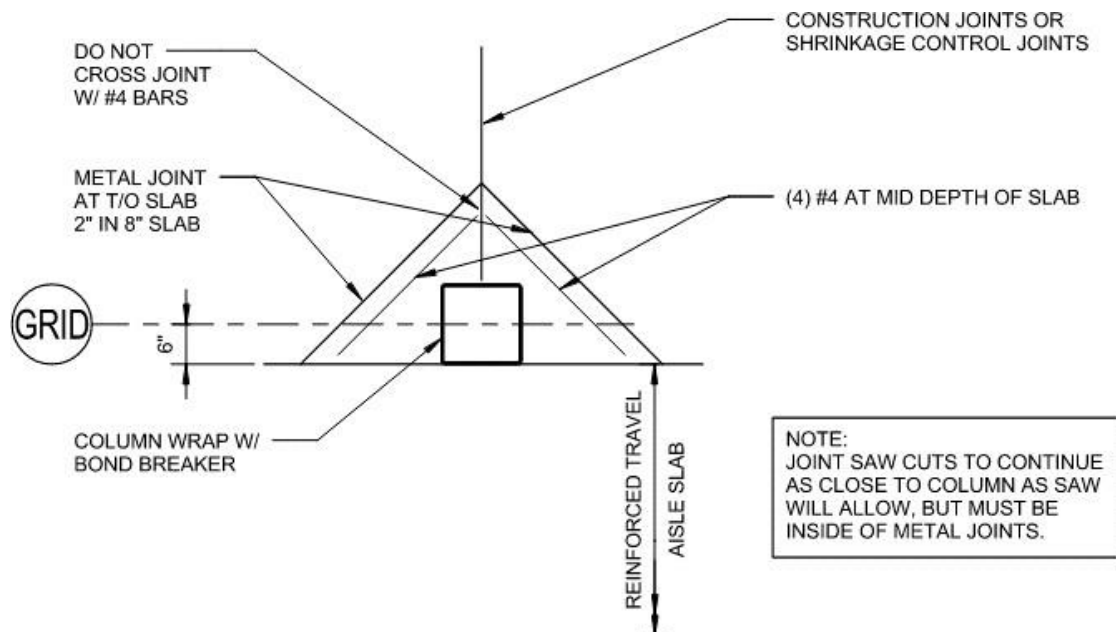
Fig. 20, Joint at side of high speed aisle

Fig. 21, Joint near column at high speed aisle

ACI recommends restraining the slab near the ends of long runs of continually reinforced slabs. The author's approach has been to not restrain the slab at the ends of long pours, and to allow the slab to be unrestained in as much as the soil friction and interaction with adjacent pours would allow. The largest cracks previously noted of roughly 0.03" were near the ends of these long runs. And again, the operations teams have found them acceptable. It should be noted that not all owners may be as forgiving, and expectations should certainly be set.

4) <u>High Performance Slab Topic #4</u>
<u>Post-tensioned slabs-on-grade</u>

Post-tensioned (PT) slabs-on-grade are poured with post-tensioning tendons and, as needed, mild steel reinforcing (standard rebar) in them. Once the concrete has reached sufficient strength, the tendons are pulled to induce a state of compression in the slab. 100psi final compressive stress is typical. The compression allows for the elimination of shrinkage control joints, resulting in wide, joint-free areas of pours. See Figs. 22 through 27.

There are several resources for post-tensioned slab design. Here our attention will be on slabs-on-grade. Some of the resources relevant to slab-on-grade are:
1) ACI 360
2) PTI DC10.3-06, "Design and Construction of Post-Tensioned Sport Courts"
3) PTI DC10.1-08, "Design and Construction of Post-Tensioned Slabs On Ground" (This is primarily for use in designing slabs on expansive clays)
4) While this portion of the course only addresses slabs-on-grade, there are other SunCam courses that address the more tradtitional post-tensioned structural elements such as supported slabs and beams. There is additional information on post-tensioning theory and applications included in those courses by John Miller, P.E. (www.suncam.com).

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https://commons.wikimedia.org/wiki/File:Post-Tensioning-Cables-3.jpg;
Shakespeare at English Wikipedia, CC BY-SA 3.0 <https://creativecommons.org/licenses/by-sa/3.0>, via Wikimedia Commons

Fig. 22, Post-tensioning tendons ready to be placed

Fig. 23, Post-tensioning tendons in place over poly

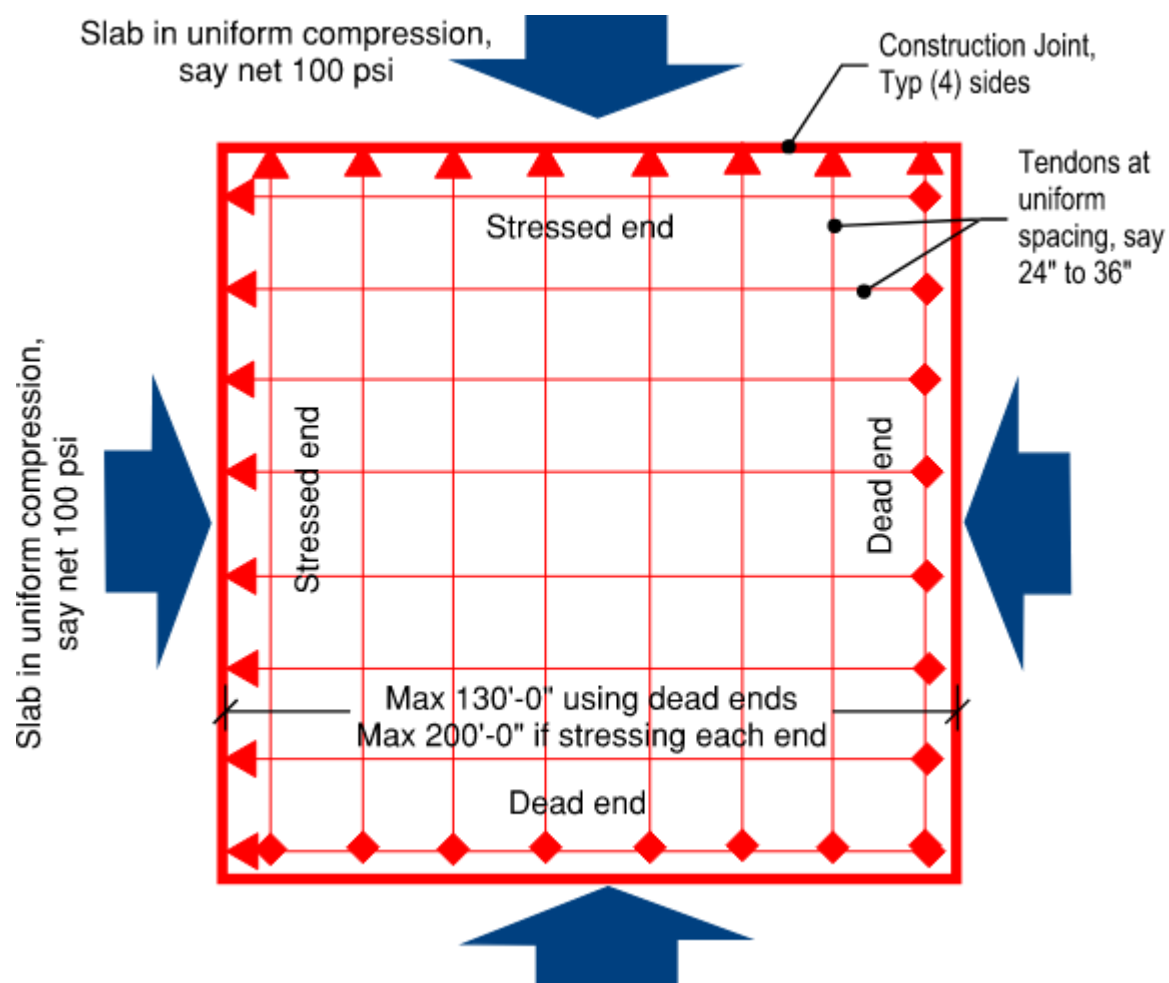Concrete Slabs-on-Grade: Warehouses III - High Performance Slabs

