Tech Brief

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Precast Concrete Panel (PCP) Roundabouts

U.S. Department of Transportation
Federal Highway Administration

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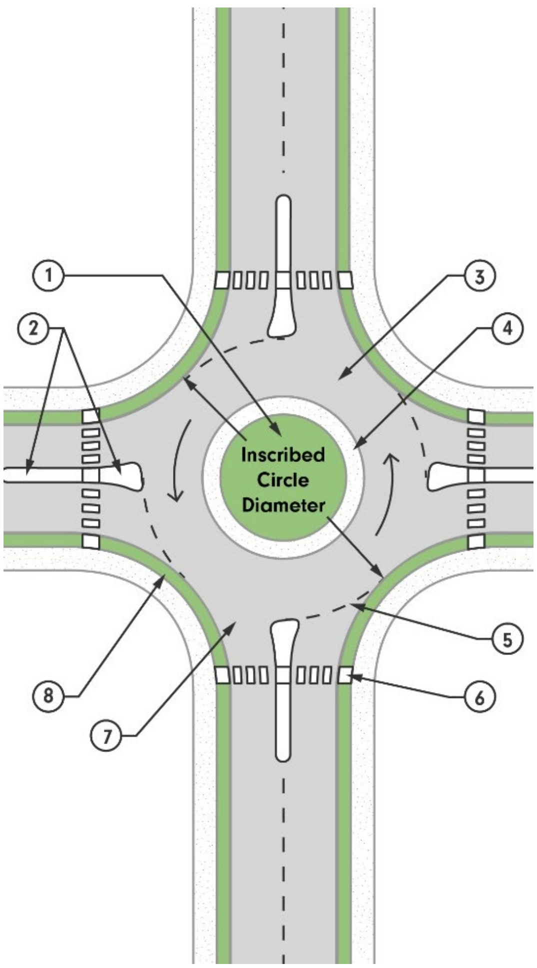
Introduction

General Background on Roundabouts

A roundabout is a form of circular intersection in which traffic travels counterclockwise (in the United States and other right-hand traffic countries) around a central island and in which entering traffic yields to circulating traffic (Rodegerdts et al. 2010). Compared with signalized and stop-controlled intersections, modern roundabouts can provide better overall safety performance, shorter delays and shorter queues, better management of speed, and lower management and operation costs while also adding aesthetic value (FHWA 2010). Figure 1 presents a general schematic of a roundabout, along with a brief description of some of the key design features.



1. Central Island – Raised area around which the traffic circulates.

2. Splitter Island – Raised or painted area on the approach used to separate entering and exiting traffic, control entering traffic, and accommodate pedestrians crossing the roadway.

3. Circulatory Roadway – Curved path used by vehicles to travel around the central island in a counterclockwise direction.

4. Truck Apron – Part of central island that facilitates wheel tracking of large vehicles.

5. Entrance / Yield Line – Marks the point of entry to the circulatory roadway. Also functions as a yield line in the absence of a separate yield line.

6. Accessible Pedestrian Crossings – Provided before the entrance / yield line; splitter island is cut to allow access for pedestrian, wheelchairs, strollers, and bicycles in accordance with ADA requirements.

7. Exit – Marks the point of exit from the circulating roadway.

8. Landscape Buffer – Separates vehicular and pedestrian traffic and guides pedestrians to designated crossing locations.

Figure 1. Key roundabout design features.

Roundabouts are typically classified into three basic categories: mini, single lane, and multilane (FHWA 2010). Most roundabouts constructed in the United States are single lane (roughly 70 percent) and multilane (28 percent) (Rodegerdts 2017). As shown in figure 2 (WSDOT 2019), a cross slope of 2 percent away from the central island is typical for the circulatory roadway on single-lane roundabouts. This not only helps in surface drainage, but also promotes safety by raising the height of the central island and improving its visibility, encourages lower circulating speeds, and minimizes breaks in the cross slopes of the entrance and exit lanes (FHWA 2010).

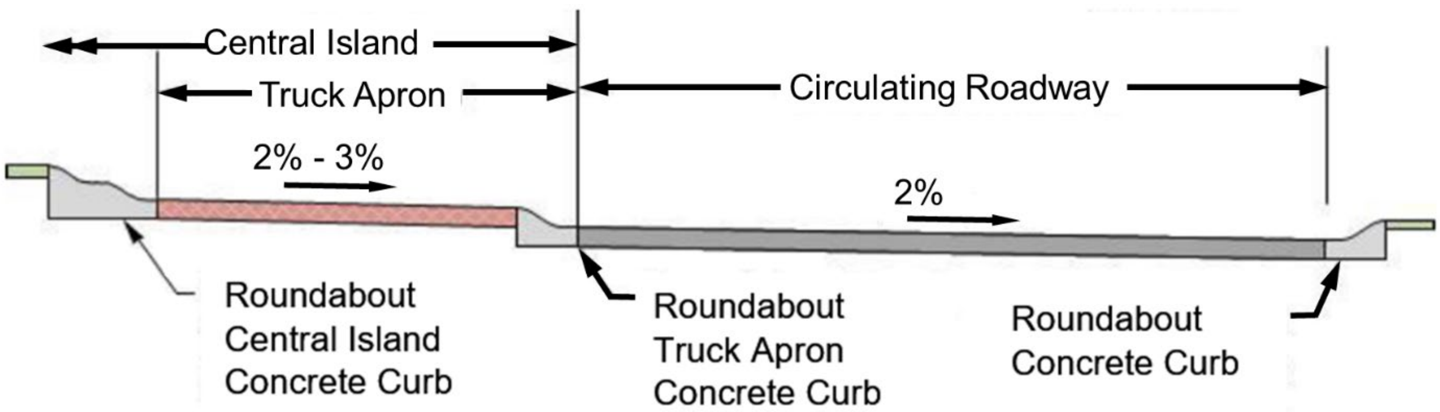


Figure 2. Typical circulatory roadway section with truck apron.

Various pavement types can be used in the construction of roundabouts, including hot-mix asphalt pavement (HMAP), jointed concrete pavement (JCP), continuously reinforced concrete pavement (CRCP), and precast concrete pavement (PCP). The use of PCP may be considered for rapid rehabilitation of the circulating roadway and the truck apron in existing distressed HMAP and JCP roundabouts. PCP is suggested for heavily trafficked roundabouts where the roundabout pavement rehabilitation work can only be performed during short nighttime (i.e., off-peak) closures (partial or full).

This Tech Brief describes the application, design, and construction aspects of PCP roundabouts for rapid rehabilitation of existing distressed HMAP and JCP roundabouts. The description is focused only on the rehabilitation of the circulating roadway and the truck apron without any changes in alignment and geometry. It is assumed that all other pavement areas in the roundabout rehabilitation/improvement would be handled using conventional concrete or asphalt paving. While PCP panels could be fabricated and installed in those areas, the cost of multiple PCP panels with unique geometry could be prohibitively expensive.

Background on PCP

PCP technology is gaining wider acceptance in the United States for rapid rehabilitation of concrete pavements and for reconstruction of heavily trafficked asphalt concrete intersections (Tayabji 2019a). Widespread use of PCP in the United States is relatively recent, with most projects in service since about 2005. PCP technology is being used for intermittent repairs (both full-depth repairs and full slab replacement) and for continuous applications (longer-length/wider-area rehabilitation) with low-maintenance, long-life expectations.

