Building Contoured Pavements With Precast Concrete Pavement Slabs

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When precast pavement slabs were first introduced for rapidly replacing and repairing concrete pavement in the early 2000's, it was commonly believed by roadway engineers and precasters that flat, single-plane slabs could be used in most roadway locations. It has now become apparent that, while flat single-plane panels works in locations where the original roadway is straight and even slightly curved, contoured roadways require similarly-contoured (warped) precast replacement panels. This paper focuses on how highway geometrical features, such as horizontal and vertical curves, super-elevation transitions, vertical and horizontal departures of existing pavement from as-built locations and vertical and horizontal geometry of intersecting roadways, may significantly affect the geometric design, fabrication and installation of mildly-reinforced and precast prestressed pavement slabs. Particular reference will be made to the importance of including parameters for designing and installing non-planar precast pavements in contract plans and specifications.

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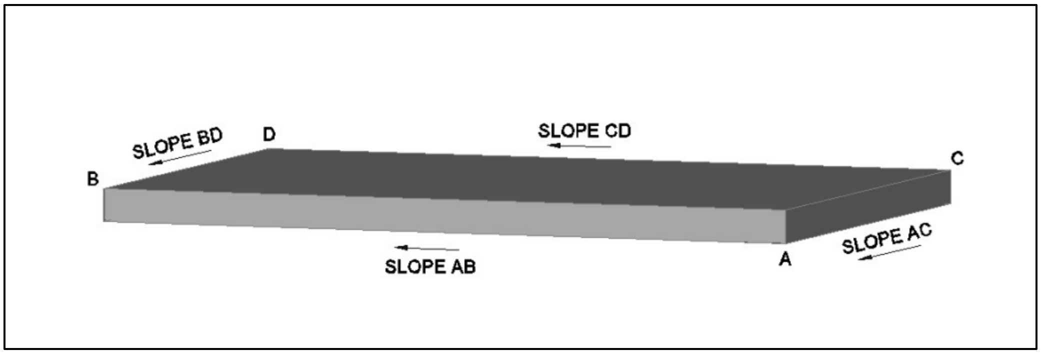
Introduction

The use of precast pavement for rapid repair and replacement of concrete pavement has grown significantly in the last 10 years, to installations totaling nearly 30 lane-miles on nearly 60 projects in the US and Canada. This expanded use had led to improvements in design, installation techniques, and to an ever-increasing variety of installation types, from simple intermittent repair projects (patching) to more complex projects, such as Interstate mainlines, ramps, intersections and bridge approach slabs.

While much progress has been made in the structural aspects of precast pavement, such as load transfer mechanisms and bedding techniques, little attention has been given to "global" geometry of a multiple of panels or as to how well individual panels fit the "global" pavement surface geometry of the surrounding pavement. Most designers and fabricators have worked only with flat single-plane panels, as shown in Figure 1, and have purposely limited their choice of precast pavement projects to single-panel repair projects (intermittent repairs) or to continuous straight, constant-cross-slope and straight-alignment ones to keep the construction process simple.



Single-Plane Panel Schematic

Figure 1

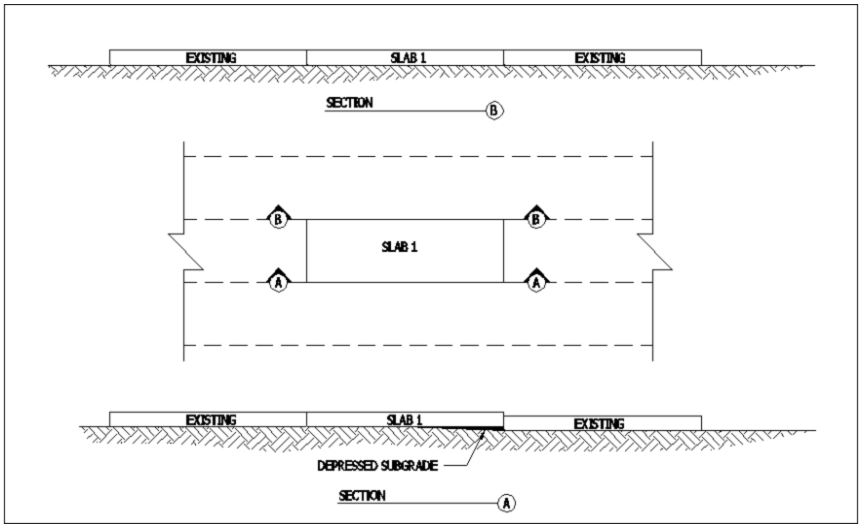
Building Precast Pavement with Flat Single Plane-Panels

Flat single-plane panels, as shown in Figure 1, may be defined as those whose slopes of opposite sides are equal, such that Slope AB = Slope CD and Slope AC = Slope BD. The significance of the form of this definition will become apparent later in this paper.