Fig. 24, Post-tensioning tendon typical plan layout and state of stress

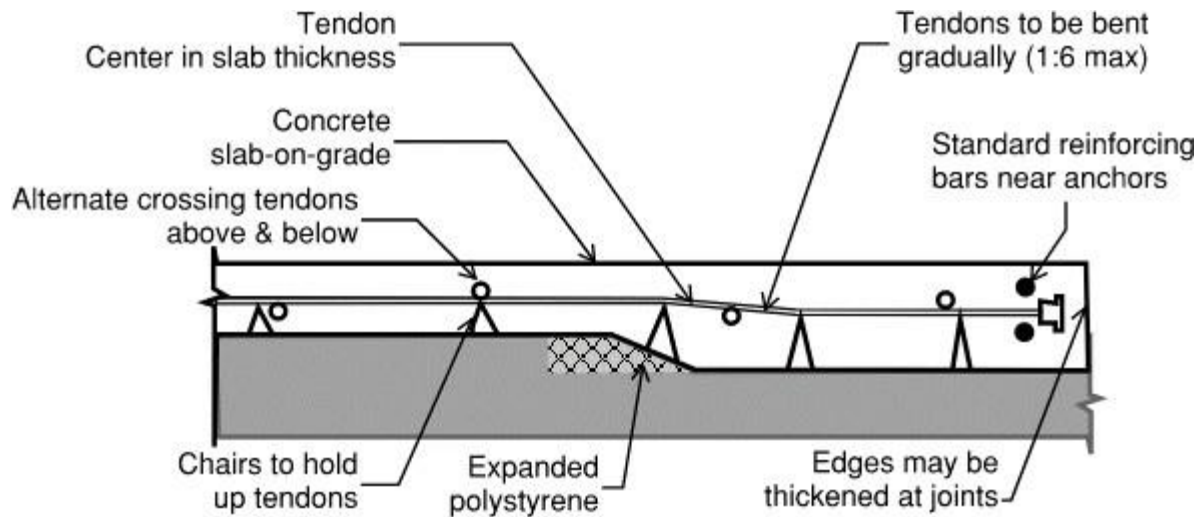Concrete Slabs-on-Grade: Warehouses III - High Performance Slabs

Fig. 25, Post-tensioned slab section

Fig. 26, Post-tensioning hydraulic jack for pulling tendons

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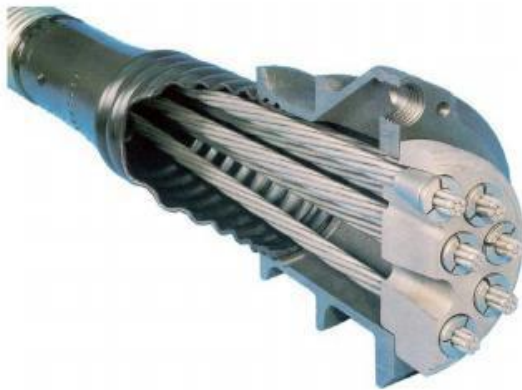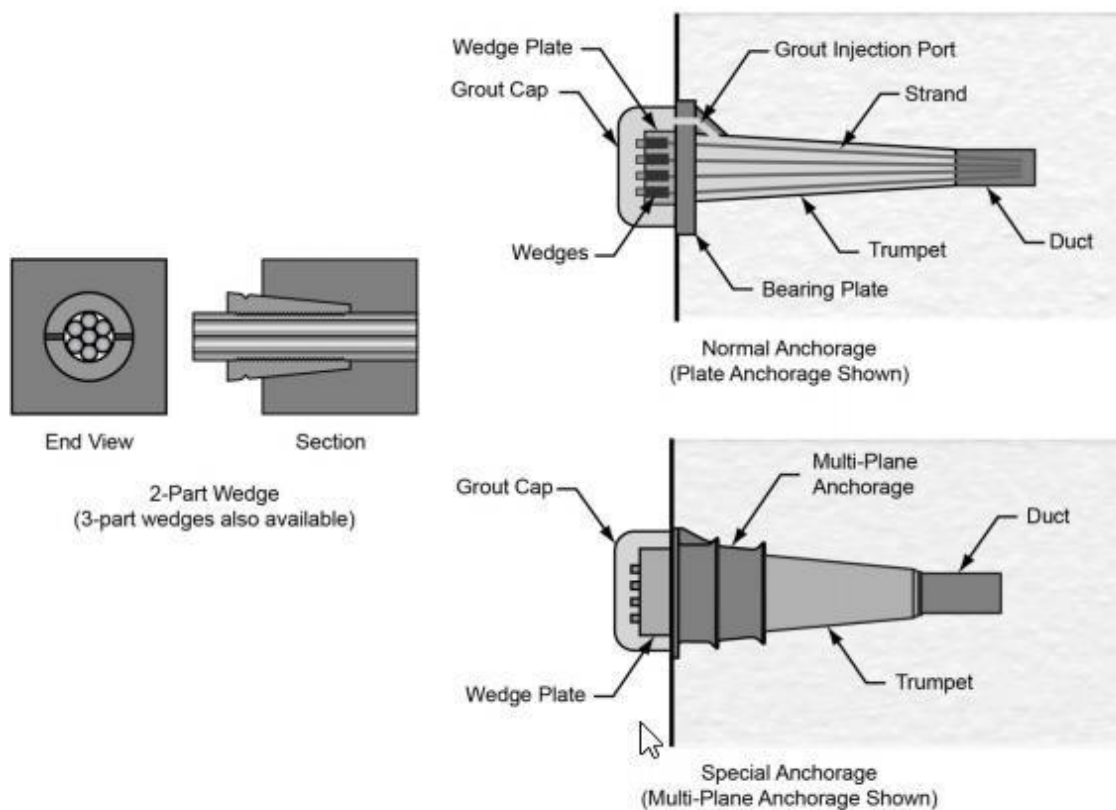

Fig. 27, PT tendon bundled end and section (Berg and Schokker)

Figure 1.3 - Typical Post-Tensioning Anchorage Hardware for Strand Tendons

Figs. 28, PT end anchorages (FWHA)

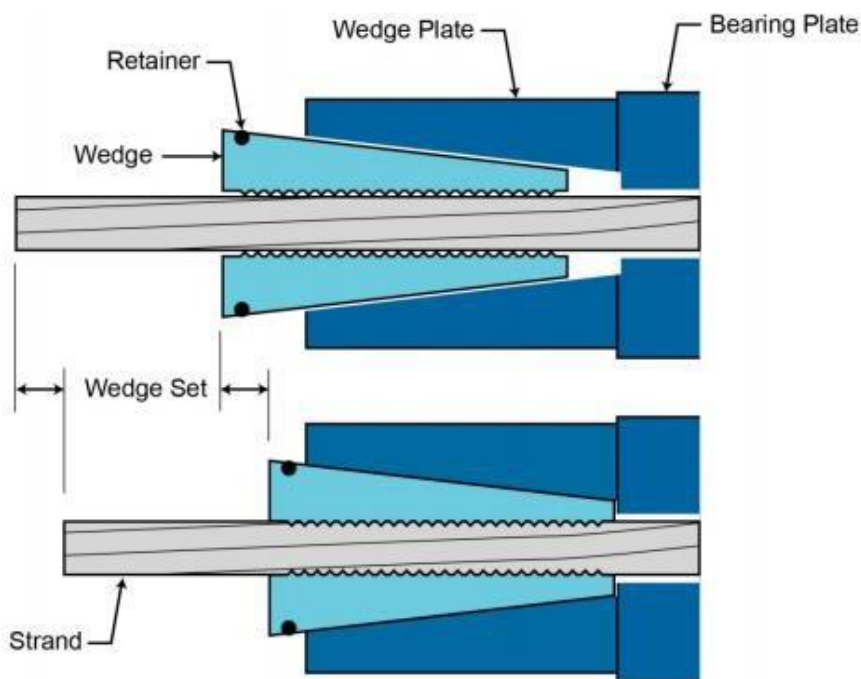Concrete Slabs-on-Grade: Warehouses III - High Performance Slabs

Figure 3.34 - Anchor Set or Wedge Set

Figs. 29, PT end anchorages (FWHA)

The practical limit for the size of single poured area with post-tensioning is about 200 feet (Tarr, 2008) in each direction. There are limits on the practical jacking forces used and internal and external friction forces that can be reliably overcome. Slabs of greater size should be divided into smaller areas. At the joint between isolated areas, there are a few options:

1) Separate areas by gaps called pour strips that allow for the post-tensioning operations to occur, and these strips might be on the order of 2 to 4 ft wide. Once the cables are pulled, the pour strips are filled with an ordinary concrete slab.