The use of PCP technology can significantly reduce traffic impacts of roadway repair and reconstruction projects, particularly on heavily traveled routes. The technology is applicable to small segments, enabling flexibility in construction phasing, as well as for use in corridor-wide pavement rehabilitation/reconstruction. As shown in figure 3, PCP has been adopted for routine use by several highway agencies, while a number of other highway agencies have constructed demonstration projects (Tayabji 2019b).

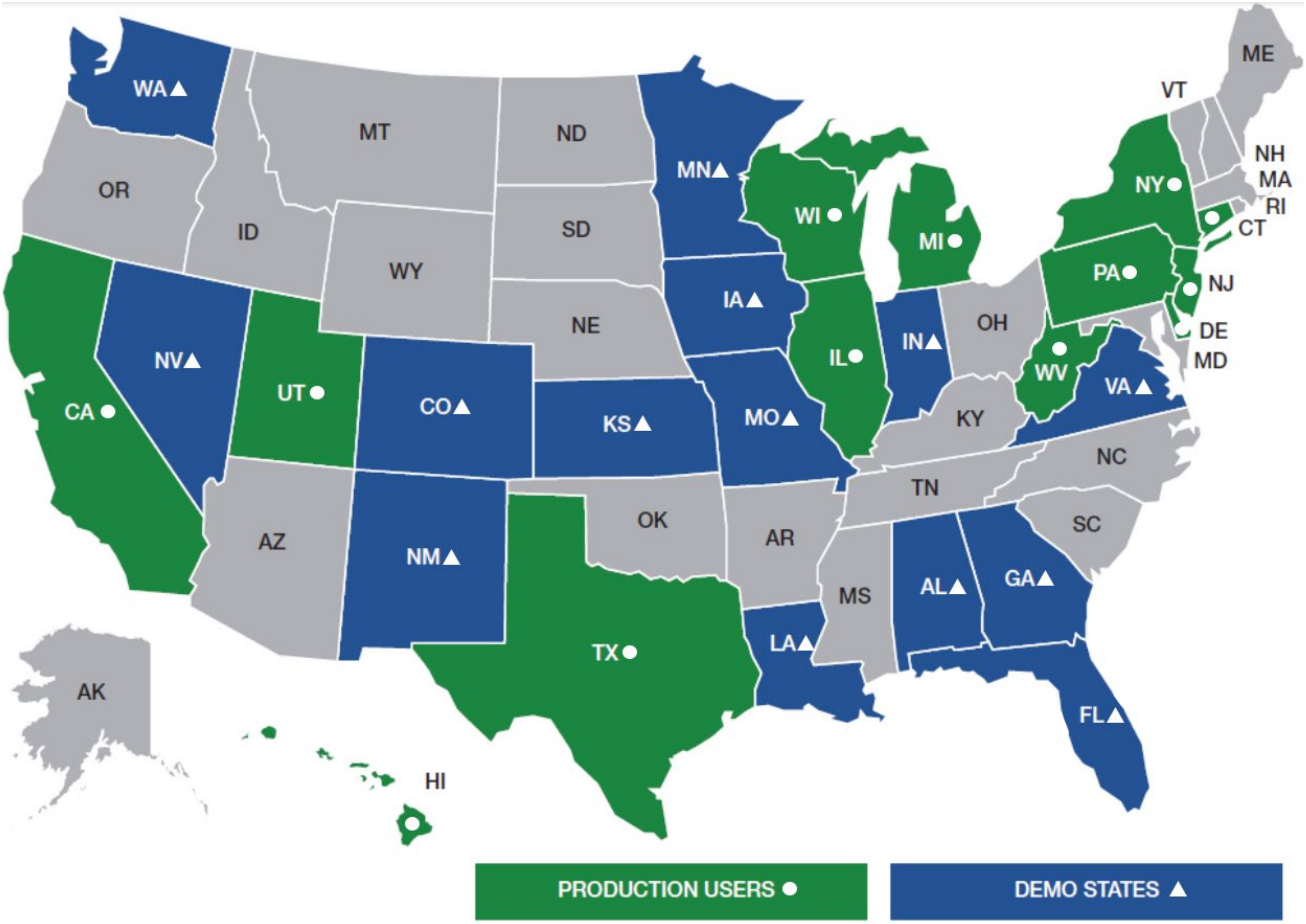


Figure 3. Use of precast concrete pavement in the United States as of January 2019.

PCP Applications

PCPs are used for intermittent (localized) repairs and for continuous applications. The intermittent repairs are for full-depth repairs at joints or for full slab replacement, while continuous applications (such as shown in figure 4, Tayabji 2019b) include reconstruction of distressed freeway lanes, ramps, and busy intersections. It is the continuous application that is considered applicable for the rehabilitation of existing JCP and HMAP roundabouts.

The panels used for PCP may be reinforced or prestressed. As described later, several different panel types have been developed and are in routine use, and all panel types are engineered to provide load transfer at transverse joints and to ensure good bedding support over the base.

Although there is no experience with PCP use in roundabouts, there is good experience now with PCP applications for curved highway sections and ramps. At these locations, use is made of trapezoidal panels or non-planar panels. For this Tech Brief, the application of only the trapezoidal precast panels is described. PCP roundabouts using trapezoidal panels should perform as well as or better than a conventional JCP roundabout with a trapezoidal joint layout, a schematic of which is shown in figure 5 (Rodden 2009).

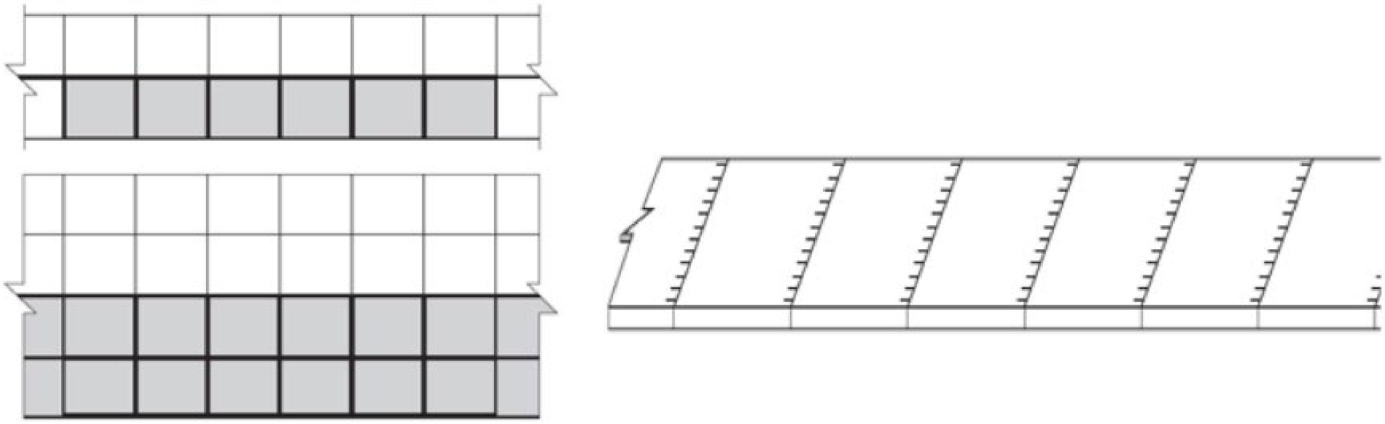


Figure 4. Examples of the continuous application of PCP.

