There are many opinions floating around as to the benefits, or lack thereof, of reinforcement in slabs on ground. Not all reinforcement works the same way. To be able to understand the potential benefits and negatives of any particular reinforcement system, one has to understand how that system theoretically works and also what happens in the real world. The purpose of this article is to discuss some of these reinforcement systems, plus what they will and will not do.

REINFOR

The Nestle Distribution Center developed by LaCasa de Pietra in Santiago, Chile, is approximately 400,000 square feet of post-tension reinforced floor. Each placement is 13x75 feet. Five placements were tensioned at one time in both directions. These were tensioned to other panel groups until the entire floor was stitched together with PT tendons. Photos: Jerry Holland

CEMENT FOR SLABS ON GROUND

What It Will and Will Not Do

By Wayne W. Walker and Jerry A. Holland

STEEL REINFORCING BARS AND WELDED WIRE REINFORCEMENT

Concrete is very strong when it is squeezed in compression but very weak when it is being pulled apart in tension. A good rule of thumb is that it is about 10 times as strong in compression as it is in direct tension. Thus, whenever you see a crack in a slab on ground, it is due to it having more tensile stress applied to it (from linear shrinkage, restraints to that shrinkage, curling, loads, etc.) than its tensile strength. Steel reinforcing bars and welded wire reinforcement are very strong in tension, have similar thermal expansion and contraction properties to those of the concrete, and thus can handle high-tension stresses while the concrete can take substantial compressive stresses.

One important concept is that typically used reinforcing (post-tensioning tendons and shrinkage-compensating concrete reinforcement are the exceptions) will not prevent the concrete from cracking. The reason for this is that the reinforcing cannot begin to start resisting significant tension until the concrete cracks. Until that point, it is mostly inactive inside your slab. Properly sized and located reinforcing will keep cracks reasonably tight and serviceable, if they occur, but will not prevent them. Furthermore, the great majority of reinforced concrete designs that have been reviewed for slabs on ground do not have enough reinforcing to actually increase the slab's load-carrying capacity above that of an unreinforced slab. Thus, unless the reinforcing is being used for other purposes (such as the "long dowel/enhanced aggregate interlock" concept noted later in this article), it is typically somewhat expensive insurance for a cracking problem that may never occur if other appropriate

Light reinforcing continued through contraction joints for load transfer and chaired up just before concrete placement.

Heavy continuous reinforcing to eliminate contraction joints and only have tight cracks.

procedures are followed, such as proper joint spacing, dowels at joints, consistent slab thickness tolerance control, good base control, and low shrinkage mix design.

Many people believe that slabs on ground typically should have some reinforcing, but most slabs in North America are unreinforced concrete and perform well. If reinforcing is utilized, the amount that should be used depends on what is to be accomplished. The percentage of reinforcing refers to the cross-sectional area of the steel for a given width of slab divided by the cross-sectional area of the slab area considered. For example, if a 6-inch-thick slab is used with #3 rebar at 18 inches on center, the percentage of steel for a 12-inch width would be:

(0.11 in.^{2})(12 in./18 in.)(100)/(6 in.)(12 in.) = 0.10%

For enough reinforcing to accomplish enhanced aggregate interlock, the American Concrete Institute (ACI) Committee 360, Design of Slabs on Ground noted that designs using 0.10% deformed reinforcement through the contraction joints have been used successfully. Reinforcement amounts much less than 0.10% have not provided dependable load transfer; and much more than this has caused excessive out-of-joint cracking. This deformed reinforcement is an alternative to smooth steel dowels, and slab expert Eldon Tipping has coined the term "long dowels" for this concept. By continuing the reinforcement through the contraction joint, the cracks that form below the sawcuts will be tighter than they would otherwise be. Thus, the reinforcing is supposed to enhance aggregate interlock, which normally cannot be depended upon for long-term load transfer of repetitive loads if the crack is 0.025 to 0.035 inches or wider, per Portland Cement Association's research. #3 reinforcing bars at 16 or 18 inches on center are the most common reinforcing schemes used on slabs constructed with a laser screed. This is due to being able to drive the concrete trucks and laser screed over them as they lay on the base and then chairing them up just ahead of the concrete placement, as the workers stand between the bars. Generally, the reinforcing is located a third to a half of the slab depth from the top so that the sawcut will not cut the reinforcement. The availability and use of early-entry saws has made this method even more dependable because the sawcuts must be made as soon as feasible.