2) Adjacent areas can joined via intermediate stress joints. The first slab pour is made. Then, at the appropriate time, tendons are pulled at the end where the slabs will join, then uncoiled and stretched out for the second pour. The second pour is made and tendons are pulled again once the second pour cures sufficiently.

3) Areas can be abutted as independent pours, with a dead end at the abutting end of the second pour.

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Similar to shrink comp slabs, the elimination of tensile shrinkage and curling stresses in the slab allow for large joint free areas. Slabs can be designed for "interior" conditions, but without adding curling and shrinkage streses to flexural stresses when determining the limits of slab bending strength and fatigue analysis. Again, the main benefit is adding compression stresses to the tension stresses due to bending in slabs. In the normal stress equation, $f = \dfrac{M}{S} + \dfrac{P}{A}$, there is an initial compression from the P/A portion. The residual compression stress in the unloaded condition of 100 psi or more can be applied against the tensile stresses. This will reduce bending stresses significantly, and allow for a thinner slab, assuming the practical minimum thicknesses are exceed for warehouse slabs.

Post-tensioned tendons can be bonded or unbonded. **Unbonded tendons are housed in plastic sleeves with grease reducing the friction between the sleeve and tendon.** The plastic sleeves do not bond with the concrete. Those not in sleeves are called bonded tendons. Tendons are anchored at the pourstops with wedge-type anchors. See previous Figs. 28 & 29. Several factors weigh into the force used to tighten the cables, which are discussed in the foregoing discussion.
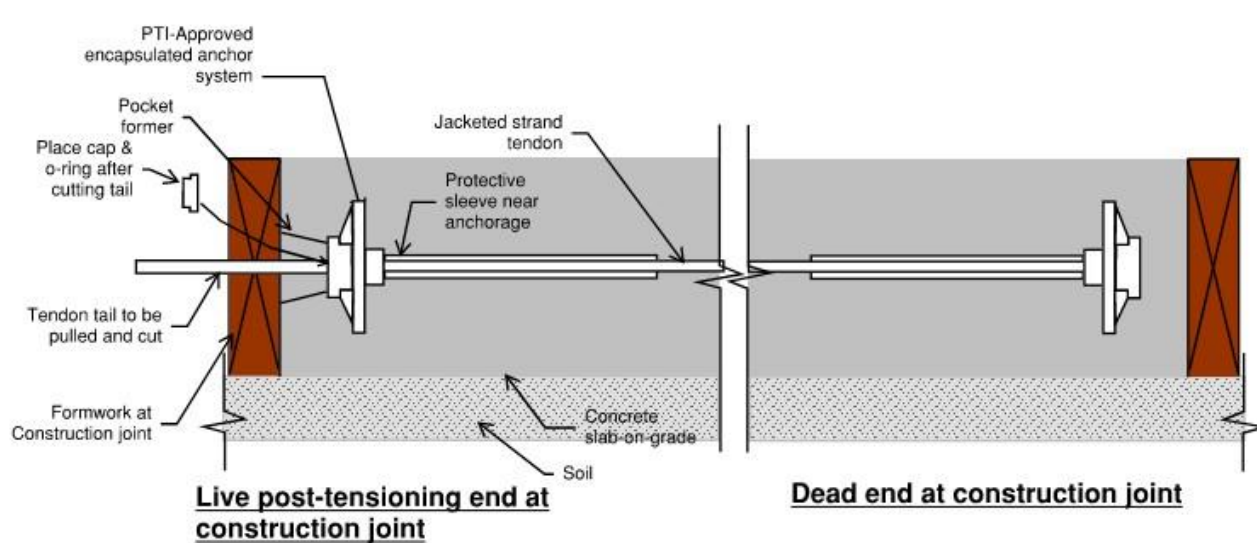

Fig. 30, Post-tensioned live and dead end anchorages

Post-tensioned slabs are generally poured directly on a vapor barrier or two sheets of poly to allow any movement to occur in a manner as predictable as possible while eliminating frictional restraint.

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Tendons are placed in the middle of the slab, but often thickened at slab edges (See Fig. 25) to counter upward warping of the edge. (Tarr, 2008). Spacing is usually in the range of 20" to 40". Expanded polystyrene can be used as a crushing zone for the thickened section so the edges can move towards the center of slab area during pulling.

The timing of pulling the post-tensioning tendons is critical to keep the slab from developing random shrinkage cracks**. Pulling should occur as early as possible, when the concrete has achieved sufficient compressive strength to resist the compression, especially at the anchorage zones.** The pulling of tendons is usually done in increments to avoid undue stresses between areas that have been stressed versus those that haven't been stresses. This might be 50% of full force at all tendons for the first increment, then 100% of full force for the second increment. There are usually two minimum compression strengths specified for post-tensioned concrete: f'c at 24 hours, and f'c at 28 days. The 24-hour strength is for minimum strength gain prior to pulling of tendons, and the 28-day strength is for loading and durability for the life of the slab.

Tendon pulling can happen at one or both of the opposing ends of a tendon. When tendons are pulled at one end only, the non-pulled side is called a dead end anchorage. The pulled end is called a stressed end anchorage. See Fig. 30. Single-end pulling is limited by a length of about 130 feet. The anchors should be part of an encapsulated system approved by the Post-Tensioning Institute (PTI). A typical tendon is on the order of 1/2" in diameter and has an ultimate strength of 270 ksi. Plastic sheathes around the tendons are made of medium or high density polyethylene or polypropylene. Tendons are usually pulled to 80% of the ultimate tensile strength of the tendon. ASTM A416 outlines requirements for tendons, and the tendon assembly should comply with PTI's "Specification for Unbonded Single Strand Tendons."

As tendons are laid out, they can be woven above and below crossing tendons from the other direction in an alternating fashion so the average resultant force from the tendons can pull against the center of the slab cross section in each direction. See Fig. 25.

When pulled, the tendons lengthen significantly, on the order of 5" to 10". The pulled ends are cut off and the ends capped with a greased plastic cap.

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As tendons are pulled, the force in the tendons is mostly being used to bring the slab into compression. But, a portion of the force is resisted by the friction between the slab and the subgrade, resulting in a loss of force. Also, the tendons may be working against the a spring in the anchorage, so there may be a loss of force in the seating. These losses are called initial losses, and may be compensated for by additional stressing forces.

After the tendons are pulled, there are additional long term effects that tend to reduce the forces in the tendons. These are called long term losses. They all shorten the concrete length, and include:
a) **Creep (time-dependent movement characteristic of concrete under stress)**
b) **Shrinkage (normal drying shrinkage)**
c) **Relaxation of the PT tendons**
d) **Elastic shortening of the concrete under stress**

The sum of these forces is normally estimated by the PT tendon supplier, and generally amount to about 10 to 12 % of the initial stressing force in the tendons.

The size of the joints at the ends of pours also must account for shrinkage due to drying, creep from the compression of the slab, any temperature changes expected. Similar to shrink comp slabs, the author recommends armored joints for areas with lift traffic. These joints should be filled with semi-rigid epoxies capable of spanning the joint.

As a rule of thumb, post-tensioned slabs should not be cut or cored. Any inclusions in the slab should be cast in with an expansion joint or with the use of a crushing zone with expanded polystyrene so the slab and the embedded object can be allowed to move in an unimpeded fashion towards the center of slab area during pulling. See Fig. 31. Ideally, objects near edges should be moved outside the post-tensioned slab if possible. Enlarged openings can be cast in for groups of objects that project through the slab or for those that are odd-shaped or that have articulations. There should be a allowable distance specified for the contractor to move tendons some distance from their projected path to get around objects, say on the order of 25% of the spacing, and with a transition angle, say 1 unit of movement per 6 units of length.