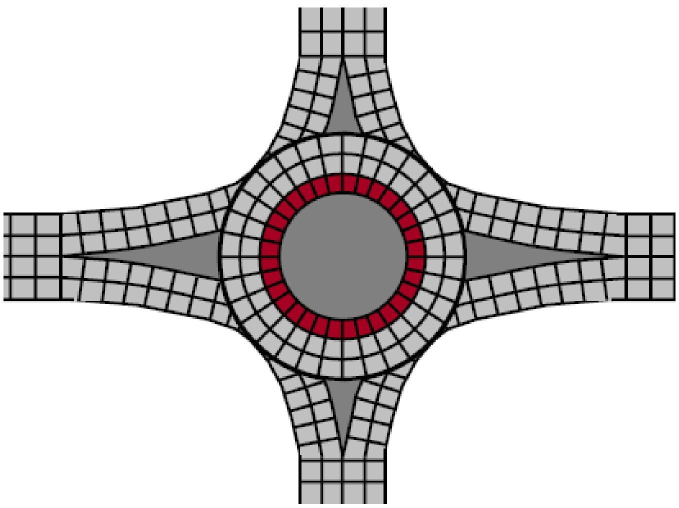


Figure 5. Layout of a roundabout showing trapezoidal joint layout in the circular roadway and truck apron.

PCP Technology

Although PCP roundabouts have not been constructed in the United States, it should be noted that the primary difference between a PCP roundabout and a JCP roundabout is the method of construction. Once constructed, a PCP roundabout typically would perform similar to a like-designed JCP roundabout because:

- The concrete used for the precast panel is placed under controlled conditions at the precast concrete plant and should therefore be more durable. Hot- and cold-weather paving conditions and unexpected rain events do not impact concrete quality and durability.
- Concrete used for precast panels is designed to achieve higher strength to allow for form-stripping the next day. The higher concrete strength allows for longer service life.
- The precast panels are reinforced or pretensioned for safe handling purposes. Therefore, any panel cracking that may develop in service typically remains tight and does not impact the roundabout performance.

Applications and Limitations

Typical Applications

Based on current experience with PCP implementation for highway applications, any project where a JCP is viable may be a candidate for PCP. The PCP technology is implementation-ready for the reconstruction of existing distressed HMAP and JCP traveling lanes at high traffic-volume roundabouts. The precast panel installation technique allows for nighttime rehabilitation, typically one lane at a time, without impacting daytime traffic operations. The following applications could be considered:

- Complete rehabilitation or reconstruction of an HMAP roundabout.
- Rehabilitation or reconstruction of distressed lanes of a JCP roundabout:
  - Partial-lane rehabilitation or reconstruction.
  - Complete single-lane rehabilitation or reconstruction.
  - Complete multiple-lane rehabilitation or reconstruction.

Based on the use of PCP construction in highway applications, the panel installation for roundabouts would be done along a single lane and it is expected that about 10 to 20 panels can be installed per nighttime lane-closure window. As such, a typical 100- to 200-ft outside diameter roundabout lane can be rehabilitated using precast panels over a period of 3 to 5 nighttime work windows, depending on lane-closure availability. The panels along a roundabout lane can be installed in stages while allowing normal traffic flow on a partially completed roundabout segment during the daytime.

Limitations

As with PCP highway construction, one limitation related to the use of PCP on roundabouts is the partial closure of the roundabout during nighttime construction. However, PCP roundabouts can be constructed during regular daytime work shifts because it is still an accelerated construction technology that allows early opening to traffic due to no cure time and no sensitivity to weather conditions. Also, since a crane typically is used, some site conditions may preclude the use of the PCP option if overhead or lateral clearances for the crane operation are not available.

PCP Technical Considerations

There are several different precast panel types available for continuous applications. Although the panels may differ with respect to certain aspects of design, fabrication, and installation, they share many common features. The differences in the panels typically relate to how the load transfer is achieved at transverse joints and the provisions for placing the panel over the prepared base (support condition). The key design and construction items for PCP include:

- Concrete properties.
- Joint spacing.
- Consideration of non-planar panel geometry.
- Overall panel support conditions.
- Panel placement and bedding layer.
- Load transfer at transverse joints.
- Panel reinforcement.
- Panel fabrication.
- Panel installation.

Detailed discussions on PCP technology are given in Tayabji et al. (2013), Smith and Snyder (2019), and Tayabji (2019b). The application and design of non-planar panels is described in Smith and Snyder (2019). This Tech Brief only presents technical details that are applicable to roundabout applications using flat nominally trapezoidal panels.

Concrete Characteristics

Concrete mixture characteristics for PCP panels are like those for cast-in-place concrete pavements. An advantage of PCP is that early-age concrete volume changes associated with drying shrinkage are not a concern, since these effects take place over a smaller panel length and typically before panel installation. In addition, many of the concerns related to cast-in-place concrete (such as hot- or cold-weather placement, placement during rainfall, equipment breakdown, concrete delivery delays, and stop-and-go operations) are not applicable to PCP panel fabrication. Fabrication of panels in well-monitored precast concrete plants is a significant benefit of using PCP. While there are no relevant Federal regulations, typical concrete characteristics for PCP are similar to those of cast-in-place concrete, and could include (Kosmatka and Wilson 2016; ACI 2017):

- Concrete strength (at 28 days):
  - Flexural strength for design purposes—650 psi.
  - Compressive strength for acceptance purposes—4,000 psi.
- Maximum water-cementitious materials ratio—0.42 to 0.45 for pavement exposed to cycles of freezing and thawing, 0.45 to 0.50 for other pavements.
- Air content—As appropriate for the maximum aggregate size used and severity of exposure (climatic region).
- Durability—Concrete must be durable and should not be susceptible to materials-related distress, such as alkali-silica reactivity, sulfate attack, or D-cracking.
- Surface texture in accordance with the agency's standards.

The strength at the time of stripping the panel from the form is also an important consideration for PCP construction. To maintain daily panel production, precasters generally strive to strip panels at about 16 hours after casting, and the concrete compressive strength at the time of form stripping is typically at least 2,500 psi. Many precasters use steam curing to achieve rapid strength gain.

Joint Spacing

Joint spacing is an important design parameter for PCP. For continuous applications, transverse pavement joint spacing is often based on traditional cast-in-place pavement joint spacing but also may be limited by the highway agency's panel shipping rules. Joint spacing details for PCP continuous applications include the following:

- PCP panels used for continuous applications are a single-lane width, typically about 12 to 13 ft. The panel dimension in the direction of traffic is generally 15 ft for 8- to 12-inch thick panels, resulting in transverse joint spacing matching that of typical cast-in-place jointed concrete pavement, which has provided good performance. One panel dimension should be less than 12 ft because of over-width permitting during transport. If the panel width is more than 12 ft, then the panel length, including exposed dowel bars, should be limited to 12 ft to avoid over-width permitting.
- A typical jointing pattern for PCP roundabouts would allow for the use of a standard panel size. By design, the panels should be nominally trapezoidal in shape, as illustrated previously in figure 5. A radial transverse joint pattern across the travelling lanes and the apron lane should be used or preserved from an existing JCP roundabout that is being rehabilitated. The following details should be considered when developing the jointing layout:
  - The panel size determines the contractor's crane capacity.
  - If the lane width exceeds 12 ft, the exterior perimeter length of the panel, including the exposed dowel bars, should be limited to 12 ft to avoid over-width permitting issues.
  - The maximum exterior perimeter length for the inner lane panels should be equal to the inner perimeter length of the adjacent outer lane panels so that the transverse joints across the lanes line up. This applies to the truck apron panels too if precast panels are to be used for the apron-lanes.

