Author Biographies:

Ed McLean, has a BS in construction/civil engineering from Bradley University. been involved in the materials industry since 1975 in ownership and professional capacities in aggregate production, concrete ready mix, specialty concretes and ICRI Board of Directors. McLean has championed numerous solutions to reduce effects of shrinkage in concrete and various concrete wearing surface technologies/methods. Currently Executive Director of Save Our Structures Alliance, he is assisting companies with leading edge technologies to gain traction in structural repair

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INTRODUCTION

Cracking in concrete

The fundamental goal of this paper is to draw attention to the fact that much of the conventional wisdom concerning crack control in a concrete slab-on-ground is no longer universally true. Specifically, this paper seeks to demonstrate that the concrete industry need no longer accept solutions that fail to solve the fundamental problems which drive early-age cracking in a slab. All engineers have knowledge of, and access to, the traditional tools and methods used to reduce the possibility of structural cracks in most concrete elements. These include proper selection and compaction of base material, proper consolidation of concrete, adequate reinforcement, loading considerations, and reducing the risk of re-entrant cracks.

Despite these precautions against structural cracking, however, it is a well-known fact that slabs cast with ordinary PCC have a natural tendency to undergo cracking (especially during early-age) that is not explicitly associated with structural and loading issues. This non-structural cracking is predominately driven by drying shrinkage during the curing process. This shrinkage is primarily due to the fact that, in order to facilitate placement and finishing, portland cement concretes contain more water than is needed for the hydration process. However, since it is not consumed during hydration, this so-called "water of convenience" must escape the concrete in the form of bleed water as curing progresses. This loss of moisture inevitably results in an overall volume reduction, which can cause cracking if restrained by reinforcement internally or other elements, such as the subgrade externally. A simplified illustration of this cracking process appears in Figure 1.

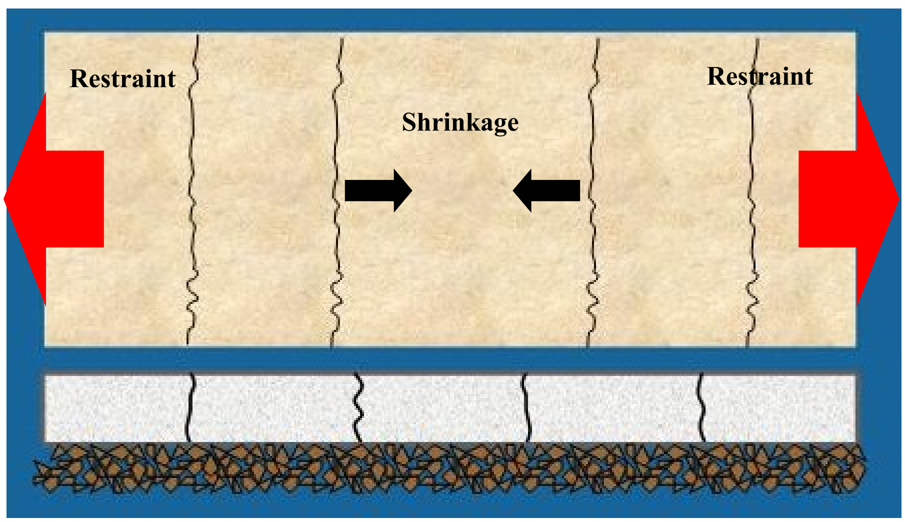

Figure 1: PCC Shrinkage Combined with Restraint Results in Cracking

The situation illustrated in Figure 1 is analogous to the temperature shrinkage problem studied in classical solid mechanics. When a structural element with fixed-end restraint undergoes a length reduction, the result is a uniform tensile stress. This means that in order to prevent this cracking due to drying shrinkage, a restrained concrete specimen is essentially in a race against time. If the concrete can develop sufficient tensile strength to resist the tensile stress, it will not crack. However, the member also experiences a time-dependent stress relaxation due to creep under prolonged loading. The balance of these three mechanical processes is illustrated in Figure 2.

