Key Design Considerations for Concrete Topping Slabs in Split-Slab Construction

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Split-slab assemblies for plaza decks use a concrete topping slab over insulation, waterproofing, a drainage board, and a structural concrete deck. The topping slab primarily functions as a wearing layer and protects the underlying components. Concrete topping durability can be adversely affected by improper subsurface drainage, inadequate resistance to freezing and thawing, inadequate joint design, and deformation of the insulation used in the assembly beneath the topping. Improperly designed concrete topping slabs can adversely affect the waterproofing system and the structural deck.

The authors have firsthand experience in investigating issues with split-slab construction and waterproofing directly linked to the concrete topping slab. This article discusses key considerations for designing and specifying concrete topping slabs in split-slab construction, and it provides two case studies of representative projects.

BACKGROUND

Open versus Closed Wearing Layers

In most plaza decks, the waterproofing system is protected by either an open- or closed-system wearing layer. The most popular open-system wearing layer consists of pedestal-supported pavers. However, other open wearing systems such as granular supported pavers are also used. In an open wearing system, water drains through the joints of the wearing system down to the waterproofing layer. This is typically referred to as "subsurface drainage."

Open wearing systems offer many advantages, including ease of construction (particularly when concrete placement is not practical, as is the case for plaza decks on high-rise building roofs), flexibility in achieving aesthetic effects, and ease of access to the waterproofing system for maintenance or repairs. Furthermore, open wearing systems can be constructed to be level because the drainage occurs primarily below the wearing layer. In most open wearing layers, the drains can be concealed below the pavers, and a conventional, single-stage drain can be used.

However, there are limitations to open systems. They cannot support concentrated loads, and there may be issues with paver displacement. Pedestal-supported pavers can also be problematic when used in ramps or level surfaces that are subject to horizontal thrust from vehicle tires due to turning, acceleration, or deceleration of the vehicles. It should be noted that many plaza decks that are primarily intended for pedestrian traffic are periodically subject to vehicular loads. For example, in cold climates, large snowplow vehicles may be used to remove snow from plaza decks. In some cases, plaza decks must be designed to provide access to fire trucks.

A closed wearing layer consists of a continuous surface that does not provide for positive drainage through its upper surface. Although some water does drain through activated control joints in a closed system, the primary path of drainage is surface drainage. Positive drainage of a closed system is provided by the wearing surface profile being sloped to direct runoff toward drains. These drains are two-stage drains with the ability to remove water from the wearing surface as well as any water entering through joints that collects at the waterproofing layer. The subsurface drainage system also includes a drainage layer to facilitate lateral movement of water to the drain.

The most common closed-system wearing layer consists of a cast-in-place concrete topping slab. However, other closed systems such as mortar-set pavers or stone slabs are also used in many areas. These alternative closed systems should be used with caution in climates where repeated freezing-and-thawing cycles can cause deterioration of the setting mortar.

The term "split slab" generally refers to a plaza deck assembly with a cast-in-place concrete closed-system wearing layer. Such

Figure 1. Example of split-slab construction.

assemblies incorporate a concrete topping slab over a structural concrete deck, which is separated by a waterproofing system (**Fig. 1**).

The waterproofing system typically consists of several components, including rigid insulation, one or more drainage mats, a protection layer, and a waterproofing membrane. The configuration of the assembly can vary based on the designer's preferences and specifications from the waterproofing system manufacturer. The most significant variable is the placement of the drainage mat. It can be installed below or over the insulation layer, or mats can be installed at both locations.

The most significant advantage of a cast-in-place concrete topping slab is that the topping slab can spread concentrated loads from vehicles over larger areas. This enables split slabs with properly designed cast-in-place topping slabs to resist much higher plaza loads than plaza decks using open systems such as pedestal-supported pavers. Cast-in-place concrete toppings also have better resistance to horizontal forces (thrust) imposed by turning, accelerating, or decelerating vehicles, or by sloped wearing surfaces. However, they still need to be restrained against horizontal movement in some cases.

Although many aesthetic features, such as pigmented concrete or stamped concrete, can be incorporated into concrete topping slabs, the slabs are generally more limited than other options with regard to aesthetics. In addition, concrete topping slabs are typically heavier and more difficult to place at project sites than open systems such as pedestal-supported pavers.

Function of Topping Slabs

The topping slab's primary function is to provide protection of all the underlying components. The topping slab does not contribute to the load-carrying capacity of the slab; therefore, it is not considered to be a structural member. However, it is required to resist loads imposed by vehicles, maintenance operations, pedestrians, and impact of various objects. Those loads are then distributed by the topping slab over a larger area and transferred through the insulation, drainage mat, and other components to the structural slab. For this reason, the structural behavior of the concrete topping slab must not be overlooked.

Because cast-in-place concrete topping slabs are exposed to elements and traffic, they must be durable. Their durability will primarily depend on their resistance to freezing and thawing, which can be measured through laboratory testing of the proposed concrete mixture design in accordance with ASTM C666, *Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing*.[1]

The topping slabs should also be resistant to abrasion posed by vehicular traffic. Abrasion resistance of concrete mixture designs can be determined in accordance with ASTM C779, *Standard Test Method for Abrasion Resistance of Horizontal Concrete Surfaces*.[2] However, this test is not commonly performed because most durable concrete mixtures have sufficient abrasion resistance for typical topping-slab applications.

In cold climates, the topping slab may also be exposed to deicing salts. Resistance of concrete mixtures to deicing salts can be evaluated through ASTM C672, *Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals*.[3] It should be noted that this standard was withdrawn without replacement in 2021.[3]

The topping slab could be composed of normalweight concrete or lightweight structural concrete. In either case, the concrete mixture design for the topping slab should be carefully formulated in accordance with the American Concrete Institute's *Specifications for Concrete Construction* (ACI 301).[4] A detailed discussion of considerations for a durable concrete mixture is beyond the scope of this article. However, specifiers should be aware that many factors such as the water-cementitious materials ratio (*w/cm*), air content, and proper use of admixtures and pozzolans are critical in achieving a durable concrete mixture.

Bonded concrete topping slabs are bonded to the structural slab below, so that the topping and the slab behave compositely (without slippage). It should be noted that bonded concrete topping slabs are also used in plaza deck construction, but for different reasons such as creating sufficient slope for drainage at the waterproofing layer. The design of such topping slabs is also beyond the scope of this article.

