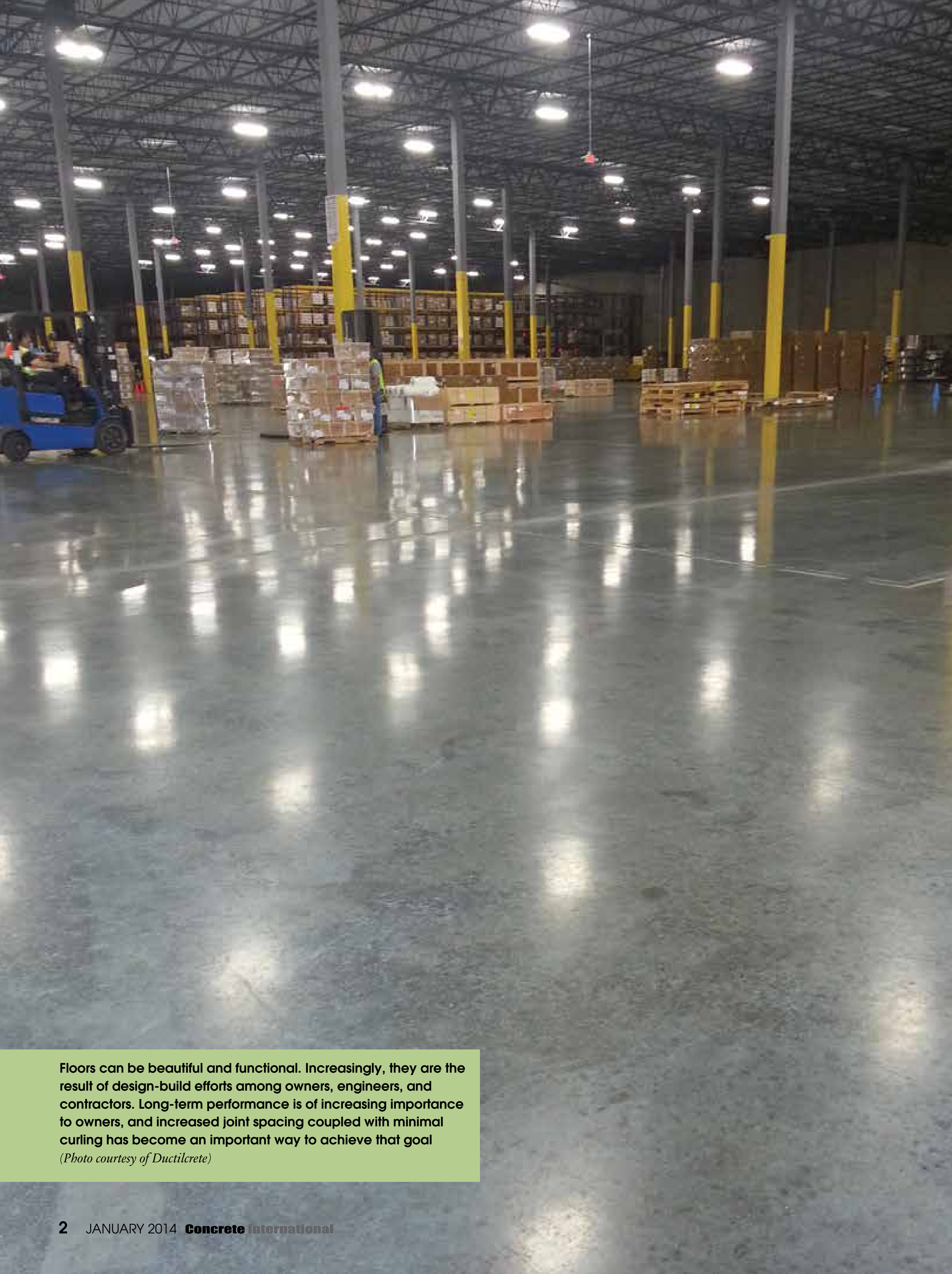


Floors can be beautiful and functional. Increasingly, they are the result of design-build efforts among owners, engineers, and contractors. Long-term performance is of increasing importance to owners, and increased joint spacing coupled with minimal curling has become an important way to achieve that goal
(Photo courtesy of Ductilcrete)

Reinventing Floor Construction

Disruptive technology is changing the way we construct floors

By Jack Gibbons and Joe Nasvik

The technologies used to construct industrial and commercial floor slabs have evolved in significant ways through the years. Changes have included:

- Ongoing development of concrete mixtures, often with the goal of reducing paste content and shrinkage;
- Refinement of design rules for laying out saw-cut contraction joints, normally resulting in more joints;
- Development of more efficient placing, finishing, and jointing technologies;
- Development of hardware to ensure load transfer across joints; and
- Development of technologies and protocols for measuring slab flatness and levelness (F_F and F_L per ASTM E1155, "Standard Test Method for Determining F_F Floor Flatness and F_L Floor Levelness Numbers") to verify contractor placing and finishing skills.