An example schematic of a trapezoidal panel is shown in figure 6 (L = maximum length, W = width, d = offset).

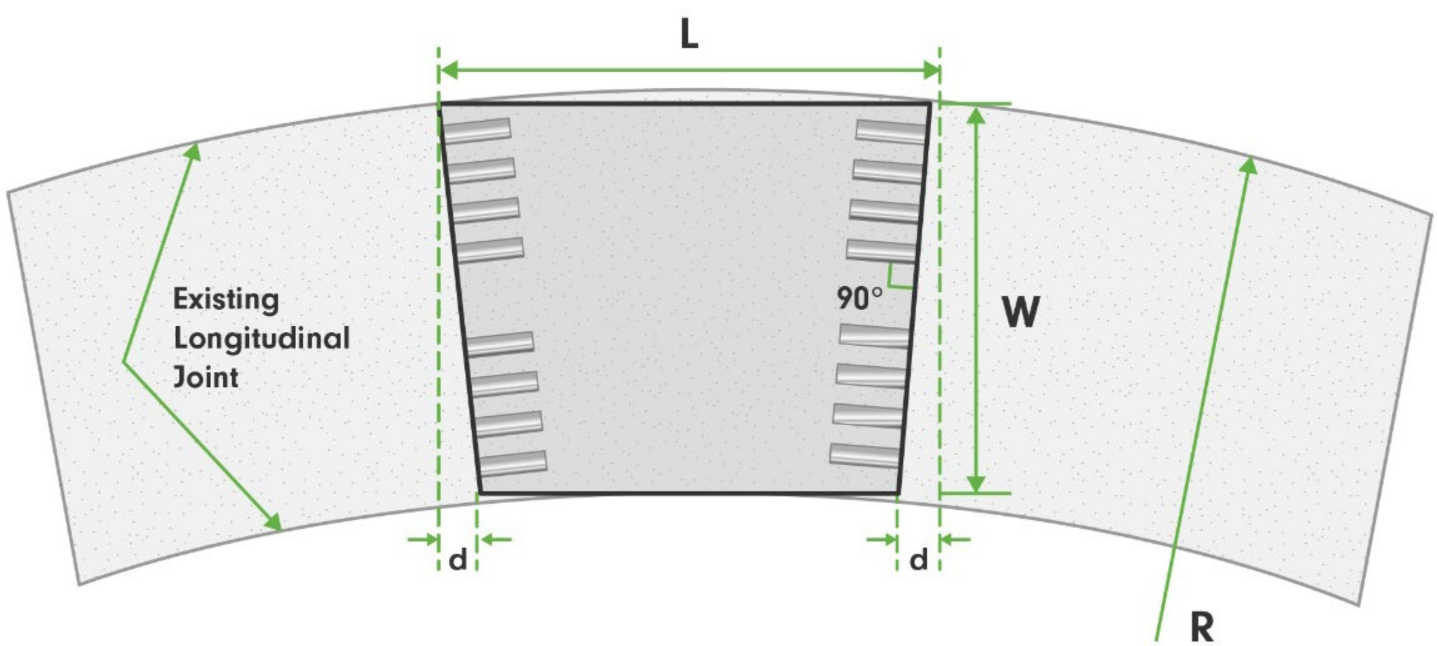


Figure 6. Schematic of a trapezoidal panel.

As shown in figure 6, the inner circumferential length of the panel is shorter than the outside circumferential length of the panel. For illustration purposes, a summary of the differences in length between the outside circumferential length and the inside circumferential length for a panel width of 12 ft and outside circumferential length of 10 and 12 ft is provided in table 1.

Table 1. Calculated shortening of the panel inside circumferential length.

Lane Outside Circumferential Radius, R, ft	Lane Width, W, ft	Panel Outside Circumferential Length, L, ft	Shortening of the Panel Inside Circumferential Length at Each Corner, d, inches (Rounded)
60	12	10	12 1/8
80	12	10	9 1/8
100	12	10	7 1/4
60	12	12	14 1/2
80	12	12	10 7/8
100	12	12	8 3/4

Overall Panel Support Conditions

For JCP or HMAP roundabout rehabilitation (reconstruction) applications, panel support alternatives include reusing an existing base or installing a new base. An existing granular base may be reworked, trimmed, graded, and compacted, and a thin bedding material can then be used to level the base grade. If not damaged in the process of removing the existing slab, an existing stabilized base (cement-treated soil or lean concrete) may be used as is. It also may be trimmed to accommodate the panel thickness. In either case, a thin bedding layer is used to provide a level surface for setting the panels. A new base may be placed if it is determined that the existing base could be damaged during existing slab removal or would not support the long-term performance of the new PCP. This option is common when PCP is used to rehabilitate existing hot-mix asphalt pavements. The new base type may include dense-graded, free-draining granular base for lower levels of truck traffic (<60 trucks/day), or rapid-setting lean concrete base (RSLCB) for higher levels of truck traffic. Many PCP applications, particularly in California, have successfully used RSLCB material produced at the site using mobile mixers. The typical compressive strengths for this material are (Tayabji 2019b):

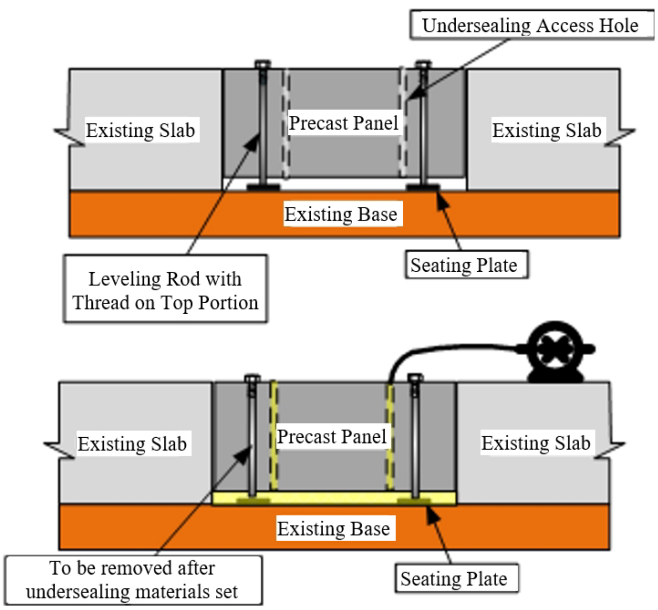
- 500 psi minimum within 1 hour of placement to allow installation of panels.
- 750 psi minimum at 7 days.