In some situations, it is desirable to eliminate contraction joints in large placements and use enough reinforcing to have many, very tight cracks that do not spall under wheel traffic and are not an aesthetic issue; a common example is a true "superflat" slab strip placement. To have this kind of performance, sometimes called a "joint-less" floor, at least 0.50% to 0.60% reinforcing must be used near the top of the slab. These cracks will be visible, thus the aesthetics of these cracks should be discussed with the owner. In the majority of larger projects, some doweled construction joints will be required to transition to a different slab type. These joints usually will open more than those with joints at typical spacings of 10 to 15 feet. Thus, if there will be significant wheel traffic, consideration should be given to having a very good dowel system, such as plate dowels, at the construction joint and armoring the joint.

For 0.10% reinforcing, the slab joint spacing should be the same as for an unreinforced slab. Guidance for joint spacing to minimize out-of-joint cracking for such slabs is given in ACI 360 and typically should be in the 10- to 15-foot range noted earlier. Extreme care should be taken if the decision is made to extend the joint spacing somewhat by increasing the reinforcing but not to the 0.50% to 0.60% appropriate for "joint-less" floors. The main reason for the extra care is that curling increases significantly with every 1-foot increase in joint spacing, thereby significantly increasing the chances for out-of-joint cracking of unacceptable widths and joint problems.

Many opinions have been voiced regarding the best vertical location for a single layer of reinforcing for slabs on ground. Some think it should be in the lower portion of the slab due to tension in the bottom of the slab when concentrated loads were to be applied. Others feel it should be in the middle in order to provide some tensile resistance for flexural tension either in the top or the bottom of the slab. However, it is best to design the bottom of the slab as unreinforced and locate the reinforcement in the upper part of the slab.

Locating the reinforcement in the upper part of the slab is best when trying to control the visible crack widths due to the loading, curling, and base friction. Slab curling produces a significant tension stress in the top of all normal concrete slabs; if cracks do occur they are V-shaped with the widest portion at the top of the slab. Thus, the higher the reinforcement, the tighter it will hold any cracks running perpendicular to the direction of the reinforcement. However, if the reinforcing is too high it can cause plastic settlement cracks, which run directly over the top and parallel to each bar or wire. So, if the bars are spaced at 12 inches on center and relatively straight cracks are observed every

A 127x60 foot warehouse floor slab 6 inches thick with HVSF and no joints or cracks after three and a half years.

A 340x125-foot distribution center floor slab with two-way bundled PT tendons and no joints or cracks after eight years. Note void former offset so that bollard will be centered after 1 inch plus of slab movement.

12 inches, this type of cracking has occurred. The chances for plastic settlement cracks increase as one or more of the following occurs: reinforcing diameter increases, concrete cover decreases, reinforcing temperature increases typically from sunlight, concrete bleed rate increases, reinforcing movement while the concrete is still plastic, or anything that increases moisture evaporation rate from the slab surface, such as higher concrete or ambient temperatures, higher wind speed, or lower humidity.

STEEL FIBERS

Steel fibers have been available in the U.S. since the mid-1970s. Type 1 fiber is made of drawn wire of various geometries and Type 2 utilizes slit sheet steel. As with steel bar and wire reinforcement, steel fibers will not prevent cracks but can keep cracks, if they occur, reasonably tight if a sufficient amount of fiber and an appropriate joint spacing are used. If there is a sufficient quantity for a particular situation—based on slab usage, joint spacing, concrete shrinkage potential, etc.—the post-crack load-carrying ability of steel fibers can be very beneficial. However, if the cracks become wide enough to spall, this can be major problem. Thus, as with other types of reinforcing, the fiber dosage must be carefully considered with regards to the particular situation.

If steel fibers are to be used for long-term enhanced aggregate interlock and the joint spacing is to be from 10 to 15 feet, the minimum amount of fiber considered for concrete with typical shrinkage properties is 40 pounds per cubic yard. If the concrete is expected to be high shrinkage, the joint spacing should be at the low end of the range and/or the fiber dosage should be higher. As with steel bar or wire reinforcing, care must be taken if the joint spacing is extended beyond this specification. For longer joint spacings, at least 75 pounds per cubic yard is recommended.

The fibers decrease the slump of the concrete, but this can be compensated for by proper mix materials and proportioning. Generally, the same things that make a good mix without fibers will make one with them. At 40 pounds per cubic yard or more, a good midrange or high-range water reducer (the latter at a low dosage) can be very helpful and is necessary as fiber dosages increase.