Many of these developments have been made to address contractors' demands for greater productivity or owners' demands for flatter, more level floors. However, most have done little to reduce slab curling, some may have actually exacerbated the problem, and others may have created their own unique problems. Mixtures with minimal paste contents have been developed to minimize shrinkage, for example, but when used with modern finishing technologies and methods, mortar flaking may result.[1]

Although it's rare for an engineer or contractor to track long-term slab flatness or evaluate a floor's performance over time, owners do track floor performance over a building's lifetime—and many are not happy with the maintenance problems associated with curling. So today, designers and materials manufacturers are exploring ways to minimize curling.

Rather than make incremental changes, Ductilcrete® Slab Systems, LLC, of Gilberts, IL, has developed a radically different way to construct floors. Their new system, which includes a concrete mixture that exhibits almost no shrinkage, is practically eliminating curling. The company is also testing their low-shrinkage concrete mixtures in thin toppings for exterior asphalt and concrete paving. The toppings have withstood even the harshest exterior conditions, including multiple freezing-and-thawing cycles, salt applications, snowplow abrasion and impact, and the regular wear and tear of cars and trucks.

What Owners Want

The owners and developers of distribution centers, industrial buildings, and commercial spaces influence how floors are built. If you think they only care about paying the lowest price and how much maintenance will cost over time, you would be wrong. They are concerned that their floors will work with the latest technologies in warehouse material handling equipment, are interested in aesthetic appearance, and consider how a space might be used when they are done with it. Robert Guarnaccio, President of Stout Development Services, Libertyville, IL, a company that develops and sells industrial space, says most owners and developers of commercial space are concerned about performance over the long haul and understand the importance of curling issues more than anyone. Here's his list of what owners consider to be important floor issues:

- Aesthetics—They want their floors to shine and be lustrous;
- Load-bearing capacity—They need to know what can be stored and moved across the floor;
- Residual value—They know their properties will be sold someday, so they want to maximize resale value by meeting the needs of the next owner;
- Damage to and by floor joints—They want to minimize wear and tear on material handling equipment as well as the slabs themselves;
- Flatness in traffic lanes and racking areas—They need floors that remain flat over the lifetime of the building;
- Joint layout—They are concerned, for example, about how the joints will affect wire-guided pallet racking layouts;

- Maintenance needs—They need to be able to develop realistic operating budgets;
- Column and contraction joint spacings—They want to minimize obstructions and joints, the sources of many of their maintenance problems;
- Sealers—They try to avoid them because of the down-time associated with their reapplication;
- Versatility—They want floors that can be adapted for narrow-aisle traffic without expensive slab modifications;
- Warranties—Many want warranties on F_F and F_L values for the life of a lease, and leases may last 5 to 10 years;
- Initial cost—They obviously want to minimize construction costs; and
- Improvement—They want a higher level of performance than they currently receive.

Guarnaccio says many owners know little about the structural aspects of floor construction, floor components, or how they work together. He sees this as part of his responsibility: to inform them about what they need to know. "I particularly like customers who have experienced problems with their floors in the past because they are the most knowledgeable about what they want to avoid," he adds.

Shrinkage and Curling

All concrete shrinks, primarily because concrete mixtures include more water than is necessary for cement hydration. This "water-of-convenience" helps with placement and finishing but evaporates as slabs cure and age, reducing slab volume in the process. But there are other factors, such as void spaces between aggregates and the amount of paste in a mixture, that also influence shrinkage. For standard concrete mixtures, the typical shrinkage in slab-on-ground floors and pavement is about 0.06%, or roughly 0.75 in. in 100 ft (20 mm in 33 m).

The top part of the slab-on-ground almost always has greater shrinkage than the lower part because the upper surface is free to dry faster and the upper portion has higher unit water content when it sets.[2] The resulting differential shrinkage between the upper and lower parts of the slab causes the panel edges to lift up. This ultimately causes problems at the joints, particularly when heavy lift trucks rock the panels and pound the joint edges as they move across the joint.