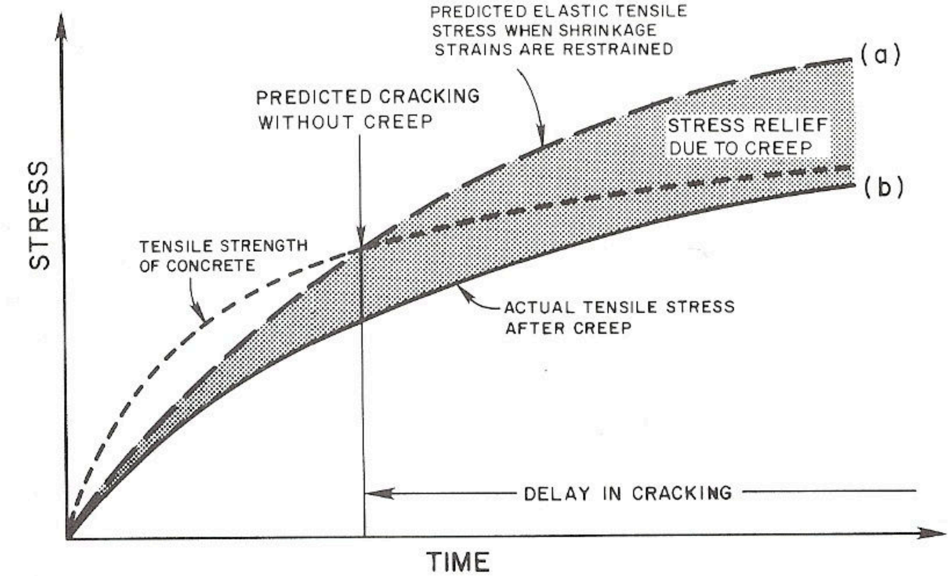

Figure 2: Influence of Shrinkage and Creep on Cracking (Mehta, 1986)

In Figure 2, the concrete cracks at the point where the stress curve crosses above the tensile strength curve. In a slab cast with conventional PCC, the concrete is typically at its most vulnerable to cracking during early age. It is during this period that the concrete is often beginning to experience severe shrinkage but has not yet developed sufficient tensile strength.

Conventional crack control

Shrinkage cracking in concrete (especially in slabs-on-ground) is now a universally recognized problem in the concrete industry. The question that now faces the industry is how to mitigate its effects and produce durable, long-lasting concrete. For many years, concrete designers, contractors, and ready mix companies have experimented with various means of reducing shrinkage. These methods (which include reduced water/cement ratio, surface sealant curing compounds, and shrinkage reducing admixtures) have each met with small degrees of success but have certainly not resolved the issue. As a result, conventional wisdom presents concrete users with the simple assumption that concrete will crack no matter what precautions are taken. For this reason, the industry-standard practice is based on the idea that if concrete cracking cannot be prevented, it should at least be controlled.

This cracking control is achieved by placement of control/contraction joints in a slab or pavement system. A joint is essentially a shallow saw cut placed in a slab in order to ensure that the section cracks at the specified location rather than in a damaging random pattern across the element. Guidelines for the placement of control/contraction joints are available from the Portland Cement Association (PCA) and the ACI 360R design specification for slabs-on-ground. Many designers in the industry today use these "rules of thumb" for providing joints based on concrete thickness. The PCA indicates that a control/contraction joint must have a minimum depth equal to ¼ of the slab thickness. This concept of joint placement and the resulting "controlled" crack is illustrated in Figure 3.

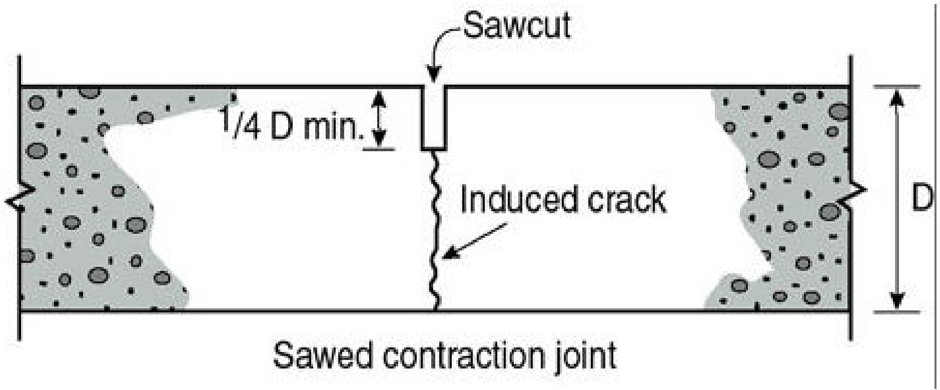

Figure 3: Control/Contraction Joint Sawcut Example (PCA)