The design of concrete wearing slabs for a split-slab assembly is often based on empirical methods and prior experience of the designer, and many designers do not carefully consider the topping slab design because they consider topping slabs to be merely "sacrificial." However, improper design of topping slabs can result in adverse effects. For example, problems can arise if the designer does not consider how surface drainage on a closed system such as a concrete topping differs from that of an open system such as a paver system. Whereas paver systems allow water to drain into the assembly below through each joint, split slabs require sufficient slope and adequate drainage systems to properly shed water from their exposed surface. In addition, concrete topping durability can be adversely affected by improper subsurface drainage, improper resistance to freezing and thawing, inadequate joint design, and deformation of the insulation used in the assembly below. More importantly, improperly designed concrete topping slabs can adversely affect waterproofing and the structural deck.

KEY CONSIDERATION FOR CLOSED SYSTEMS

Resistance to Freezing and Thawing

One cause of deterioration in closed systems is cyclical freezing and thawing between materials or within cavities of a particular material. Because concrete materials are porous, they can absorb moisture. When moisture fills most of the pores in the concrete, that water can freeze, expand, and cause microcracks in concrete. When the ice in the crack thaws, microcracks are left behind that can allow more water to accumulate within the concrete. Thus, deterioration escalates with each cycle of wetting, freezing, and thawing. In some climates, the freezing-and-thawing cycle can repeat daily. Topping slabs are particularly affected by these cycles because their surfaces are nearly horizontal, they have a low thermal mass due to their relatively thin section, and they are insulated from below, which prevents the conduction of heat from inside the building into the topping slab.

The quality of the concrete mixture affects the extent of the cracking and deterioration caused when concrete is subjected to repeated cycles of wetting, freezing, and thawing. Deterioration from freezing-and-thawing effects of properly proportioned air-entrained concrete made with aggregate susceptible to freezing-and-thawing damage is referred to as "D-cracking."[5] According to ACI 201.2R-16, *Guide to Durable Concrete*,[5] young concrete (concrete that has not yet attained a compressive strength of at least 500 psi) can be damaged by a single freeze. Resistance to freezing and thawing refers to the concrete's ability to resist such deterioration when subject to repeated cycles of freezing and thawing.

ACI 318-19, *Building Code Requirements for Structural Concrete*,[6] defines classes of various conditions of concrete exposure to freezing-and-thawing cycles. These are designated as Exposure Classes F0 through F3. Based on the Exposure Class, maximum *w/cm* provisions are established in Table 19.3.2.1 of ACI 318-19. For example, Exposure Class F0—which is defined as exposure with no freezing-and-thawing cycles—does not have a restriction on *w/cm*. In contrast, Exposure Class F3—which is defined as exposure to freezing-and-thawing cycles along with frequent exposure to water and exposure to deicing chemicals—is restricted to a maximum *w/cm* of 0.40. As explained in ACI 318-19 Commentary R19.3.2, the purpose of limiting the *w/cm* is to achieve low permeability and the intended durability.

Air entrainment is also typically used to resist effects from freezing and thawing. It entails introducing entrained air bubbles of diameters larger than 3 μm (0.0001 in.), which are distributed in the cement paste at a spacing not greater than 0.2 mm (0.008 in.), by use of air-entraining admixtures or air-entraining hydraulic cement. These closely spaced air bubbles provide relief from the pressure built up by the freezing of water in capillary cavities in the cement paste, which minimizes damage to the hardened paste.[7] Table 4.2.3.2.4 in ACI 201.2R-16[5] provides recommended air contents for various maximum aggregate sizes and Exposure Classes. These values range from 5.5% through 7.5%. It should be noted that overfinishing or hard-troweling concrete with air content of more than 3% can lead to problems and should be avoided.[4]

ASTM C666[1] provides two procedures for determining resistance of concrete specimens to rapidly repeated cycles of freezing and thawing. Procedure A is Rapid Freezing and Thawing in Water. Procedure B is Rapid Freezing in Air and Thawing in Water. Both procedures determine the effects of variations in the properties of concrete on the resistance to freezing-and-thawing cycles. Neither procedure is intended to provide a quantitative measure of the length of service that may be expected from the concrete. Testing involves subjecting a specimen to (a) freezing-and-thawing cycles until its relative dynamic modulus of elasticity reaches 60% of its initial modulus or (b) 300 freezing-and-thawing cycles, whichever comes first. Based on test data, a durability factor can be calculated. If the test indicates that the concrete is relatively unaffected by freezing and thawing, it can be assumed that it was made with sound aggregates and a proper air-void system, and that it was allowed to cure properly.

If subsurface drainage is ineffective, water will saturate the concrete topping slab and cause premature deterioration in the form of extensive cracking and spalls. If a drainage mat is only provided below insulation in the assembly, the topping slab can become saturated and be prone to freezing-and-thawing effects. In many cases, designers specify a drainage mat above insulation in the assembly to mitigate freezing-and-thawing effects. However, drainage mats can get clogged with lime deposits from the topping slab above. Although it may diminish thermal values, the authors recommend providing a double layer of drainage, with one drainage mat placed directly beneath the topping slab and another placed between the insulation and structural deck below. An open drainage mat directly beneath the topping slab will provide drying potential for the insulation.

Deicing Salt Resistance

The most common damage from freezing-and-thawing effects in exposed concrete slabs is surface scaling, which is loss of paste and mortar from the surface of the concrete. Scaling is accelerated considerably by deicing salts, which are used to remove ice from pavements.[5] Alkali-aggregate reaction (AAR) can cause damaging expansion in concrete structures. Two types of AAR have been recognized: alkali-carbonate reaction (ACR) and alkali-silica reaction (ASR). ACR causes rapid expansion and extensive cracking of concrete, with cracking usually exhibited within five years of concrete placement. ASR is a major cause of premature concrete deterioration.[5] Table 5.2 of ACI 201.2R-16[5] provides examples of rock types and minerals susceptible to ASR. Some examples include shale, sandstone, and chert. ACI 201.2R-16 also notes that research has shown resistance to D-cracking is reduced for concrete containing susceptible aggregates when the concrete is exposed to deicing salt. Chemical deicers may also contribute to advanced deterioration of joints in exterior flatwork when subsurface drainage is not functioning properly.