Engineers and contractors try to minimize shrinkage because increased shrinkage can increase joint width and cracking, and those impact maintenance costs. The following paragraphs describe some of the

Evaluating Curl

Curl numbers provide a very simple and convenient means for gauging slab curl. They are derived from the same profile readings used to compute F_F and F_L numbers per ASTM E1155, so they are also very inexpensive to obtain. To establish a slab panel's baseline (that is, "uncurled") condition, the diagonals of a panel are surveyed on 1 ft centers. If the length of diagonal is L ft, the index numbers i for the survey points will be given by $-L/2$, 0, and $L/2$ for the start point, the panel centroid (intersection of two diagonal runs), and end point along the diagonal, respectively. The values for i between these points will be integers sequenced accordingly.

The uncurled state of the slab panel can be described using the elevations b_i (calculated for each point i per ASTM E1155) using the data from an initial baseline survey of the diagonals. The curling of the panel can then be determined at any later date by repeating the diagonal survey and calculations to find the current elevations c_i for each point i.

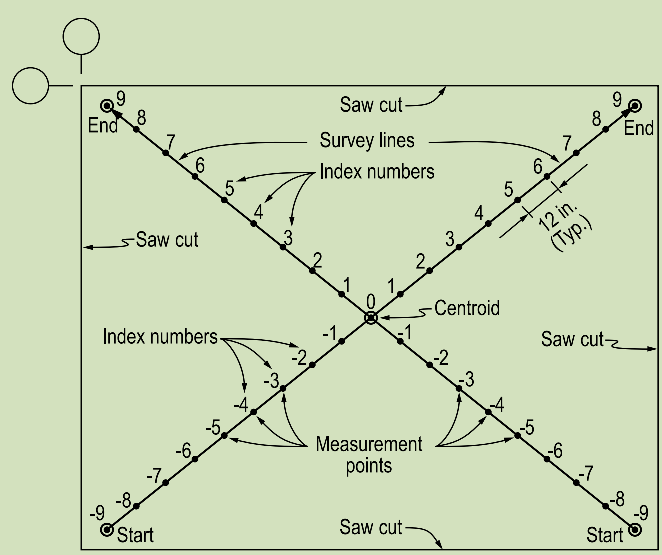
The current curl number C is given by

$$C = \frac{10{,}608{,}000S}{3L^5 + 15L^4 + 20L^3 - 8L}$$

where S is given by

$$S = \Sigma_{i=-L/2}^{L/2} i^2 (c_i - c_0 - b_i + b_0)$$

Physically, the radius (in ft) of the least-squares regression circle fitted through the diagonal is 265,200/C. Long-term C values on conventional slabs usually range from 50 to 150. In contrast, Ductilcrete slabs have been found to have C values that are practically zero.



The curl number for a slab panel can be calculated using surveys along panel diagonals and calculating the elevations at measurement points along the runs per ASTM E1155 (Note: 12 in. = 305 mm) *(Illustration courtesy of Allen Face Companies)* traditional ways to control shrinkage and reduce cracking.

Shrinkage-compensating concrete

This type of concrete is made with Type K or Type M cements or ordinary cement with a Type G expansive additive. Slabs constructed with shrinkage-compensating concrete are continuously reinforced in two directions. The expansive cement or additive causes the concrete to expand shortly after hardening, placing the reinforcing bars in tension and the concrete in compression. As the concrete dries, the slab slowly shrinks back to its original volume. As it shrinks, the reinforcing steel maintains a compressive stress and minimizes cracking, even in a slab with minimal joints. A drawback of this type of construction is the requirement for a 7-day moist cure to ensure the concrete expands sufficiently to place the reinforcing in tension.

Post-tensioned slabs

Another technology for minimizing cracks and avoiding joints altogether is post-tensioning (PT) with high-strength steel. PT reinforcement is used to compress concrete floors after the concrete has hardened. As the concrete shrinks, the compressive stress is sufficient to overcome tensile stresses that could cause cracks to develop. A drawback of this type of construction is the development of wide joints around the perimeter of the panel.

Optimized concrete mixtures

The best concrete mixtures are engineered to have "well-graded" aggregate distributions to reduce void spaces between aggregates. These mixtures require less cementitious material and water, and therefore have lower paste contents than more common mixtures. However, consideration must be given to local aggregate supplies; some aggregate sizes may not be available. Additional benefits can be obtained by using shrinkage-reducing admixtures (SRAs), which reduce shrinkage by lowering the surface tension of the pore water in the concrete. Finally, mixtures with high dosages of fibers, steel, or synthetic macro have been found to need fewer contraction joints than ordinary mixtures.