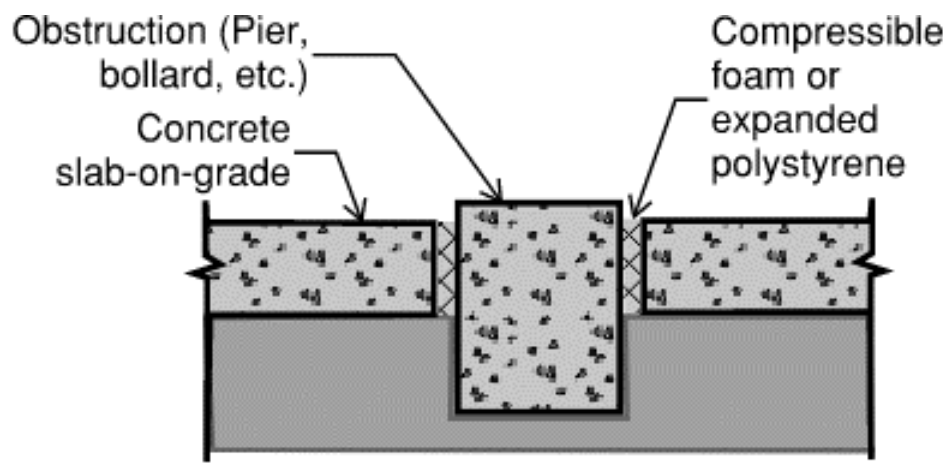Concrete Slabs-on-Grade: Warehouses III - High Performance Slabs

Fig. 31, Obstruction in PT slab

During concrete pouring, vibration of the wet concrete is critical to performance to avoid honeycombing and voids, especially near the tendon anchors.

Post-tensioned slabs are required to be designed by a licensed professional engineer. Factors include tendon size (diameter), strength and spacing. Again, initial tendon forces are generally 80% of their ultimate capacity. Tendon spacing can be determined by the following formula:

$$s = \frac{F_e}{(f_p x 12H) + [W_{slab} x \frac{Ls}{2} x\mu]}$$

s = tendon spacing, ft
F_e = Final effective force per tendon, lbs
f_p = Desired min. avg. residual prestress force, psi
H = slab thickness, in
W_{slab} = Weight of slab, psf
Ls = Total slab length, ft
μ = Coefficient of friction between slab and subgrade
(PTI, DC10.3)

The structural drawing showing the post-tensioned slab should call out effective forces in the tendons after short and long term losses are factored in. The engineer of record calculates an effective force based on the minimum compression stress desired in the slab section, and factors in an estimate for the friction with the subgrade. The friction

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value can be substantial. Even when a polyethylene sheet or vapor barrier is used, the friction coefficient value can be on the order of 0.6.

Because tendons are just bundled cables in plastic sleeves, they sag betwwen supports. Thus, either reinforcing chairs or a grid of rebar can be effectively used as a chairing system for the tendons.

Due to the large loads encountered in some industrial slabs, the thickness of the slab may be 6" or more. As a result, single tendons at a reasonable spacing may not provide adeqaute post-tensioning force in the slab to induce sufficient compression. There are practical limits on the stressing forces of individual tendons. As a result, tendons may be bundled into groups and placed into ducts. See Fig. 32. The tendons can be carefully splayed at the anchorage and stressed individually.
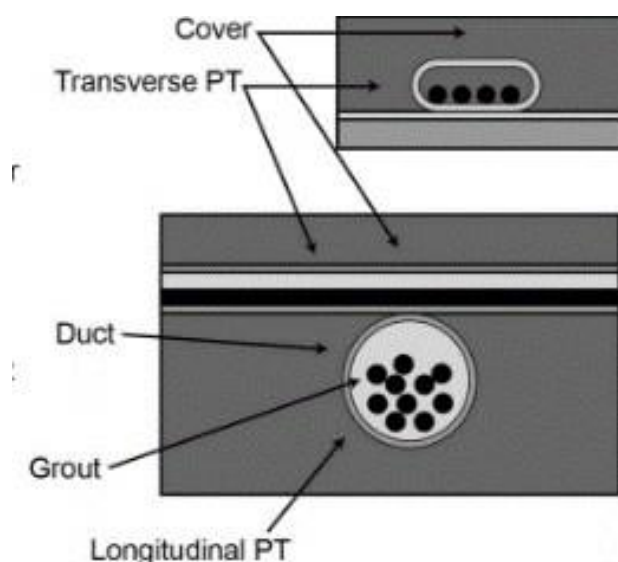
Fig. 32, Ducts housing multiple PT tendons (FWHA)

Shop drawings from the post-tension contractor should show tendon sizes, grouping, spacing, placing sequence, supports and locations (tendon supports, accessories, supplemental reinforcement, clearances required for jack, and pressure plate stresses calculations of friction and anchorage stresses). Shop drawings should be accompanied by calculations signed and sealed by the registered professional engineer responsible for their preparation. The supplier's structural engineer should review field reports and

stressing records and compare them with the calculated effective post-tensioning forces, and acknowledge compliance in writing. In addition, shop drawings should describe the tensioning sequence, type of jack, pressure monitoring devices, anchorage set, tendon elongation, and tendon cutoff procedures. A tendon manufacturer's certificate should be provided that verifies tendon strength meets or exceeds specified requirements. Stressing records performed during the tensioning operation should document data on the stressing for each tendon, including tendon elongation.

5) High Performance Slab Topic #5: Cold Storage Warehouse

Note: Hereafter, temperatures are noted in the following form:
-15F = Minus 15 degrees Fahrenheit

Food distribution centers are a special case of warehouses. Many of the products handled and stored in these facilities require refrigeration in order to maximize storage life. Temperatures range from -15F or lower for frozen goods to +34F or more for products that are to be kept cool but not frozen.

Frost Protection of the Soil Matrix
As with any of the warehouses being reviewed, understanding the influence and behavior of the soil is paramount to predictable and adequate performance of the building slabs. Frost protection of the soil below the slab is most often required, especially with frost susceptible clay soils with any amount of moisture. **If a warehouse area with temperatures in the-15F to 0F range is allowed to operate without frost protection of the ground below, frost lenses can penetrate into the soil matrix, and create a permafrost condition where the frost continues to grow over the years.**

Some retail stores operate smaller freezer storage spaces for frozen foods (-15F). Often the frost protection offerred is a 4-inch thick layer of rigid insulation. The author is aware of many instances in freezers so constructed where several feet of frost resulted from the continual use of these freezers over the years with attendant frost heave movement of the slab. Poor continuity of the insulation layer is normally the cause. Operations within a retail store may not be severely impacted, but for a warehouse this would be absolutely unacceptable.

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For cold temperatures below zero (some freezers kept at -15F or below), the combination of moisture and frost susceptible soil may need to be addressed. Moisture-conditioned clay under a freezer slab may lead to frost heave, even in warm climates such as Texas and Florida. One strategy is to provide a system of warming tubes in an insulated layer below the slab (glycol), and a bed of clean sand or crushed rock under the insulation. See Fig. 33.

Footings will need to be dropped to accommodate this as well, and a knowledge of the water table level will need to be obtained so adverse water and mud conditions won't inhibit construction activities with a deeper resulting excavation.
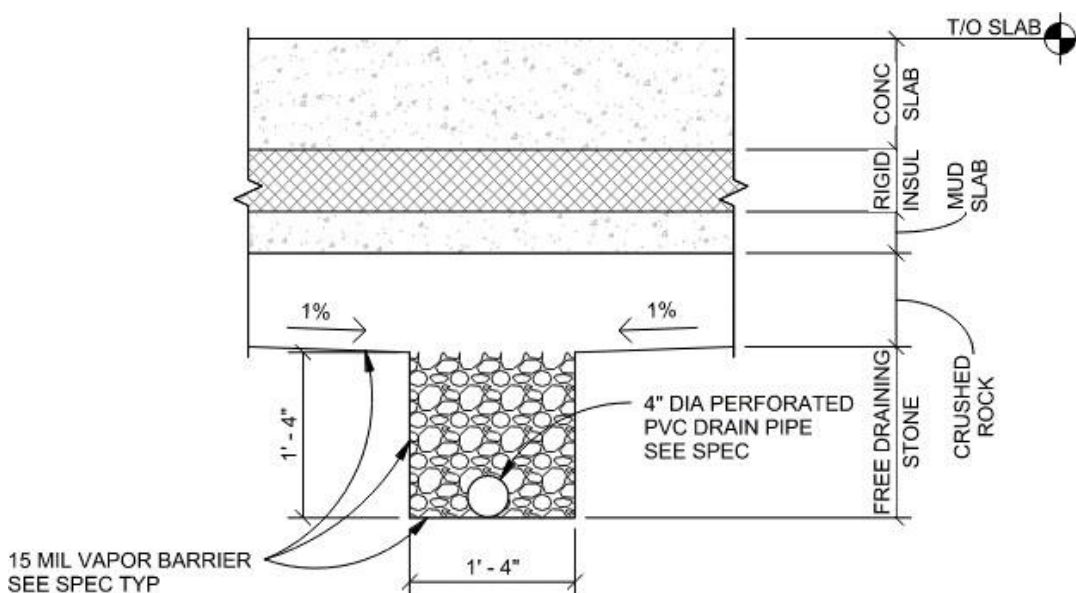

Fig. 33, Freezer slab with insulation and mud slab (housing glycol tubing)

The use of warm glycol fluid in flexible tubing to prevent a frozen soil matrix is fairly common. The tubing with glycol is embedded under the warehouse slab system within a layer of concrete called a mudslab. The mudslab is under an insulation layer, which provides the buffer between the refrigerated side (below freezing) and the soil side (above freezing). Individual loops of tubing run in paths parallel to other loops spaced a few feet apart. The freezer slab is poured directly on the insulation layer. (See Fig. 34).