An example of the prescriptive joint cutting schedule recommended by the PCA appears in Table 1. This table gives the maximum recommended joint spacing (in feet) based on the largest aggregate size in the mix and the thickness of the slab. Notice that for thinner slabs (which are presumably more vulnerable to full-section cracking), the joints are required to be closer together. For a slab with more inherent structural capacity (due to a larger section), the joints are allowed to be farther apart. Note also that use of a larger aggregate enables the designer or builder to use a larger joint spacing.

Table 1: PCA Prescriptive Joint Spacing (in feet) Based on Slab Thickness

Slab Thickness (in.)	Maximum Aggregate Size Less Than 3/4 in.	Maximum Aggregate Size 3/4 in. and Larger
4	8	10
5	10	13
6	12	15
7	14	18
8	16	20
9	18	23
10	20	25

Table 2: PCA Prescriptive Joint Spacing (in meters) Based on Slab Thickness

Slab Thickness (mm)	Maximum Aggregate Size Less Than 19 mm	Maximum Aggregate Size 19 mm and Larger
100	2.4	3.0
125	3.0	3.75
150	3.75	4.5
175	4.25	5.25
200	5.0	6.0
225	5.5	6.75
250	6.0	7.5

For example, consider a case in which a 240-ft. long by 210-ft (73.6 m by 64.4 m) wide slab will be constructed 6 in. (150 mm) thick with aggregate exceeding ¾ in.(20 mm) in nominal diameter. According to the PCA requirements, the contractor would cut one joint every 15 feet (4.6 m). Based on the geometry of the slab, this will require the crews to cut a total of 15 transverse joint lines and 13 longitudinal joint lines across the slab. This corresponds to a staggering 6270 linear ft. (1922.8 m), which requires well over a mile of saw cutting in order to protect the slab from cracking.

Crack control using type K shrinkage compensating concrete

In contrast to the conventional passive methods, the use of shrinkage compensating concrete offers a more active solution for combating the damage associated with early age shrinkage cracking. The simple objective of a shrinkage compensating concrete is to induce a chemical expansion during early age that is capable of offsetting the expected shrinkage. This technology offers a more aggressive solution through which users are no longer forced to accept cracking as a natural process. The properties and performance of type K shrinkage compensating cement are standardized in ASTM C845. This cement differs from ordinary portland cement in that it is chemically based on hydration of calcium sulphoaluminate (CSA) to produce an ettringite crystal structure rather than the hydration of alite, belite, and tricalcium aluminate (which ultimately produces a C-S-H structure).

The chemical composition of ASTM C845 Type K cement causes the controlled development of early age ettringite which results in an overall volumetric growth of the concrete. Typically derived by combining ASTM C845 cement with ordinary Type I or Type II portland cement, this expansion may be harnessed to offset the shrinkage expected in a concrete. The ratio of portland cement to expansive cement may be modified as desired in order to achieve varying levels of expansion (and thus compensation). For example, if a conventional PCC mix has 0.054% shrinkage then the shrinkage compensating concrete would be designed with sufficient expansive cement to "compensate" for that magnitude of shrinkage.

Another important manifestation of the chemical difference between Type K cement and ordinary PC is that shrinkage compensating concrete has a much higher water demand than conventional PCC. The theoretical w/c ratio for portland cement is 0.27 while with SCC it is 0.45 to 0.47. A typical water/cement ratio for Type K concrete would fall in the range of 0.44 to 0.55. So the vast majority of this water is fully consumed by the hydration process and as a result the concrete does not display any bleed water. This lack of bleed water contributes to overall volume stability by mitigating the severity of desiccation after placement and the elimination of bleed channels. Thus, use of shrinkage compensating cement in a concrete mix can not only actively counteract shrinkage by growth, but also can passively counteract it through reduction of the drying shrinkage associated with eliminating bleed water.