In addition to lowering the freezing point of water, deicing chemicals change physical and chemical properties of solutions that fill joints, such as their viscosity, surface tension, and sorption. These changes create a higher degree of saturation and increase the frequency of cracking and microcracking under certain temperature cycling conditions.[5]

Strategies to mitigate the effects of chemical deicers include minimizing the permeability and controlling the reactivity of concrete.[5] According to ASTM C33, *Standard Specification for Concrete Aggregates*,[8] cement-aggregate combinations that have an expansion greater than 0.05% at three months or 0.10% at six months are reactive. Aggregates have different transport properties from those of cement paste, and the water permeability of concrete with low-permeability aggregates is approximately one or two orders of magnitude lower than that of cement paste.[5] The use of supplementary cementitious materials such as slag can significantly reduce the permeability and diffusivity of concrete. The material may not reduce the total porosity significantly, but it refines and subdivides the pores so they are less continuous.[5]

Proper curing of concrete is important for mitigating the effects of deicers. Care should be taken to avoid exposing concrete to deicers during the first year of service. Mitigation of chemical deicers' effects also requires adequate surface drainage to minimize the duration of exposure.[5] During service, annual cleaning and washing to remove excess surface deicing salts may also be helpful in reducing the potential for deicing salt damage.

Slip and Abrasion Resistance

Topping slabs must be designed to minimize the risk of slipping by pedestrians and vehicles, especially when the slabs are wet. Finishes, textures, and sealers can all affect slip resistance, as follows:[9]

- Rougher textures generally provide more slip resistance than smoother ones.
- Sealers that fill the surface and form a film generally reduce slip resistance when the surface is wet. Slip-resistant additives can be added to the sealer to counteract this effect.
- Stamped and broom finishes tend to provide similar slip resistance.
- Broom finishes provide more slip resistance across the grain rather than along it. Therefore, broom finishing should be performed perpendicular to the usual direction of movement, if possible.
- Abrasive blast finishes provide variable slip resistance because the removal of surface mortar is uneven.
- When using stamped and stenciled finishes, sufficient surface texture should be provided to ensure adequate slip resistance.

Abrasive grains in the surface of concrete can be added to provide slip resistance.[10] When embedded in concrete, silicone carbide and aluminum oxide cause an effective abrasive action that produces long-lasting slip resistance. These materials are typically introduced into the concrete surface after it has been floated and troweled once.

Polyurethane coatings provide a long-lasting thin topping for concrete surfaces and permit evaporation of water vapor through the topping.[10] However, such coatings should be avoided in a split-slab configuration because they will entrap moisture in the assembly. Acid-etching to achieve surface texture is not recommended because it can lead to damage to the concrete topping and the waterproofing below.

Resistance to abrasion helps concrete topping slab maintain durability. ASTM C779[2] describes three testing methods to determine variations in surface properties of concrete. Each method simulates abrasion conditions to evaluate their effects on the abrasion resistance of concrete, concrete materials, and curing or finishing procedures. Because the equipment used in each testing method can be portable, the methods are suitable for field testing. Each procedure determines the relative wear of concrete surfaces. Procedure A uses a revolving-disk machine that operates by sliding and scuffing of steel disks in conjunction with abrasive grit. Comparison of measurements of average depth of wear of representative surfaces at 30 and 60 minutes of exposure to abrasion indicates the relative abrasion resistance. Procedure B uses a dressing-wheel machine that operates by impact and sliding friction of steel dressing wheels. The apparatus depends on the abrasive action of three sets of steel dressing wheels riding in a circular path over a horizontal concrete surface. Similar to Procedure A, comparison of measurements of average depth of wear of representative surfaces at 30 and 60 minutes of exposure to abrasion indicates the relative abrasion resistance. Procedure C uses a ball-bearing machine that operates by high-contact stresses, impact, and sliding friction from steel balls. The apparatus uses abrasive action of a rapidly rotating ball bearing under load on a wet concrete test surface. Water is used to flush out loose particles from the test path, bringing the ball bearing in contact with sand and stone particles still bonded to the concrete surface. This provides impact as well as sliding friction. Comparison of depth of wear versus time for each surface tested indicates the relative abrasion resistance.

As previously noted, in most conventional applications, a durable concrete mixture typically provides sufficient resistance to abrasion. However, in highly abrasive applications (such as a topping slab used in a loading dock subjected to frequent abrasion by garbage disposal equipment), abrasion resistance should be evaluated.

Control Joints

As concrete cures, it loses moisture and undergoes drying shrinkage. This shrinkage typically results in cracking of the concrete.

In reinforced concrete structures, cracking is controlled using reinforcing steel bars, which distribute cracks and control their width. In unbonded topping slabs and most slabs on grade, shrinkage cracking is controlled through the use of control joints, which create weak planes in the cross section of concrete to promote cracks at "controlled" locations. These joints can be tooled during finishing or cut into recently placed concrete (typically within 42 hours of placement and before drying-related shrinkage can cause cracks). Although reinforcing steel can be used in concrete topping slabs, the authors advise against it for the following reasons:

- Reinforcing steel bars are prone to corrosion-related issues, particularly on exterior horizontal sources that are subjected to deicing chemicals. Even when epoxy-coated reinforcing is used, discontinuities in the epoxy coating can lead to corrosion. Noncorrodible reinforcement is typically considered too costly for such applications.
- Placement of the reinforcing before concrete is cast may result in damage to the underlying waterproofing, and this damage may be difficult to detect and correct after placement.
- The reinforcing (particularly welded wire fabric) is often placed near the bottom of the slab, where it is ineffective.

Typically, the design guidelines for locating control joints are based on recommendations provided in industry publications. For example, both the Portland Cement Association[11] and ACI[12] provide tables indicating recommended control joint spacing for unreinforced concrete slabs based on slab thickness. Notably, these empirical recommendations are intended for use at slabs-on-grade, which means they are based on shrinkage of concrete restrained by contact of soil below. However, topping slabs behave differently than slabs-on-grade because topping slabs are not restrained by friction to soil. The only restraint is provided by the insulation or drainage mat below the topping slab. Therefore, topping slabs are susceptible to more shrinkage cracking than slabs-on-grade.

Because insulation in split slabs does not provide a thermal sink similar to slabs-on-grade, topping slabs are also more prone than slabs-on-grade to movement caused by thermal changes. It is typically assumed that the thermal movement of topping slabs will be accommodated by the openings at each control joint. Control joints are typically left open because the system as a whole is designed to handle water at the waterproofing layer, and sealing the control joints, therefore, does not do much to improve the system's waterproofing function. In addition, sealing the control joints will create a maintenance issue. However, dirt and debris can wash into and clog the unsealed control joints, which prevents them from acting as small expansion joints to relieve thermal movement. Therefore, large sections of topping slabs require accommodation for expansion in addition to contraction/control joints.