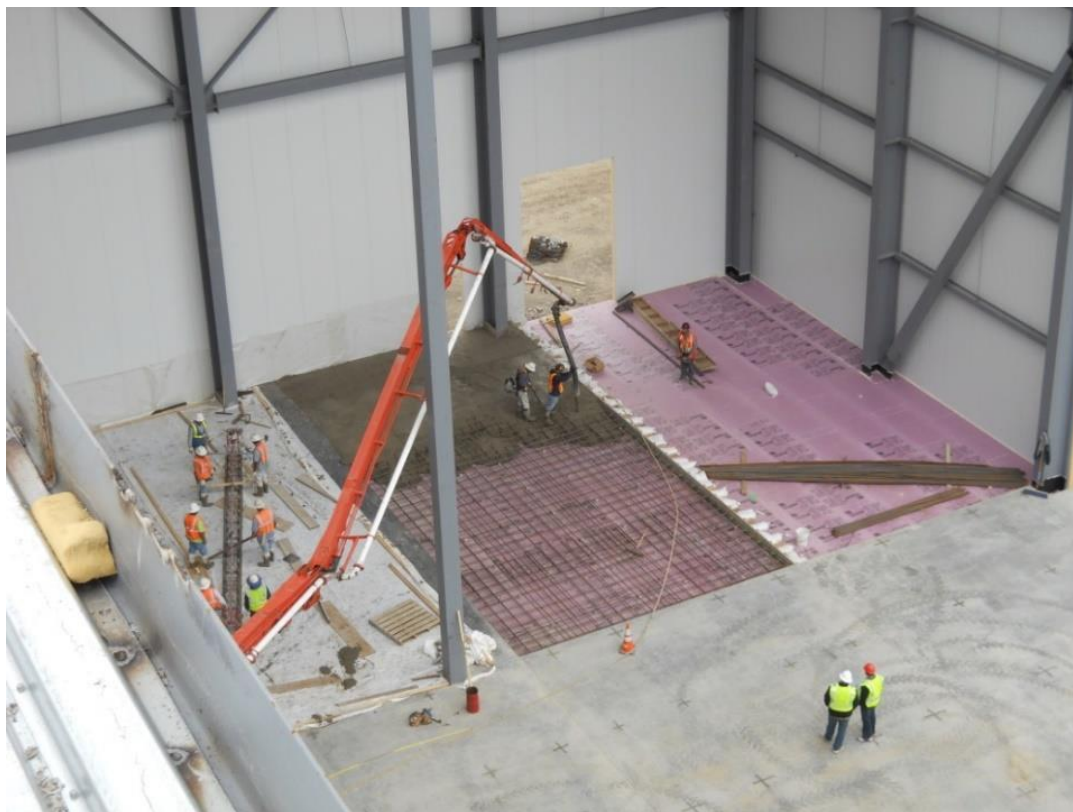Concrete Slabs-on-Grade: Warehouses III - High Performance Slabs

Fig. 34, Freezer slab being poured

There are many things to consider for freezer/refrigerated slabs:

1. If a soil matrix is particularly susceptible to frost heave, such as expansive clays, additional methods of mitigation can be used. For permanent rack systems that have absolutely no tolerance for subgrade movement, redundant protection might be an option that an owner finds worth the cost. Temporary issues with glycol tubing may not be discovered for some time, and the resulting impact may be very difficult to reverse. An added layer of rigid insulation could be used, or a sand layer between the clay and the frost protection system could be provided in a belt and suspenders approach. Where any risk to slab movement was unacceptable, and extreme caution was thought worthy, the author has called out drain tile and added a sand layer to eliminate moisture from the sand. Obviously, a high ground water table would require some serious thought, and some permanent and highly reliable means of keeping groundwater from reaching potentially affected soils would be desired.

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2. Because the insulation will be part of the load path to the soil below it, its integrity needs to be checked. Extruded polystyrene insulation should be manufactured to comply with ASTM C 578. Per Tarr (2007), a couple of rules of thumb are to "limit live and dead load stresses to 1/5 and 1/3 times the strength of the insulation", respectively, to "limit long-term creep to 2% of the insulation thickness over a 20-year period".

3. Slabs-on-insulation need to be designed for their own subgrade modulus (k-value), and the long-term settlement needs to be quantified. There is much data from insulation suppliers on this, but the testing methods to obtain moduli should be closely watched to see if the stiffness method used matches the modulus used in design. Tarr (2007) recommends using a modulus of subgrade reaction based on ASTM D1196, and that results from ASTM D1621 give higher values that may not be applicable for slab design.

4. Technical guide from Owens Corning for stiffness calculations:
    a. Imperial units: http://insultherm.com/wp-content/uploads/2015/08/OC-foamular-coldstorage-applications.pdf
    b. Canadian version for metric (more current: http://www2.owenscorning.com/worldwide/admin/tempupload/pdf.2-74495-157_HighDensBro_E.pdf

5. Where doors to adjacent warmer spaces are located, extend the zone of insulation beyond the freezer due to tendency of the freezer's air and conductive slab to affect and perhaps freeze the adjacent slabs the ground supporting them. Think 25 years of -15F on the other side of a thin door that is constantly opening and closing. See Fig. 35.
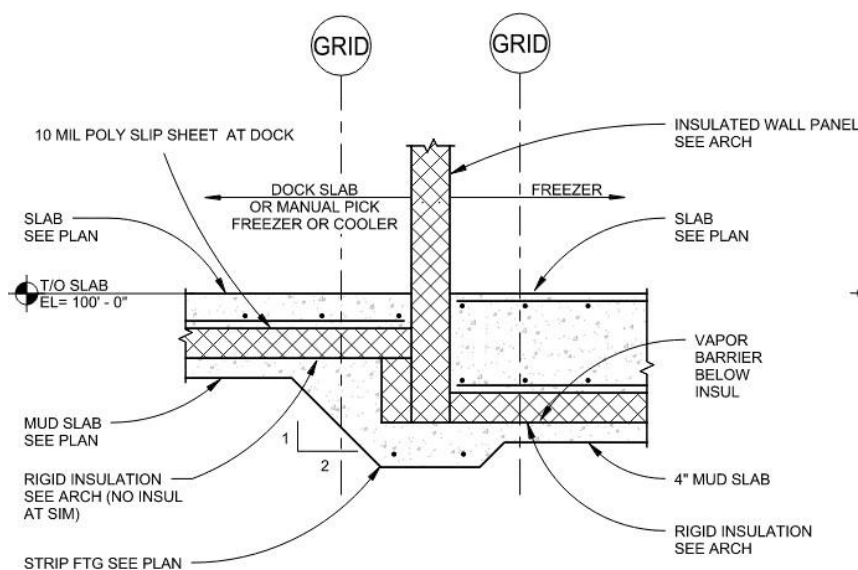

Fig. 35, Slab transition.