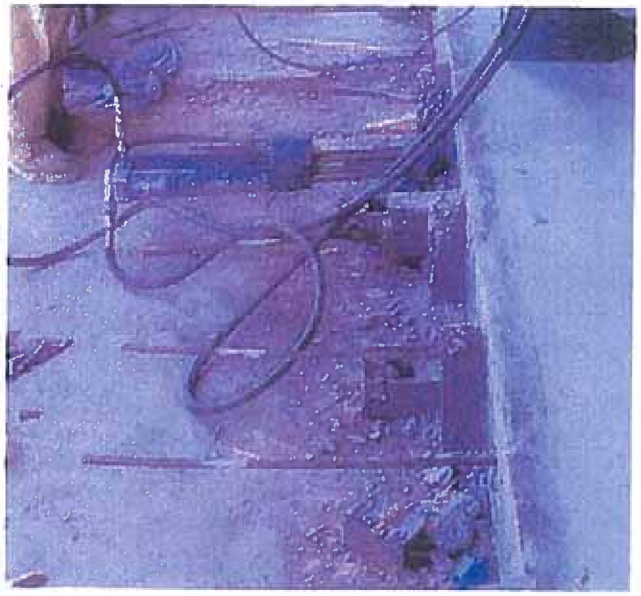
LOW VOLUME SYNTHETIC FIBERS

Low volume synthetic (non-steel) fibers (LVSF) have been available in the U.S. since the late 1970s. The main types are fibrillated (fibers joined together at the ends like paper dolls), monofilament (individual fibers of the same length), and multifilament (fibers of varying lengths). The dosage rate typically varies from ½ to 1⅗ pounds per cubic yard, and the common lengths are from ⅜ to 2¼ inches. At these dosages, the benefits are primarily during the first 48 hours or so. The early benefits are reduced potential for the following: plastic shrinkage cracking (cracks that form while the concrete is still plastic below the surface and because the surface evaporation rate exceeds the rate of moisture rise within the concrete to the surface), bleeding, significant segregation, and plastic settlement cracking over steel reinforcing bars or wires. Hardened state benefits include reduced potential for spalling due to fire.

HIGH VOLUME SYNTHETIC FIBERS

High volume synthetic fibers (HVSF) have been available in the U.S. since the turn of the century. Typically, these fibers are longer and thicker than LVSF. The geometry of the fiber, plus improvements in concrete mix proportioning and admixtures, allows HVSF to be used at higher dosages than LVSF. Some believed in the early days of LVSF that significant benefits would accrue if a much larger amount could be put into the mix; however, at anything more than about 3 pounds per cubic yard, there were major issues with mixing, workability, and finishability. At 3 pounds per cubic yard, there was improvement in some areas of performance but usually not enough to justify the increased cost and difficulties. Now with good mix proportioning and user-friendly fibers, it is possible to have up to about 7½ pounds per cubic yards of HVSF and still have surprisingly good mixability, placeability, workability, and finishability.

At fiber dosages of about 7½ pounds per cubic yard, HVSF concrete appears to behave in a substantially different manner than concrete with LVSF or steel fibers. This is probably due to extensive micro-cracking and a high degree of ductility that allows a substantial increase in joint spacing and reduction of curl. HVSF has been used in many, varied applications—industrial, warehouse, and high-end retail floors; truck pavements; and both bonded and unbonded topping slabs. Joint spacings for these applications have been from 25 to 168 feet, the great majority of these slab panels have no visible cracks after three to seven years. ACI recommends a maximum slab aspect ratio (length to width) of 1.5:1 in order to minimize the possibility of transverse cracks. However, some of the applications have aspect ratios from 3:1 to 23:1 with no cracks after up to seven years. It could not be said that HVSF concrete



PT jack and tensioned tendon with total elongation of 27 inches. Note white paint marking partial elongation in staged jacking.

slab panels will not crack, because they can crack if not properly designed and constructed, but the propensity for out-of-joint visible cracking is greatly reduced. Reduced curling from what would normally be expected also is measured.

Many of these projects had burnished, steel-troweled finishes with very little fiber visibility. Other applications had exterior broom finishes, also with very little fiber visibility. A good-looking broom finish requires keeping the broom clean and moving the broom continuously in one direction only; reversing the broom direction will make the fibers stand up like soldiers and make them extremely difficult to lie down again.