Panel Placement and Bedding Layer

Use of a bedding layer (or interlayer) is important to ensure uniform contact between the smooth bottom of a panel and the graded/finished base. The choice of this interlayer material is affected by the way the panels are installed. Panels may be placed directly on grade (grade-placed option) or may be set over a thin layer of bedding grout (grout-supported option) using leveling lifts, as described below:

- Grade-placed option—Panels are placed over a thin bedding layer of cemented granular material or cemented sand for grade-placed systems. It should be noted that some agencies allow the use of unbound granular material or sand as a bedding layer. The bedding layer thickness is typically about 0.5 inch and is placed over the graded and compacted base. Because this method provides little means for adjustment, surface grinding of the panels is normally performed at transverse joints to provide pavement smoothness. Subsealing is performed when using the bedding layer to fill any voids that may exist under the panels. The subsealing material, typically a fast-setting cementitious grout, is free-flowing and is introduced through grout ports at the panel surface. For subsealing materials, the compressive strength typically is about 500 psi at the time of opening to traffic.
- Grout-supported option—Under this option, panels are set about 0.25 to 0.5 inch above the completed base using leveling-lifts (see figure 7a, Tayabji 2019b). A fast-setting flowable cementitious grout is then used to fill the gap under the panel, as shown in figure 7b (Tayabji 2019b). The grout is introduced through grout ports at the panel surface. The compressive strength for the grout typically is about 500 psi at the time of opening to traffic and about 3,000 psi at 28 days. Because the level of the panel surface can be adjusted to match the adjacent pavement and adjacent panels, surface grinding of the panels may not be necessary for smoothness at joints, especially for lower traffic speeds, as are typical in roundabouts.

a. Panel leveling-lift.



b. Schematic

Figure 7b. Grout supported panel placement.

Load Transfer at Transverse Joints

Load transfer at transverse joints is an important design feature. Load transfer for jointed PCP systems is like dowel bar retrofitting in existing concrete pavements. Essentially, load transfer is provided by dowel bars installed in slots or ducts fabricated along one transverse side of a panel. One patented system consists of dowel slots formed in the bottom surface of the panel, whereas other systems have dowel slots formed in the top surface of the panel. The surface slots typically incorporate a narrow mouth at the surface and may be fully open at the surface or open along a partial length of the slot.

The following techniques and features associated with dowel bar slots are commonly used in the United States:

- Panels with dowel bar slots at the panel bottom—This panel system incorporates slots at the slab bottom (figure 8, Tayabji 2019b). A flowable, high-strength grout is used to fill the slots and the vertical gap along the transverse joints. Some applications use a polyfoam filler board in the transverse joint gap. The slot locations in a panel are fabricated to match the locations of the projecting dowel bars in an existing pavement or in a new adjacent panel.

Figure 8. A PCP panel with dowel bar slots at the bottom.

- Panels with Slot/Duct Combination—In this proprietary system, dowel bars are pre-placed in 18-inch long narrow-mouth slot/duct combinations, in which the slot portion is open at the surface (see figure 9, Tayabji 2019b). After the panel is installed, the dowel bar is pushed into a 9-inch long circular hole in the adjacent panel or existing slab. The dowel bar slot/ducts are then patched using a fast-setting high-strength repair material.

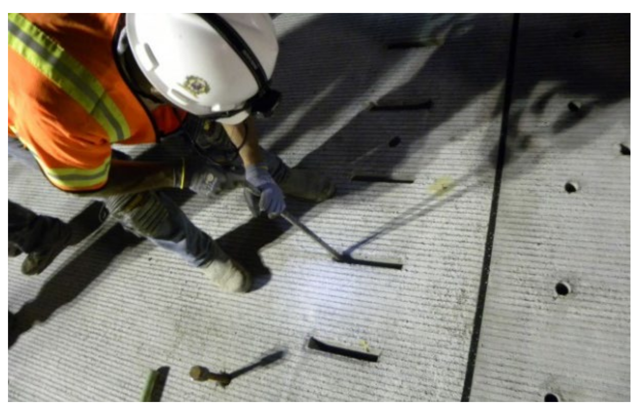


Figure 9. A panel with partially open narrow slots at the surface.

- Panels with Full-Depth Bulgy Slots—This generic panel design is like the panel with bottom slots, except full-depth bulgy slots are used instead of bottom slots, as shown in figure 10. The slots have a narrow opening of about 1 inch at the surface and a slightly wider opening at the bottom of about 2.5 inches, like the opening in the bottom slot panel. The middle portion of the slot at the location of the dowel bar has a bulge of about 3 inches, hence the name bulgy slot.

Figure 10. A panel with full-depth bulgy slots.

Dowel Bar Features

Dowel bars used in highway pavement application are typically smooth, round solid, or tubular steel bars. In addition, corrosion protection is typically provided in the form of a fusion-bonded epoxy coating. Dowel bar features critical to long-term PCP performance may include:

- Dowel bar diameter—A solid dowel bar of diameter 1.25 inches is typical for precast panels less than 10 inches thick. A solid dowel bar of diameter 1.50 inches is typical for precast panel thicknesses between 10 and 14 inches.
- Dowel bar length—Typical dowel length used in the United States for cast-in-place paving is 18 inches. However, since precise locations of the dowel bars are known in PCP, the use of 14- or 15-inch-long dowel bars is considered adequate, allowing for embedment of about 7 inches at each side of the joint and accounting for a joint width of up to 0.5 inch.
- Dowel bar spacing—Dowels are typically placed at a spacing of 12 inches. For roundabout applications, dowel bars along the full length of the transverse joints should be used because of cross-lane traffic movements.

Dowel Bar Slot Grout and Patching Materials

The dowel bar slots are typically grouted or patched right after the panel installation; that is, during a single lane closure. The joint slot grout or patching material should develop strength rapidly. Typical strength values specified by highway agencies are 2,500 psi within 1 hour or by the time of opening the PCP section to early morning traffic. The dowel bar slot grout or patching materials are typically rapid-setting proprietary materials and may be free-flowing cementitious or polymer-based, with or without aggregate.

Panel Reinforcement

To mitigate any cracking that may develop due to the lifting and transport operations, a double mat of reinforcement is typically used for jointed PCP panels. Reinforcement keeps any developing cracks tight, thus extending the service life of the panels. The amount of reinforcement is typically at least about 0.18 percent of the panel cross-sectional area in both directions. For pretensioned panels, a single layer of reinforcement, transverse to the pre-tensioning strands, is used. All steel used in the precast pavement system should be protected against corrosion. The type of steel and steel cover should follow established highway agency practices.

Pavement Design Considerations

The design considerations for new PCP roundabouts are like those for JCP roundabouts. The first step in the design process is to estimate the design truck traffic over the design period that would use the roundabout travelling lanes and the apron lane. Then, the design procedure or the agency's catalog design procedure is used to develop the pavement design that includes the following details:

- Panel thickness.
- Base type (existing or new).
- Edge treatment (support conditions) for the outer and the apron lanes.

In addition to the PCP roundabout pavement design for the traveling and the apron lanes, additional design features should be addressed. These features include the jointing details between the approach/exit pavements and the outer PCP lane and the use of a sleeper slab at approach/exit intersections.

For the rehabilitation of a partial length of a JCP lane, the panel design typically matches the existing slab thickness and the trapezoidal joint layout. The perimeter sides of the panel may be straight or curved to match the curves of the slabs being replaced. The existing base may be reused if granular, or replaced with a rapid setting lean concrete base (RSLCB) or other suitable material.

Structural Thickness Design

Roundabout PCP typically is designed for a service life of 40 years or longer. The structural design procedures used for JCP are directly applicable for the structural design of the precast panels. The highway agency's design procedure should be used to determine the panel thickness for the site-specific design factors. These factors include the following:

- Truck traffic projection over the design period.
- Concrete strength to account for the higher strength of concrete used for precast concrete panels.
- Base type:
  - Existing or new granular base.
  - Rapid-setting lean concrete base (RSLCB).