6. Within ACI 360 is a chapter on slabs in refrigerated facilities. Guidance is provided on many topics, including draw down temperature sequence. **This is normally performed by gradually dropping to a temperature of 35F and holding the temp for several days while the concrete temp catches up to the air temp. The final drawdown is 10F per day until the final freezer temp is reached.**

7. Joints:
   a. Plan for slab movement due to temperatures. This might add 3/8" or more, depending on joint spacing. Consider using armored joints. If using continuous reinforcing, tie the slabs together with laps that develop the strength of the bars. See Fig. 36.
   b. Wait to fill joints after drawdown, and as long as practically possible to allow slab to accilimate to the low temps. Use durable material such as semi rigid epoxy for a long service life.
   c. Cracks are difficult to repair with cold temps. Consider use of shirink comp slabs or increasing factors of safety for service life to prolong routine maintenance cycles.
   d. Also, note that building columns will be attached to footings, which presumably will stay at the temperature of the subgrade, or relatively warm compared to the slab, and where they protrude through the slab, there may be some difference in how the slab moves versus the column. So, isolation joints around the need to be used if there's a chance the slab would bear against the column due to movement. Use a detail similar to Figs. 8a & 8b.

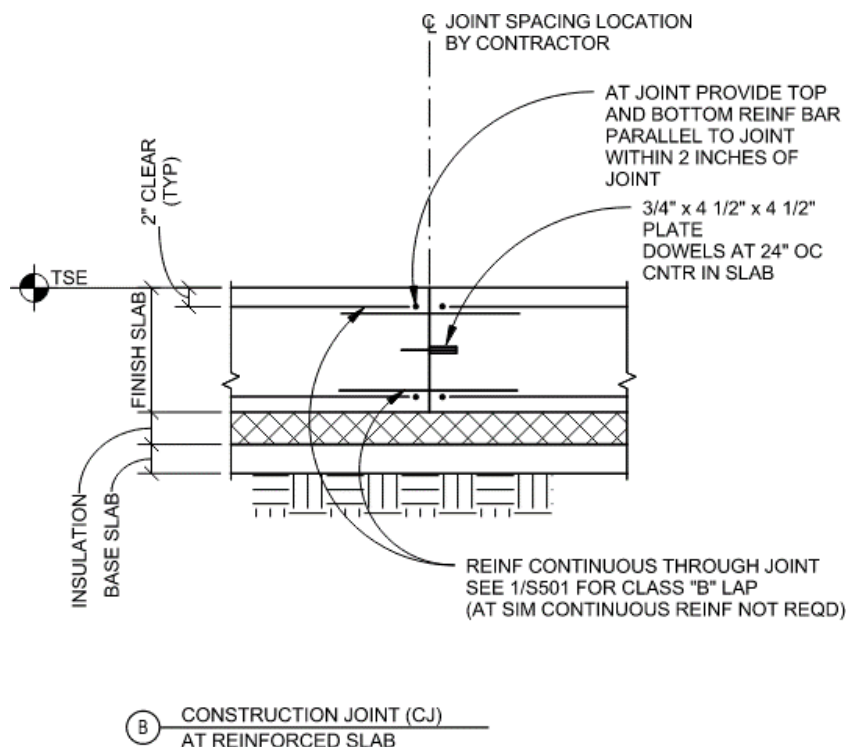Concrete Slabs-on-Grade: Warehouses III - High Performance Slabs

Fig. 36, Continuous reinforcing at joint

8. The operation of these buildings requires a massive electrical load to keep them cold. In the event of a power outage, these facilities are often equipped with emergency backup power generators that keep the buildings near their normal operating temperatures to maintain the shelf life of refrigerated and frozen foods. The result is heavy bands of conduit that will be difficult to fill and compact soil around. Consider using flowable fill around conduit bands (500 psi strength). This is also a good way to protect the conduit if future excavations are required. The concrete is normally painted pink to distinguish it.

9. Certain areas of warehouses may require additional slip-resistance. Areas with wet produce that are kept moist and somewhat cold (34F-40F) may have moist concrete that will have organic particles as that collect on the surface of the concrete. In such cases, a bead-blasted finish may provide a surface roughness that keeps friction at an adequate and safe level for workers and equipment.

10. Also, these same areas will need to be washed regularly. The introduction of water and surfactants along with scrubbing equipment may take its toll on the concrete surface over time. There are deferred concrete toppings that can be used that are sacrificial and

can be replaced by only removing and replacing the layer of deferred topping, as opposed to the whole thickness of concrete slab.

11. Surface trench drains and sloping surfaces to drain may also be required to limit the amount of standing water present in these areas.

12. Certain food products can stain concrete. For example, spills of ketchup bottles can results in acetic acid (vinegar) on the slab. Make sure the slab has a protective hardener/sealer to protect it from acids and the like if stains are undesirable.

6) High Performance Slab Topic #6:
Automated Racking Systems

For facilities requiring advanced operations, racking systems with automated materials handling equipment are often used. The use of lifts and pallet jacks with conventional racking are not optimal in many cases. Automated racking systems are designed to handle products that are stored in many different sizes of packaging, in very dense racking that can have a height of 100 feet or more. **Automated racking systems, or Automated Storage & Retreival System racking (ASRS) systems, basically have no conventional lift traffic. Products are placed and retrieved from rack postions by automated crane-type lifts.** See Fig. 37. There is a whole market segment dedicated to the use and advancement of such technology. So, a very integral process of materials handling logistics and functionality and how that tranlates to racking design will need to take place for all of these systems. A photo of this type of racking is shown in Fig. 38, and examples of the adjoining and integral structure are shown in Figs. 39 & 40.

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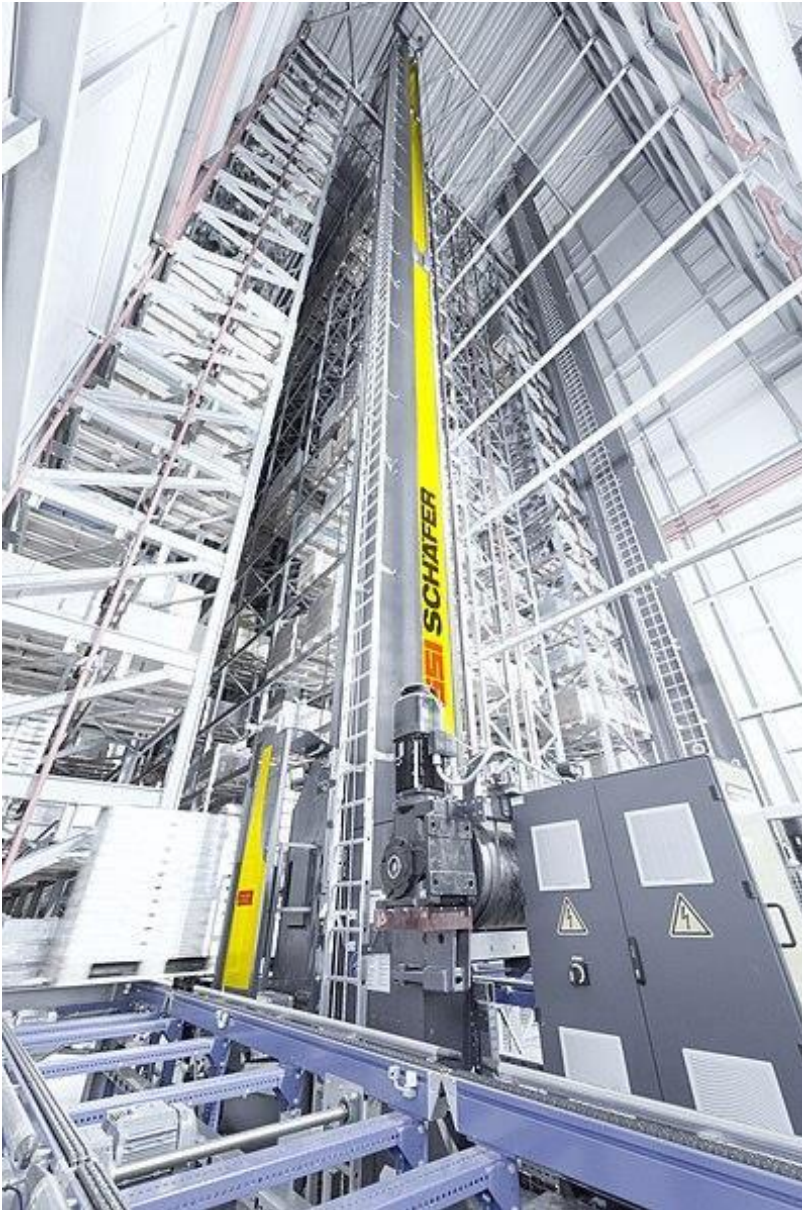
Fig. 37, Crane-type lift