Concentrated Loads

Topping slabs are susceptible to cracking due to high concentrated loadings. Because topping slabs are supported by rigid insulation above the waterproofing, deformation of the insulation may cause the topping slab to crack. Distribution of loads depends on the thickness of the topping slab and the stiffness of the substrate (the drainage mat, insulation, and waterproofing membrane). Consider this simple example: A 4000-lbf (18-kN) wheel load over a 2- × 2-ft (0.6- × 0.6-m) effective area of topping slab creates 7 psi (48 kPa) of compressive pressure on the rigid insulation below. ASTM C578, *Standard Specification for Rigid, Cellular Polystyrene Thermal Insulation*,[13] stipulates compressive resistance for various types of rigid insulation at yield or 10% deformation,

Figure 2. A filter screen around a two-stage drain is clogged due to decalcification of the concrete topping.

whichever occurs first. For insulation having 60-psi (414 kPa) compressive resistance, 7 psi (48 kPa) of compressive pressure will result in 1.2% deformation (assuming a linear relationship between deformation and pressure). If there is 10-in.-thick (250-mm) rigid insulation under the topping slab, the insulation will compress approximately ⅛ in. (3 mm). This localized deformation of the insulation can cause the topping slab to crack.

Clearly, the topping slab should be designed such that it has sufficient flexural strength to resist stresses that cause cracking. The design analysis should consider the specified compressive strength of the insulation, the type of anticipated vehicular load, and the thickness of the insulation. Reinforcing steel could be provided within the topping slab to improve flexural strength, distribute the loading over a larger area, and assist in controlling cracks. However, as mentioned previously, the authors advise against using reinforcing steel where its use can be avoided.

Vaca and colleagues[14] used structural software in a parametric study to provide an elastic analysis of a topping slab supported on spring supports above a structural floor. Based on their findings, they recommend using a topping slab that is at least 3 in. (75 mm) thick for light traffic, or at least 5 in. (125 mm) thick for heavy traffic. Unreinforced topping slabs can be designed to adequately resist cracking from anticipated concentrated loads.

Certain enhancements in concrete such as addition of fibers can increase ductility of the concrete and reduce cracking. Use of fibers in concrete is a complex and often debated topic that is beyond the scope of this article.

Subsurface Drainage

In a closed system, water drainage primarily occurs over the upper surface of the topping slab, but some water will penetrate through cracks and control joints within the concrete topping slab. Therefore, a subsurface drainage system must be properly designed and constructed to drain water. Specifically, the waterproofing membrane must be sloped toward the drain assembly, a capillary break such as a drainage composite must be provided, and two-stage drains are needed to allow water drainage at the waterproofing layer and the top surface.

Our experience has shown that the drainage composites and two-stage drains are prone to clogging due to concrete leachate or accumulation of calcium hydroxide. When water flows through cracks, microcracks, and joints, it dissolves free calcium hydroxide, which is subsequently deposited elsewhere within the system when the water evaporates. In many cases, we have observed substantial clogs in two-stage drain screens or the fabric layer of the drainage composite due to this phenomenon (**Fig. 2**).

To reduce potential clogging of two-stage drain screens, the authors use a granular fill in an area surrounding the drain. This increases the effective filter area and traps some of the leachate before it reaches the drain screen, where the water can evaporate.

To minimize the clogging of drainage composite filter fabric, we typically recommend the use of two layers of drainage composite. One layer is placed between the insulation and the concrete topping slab, and the other is placed between the insulation and the waterproofing system. In this arrangement, if the top-layer drainage composite fabric is clogged, water will pass through joints of the drainage composite and insulation and eventually reach the lower layer of drainage composite, where it can freely drain.

This practice is not ideal because it does not necessarily prevent critical saturation of the topping slab if the top-layer drainage composite fabric is clogged. It can also be argued that allowing the water to freely drain to the lower drainage composite layer will reduce the effectiveness of the insulation during cold conditions when melting snow at low temperatures bypasses the insulation.

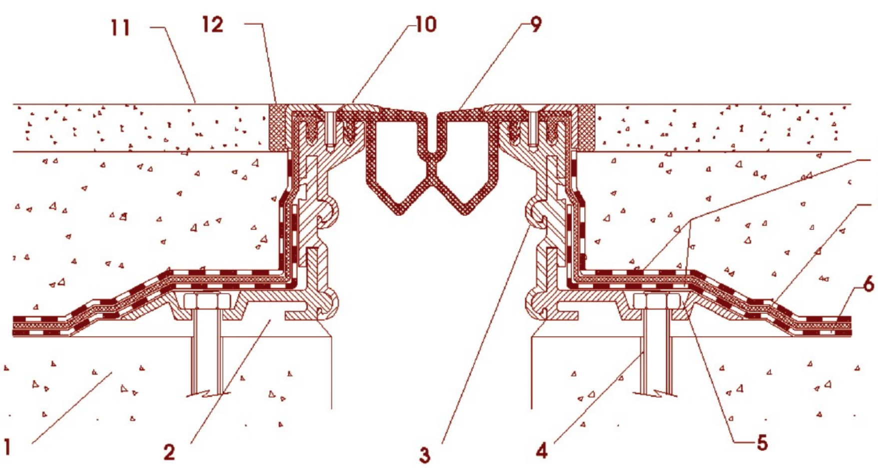

Figure 3. Example of a proprietary joint system using a raised flanged connection to the structural deck below.

Figure 4. Deformation around a retaining cap.

Figure 5. Water penetration testing along an expansion joint.

Thermal Expansion and Contraction

Materials expand and contract due to increases and decreases in temperature. The dimensional change due to thermal effects is the product of a material's length, its coefficient of thermal expansion, and the change in temperature. The coefficient of thermal expansion for concrete is approximately 0.0000055 in. per degree Fahrenheit. For a given length of concrete, the larger the temperature change is, the more thermal movement the concrete will exhibit.

Shear Stress Transfer to Substrate

The interaction of topping slabs and substrate below can create large stresses that will damage adjacent materials. Forces due to friction, thermal expansion and contraction, and other effects can transfer to abutting members, or they can transfer through components in the assembly into the structural deck. A 50-ft-long (15-m) portion of concrete topping subject to a temperature change of 60°F (33°C) will theoretically move 0.2 in. (5 mm). If this movement is transferred to substrate, adjacent walls, or other elements to which the topping connects, it will impart incredibly large forces. Unless the movement can be accommodated, failure of materials is inevitable. Therefore, the thermal movement of the topping slab should be carefully considered and accommodated properly.

LESSONS LEARNED FROM CASE HISTORIES

The following are two case histories that illustrate some of the issues discussed in the previous sections of this paper.