Curling

Although shrinkage and curling are related, curling is the most serious long-term problem for owners. If curling problems arise, the contractor will often catch the blame—even though the floor met the project specifications. The engineer may not hear about the problems, however, and will probably repeat the errors of the past.

It's common to think that curling occurs only at the edges of a panel. But Allen Face, Owner of the Allen Face Companies of Wilmington, NC, points out that curling causes a slab panel to form a spherical shape, with the centroid of the panel at the lowest point (Fig. 1). "Curling is the result of drying shrinkage in the surface region of a floor panel, so this is where preventative efforts should be focused. There is very little shrinkage at the bottom portion of a slab because water is retained for a much longer period of time," he says.

As differential shrinkage develops, panel edges lift off the ground, requiring the center portion of the panel to carry more load and compress the base and soil. As a result, the centroid of a panel loses elevation as the edges of the panel gain elevation. When floor panels curl, "panel rocking" occurs as forklift traffic passes over them, eventually causing cracks to develop parallel to the perimeters of the panel as the flexural strength of the slab is exceeded.

Fig. 1: Floor panels curl in spherical shapes. The perimeter of a panel can rise from 1/8 to 1 in. (3.2 to 25.4 mm) above the base *(Illustration courtesy of Ductilcrete)*

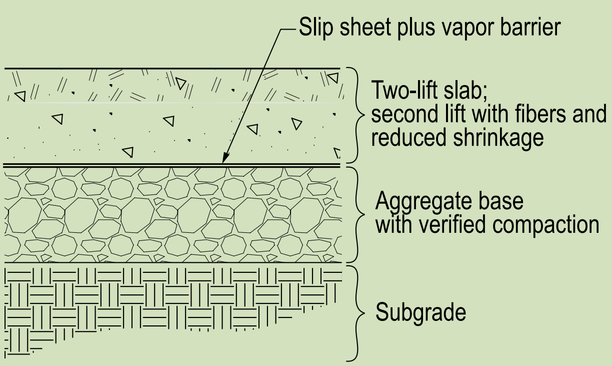
Fig 2: This core sample shows how integrally the first lift and second lifts bond. The frayed fibers visible on the cut surfaces of the core provide the only obvious evidence that the slab was placed in two lifts *(Photo courtesy of Joe Nasvik)*

At present, there is no ACI-approved method for measuring curl. Floors are measured to verify F_F and F_L, but this is done to verify that the slab has been finished per the specification and it's therefore completed before curling develops. However, Face has designed a method to measure curl in floor panels. The same instrument for measuring F_F and F_L is used—one capable of recording 0.005 of an inch (0.127 mm) elevation changes—but curling measurements are recorded along diagonal lines across the corners of a panel defined by sawed contraction joints. "As with F_F and F_L measurements, profiles are taken just after finishing and sawing operations are complete to profile the original surface of the slab and this information is compared with later measurements," he adds (refer to the sidebar on "Evaluating Curl").

Key Ductilcrete System Elements

The Ductilcrete System includes:

- Floor drawings and specifications sealed by a Ductilcrete engineer;
- Contraction joints limited to column lines, resulting in 80% fewer joints than traditional designs; and
- F_F and F_L numbers guaranteed to remain within 90% of specified values.



Specifications for the two-lift floor system require placement over a level, proof-rolled base covered by a double slip sheet

Reducing Curling

Several construction companies and product manufacturers have introduced ways to reduce both shrinkage and curling in floor slabs. Any designer can specify high dosage levels of steel or synthetic macrofibers or SRAs to improve the long-term performance of their floors. Other products are proprietary and require licensed installers. Ductilcrete is an example of a proprietary system that works through an alliance of contractors to deliver floors that hold their F_F and F_L numbers. Since the inception of the concept, the company has successfully placed over 30 million ft^2 (2.8 million m^2) of floors, toppings, and paving. They employ a systems approach, bringing many elements together to produce the desired results (refer to the sidebar "Key Ductilcrete System Elements").

Bruce Randall, who heads the engineering division for Ductilcrete, says that they supply the engineering for every project contracted. Their involvement starts during the bid process—Ductilcrete contractors submit a set of contract documents to Randall's group, who re-engineer the floors to meet Ductilcrete standards. Ductilcrete alliance contractors then install the slabs per new slab construction documents produced and sealed by Ductilcrete engineers. These projects are warranted to have near-zero curling for up to 5 years. Randall says they often work as delegated engineers for the floor slab, along with the prime professional that has overall responsibility for a project.