Typically, a minimum thickness of the precast panel is 8 inches. This minimum thickness is necessary to accommodate the reinforcement, the lifting/leveling inserts, and the dowel bar slots.

As noted previously, the precast concrete panels are reinforced in both directions to alleviate safety concerns during handling and shipping of the panels. Although the use of the panel reinforcement is not directly accounted for in the structural design of the panel, the use of the reinforcement does have a significant performance advantage. Any panel cracking that may develop under traffic loading is kept tight and does not impact the panel performance.

Traffic Staging

As noted previously, PCP work is typically performed in stages during short nighttime work windows. Work can be performed along one lane and one additional lane, or the apron or the outside shoulder can be used for construction traffic. The length of the lane that can be worked upon typically ranges from about 150 to 200 ft (outside perimeter length), involving placement of about 15 to 20 panels. The panel length (outside perimeter length) typically may range from 10 to 12 ft. The staging of the panel placement operation can allow for partial use of the roundabout during the nighttime beginning typically by about 7 pm, with full traffic operation resuming typically by about 6 am.

Edge Support

The following edge support features may be incorporated into a PCP roundabout project, depending on the functional use of the facility:

- Exterior lane:
  - Use of a sleeper slab at intersections with approach/exit lanes.
  - Use of a curb placed along the PCP edge.
  - Use of a curb and gutter adjacent to the lane.
  - Use of an asphalt or a concrete shoulder in rural setting.
- Interior lane:
  - Use of a transition curb between the lane and the apron lane.
- Apron lane:
  - Use of a transition curb between the apron lane and the central island.

Longitudinal Joint Details

In concrete roundabouts, deformed tie bars are often used to tie the interior concrete curb and gutter of the truck apron to the circulatory lane (see figure 11). Tie bars are also used to tie the truck apron to the concrete curb of the central island and to tie the outside curb/gutter to the outside circulatory lane. The tie bars are used to maintain alignment and restrain movement at tied "longitudinal" contraction and construction joints. Typical tie bar considerations during construction may include (ACPA 2017):

- Tie bars are placed at mid-depth of the slab across the joint. These are typically No. 4 or No. 5 bars, 30 inches long, and spaced on 30-inch centers.
- Tie bars can be placed and aligned during concrete placement using various means including positioned on chairs or baskets, through proprietary systems that attach to formwork, through the use of a tie bar inserter if the pavement is slipformed, or manually drilled into the existing slab and anchored with a cement grout or epoxy material.

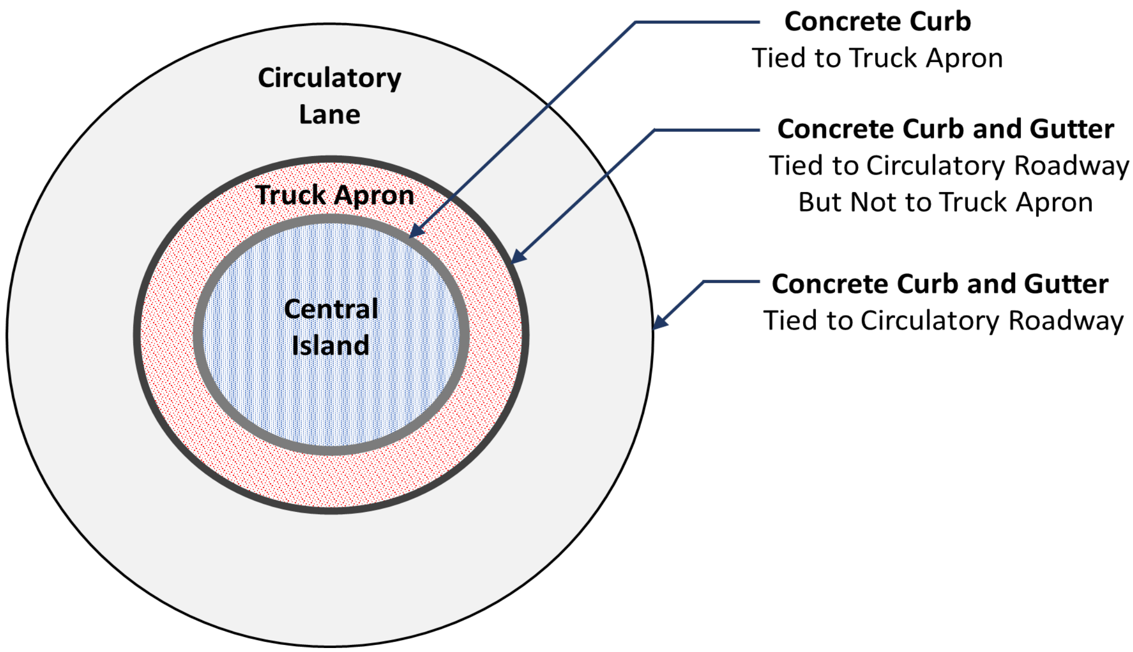


Figure 11. Tie bar locations for concrete roundabout designs.

It is possible to construct the roundabout without tie bars at these locations. This is because slab drifting or migration is unlikely to occur since the pavement is constrained by its geometric layout and by the dowel bars provided in the transverse joints. The resulting free edge condition of untied longitudinal joints may lead to slight increases in the thickness of the slabs used in the circulatory lane.

Isolation Joints and Roadway Transitions

The PCP roundabout pavement is constructed in a circular pattern. The approach and existing roadways typically consist of HMA, JCP, and CRCP. For the case of the approaching and exiting HMA pavements, the termination portion of the roadways at the roundabout should be a jointed concrete pavement and an expansion joint should be used around the outside perimeter of the exterior roundabout PCP lane at the location of the juncture with the approach and the exiting roadways. For this application, precast panels may be used. Also, a support slab should be used under the approach PCP section and the ends of the approach and exiting roadways to reduce deflections as heavy vehicles cross the juncture. The same transition detail is applicable to the approach and exiting roadways that are JCP.

Truck Apron

As shown in figure 1, the truck apron is the area between the circulating roadway and center island whose purpose is to provide a paved surface for wheel tracking of trailer axles as long trucks pass through the roundabout. Colored concrete or stamped patterns are several options used to differentiate the appearance of the truck apron from the circulatory roadway; but in some cases, these may discourage truck drivers from using the truck apron (ITE 2008).

The truck apron may be PCP, JCP, or in some cases block pavers, with an expansion joint used to isolate it from the back of curb of the circulatory pavement. If the truck apron is JCP, some standard detail drawings (e.g., SDD 13C18-e, WisDOT 2018) show the truck-apron transverse joints without dowels, which may satisfy most design situations. Highway agencies may choose not to place dowels in the truck apron if it is assumed that few if any trucks could traverse the transverse joints. Alternatively, dowels could be used along the full length of transverse joints in the truck apron, especially for smaller-diameter roundabouts, if it is assumed that a significant number of trucks could traverse them. Similarly, a logical design detail for transverse joints in the truck apron could also show dowels along the outer half of the transverse joint if this is assumed to be the portion of the transverse joint that could be subjected to a significant volume of truck traffic.

