# Designing the Cost-Effective Slab-on-Ground

## Least Likely to Crack or Spall

*By Nigel Parkes*

Crack-free concrete slabs-on-ground simply do not exist. It is not a matter of how much a slab will crack, but the location of cracks and resulting issues they cause for the owner. And, with the advent of lift truck equipment with small, hard wheels, joints and cracks spall more rapidly. Random cracking in slabs-on-ground and joint spalling are the causes of many lawsuits every year, leading to millions of dollars in damages awarded, as well as lost productivity.

*Figure 1: The use of the new style lift trucks with small, hard wheels requires better slab designs to prevent joint spalling*

### What Causes Cracking in Concrete Slabs-on-Ground?

When asked the question, "What is the biggest cause of random cracking in concrete slabs on ground?" most designers and contractors alike say shrinkage. However, that is only partly right. The correct answer is restraint to normal drying shrinkage and/or curling stresses.

In an attempt to set reasonable expectations, ACI 360R-06, *Design of Slabs-on-Ground*, suggests that some random cracking should be expected; a reasonable level might be random, visible cracks to occur in 3 percent or less of the surface area of floor slab panels formed by saw cutting, construction joints, or both.

### What Causes Joint Spalling?

Curled joints deflect under load and allow wheeled traffic to impact the joint edges (*Figure 1*). Joints without sufficient load transfer, proper joint filler application, or both can spall very quickly.

Of course, anything that reduces total shrinkage of concrete will help reduce curling and cracking, but until non-shrinking concrete is developed and becomes readily available, it is necessary to consider design and construction methodologies that will best accommodate concrete's normal drying shrinkage. The best design is one that will:

- limit restraint as much as possible,
- minimize curling stresses,
- provide stable joints,
- conform with industry guides (to reduce the designer's liability),
- be easily constructible (to reduce design execution risk), and
- meet the owner's budget requirements.

### Curling/Warping Stresses, Joints, and Joint Spacing

Recent analysis has shown that curling stresses play a much larger role in the development of random cracking in slabs-on-ground than has been considered before. All three thickness design methodologies listed in the recently released ACI 360R-06 – PCA, WRI, and COE – were based on work by Westergaard in the 1920s that assumed the slab was in intimate contact with the base.

It is now known that all slabs curl and therefore rely on positive load transfer across joints to simulate Westergaard's core assumptions: "effective shear transfer at both construction and intermediate saw cut contraction joints is required to avoid a loaded free edge."(ACI 360R-06)

Designers are also strongly cautioned that aggregate interlock will not provide sufficient load transfer at joints that open more than 0.035 inches. The recommended joint spacing is intended to minimize potential for mid-panel out-of-joint random cracking, and is independent of load transfer at joints. The new ACI 360R-06 recommends a maximum joint spacing of 15 feet for high shrinkage concrete. Credit in the form of a slightly increased spacing is afforded to designers and contractors who develop and employ lower shrinkage concrete mixes, but designers should be cautioned that unless they can be sure that the concrete will produce a shrinkage strain of less than 780 millionths when placed on a dry base material, they should adopt the more conservative spacing recommended for "high shrinkage concrete."

### Curling vs. Warping

The terms "curling" and "warping" are used in some ACI documents interchangeably. In others, the term "curling" is used to describe the distortion of the slab profile due to moisture gradient and "warping" is used to describe the distortion due to thermal gradient. For the purpose of this article, the terms are used interchangeably.

### What is the Difference Between a Crack and a Joint?

A joint is actually a crack that the designer intended, and a crack is a joint that the concrete intended. The correct design, spacing, and installation of joints will have the single largest effect on the reduction of random cracking. ACI 360R-06 states that "the designer should provide the layout of joints and joint details. If the joint layout is not provided, the contractor should submit a detailed joint layout and placing sequence for approval by the designer before proceeding with construction." Improper design and/or installation of joint details and layout causes more

conflict and litigation regarding slabs-on-ground than any other construction factors.

There are three types of joints needed for concrete slabs-on-ground: contraction, construction, and isolation joints. All three are intended to relieve stresses in the concrete and limit the number of random (out of joint) cracks.

Contraction joints are simply controlled cracks. Saw-cutting a straight line in the concrete surface creates a weakened plane to induce a crack (joint) to form below the saw-cut. By causing the concrete to crack where the designer intends, suitable load transfer devices can be provided across the joint (crack) and a properly installed semi-rigid joint filler can protect the joint edges (full depth of the saw-cut), thus preventing joint spalling.

Formed construction joints are used to create a "stopping place" for contractors. As such they define the extent of an individual concrete placement but should otherwise be treated just like contraction joints. Unless specifically prohibited by the designer, contractors should be free to interchange construction and contraction joints to suit their construction sequences and schedules. Again, load transfer and joint filling are essential to prevent joint spalling under wheeled traffic.