POST-TENSIONING TENDONS

Post-tensioning (PT) compresses the hardened concrete in the slab on ground by pulling and anchoring PT tendons with hydraulic jacks. If the concrete slab has a reasonable amount of compression for its full depth, theoretically it can never crack (see previous crack discussion). Doing so can allow thinner slabs and very long construction joint spacing (contraction joints are not used). Single placements up to 500 feet long and up to 125 feet wide have been placed without cracks. Areas up to about 400,000 square feet without open joints have been constructed by post-tensioning individual placements together.

PT tendons consist of very high-strength steel (three to four times stronger than typical rebar), 7-wire, ½- or ⅗-inch strands with anchors at the ends and wedges to hold the tendons' tension after they are jacked. Unbonded PT tendons are encased in corrosion-resistant grease and plastic sheathing. Bonded PT tendons are used far less in slabs on ground than unbonded ones and are placed in ducts that are grouted after the tendons are tensioned. Tendons can be run in one direction (one-way PT) or at right angles to each other (two-way PT), but each system has considerations that must be carefully thought out in design and construction. Draped tendons sometimes are used for PT slabs on potentially expansive or collapsing soils, but flat-bottomed PT slabs on normal soils typically use straight tendons in the middle of the slab depth. As long as the tendon is located in the middle third of the slab depth, no tension will be produced in any portion of the unloaded slab. For example, a 6-inch slab must have at least 2 inches of cover top and bottom to have compression over the full depth. Thus, proper vertical tendon location can help prevent cracks, but improper location can actually cause cracking. Tendons located in the bottom third are of special concern in slabs on ground because they can induce cracking in the visible top surface.

The timing and staging of tendon jacking is extremely important for large PT placements where cracking potential must be minimized. Tendons are partially tensioned the next morning, no matter what the concrete strength is, and have a second stage tensioning later. For very large placements or during cooler weather, a third stage is needed. If a crack occurs before tendon tensioning, the crack can sometimes be closed if tensioning can be done soon enough. One major mistake many people make with PT slabs on ground is not detailing and constructing the slabs to move freely. All slabs want to move somewhat, but very large PT slabs can move over 2 inches at the ends, and two-way slabs will move in both directions. A choice has to be made: the PT slab must be able to move or it will experience severe cracking.

SHRINKAGE-COMPENSATING CONCRETE REINFORCEMENT

Shrinkage-compensating concrete (SCC) is made with special cement called Type K or an additive component plus normal portland cement, which causes volume of the concrete to increase after setting. If the SCC is properly and elastically restrained, it induces compressive stresses that are intended to approximately offset the tendency of concrete drying shrinkage to induce tensile stresses. In SCC floors and pavements, properly sized reinforcing steel (not too much and not too little) that is correctly located (which is critical) provides the restraint noted, along with the appropriate base friction. If properly designed and constructed, the SCC expands during the first seven days, thereby stretching and actually prestressing the reinforcing steel. Afterward, the SCC shrinks like normal concrete and the tensioned reinforcing acts like a stretched rubber band to keep the SCC in compression as it shrinks. Finally, the concrete volume decreases to approximately its original volume, if everything functions as it should. It sounds like "black magic" but really works well if done correctly.

This system has been used successfully since 1964 to produce typical joint spacings from 100 to 150 feet without cracking or curling. Even larger slabs with joint spacings up to 340 feet have been produced with special designs. No contraction joints are used in SCC slabs. Because there is no curling if properly done, SCC slabs are designed to be to be thinner and have fewer dowels than normal concrete slabs. Reinforcement for a 6-inch SCC slab is commonly #4 rebar at 18 to 24 inches on center with 1½ to 2 inches of top concrete cover. Detailing is very important because these slabs must be allowed to move; they will not move as much as PT slabs but can easily move ⅜ inches or more.

STRATEGIC REINFORCEMENT

The No. 1 problem for exposed jointed slabs in industrial and commercial environments is joint deterioration—concrete

One major mistake that many people make with PT slabs on ground is not detailing and constructing the slabs to move freely.

Tapered plate dowel baskets being installed just ahead of concrete placement at contraction joint location painted on base.

spalling, joint filler splitting and separation—due to shrinkage, curling, and wheeled traffic crossing joints that have too much differential vertical movement (or poor joint stability). The previously described concept of providing continuous light reinforcing to enhance joint stability only makes economic sense when the cost of that reinforcing is less than that of providing other types of mechanical load transfer mechanisms at joints. Where this cost advantage is not apparent, a better solution is to strategically relocate the cost of the reinforcement that was inefficiently located between the joints and use that value at the joints where it can be optimally utilized. Many slab designers and contractors now are turning to this strategic relocation concept (some have termed it "strategic reinforcement"), are using dowel systems that provide for lateral movement as well, and have eliminated the more costly reinforcement consisting of bars, mats, heavy welded wire reinforcement, or fibers. This concept has saved on total steel costs while typically providing other advantages over one or more of the reinforcement options previously noted.