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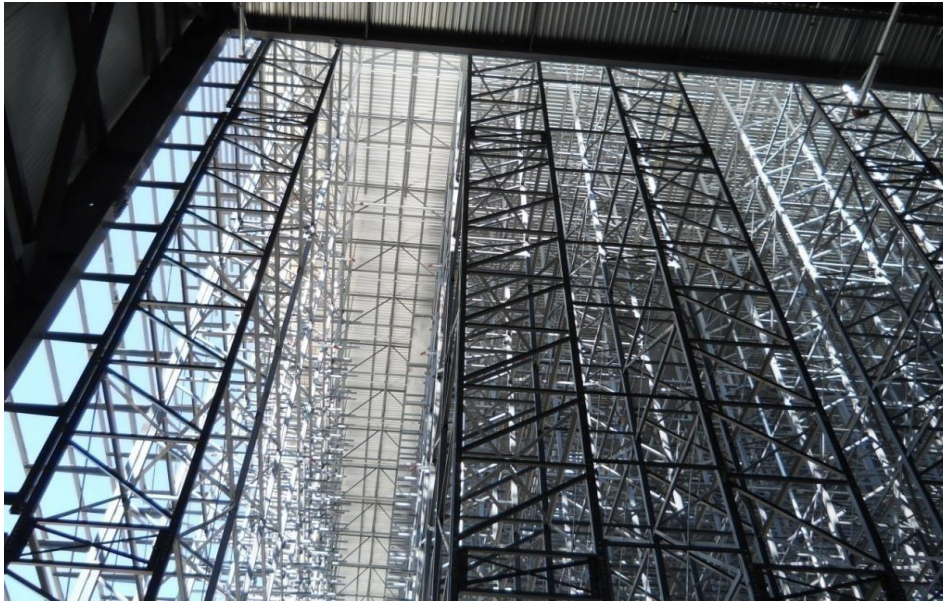

Fig. 38, Storage racking that supports the roof and braces the wall panels

Fig. 39, Roof-supporting storage racking being placed adjacent to conventional steel-framed warehouse strucure

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Fig. 40, Roof-supporting storage racking being placed adjacent to conventional steel-framed warehouse strucure

There is much variability in ASRS racking systems, and there is a vast array of equipment supporting the numerous steps involved in collating products into shippable form. The components occupying the greatest floor area are the racking and cranes. These also generally control the slab design. Some of the things to consider for slab design:

1) Leg racks may be spaced much closer than typical storage racks. Interferences with joints and reinforcing will be much more common, and either space planning or detailing should account for this.

2) The anchors and racking will be largely inaccessible for repairs due to the density of the racking and round-the-clock operations, and will likely have a lower tolerance for movement due to things such as subgrade settlement. Thus, post-construction movements should minimized, and slab designers may want to add factors of safety against cracking.

3) Emergency crane crash loads will likely be a load case, with an impact factor included or to be applied. The author believes that the strict movement criteria for slab design can be relaxed to a "let-it-crack" approach, or the use a typical ultimate slab

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strength that allows for the slab to crack and be repaired locally in the unlikely event of a crane crash.

4) Cranes will be supported by rails. These may need to run in continuous recessed pits to maximize the lower reach of the crane for things sitting on the slab (Fig. 41).
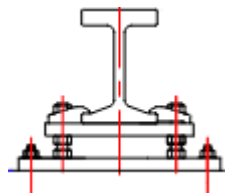

Fig. 41, Crane rail

5) The storage racking may be used as the support for the building's roof and walls. In this case, the slab will need to be designed as a foundation with steel reinforcing under the building code using ACI 318 design provisions. Note that foundations that have negative bending (tension in top of slab) will need to follow the newer provisions for two-way slabs. Minimum reinforcing will be required in the top of the slab.

6) For Item 5), reconcile the potential of the slab reinforcing to be cut when drilling for deep post-drilled anchors occurs.

7) **Installation and operation of the automated equipment in ASRS racking systems may require that FEM (European Federation of Materials Handling) Specifications 9.831 and 9.832 need to be met.** One of the main restrictions is a top of slab elevation tolerance of 0.59"+/- within the entire length of racking. The concrete contractor will need to be made aware of this, and it needs to be part of the construction documents. Movement or settlement criteria to meet strict "quasi-rigid" requirements from section 4.2.2 is noted in Fig. 42.

A floor slab is quasi-rigid if the following vertical deformations are not exceeded:

– overall vertical deformation:
  – 1/3000 of the total storage length
  – 1/3000 of the total storage width

– local vertical deformations:
  – l/2500 over distances up to l = 3 m in comparison to the reference plane in the X and Z directions in the rack area. l is the frame depth and/or width for stiffening towers.

The short-term and long-term behaviour of the floor slab/sub-structure must be taken into account when assessing these deformations.

Fig. 42, FEM 9.832 movement criteria

8) Rack suppliers use their own engineers to design their racking and anchorage. So, the supporting slab will be scrutinized for its integrity. Be prepared to defend the slab design, especially in high seismic zones. The author was asked to provide a slab that would develop the strength of the post-installed anchor rods so the anchor rods could be the fusible link in the high seismic resisting system. The author worked to revise the rack supplier's base plate design so it would bend in a ductile manner before overloading the anchors. This saved the owner from costly additional reinforcing and slab thickness.

9) As always, site soil characteristics are important to understand. The rack supplier may specify a very strict tolerance for as-built slabs, but the author's experience has been that they often don't understand the potential for post-construction movement below the slab. Depending on the site soils, such as the amount of cut and fill, the presence of expansive clays, and the uniformity of the soil profile, soils may move more than the racking systems are designed to handle. See content in previous courses on geotechnical considerations. It would be uncommon to find a geotechnical study that limits the potential vertical movement (PVM, or heave) or maximum soil settlement to less than 1/2" in 50'-0" differential and 1" overall. It would be good practice to find out the likelihood of such settlements with the geotech, communicate this to the rack supplier and owner, and find out if a contingency plan can be put in place to address future issues.

Some of the special loads that accompany ASRS systems are:
1) Automation equipment:
   a. Cranes that place and retrieve storage containers or trays in rack positions:
      i. Travel rail and anchor forces (acceleration, braking)
      ii. End run crash loading
      iii. Falling crash loading (sim to passenger elevators)
   b. Equipment within automated areas such as elevator-type lifts
2) Lateral loads (mainly seismic) from designated bracing bays within rack systems
3) Building loads from storage racks that support walkways, elevated storage retrieval vehicle pathways, storage mezzanines, roofs, exterior walls, and so on.
4) Conveyor leg loading, or conveyor mezzanines.
5) Conveyor systems with telescoping framing that reach into trucks at loading docks (large overturning forces including uplift)
6) Other special ground-supported equipment

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Project highlight: Rack-supported portion of a refrigerated warehouse

Figs. 43 & 44, Racking that supports the roof and braces the walls

The author was the engineer of record for a warehouse building with portions that were supported by the racking. See Figs. 43 through 46. The slab design approach for these areas was a continually reinforced slab. Concrete slabs for the automated racking areas were poured in lengths up to 303'-0", and ranged from 6" to 20" in thickness. The concrete contractor used a truss screed to level the slab. Reinforcing was used for strength design in areas with a rack-supported roof (ACI-318 design) and also for crack control due to shrinkage and temperatures as low as -15F. The concrete mix was

required to meet a shrinkage criteria of 0.04%. A manufactured sand base, 6 inches of rigid insulation, and tubing with heated glycol were used to mitigate frost penetration into the subgrade. The glycol tubing was poured within a mudslab.

Figs. 45 & 46, Reinforces slabs that support racking that supports roof and braces walls (ACI 318 foundation design required). -15F freezer on left on insulation. 34F refrigerated space on right without insulation.

The use of automated equipment required that FEM Specifications 9.831 and 9.832 needed to be met. This meant that a top of slab elevation tolerance of 0.59"+/- within the 303'-0" lengths of racking needed to be met. Racking at the High Bay Warehouse (HBW) pallet rack storage is 96 feet tall, resulting in a roof height of 105'-0" and a gravity slab loading up to 1500 psf between crane aisles. Again, the HBW racking self-supports the roof and surrounding walls. Wind loads within the racking ranged from a net 40 kips uplift to 100 kips downward at typical posts.