Isolation joints should provide a complete break from all other building elements, thus reducing any restraint that may be induced by contact with these elements. As such, they should not contain any load transfer devices and should be treated as free edges.

## Joint Details

Many designers erroneously assume that the means and methods of installing joint details should be the responsibility of the contractor. To minimize design execution risk, designers should clearly identify specific requirements for each joint type.

### *Contraction Joints*

Timely saw-cutting of contraction joints will significantly reduce the probability of out-of-joint random cracking. By specifying the use of an early-entry saw, designers can be sure that joints will be in place early enough to relieve the development of tensile stresses in the concrete without inducing raveling of the aggregates (joint spalling) during the saw-cutting operation. For load transfer in contraction joints, tapered plate dowel baskets allow proper joint activation, thus significantly reducing the accumulation of tensile stresses that cause random cracking. Recent research provides recommendations for size and spacing of tapered plate dowel baskets in various loading conditions (Walker & Holland, *Concrete Construction*, January 2007). The misalignment of round dowel baskets can lock joints and induce significant restraint and cracking. Tapered and rectangular plate dowels also provide an optimized use of material. ACI 360R-06 provides recommended dowel size and spacing for various slab depths and shows the increased spacing for plate dowels.

### *Construction Joints*

Improper forming of construction joints can have a significant impact on both cracking and joint spalling. ACI 302.1R-04, *Guide for Concrete Floor and Slab Construction*, suggests that bulkheads should be "wood or metal; they should be placed at the proper elevation with stakes and necessary support required to keep the bulkheads straight, true, and firm during the entire placing and finishing procedure. Keyways are not recommended."

In the absence of clearly defined specifications regarding bulkheads, some contractors choose to use partial depth forms to eliminate the need for hand finishing at joints. Unfortunately, the forms are not always sufficiently rigid to hold the form plumb or in the same alignment with the subsequent saw cut joint. As a result, the unintended keyway created by the partial depth form often cracks, thus creating a badly spalled joint.

With regard to load transfer devices, the same document states that the "diameter or cross-sectional area, length, shape, and specific location of dowels as well as the method of support should be specified by the designer." It also suggests that diamond-shaped plate dowels (*Figure 2*) allow slabs to move horizontally without restraint, and recommends that this type of dowel be placed within 6 inches of a joint intersection where the curling stresses and horizontal movement are at their greatest (*Figure 3, see page 12*). Conventional round dowels create restraint to sideways movement parallel to the joint, even when they are perfectly installed.

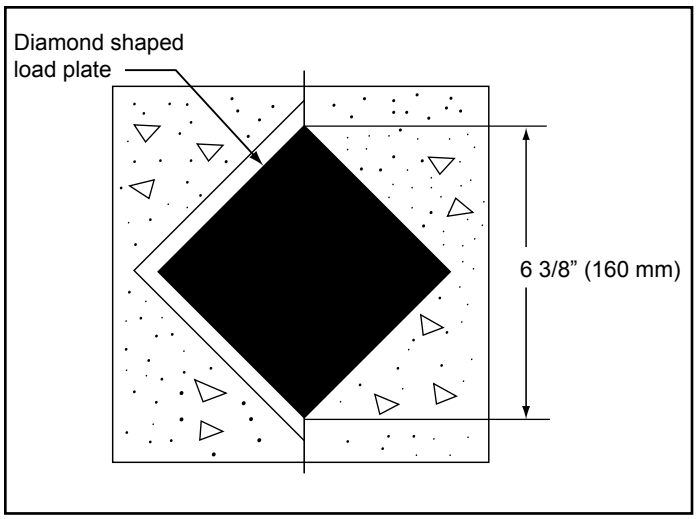


*Figure 2: Diamond-shaped load plate at construction joint.* (ACI 360R-06)

### *Isolation Joints*

ACI 360R-06 has specific recommendations for both the design and means and methods for installing isolation joints.

## Reinforcement

Possibly the biggest misconception of owners regarding concrete slabs-on-ground is that reinforcement prevents cracking. This misconception was possibly proliferated by older ACI guides that suggested reinforcement was "for crack control." The new ACI 302.1R-04 attempts to dispel this myth with the simple addition of one word, "width." The document section on reinforcement for crack-width control states that "reinforcement restrains movement resulting from slab shrinkage and can actually increase the number of random cracks experienced, particularly at wider joint spacing." Given the high cost of steel reinforcement, why is so much steel still used in slab-on-ground construction? Here are the three most common answers:

- *Marketing* – The depth and magnitude of the misconception regarding the use of steel reinforcement in slabs-on-ground makes it difficult for realtors to lease or sell buildings with unreinforced slabs. However, a 2004 article in *Concrete International* (*Cost Effective Slabs-on-Ground*) clearly shows the cost and performance benefits of a "strategically reinforced" slab, with tapered plate dowels to reinforce the joints and no mid-panel reinforcement, compared to a conventionally reinforced slab.
- *Load Carrying Capacity* – ACI 360R-06 states that "the inclusion of reinforcement (even in large quantities) has very little effect on the uncracked strength of the slab. The PCA, WRI, and COE thickness design methods may all be applied identically to the design of reinforced slabs-on-ground by simply ignoring the presence of reinforcement." Insufficient load transfer, on the other hand, will significantly impair the load carrying capacity of a slab.
- *Fear of Litigation* – In today's litigious environment, changes to the norm are resisted. However, conventional

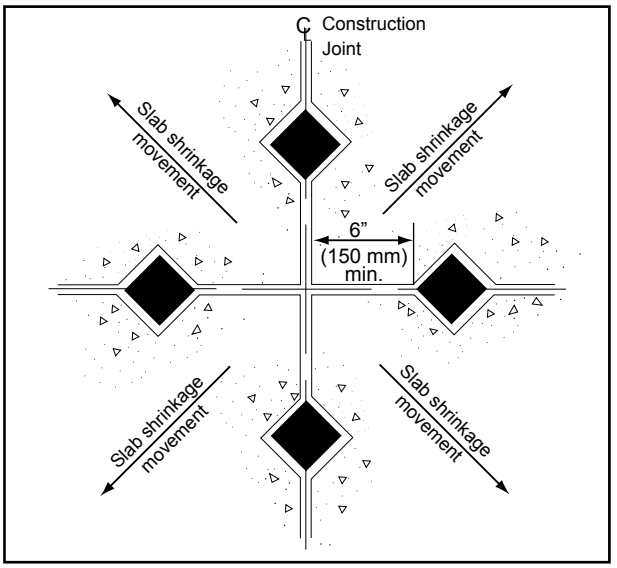


*Figure 3: Diamond-shaped load plates at slab corners.* (ACI 360R-06)

methods are causing many of the problems encountered by owners and resulting in litigation. Some might argue that mid-panel reinforcement provides "insurance" to hold tight the cracks that do occur. With the cost of steel today, this is surely expensive insurance, and as stated in key industry guides, it might actually increase the number of cracks experienced, particularly if the inclusion of reinforcement prevents remedial work to a rutted base.

## Soil Support System (base or sub grade)

Cracking is caused by restraint, internal or external, of volume change. Possibly the largest source of restraint to a slab's normal drying shrinkage is induced by the slab's contact with the base. Base friction can be reduced with the introduction of a compacted and rolled stone base. Designers should minimally specify that all bases be proof rolled with a fully loaded concrete truck and require that proper repair of rutting or pumping be performed both before and during concrete placement.

Omission of mid-panel reinforcement allows for remedial base work during concrete placement. Rutted bases often go untended in conventionally reinforced designs because the rebar mat makes it impossible for the contractor to bring a roller compactor back in to straighten grades during placement. Restraint caused by uneven, rutted bases can significantly contribute to the number of random cracks experienced. A "strategically reinforced" design negates the need for concrete pumping or telebelting, and allows contractors to truck-dump concrete and still maintain a good base.

## Curing

According to ACI 302.1R-04, "After proper placement and finishing of suitable quality concrete, curing is the single most important factor in achieving a high quality slab." Inadequate curing is a significant contributing factor to floor and slab surface imperfections such as cracking, crazing, low wear resistance, dusting, popouts, and curling. Specifying wet curing is a solution to the vast majority of these imperfections.

## Conclusions

Based on current industry guidelines and research, when trying to limit random cracking and spalling in a ground supported concrete slab, designers should either consider a premium slab design (post-tensioned or shrinkage compensated concrete; a more expensive option), or omit the use of mid-panel reinforcement and specify:

- a dense graded stone base;
- proof rolling and repair of rutting or pumping in sub-grades both prior to and during placement operations;
- joint spacing as recommended by ACI 360R-06;
- use of early-entry saw-cutting equipment;
- tapered plate dowel baskets in contraction joints to provide positive load transfer and allow for proper joint activation;
- use of full-depth, wood or steel bulkheads (forms) in construction joints;
- diamond-shaped plate dowels in formed construction joints to provide positive load transfer and reduce restraint to lateral movement of slabs;
- ACI recommendations for design and installation of isolation joints;
- a wet cure using a moisture retaining cover.

A design with this specification, a quality concrete mixture, and a competent contractor will produce a concrete slab least likely to crack or spall while keeping the engineer, contractor, and owner aligned and out of court.▪

*Big Box Retail. Many millions of square feet of 'strategically reinforced' slab are placed throughout the US every year delivering good serviceable slabs*

## References

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2."Design of Slabs-on-Ground", ACI 360R-06
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