Panel Fabrication

The panels are fabricated in accordance with fabricator shop drawings approved by the highway agency. Panel fabrication may involve the following steps:

1. Setting up the formwork. Special formwork should be considered if non-planar panels are to be used (Smith and Snyder 2019).
2. Installing the hardware (reinforcement, prestressing steel, and related hardware as per design, lifting inserts, etc.).
3. Provisions for blockouts and grout ports for dowel bars.
4. Provisions for panel undersealing or panel bedding grout ports.
5. Placing concrete.
6. Finishing concrete and applying surface texture.
7. Applying curing compound to the surface.
8. Stripping forms, removing dowel and tie-bar slot blockouts, opening grout ports, etc.
9. Applying curing compound to panel sides.
10. Storing panels at the plant, typically for a period of at least 14 days.

Concrete is typically produced in accordance with ASTM C94 and concrete plants supplying the concrete typically are certified by the highway agency, typically operating in accordance with the National Ready Mixed Concrete Association's QC3 checklist. Once panel installation work begins, 10 to 20 panels may be installed per night, so a stockpile of panels typically is fabricated before the panel installation work begins.

A typical reinforcement arrangement for a jointed PCP panel is shown in figure 12 (Tayabji 2019b). Typically, six to eight panels may be fabricated at a time per day in an indoor plant facility.

Figure 12. Typical reinforcement layout for a precast panel.

The shop drawings for the precast panels typically include details related to how the panels fit together and provide the following information for panel installation around a complete roundabout lane:

1. Design of the first permanent panel to be installed, typically with dowel bars embedded along both transverse sides of the panel.
2. Design of a 3-ft long trapezoidal dummy panel, with bottom slots along the leave side, to be installed at the approach side of the first permanent panel. This dummy panel is left in place until the last night of panel placement.
3. Design of the standard intermediate panels.
   a. Bottom slot or full-depth slot along the approach side.
   b. Embedded dowel bars along the leave side.
4. Design of a 3-ft long trapezoidal dummy panel, with bottom slots along the approach side, to be installed at the leave side of a permanent panel. This dummy panel is to be used at the end of each night's panel placement.
5. Design of the last panel (closure panel), typically with bottom slots or full-depth slots, along both transverse sides of the panel.

The above details can be easily modified if only a partial JCP roundabout lane is to be rehabilitated. It should be noted that all dowel bars and slots are oriented perpendicular to the radially oriented transverse panel joints.

Construction of PCP Roundabouts

Construction of PCP for roundabouts is essentially the same as linear PCP construction. The following subsections highlight important PCP roundabout construction factors. For PCP construction, the panel installation rate is one of the most critical factors as it affects the length of the lane-closure/roundabout closure period. An example of the typical panel installation activities conducted during a given nighttime lane closure include the following:

1. 7 pm: Put up signage for lane closures and traffic routing or detours if necessary.

   Note: Sawcuts in the pavement section to be worked on are made the night before by sawing longitudinally along the two boundary perimeters and transversely within the work area.

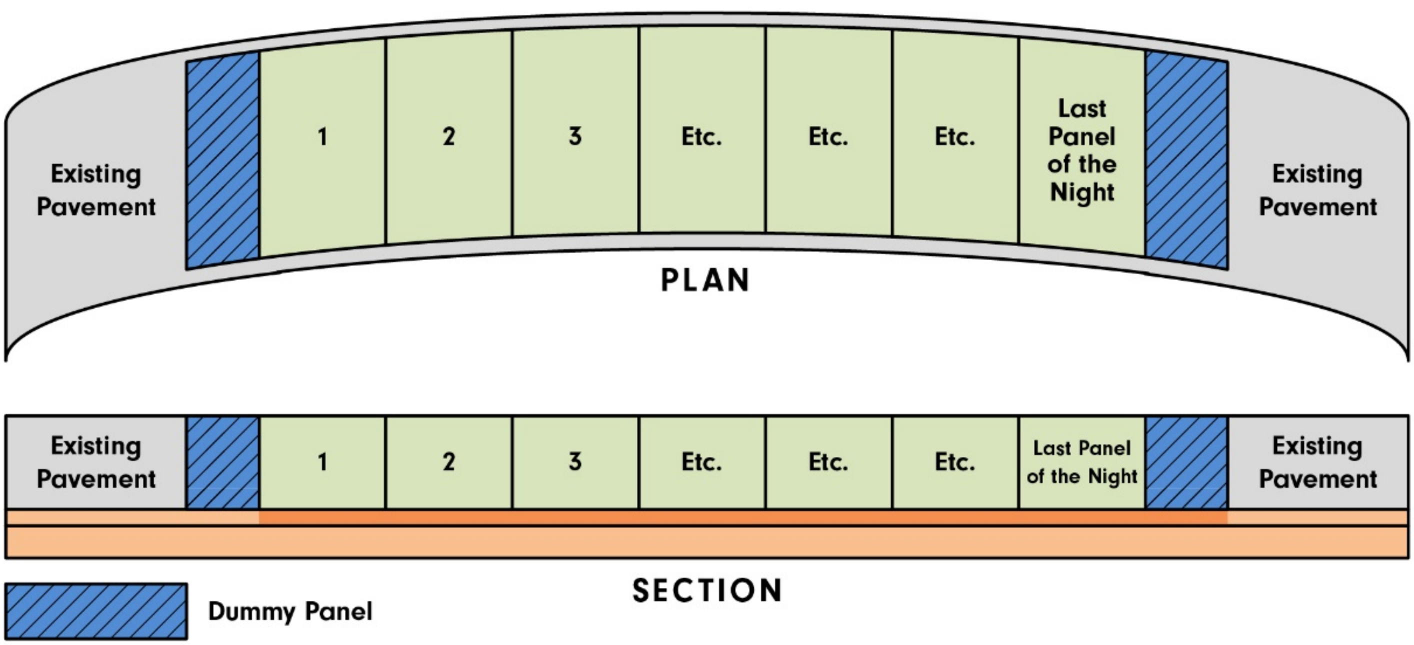
2. 8 pm: Start removal of the distressed pavement.
3. 9 pm: Start preparing the base and the bedding layer, per bedding layer option.
4. Around midnight: Start panel placement.
5. 2 am: Adjust panel elevation using leveling lifts, per panel support option.
6. 3 am: Start bedding grout placement or panel undersealing, per panel support option.
7. 4 am: Start dowel bar slot grout or patching material placement.
8. 5 am: Start roadway cleanup.
9. 6 am: Remove construction signage and open work area to traffic.

The surface grinding and joint sealing activities are typically performed within a few weeks of the final panel placement.