Plaza Deck Case Study

A four-story instructional center of a community college included a long plaza deck over occupied spaces along the side of the building. The plaza deck was approximately 30 ft (9 m) wide and 700 ft (213 m) long, and it sloped away from the remainder of the building. It was originally constructed in 1974 as a split-slab assembly with two transverse building expansion joints intersecting the plaza deck. The expansion joints were located approximately at the one-third points along the plaza's length, which aligned with expansion joint locations in the building frame.

In 2011, the plaza deck was renovated, a project that included removing existing materials down to the concrete structural slab. The new plaza deck assembly included a tapered bonded concrete filler slab over the existing structural slab to provide for better drainage, a hot fluid-applied waterproofing membrane, a drainage mat, rigid insulation, and a concrete topping slab. The topping slab was constructed with control joints saw-cut approximately 4½ ft (1.4 m) apart.

New proprietary expansion joint assemblies were provided in the renovated plaza deck at the original locations. The new expansion joint assemblies consisted of a rubber bellows clamped between two L-shaped flanges with integrated rubber glands. The horizontal legs of the L-shaped flanges were anchored into the new bonded concrete topping slab. **Figure 3** depicts the configuration of the expansion joints.

Water leakage occurred through the plaza deck at the new expansion joint assemblies shortly after renovation was completed. An evaluation was performed to assess the source or sources of the water leakage. The evaluation consisted of a review of the renovation drawings, visual review of field conditions, water penetration testing, and exploratory openings through the plaza assembly.

The visual review of the expansion joints indicated deformations around the retaining caps of the expansion joint gland (**Fig. 4**). Water penetration testing was performed along the expansion joints in 6-ft (2-m) increments using a calibrated spray bar (**Fig. 5**). At most locations, water leakage was observed in the occupied space below within 2 to 5 minutes after the start of testing.

Exploratory openings were made to identify the path of water leakage through the expansion joints. Upon removal of the expansion joint retaining caps, investigators observed that flanges of the sealing gland were severed from the body of the gland (**Fig. 6**). The investigators also observed a large tear in the vertical leg of the expansion joint flashing sheet at the bottom edge of the expansion joint retaining cap (**Fig. 7**), and they found that an expansion joint anchor bolt used to attach the horizontal leg of the expansion joint flange to the slab had failed in tension.

The damage to the waterproofing and the expansion joint assembly was attributed to differential movement between the topping slab and the supporting structural deck. The tributary spacing of these expansion joints was as much as 245 ft (76 m), resulting in significant thermal movements of the concrete topping relative to the underlying waterproofing and the structure. This differential movement resulted in large thrust forces being exerted on the expansion joint vertical legs. The thrust forces caused rotation of the expansion joint flanges and the failure of the anchors that secured them to the deck below. This, in turn, caused the expansion joint flanges to rotate and tear the membrane along the horizontal leg of the expansion joint flanges. The thrust forces also caused damage to the expansion joint gland clamping strips.

Assuming no thermal movement could be accommodated by the small gaps at the control joints, the topping slab could expand as much as 1.9 in. (48 mm) if there were a 120°F (67°C) temperature differential. In contrast, the structure below, to which the expansion joint assembly was attached, experienced only small thermal movements because the structure was conditioned, maintaining a relatively constant temperature. This differential movement of the topping slab relative to the structure below was not accommodated by the expansion joints because the entire assembly was attached to the structure. The purpose of that expansion joint was to allow building movements, not differential movements between the topping slab and the structure.

Even if the expansion joints had been designed to allow differential movements of the topping slab with respect to the structure, the spacing and size of the joints would have been entirely inadequate. Calculations indicated each expansion joint assembly must be capable of accommodating almost 2 in. (50 mm) of expansion.

To remedy the condition, the concrete topping was removed adjacent to the existing expansion joints so that waterproofing and expansion joint repairs could be performed. Included in the repairs were seven additional new expansion joints in the topping slab only, as well as bilevel expansion joints at existing expansion joint locations. The repairs were performed from the plaza deck level, and operations within the space below were unaffected during repairs.

COMMERCIAL BUILDING CASE STUDY

This case history involves a two-story commercial building. The first two floors of the structure served as commercial spaces, and the roof of the structure (the third level) served as a parking deck above the second-floor spaces. Access to the parking deck was provided via ramps.

Figure 6. Severed flange of an expansion joint sealing gland.

Figure 7. A large tear in an expansion joint flashing sheet.

The structure consisted of precast concrete columns, double tees, and inverted T beams. Typically, concrete columns supported inverted T beams, which supported long-span precast concrete double-tee planks.

Double-tee planks at the third-floor level (the roof) were superimposed by a waterproofing system and a concrete topping slab. The waterproofing system consisted of a hot rubberized asphalt waterproofing membrane applied directly over the double tees' top surfaces, a drainage mat, insulation, and a cast-in-place concrete topping slab. Before the waterproofing was applied over the double-tee planks, the joints between planks were sealed with sealant, and an uncured neoprene flashing system was used to strip in the joints.

Shortly after completion of construction, leaks were reported below the roof parking area. Several investigations of these leaks were conducted, and notable findings included the following:

- Several leaks were attributed to punctures in the waterproofing membrane caused by stakes used to form the concrete topping slab sections. The stakes were driven through the insulation after nondestructive leak detection had been completed during original construction and the drainage mat and insulation were installed. This finding underscores the risks related to post-installation activities over plaza deck waterproofing systems.
- Some leaks were traced to localized debonding of the waterproofing membrane over concrete surfaces. The examination of these areas revealed moisture below the membrane and the presence of a brown oily substance. It appeared that the membrane was adversely impacted by exposure to moisture, although not all parties agreed with this conclusion. Moisture readings of substrate surfaces revealed relatively high relative humidity levels within the concrete when measured in accordance with ASTM F2170, *Standard Test Method for Determining Relative Humidity in Concrete Floor Slabs Using in situ Probes*.[15] Most of the high moisture readings were recorded over the largest dimensions of the inverted T beams. Such members typically take far longer than thinner members to sufficiently dry. Further testing of the waterproofing membrane would have been needed to assess this issue. Detailed discussion of moisture below waterproofing membranes and the effect of water on some bituminous membrane is beyond the scope of this article.
- Some leaks were traced to failure of the waterproofing membrane over side-lap joints (flange-to-flange connections) of the precast concrete double tees. These joints were sealant joints intended to support the waterproofing membrane and the uncured neoprene flashing. However, investigation indicated that some had significantly widened (**Fig. 8**). This finding prompted a more detailed review of the joints and a visual review from below. These reviews indicated that some of the welded connections at the double-tee side laps had failed in tension. In addition, cracking and delamination of the concrete around a few of these connections provided evidence of differential lateral movements between the precast concrete double tees (**Fig. 9**).