Based on the theory that shrinkage occurs only in the top portion of a slab, much of Ductilcrete's work is placed in two lifts (Fig. 2). The bottom layer consists of a conventional concrete mixture, similar to what's used in standard floor construction. The top portion of the slab includes macrofibers, a moisture containment admixture, and SRAs. The two lifts are placed wet-on-wet, very quickly and efficiently, resulting in significant cost reductions relative to construction of slabs with conventional overlays. With almost no shrinkage in the top lift, curling is virtually nonexistent. And the macrofibers in the top lift help to ensure that cracks, if any, are minimal in width.

Randall says their leverage with owners is their warranty. "We provide specifications and details for all installations, based on owner needs and local conditions. Each project is supplied with stamped drawings and the multi-year services warranty," he says. "This, along with professional liability insurance, provides a superior comfort level for owners."

Installing a proper base, confirmed by required proof rolling, is a critical element in their system. Because there is virtually no curling in the system, floor panels rest uniformly on the subgrade and transfer loads directly to the soil. For this reason, engineers can specify thinner slabs that are capable of carrying greater loads than conventional designs.

The typical guideline for laying out contraction joints is a spacing of roughly 24 to 30 times the thickness of the slab. For example, joints for a 6 in. (150 mm) thick slab would be spaced 12 to 15 ft (3.6 to 4.5 m) apart. This means a 40 x 40 ft column bay could have 320 ft of joints (a 12 x 12 m bay could have 96 m of joints). Many designers specify floors with steel or macrofibers at high dosage levels to significantly extend joint spacing beyond current recommended limits. Because the top portion of the slab still tends to shrink, however, the design can lead to the formation of dominant joints of widths of up to 7/8 in. (22 mm). Ductilcrete's composite design includes saw-cut joints, almost through the full depth of the top lift, only at the column lines. This allows the bottom lift of the slab to crack, but overall shrinkage of the slab is minimized because the top lift includes moisture-retaining admixtures plus SRAs. Just as in the lower portion of a conventional slab, the bottom lift retains moisture and also has minimal shrinkage.

Closing Thoughts

From the owners' requirements listed previously, you might think that no single floor design could meet all the criteria. You might also think that owners shouldn't be allowed to interfere in the process of making decisions about floor construction. But in the world of design-build construction, all parties work together to solve problems and build floors based on the latest technologies.

First cost is still as important as ever, but long-term service and maintenance costs have become major factors. Curling is the 800-pound gorilla hiding in the closet. It's the cause of many or most floor problems today, but the issue of curling, or even measurement protocol for curling, is rarely discussed. Certainly, the ideal floor doesn't shrink, curl, or crack; supports higher loads on less slab thickness; looks good; is versatile and cost-effective; and has a good warranty. The Ductilcrete system has been designed to achieve these criteria, and its developers continue to research and test new ideas to improve it even further.

—Ductilcrete Slab Systems, LLC, **www.ductilcrete.com**

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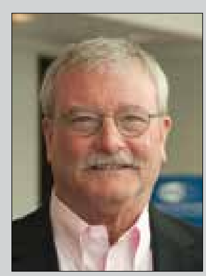
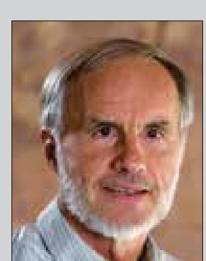
2. ACI Committee 360, "Guide to Design of Slabs-on-Ground (ACI 360-10)," American Concrete Institute, Farmington Hills, MI, 2010, p. 46.

Note: Additional information on the ASTM standards discussed in this article can be found at www.astm.org.

Selected for reader interest by the editors.



Jack Gibbons, FACI, is Vice President of Technical Services for Ductilcrete Slab Systems, LLC. He has over 30 years of experience in the concrete construction industry. Prior to joining Ductilcrete, Gibbons was Central Region Manager for the Concrete Reinforcing Steel Institute. Most of his career has been in the ready mixed concrete industry, where he developed a series of high-performance mixtures for a variety of applications. Gibbons has been a regular speaker at World of Concrete. He is a member of ACI Committees 302, Construction of Concrete Floors; 309, Consolidation of Concrete; 329, Performance Criteria for Ready Mixed Concrete; 360, Design of Slabs on Ground; and 362, Parking Structures. He is also a member of the ACI Construction Liaison Committee.



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