Although there was initially great concern about the strong influence of reinforcement on the ability of SCC to function, these fears are largely unfounded. As the use of shrinkage compensating concrete has become more widespread, research and case studies have indicated that neither heavy reinforcement nor the lack of reinforcement compromise the ability of Type K cement to compensate for shrinkage. In fact, research such as that performed by Renevier (2012) has demonstrated that quite the opposite is true. This study showed that as an SCC concrete becomes more heavily restrained, it gradually becomes more neutral (zero expansion and zero shrinkage) but is not forced into the tensile regime. It has also been observed in both academia and industry that the restraint need not necessarily be supplied by rebar. Performance has also been well-documented using micro synthetic fibers for internal restraint and using plain Type K concrete that is only restrained externally (i.e., by its boundary conditions).

One of the foremost benefits of this shrinkage compensating cement is the ability to produce slabs-on-ground with uninterrupted monolithic pours dramatically larger than was ever possible with PCC. The illustration on the left in Figure 4 shows the traditional PCC joint details for a 240 ft. by 210 ft. (73.6 m by 64.4 m) slab-on-ground. This portion of the figure shows the sample joint schedule discussed in Section 1.2. On the right side of the figure is a typical joint layout for SCC, using only one joint across the center of the slab; this reduces the total lineal feet of joint by more than a mile. This also allows the contractor to make two simple placements of concrete, which is significantly more efficient than the lengthy process of forming and detailing he would face with the conventional slab on the left. In addition to the time saved in forming and detailing, the crew now cuts only one joint with a total length of 210 ft. (64.4 m). Figure 5 shows shrinkage-compensating ASTM C845 Type K cement concrete being placed with a typical reinforcing layout. The entire slab shown in Figure 5 will be installed in one day with no control/contraction joints. As a result of these advances in concrete chemistry and placement methodology, the conventional methods of casting and laborious joint placement are rapidly becoming obsolete.

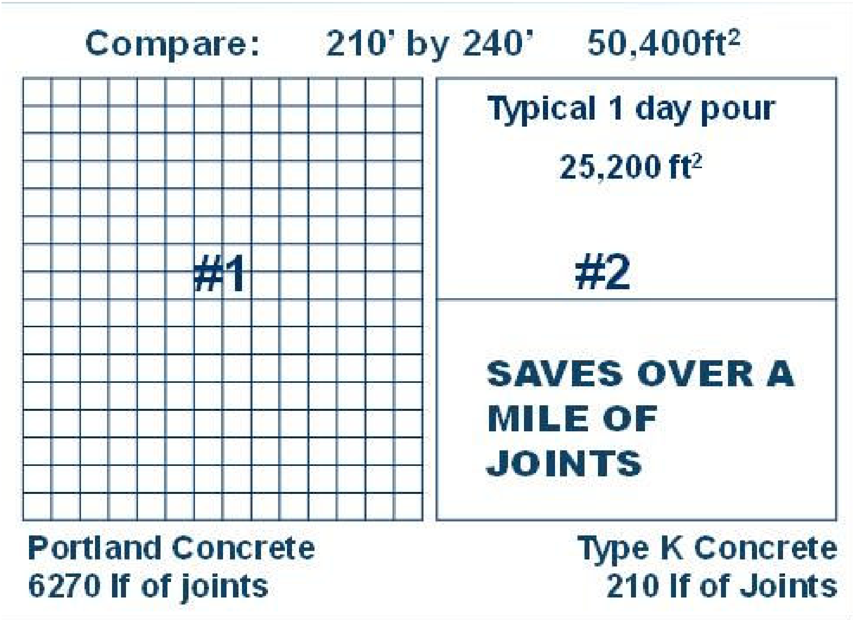

Figure 4: Comparison of Conventional PCC Joint Schedule (Left) and SCC Joint Schedule (Right) – 3.26ft. = 1m

Figure 5: Construction of a Typical SCC Slab Without Joints

It is also interesting to note that the ability of SCC to compensate for shrinkage and maximize the joint spacing is not compromised by outside, unprotected, or cold-weather conditions. Although the contractor does need to be aware of wind and evaporation considerations, none of these factors reduce the ability of the Type K concrete to extend the joint spacing. ACI guidelines for proper handling under cold weather and warm weather conditions apply to SCC and may be used to produce a high-performing concrete. Outdoor (exposed) placement of SCC under winter conditions is shown in Figure 6.