Panel Placement Logistics

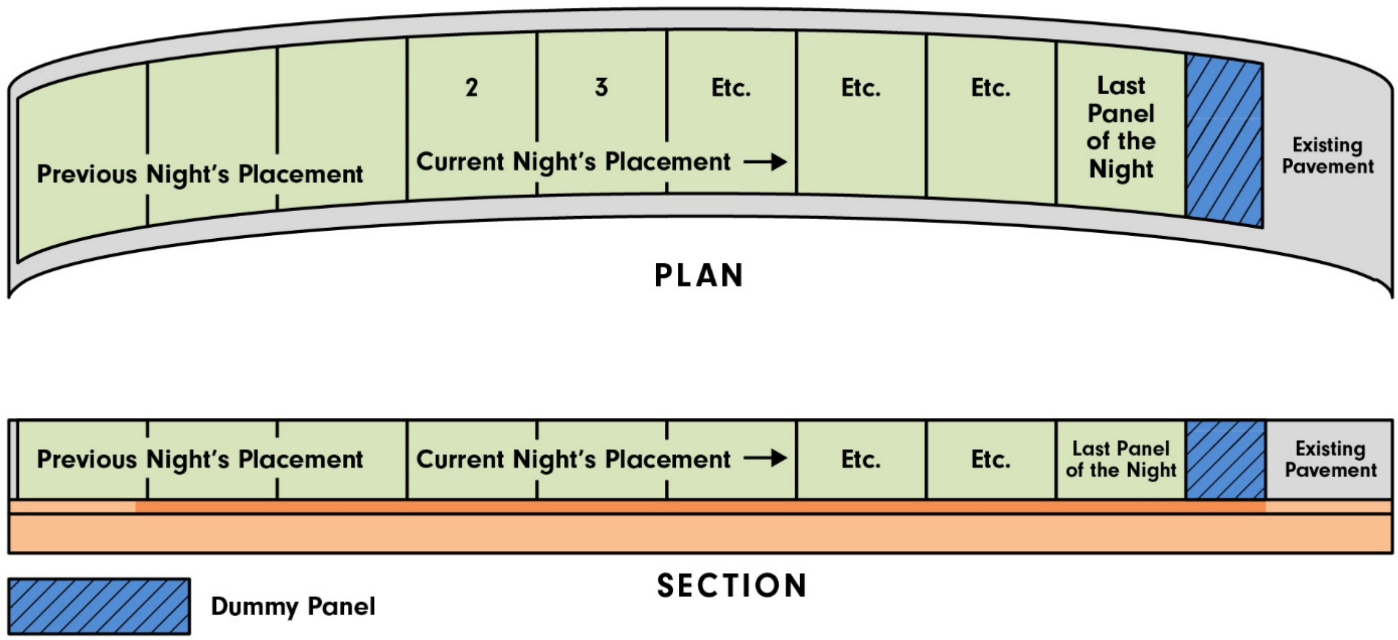
For the roundabout continuous application, the area to be worked during any lane closure depends on the number of panels to be installed during that lane closure. The work-area layout is shown in figure 13. The longitudinal width of the work area is equal to the panel width plus 1 to 1.5 inches to accommodate the roundabout curvature during panel placement. The length of the work area should accommodate the total length of the panels to be placed that night, plus 0.25 to 0.5 inch for each transverse joint gap. In addition, the work area length should account for the length of the dummy panel to be placed after the last panel.

For each successive night of panel placement, the dummy panel placed at the end of the previous night's panel placement is removed and the panel placement process is repeated. For the last night of panel placement, the dummy panel placed at the start (night 1) of panel placement is removed and the last panel is placed at that location. The panel layouts for successive nights and the final night's panel placement are shown in figures 14 and 15, respectively.



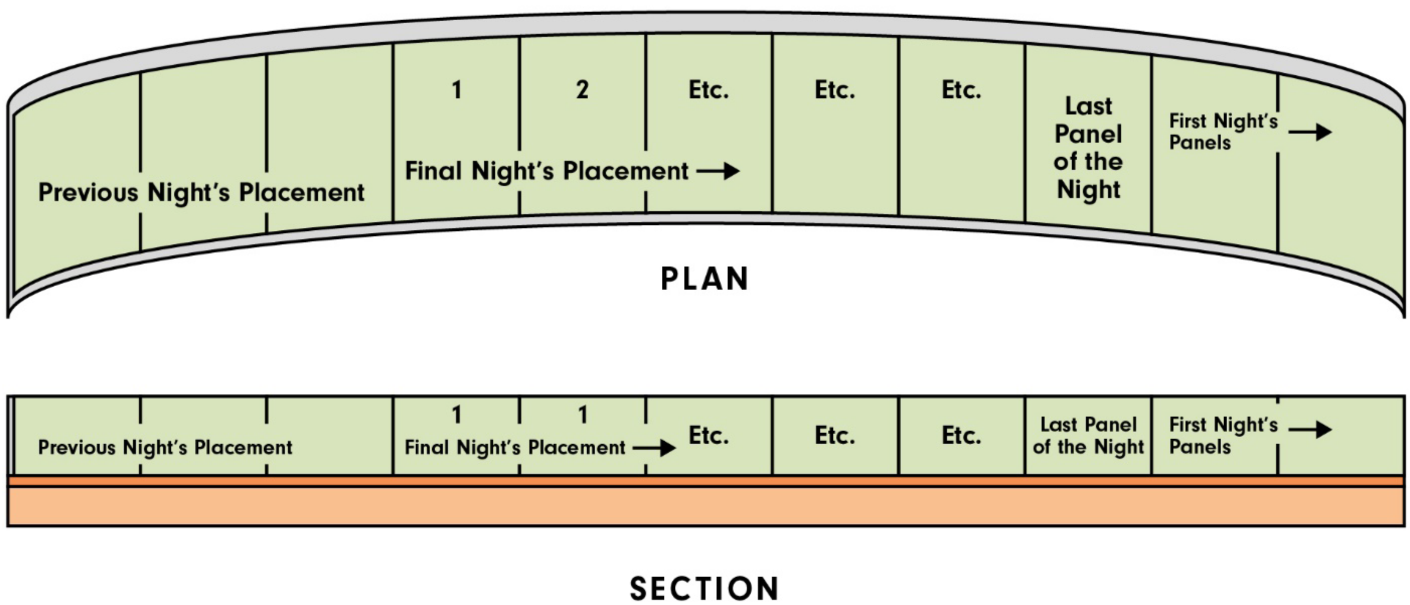
Note: For simplicity, the plan view shows rectangular panels, but trapezoidal panels would be actually used.

Figure 13. Work area for first night's panel placement.



Note: For simplicity, the plan view shows rectangular panels, but trapezoidal panels would be actually used.

Figure 14. Work area for panel placement on successive nights.



Note: For simplicity, the plan view shows rectangular panels, but trapezoidal panels would be actually used.

Figure 15. Work area for panel placement on final night.

Isolating Drainage and Utility Manholes

Ideally, the design layout of a PCP roundabout should avoid the location of utility manholes within the PCP lanes. However, blockouts can be fabricated in the affected precast panels if manholes are to be located in the lanes. With respect to drainage inlets, these are located along the outer perimeter of the roundabout and can be incorporated within the fabricated panels.

Quality Control and Quality Assurance

Successful PCP projects typically consider the following items during panel fabrication and during panel installation, as follows:

- Materials quality.
  - Granular base material—compaction control.
  - Rapid-setting lean concrete base—compressive strength.
  - Bedding material for grade-supported panels.
  - Bedding grout for grout-supported panels—compressive strength using cubes and tested at 1 hour or until 500 psi strength is achieved and tested at 7 days.
  - Dowel slot grout—compressive strength using cubes and tested at 1 hour or until 2,500 psi strength is achieved and tested at 7 days.
- Fabricated panel.
  - Panel dimensional tolerance—several parameters are typically specified (Smith and Snyder 2019).
  - Surface texture.
- Panel installation.
  - Smoothness, as per agency requirements.
  - Joint elevation difference (less than 0.125 inch).
  - Uniform transverse joint width
  - Transverse joint width not to exceed 0.5 inch.

Summary

PCP technology can be used for the rapid nighttime rehabilitation of existing distressed JCP or HMAP roundabouts that are designed to carry heavy truck traffic and buses. PCP may provide long-life service with expectations of minimal maintenance and repair. The use of PCP to rehabilitate distressed JCP or HMAP may create minimal disruption to traffic during construction.

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