Figure 8. A failed sealant joint.

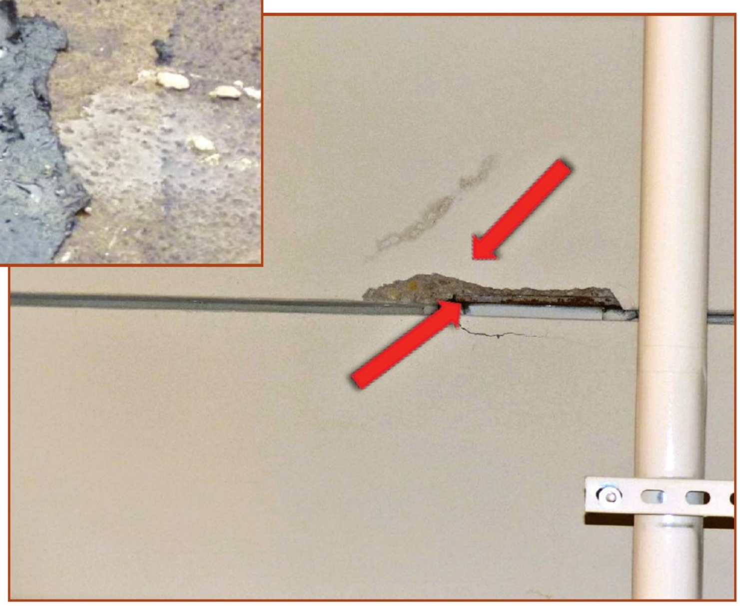

Figure 9. Cracked and delaminated concrete on the underside of a precast concrete double tee.

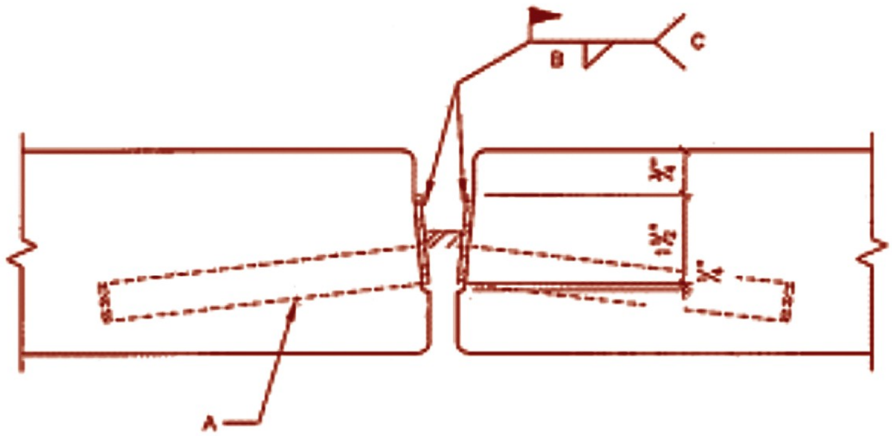

Figure 10. Excerpt of a connection detail from the precaster's engineer.

The failure of welded connections at side laps of the double tees prompted concerns regarding the structural integrity of the building. In particular, failure of side-lap connections would diminish the ability of the double-tee deck to act as an effective diaphragm to resist wind loads.

Original calculations prepared by the precaster's engineer for flange-to-flange connections between adjacent double tees were reviewed. The review indicated adequate design of the connections to resist diaphragm loads. However, the original design criteria had not required any consideration of the thermal movement of the topping slab and its impact on the double-tee deck.

The side-lap flange-to-flange connections were located at approximately 10-ft (3-m) spacing along double-tee sides (**Fig. 10**). Several additional flange-to-flange connections should have been provided to distribute loads more uniformly to adjacent double tees. Flange-to-flange connections are typically spaced periodically 5 to 8 ft (1.5 to 1.8 m) along the length of double tees, and sometimes they are spaced even closer near midspan.[16]

Although thermal movement of the topping slab is not typically considered by designers, this movement will create tension stresses in the double tees below due to frictional forces. During our original investigation, most of the parties involved, including the authors, believed that the layers of insulation, waterproofing, and drainage mat would provide sufficient bond break between the topping slab and the deck to avoid transfer of stresses between the two. However, further evaluation indicated that thermal movements of the concrete topping slab could induce shear stresses in the deck below.

Based on the weight of the topping slab, horizontal movement of the topping slab transfers to the double tees through shear friction between the two surfaces. From our research, we estimated that the lowest shear friction coefficient between various components of the assembly below the topping slab would be on the order of 0.30. Based on this friction coefficient, a 60°F (33°C) increase in the topping slab temperature (a realistic assumption based on solar gain alone) could lead to an expansion of 0.04 in. (1 mm) over a 10-ft-wide (3-m) double-tee section. Using a linear stress-strain relationship of the concrete, this equates to more than 650,000 lbf (2890 kN) of expansive forces applied to each double-tee side connection plate when the plates are spaced near the ends of 52-ft-long (16-m) double tees. Such forces can readily overcome the design capacity of the connections. In addition, these forces are cumulative in nature and can proportionately increase over multiple double-tee widths (**Fig. 11**).

Obviously, there are many other factors that can change these estimations. For example, the control joints formed in the concrete topping slab may be able to accommodate some of the expansion joint. However, as previously indicated, accumulation of debris in the control joints will minimize their ability to accommodate concrete expansion. In addition, although the insulation and the waterproofing components are somewhat elastic in nature and can deform in shear, such deformations would still result in transfer of shear stresses to the double tees below.

To evaluate this phenomenon of transferred forces, the investigative team installed highly accurate displacement data loggers on the underside of double tees at three separate flange-to-flange connections. Each data logger had three sensors, one for each direction of possible displacement, which were rigidly mounted onto custom-fabricated aluminum plates on each adjacent double tee (**Fig. 12**).

The data loggers recorded displacements every 15 minutes for more than 10 weeks. The displacements were plotted on graphs with the vertical axis indicating displacement and the horizontal axis indicating time. Exterior temperatures and sunny conditions, based on weather reports, were also plotted on the same graphs (**Fig. 13**).

When the data were analyzed, movements were found to be small. Differential movements tended to be inversely related to exterior temperature change. For example, as exterior temperature increased, the joints enlarged. This reverse correlation with outdoor temperature suggests that thermal movements of the topping slab as well as friction between the unbonded topping slab and underlying components imparted stresses on the flange-to-flange double-tee connections, as previously hypothesized.

In some locations, the failed connection plates were repaired using connection plates that allowed more flexibility in the connection to accommodate the small, anticipated movements. This work involved removing the concrete topping slab and underlying components along rows of connection plates. In addition, expansion joints were constructed through the topping slab to minimize future movements.