Figure 6: Outdoor (Cold Weather) Placement of SCC

As discussed previously, a primary characteristic of shrinkage compensating ASTM C845 Type K cement concrete is that, due to high water demand, there is no bleed water. By eliminating bleed water, the concrete surface does not have a high water/cement ratio and thus increased abrasion resistance is expected. In addition, contractors constructing large slabs using Type K SCC have been able to consistently achieve higher FF (flatness) and FL (levelness) numbers when placing a floor. Even more importantly, these numbers are stable over time, since the increased volume stability of the floor reduces risk of warping and curling.

LARGE SCALE PROJECT CASE STUDIES

The objective of this paper is to present a survey of various projects completed using ASTM C-845 Type K cement concrete. The survey was conducted in 2012 to obtain documentation of the effectiveness of Type K SCC. The survey included bridges, slabs-on-grade, containment structures, and elevated structural decks were included and ranged in age from 5 to 40 years. The common element in this study was the ability of SCC to produce structures and elements with a joint spacing that extended beyond what could be accomplished with ordinary portland cement.

Slabs-on-ground

Kraft foods cold storage facility – Shrinkage compensating ASTM C845 Type K concrete is used extensively in cold storage food warehouses. One of the primary reasons for this is that, due to sanitation concerns, joints in these facilities face tremendous scrutiny by the USDA. As a result, expensive joint sealants must be installed and require maintenance throughout the life of the slab. With access to roughly 20 years of documentation and comparison, many owners and engineers across the industry now elect to use the shrinkage compensating concrete. Cisco Foods, US Foods, Aldi, Hershey's, and others have elected to use shrinkage compensating concrete as a solution to minimize the use of expensive joints and reduce expected maintenance costs.

One such project took place in Springfield, MO. On this project, ASTM C845 Type K cement concrete was used to construct a 500,000 sq. ft. (46,000 sq. m) Kraft Foods facility for cold storage of cheese. The location was in an underground limestone quarry that had stone pillars on 80' (24.5 m) centers. If the project had been performed with conventional PCC, each pillar would have to be isolated, which would be costly because of the jagged column profiles and limited flexibility of the expansion joint material. Using SCC, however, the expansion of the material accounted for irregularities in the wall, allowing the concrete to be cast in direct contact with the pillars (shown in Figure 7).

Figure 7: Type K SCC Cast in Contact With Pillar Profile

Both the owner and contractor for this project wanted to place 80’ by 240’ (24.5 m by 73.6 m) sections without traditional continuous reinforcing. The option of using the ASTM C845 Type K Cement concrete with micro-synthetic fibers was chosen based on reduced construction costs and schedule. The use of fibers instead of traditional reinforcement generated both material and labor savings and also allowed for direct truck discharge and laser screed strike off (both of which would have been difficult or impossible if the project had used a continuous steel mat).

Figure 8: Laser Screeding for Kraft Foods Cold Storage Facility (Springfield, MO)

Dowel bar baskets were used in the control joints. In addition, (2) #5 reinforcing bars were placed around the outside edges and dock leveling boxes were detailed to eliminate re-entrant corner cracks. No plastic was installed under the concrete in this project but if desired plastic may be used to better control downward wicking of moisture.

ACI 223 states that shrinkage compensating concrete "Induces both compressive stress in the concrete and positive steel strain that approximately offsets tensile stresses and negative strains induced by drying shrinkage". In this project there was no continuous steel reinforcing, but restraint was supplied by micro synthetic fibers, perimeter steel, and external restraint. As has been observed in other projects, the synthetic fibers provided adequate restraint and few shrinkage cracks appeared in the finished floor when the project was complete. The finished slab is seen in Figure 9.

Figure 9: Finished Cold Storage Floor (Springfield, MO)