7) High Performance Slab Topic #7:
Superflat Floors

Some storage racking systems require floors that are very flat. Some of these are known as superflat, as defined below. **One rack system requiring a superflat floor is very narrow aisle (VNA) racking.** Due to the height of the racking combined with the narrow space provided for the lift that travels in the aisles, there is very little tolerance for the rack or the lift to be leaning one way or the other. See Fig. 47. A small irregularity in flatness of the slab at the slab elevation is magnified over the height of racking or the

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raised product on the forks of a lift. Lifts are generally guided by radio signal, and there is a systems of wires in the slab that allow for this.

For a VNA system, the aisles are required to be superflat, but only over defined locations and orientations. **Basically, the lifts need to travel in superflat aisles on what is known as "defined-traffic floors."** The floor flatness criteria is different than the criteria for "random traffic floors", or those where flatness is defined in every direction, everywhere based on FF/FL numbers. Defined-traffic floors are assigned an "F_{min}" number to establish the required flatness. The F_{min} number is determined by a review of several parameters, including: a) rack height, b) aisle width, c) operating speed of lift, and d) lift wheelbase width and front-back spacing. There are four numbers of interest: flatness from front to back wheels, flatness between wheels on the same axle, and the rates of change of each of these values. A typical F_{min} number is F_{min} 75. F_{min} number is a dimensionless number used in equations that establish limits in elevation differences or the rate of change in elevation differences for defined traffic surfaces (ref: https://face-consultants.com/wp-content/uploads/2017/03/Page-36.pdf). A profilograph is used to take measurements for the determination of F_{min} numbers (Fig. 48).

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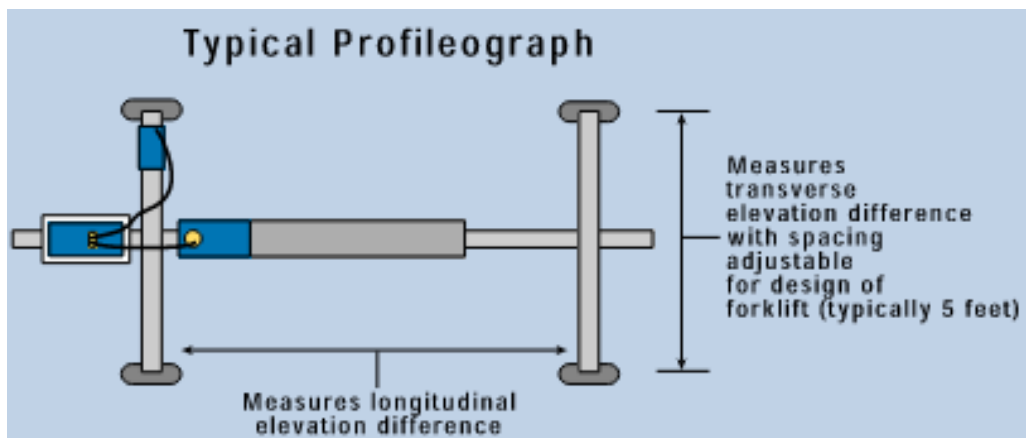Fig. 47 - Very narrow aisle racking

Fig. 48 - Profilograph (Neuber)

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Here are two ways the author is aware of to get a superflat floor slab:

1. Grinding: Pour as flat as possible and grind where necessary at aisles with a concrete contractor with extensive experience (Fricks, Kalman, etc.). Typically, 3 to 5% of the area of slab can be expected to need grinding, and this is typically less than 2% for more experienced contractors. Typical depths of grinding are 0.010-0.020" (Fricks). See Figs. 49 & 50. The use of a specialty slab system such as shrink comp concrete is recommended to eliminate as many joints and as much curling as possible. Pours can easily be 100'x100' without joints. Watch for thickness of "durable" concrete. If too much grinding takes place, the top portion of the slab with denser cement paste maybe ground through. A mineral topping such as dry shake hardener or traprock may be used to enhance the durability.

2. Narrow strips: Pour in long narrow strips without interruption, side-by-side, maybe 12' to 20' wide, again with a concrete contractor with extensive experience (Fricks, etc.). This might be good enough in one direction, but the direction perpendicular to the pours would need to be explored. Explore reinforcing, fiber, or low-/non-shrink concrete for crack control. With the reinforcing the rack installer should be informed that they'll hit some reinforcing during anchor install.

Things to review besides superflat slab placement:

1. Curling at joints. Fibers may help with curl. Suppliers would be able to provide guidance.
2. Wire guidance. Watch out for things that would interfere with in-slab wires that guide the lifts (heavy steel joints, etc.).
3. Understand the potential for any post-construction subgrade movement (settlement, heave, etc.).
4. Understanding owner needs and whether they need flexibility in rack placement over life of building. (Superflat in two directions or prescribed/permanent aisles in one direction).
5. Longer or wider pours may require armored slab joints due to potentially larger magnitude of contraction at joints.

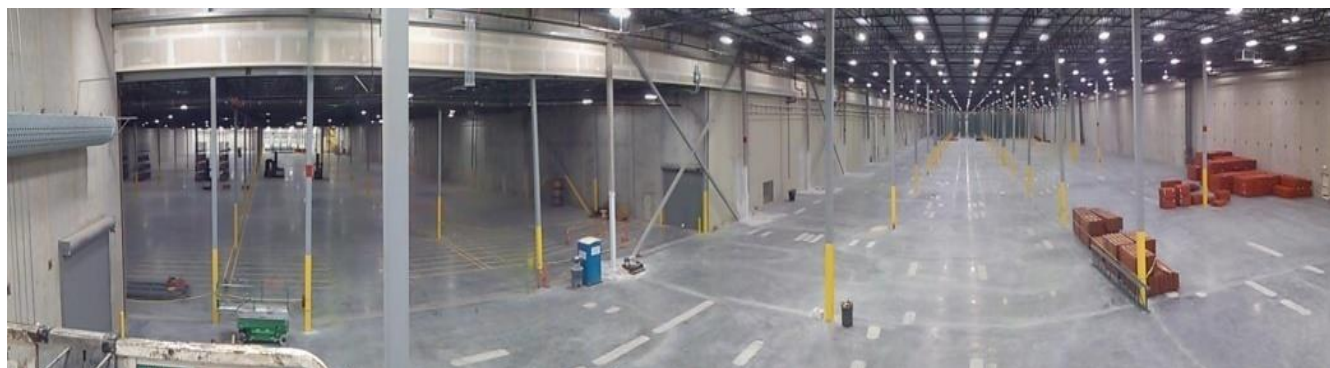Concrete Slabs-on-Grade: Warehouses III - High Performance Slabs

Fig. 49 - Areas of slab prepped by grinding for Very Narrow Aisle racking
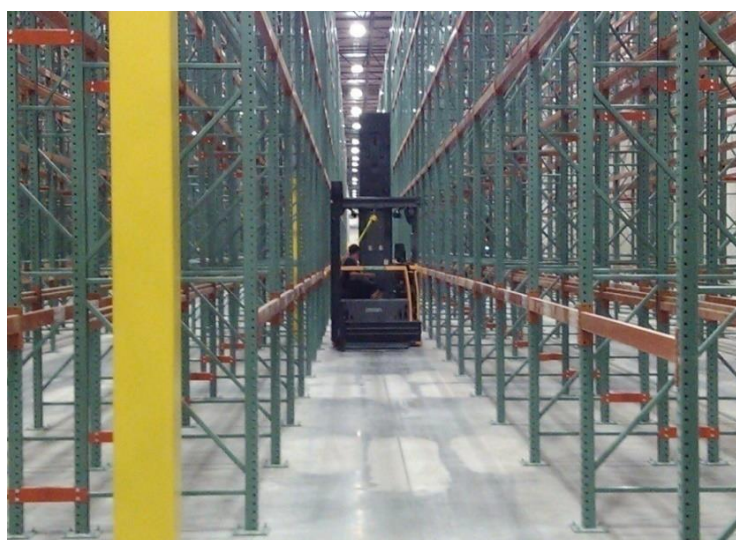
Fig. 50 - Very Narrow Aisle racking. Note grinding.

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