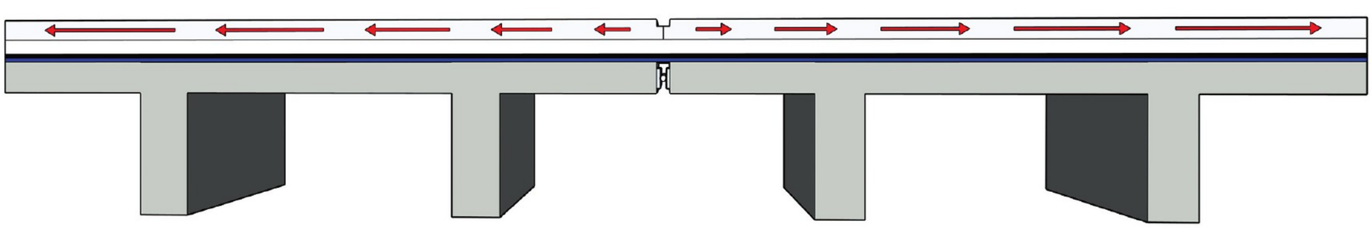

Figure 11. Expansive forces applied to a double-tee connection plate.

Investigators also determined that some yielding of the connection plates would occur as a result of normal movements. Although such movements would not compromise the structural integrity of the building, they could cause local cracking of the precast concrete double-tee flanges around the connection plates. For safety purposes, precautions were taken to prevent cracked concrete from spalling and falling. At some locations, cracked portions of concrete were removed. At other locations, steel plates were installed on the underside of cracked areas to prevent possible spalls from falling. Where connection plates could not be readily accessed, a fall protection system was installed to ensure falling concrete could not pose any safety issues.

Periodic monitoring of the structure and the connection plates has indicated that the development of cracking around the precast concrete T connection plates has decreased significantly. In addition, other waterproofing repairs performed on the top side of the deck have proven effective in controlling water leakage.

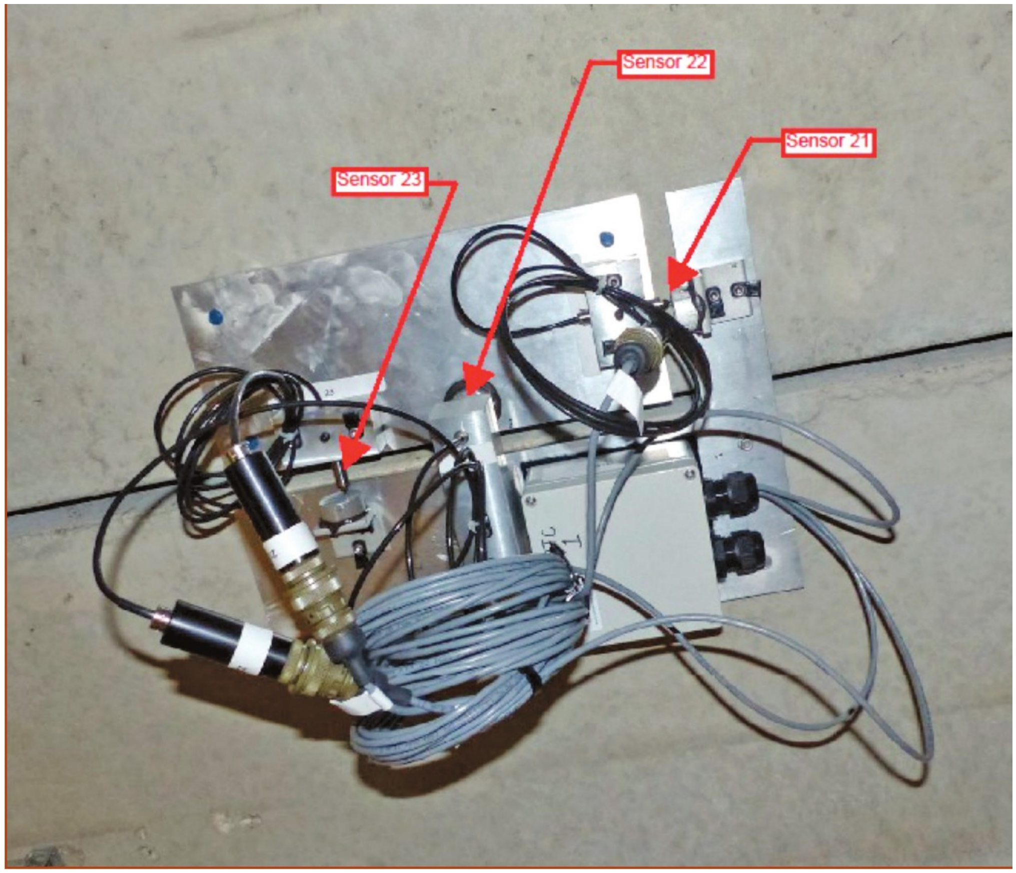

Figure 12. Data logger assembly at a double-tee flange connection.

SUMMARY

Topping slab design for split-slab construction requires careful consideration to ensure the concrete topping is durable and does not cause damage to the structure below. Concrete topping durability can be adversely affected by improper subsurface drainage, insufficient resistance to freezing and thawing, inadequate joint design, and compression of insulation used in the assembly below. Concrete topping slab movements can transfer loads to the structure below, even in the presence of several layers between the topping slab and the structure. These stresses can cause distress in the structure, adjacent parapet walls and vertical