CONCLUSIONS

There is no one reinforcement system that is always best for all projects' construction and maintenance budgets, operations, owners' expectations, and other needs. Any one or more of the reinforcement systems discussed can be beneficial in producing acceptable slabs, as long as everyone involved is aware of what those systems will and will not do. ■

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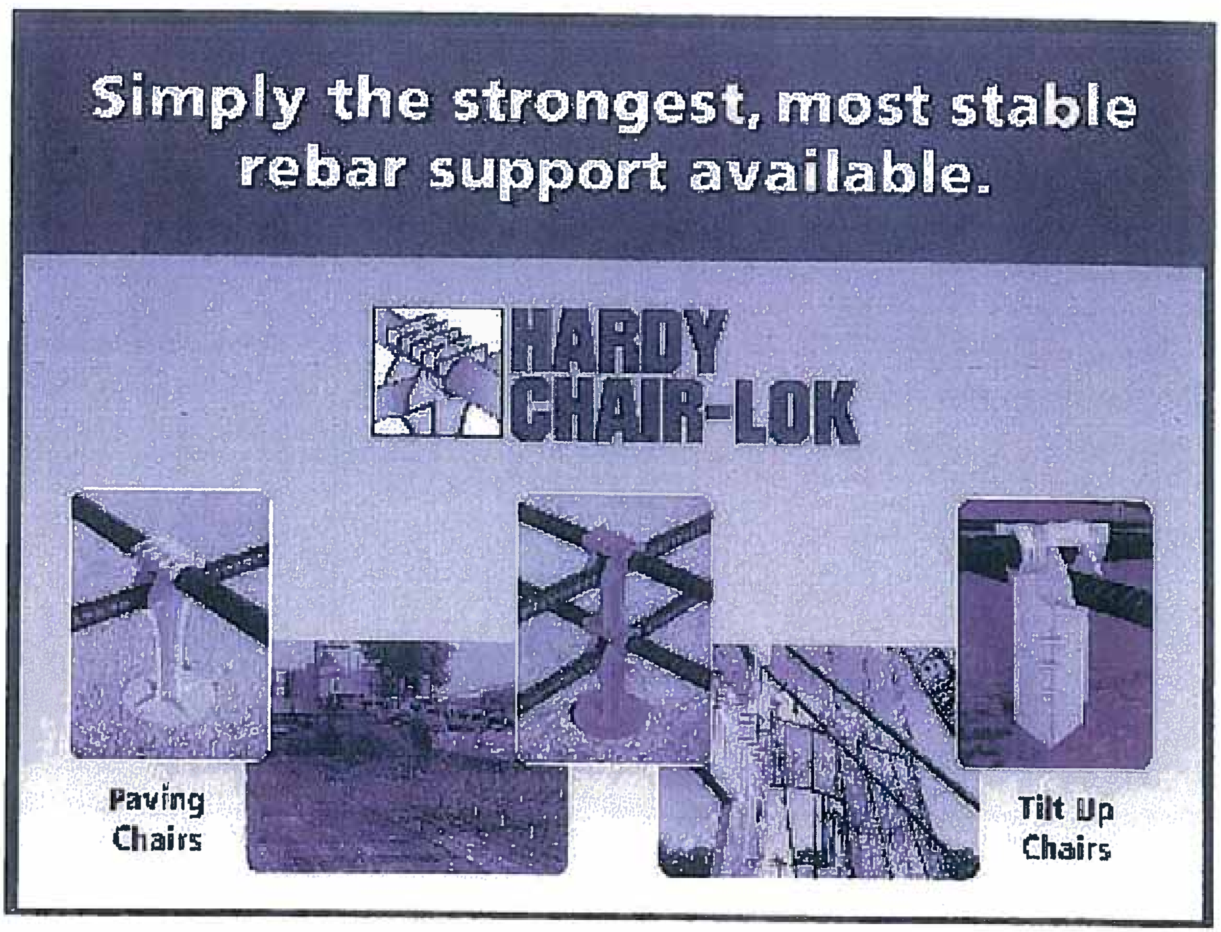

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