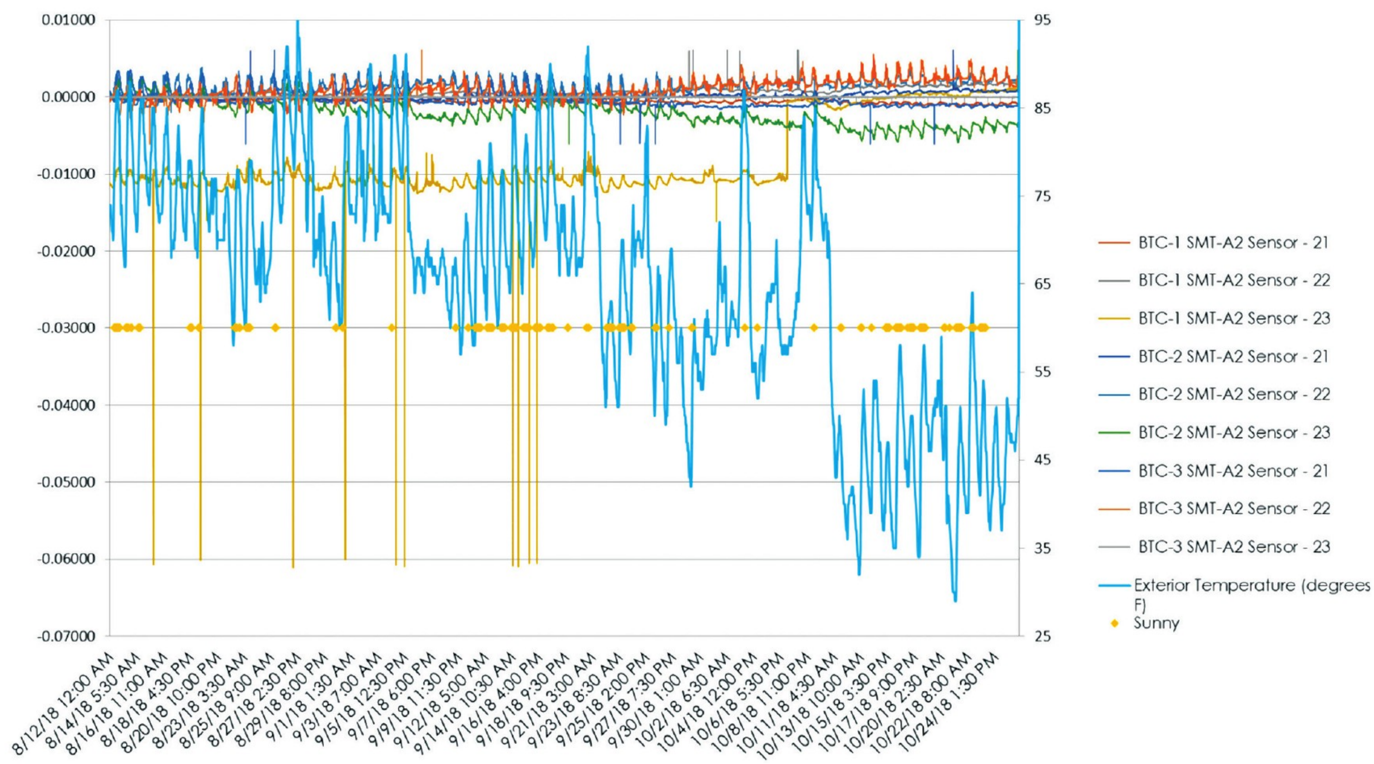

Figure 13. Data logger results.

projections, or waterproofing accessories such as expansion joints. In the design of concrete topping in split-slab construction, key considerations include adequate surface drainage, proper subsurface drainage, flexural strength of the topping slab to resist cracking under load, proper selection of insulation to resist excessive compression, control joint placement, expansion joints to accommodate thermal movements, and concrete durability.

REFERENCES

1. ASTM International. 2015. *Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing.* ASTM C666/C666M-15. West Conshohocken, PA: ASTM International. doi: 10.1520/C0666_C0666M-15.
2. ASTM International. 2019. *Standard Test Method for Abrasion Resistance of Horizontal Concrete Surfaces.* ASTM C779/C779M-19. West Conshohocken, PA: ASTM International. doi: 10.1520/C0779_C0779M-19.
3. ASTM International. 2012 (withdrawn 2021). *Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals.* ASTM C672/C672M-12. West Conshohocken, PA: ASTM International. doi: 10.1520/C0672_C0672M-12.
4. American Concrete Institute (ACI). 2016. *Specifications for Concrete Construction.* ACI 301-16. Farmington Hills, MI: ACI.
5. ACI. 2016. *Guide to Durable Concrete.* ACI 201.2R-16. Farmington Hills, MI: ACI.
6. ACI. 2019. *Building Code Requirements for Structural Concrete and Commentary.* ACI 318-19. Farmington Hills, MI: ACI.
7. ACI. n.d. "Technical Questions: Resistance to Cycles of Freezing and Thawing." Accessed September 10, 2021. https://www.concrete.org/tools/frequentlyaskedquestions.aspx?-faqid=658.
8. ASTM International. 2018. *Standard Specification for Concrete Aggregates.* ASTM C33/C33M-18. West Conshohocken, PA: ASTM International. doi: 10.1520/C0033_C0033M-18.
9. Cement and Concrete Aggregates Australia. 2008. "Guide to Concrete Flatwork Finishes." https://www.ccaa.com.au/imis_prod/documents/Library%20Documents/CCAA%20Technical%20Publications/CCAA%20Guides/CCAAGUIDE2009-T59-Flatwork%20WEB.pdf.
10. Aberdeen Group. 1966. "Non-Slip Finishes for Concrete." Publication #C660351. https://www.concreteconstruction.net/_view-object?id=00000153-8b70-dbf3-a177-9f7990b70000.
11. Portland Cement Association (PCA). 2021. *Design and Control of Concrete Mixtures.* 17th ed. Skokie, IL: PCA.
12. ACI. 2010. *Guide to Design of Slabs-on-Ground.* ACI PRC-360-10. Farmington Hills, MI: ACI.
13. ASTM International. 2019. *Standard Specification for Rigid, Cellular Polystyrene Thermal Insulation.* ASTM C578-19. West Conshohocken, PA: ASTM International. doi: 10.1520/C0578-19.
14. Vaca, E., N. K. Gosain, and G. A. Jimenez. 2015. "Design Considerations for Unbonded Concrete Topping Slabs in Plaza Deck Systems Subjected to Vehicular Traffic." *Concrete Repair Bulletin.* January/February 2015, pp. 18-23. https://cdn.ymaws.com/www.icri.org/resource/resmgr/crb/2015janfeb/CRBJanFeb15_Vaca-Gosain-Jime.pdf.
15. ASTM International. 2019. *Standard Test Method for Determining Relative Humidity in Concrete Floor Slabs Using In Situ Probes.* ASTM F2170-19a. West Conshohocken, PA: ASTM International. doi: 10.1520/F2170-19A.
16. Lucier, G., C. Naito, A. Osborn, M. Nafadi, and S. Rizkalla. 2017. "Double Tee Flange Connections—Experimental Evaluation." Paper 98 presented at PCI Convention and National Bridge Conference, Cleveland, OH, Feb. 28–Mar. 4.

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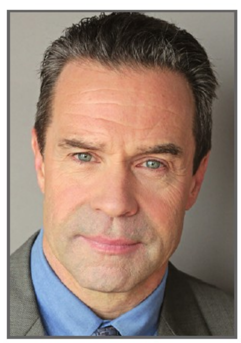

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