Flat single-plane panels play an important role in precast pavement construction for two reasons. First, fabrication costs are minimized because flat panels can be fabricated in simple cost-effective flat beds. This is especially true with Precast Prestressed Concrete Pavement (PPCP) panels that are preferentially manufactured in multiples, on long-line single-plane prestressing beds. Long-line prestress manufacturing additionally contributes to economy because panels can be adequately reinforced with a few prestressing strands rather than with hundreds of individual reinforcing bars in the same number of mildly reinforced panels.

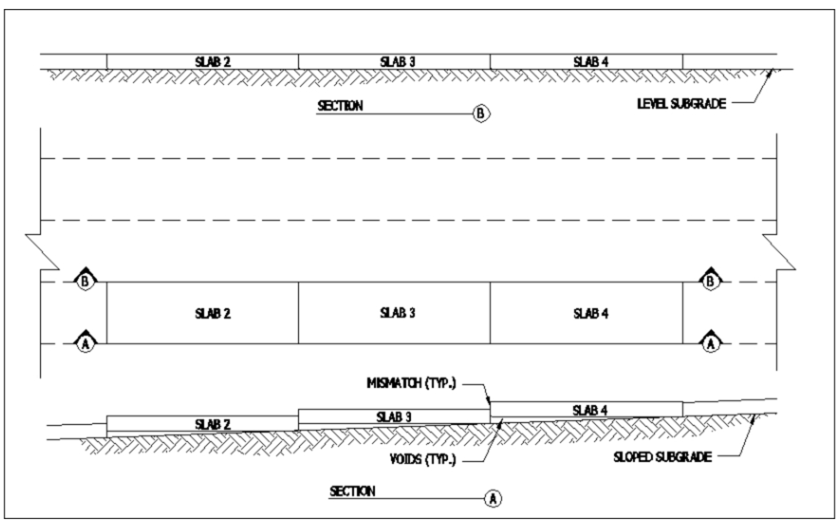
Secondly, installation costs may be minimized because single plane panels can be placed to a "best-fit" position, as shown in Figure 2 and later ground to match the surrounding pavement to meet required smoothness requirements. On many roadways the roadway surrounding the new panel is non-planar or rough to start with so grinding of the entire roadway may be required anyway.

Single plane panels may also be used in a case where the global pavement surface is theoretically non-planar as long as the panels placed upon it do not mismatch excessively. A super elevation transition is shown in Figure 3 where the entire subgrade surface is non-planar as evidenced by different grades on the A-A and B-B ends of the slabs. A series of single plane panels may still be acceptable in this case as long as the mismatch between panels is not excessive and the panels can be ground smooth without compromising the structural integrity of the panels. Most specifications set ¼ inch as the maximum allowable mismatch.



Single-Panel Mismatch

Figure 2



Multiple-Panels Placed On Super Elevated Surface

Figure 3

The success of using flat single-plane panels in a number of these cases has led to a mis-perception that flat panels can be used to repair sections of all roadways because roadway surfaces are, within the context of single panels, essentially planar and that surface mismatches can simply be ground away to achieve smooth pavements. Because of this, project plans and specifications typically address structural and material aspects of precast pavement only with little, if any, reference made to using anything other than flat single-plane panels, even though parts of those roadways may be obviously significantly non-planar.

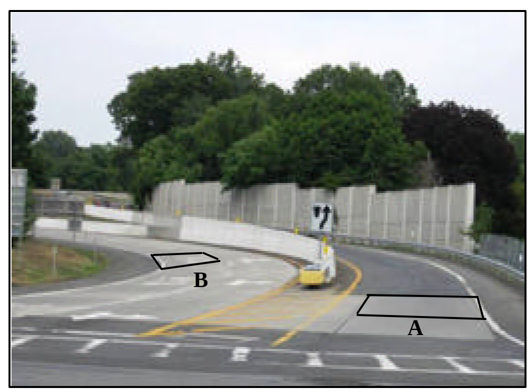
The following sections will demonstrate how portions of many roadways are significantly non-planar such as to preclude the use of flat single-plane panels. Specific roadway features will be examined in detail to show the magnitude of changes in global pavement surface geometry is frequently larger than what can be corrected by grinding away flat single-plane panels

Recognizing Non-Planar Surface Geometry

Much of the challenge associated with precast pavement design today is that non-planar surface geometry may not be visible to the naked eye. To demonstrate this, photos of two roadways that were actually replaced with precast panels are shown in Figures 4 and 5. The portion of the Interstate pavement shown in Figure 4 appears to be planar, since it resides in a straight line, yet approximately 25% of the 730 precast panels installed on this project were warped or non-planar (this will be explored in more detail in a later section).

Non-Planer Panels Installed on An Apparently Planar Alignment

Figure 4



Non-Planar Panels Comprising a Decidedly Non-Planar Surface

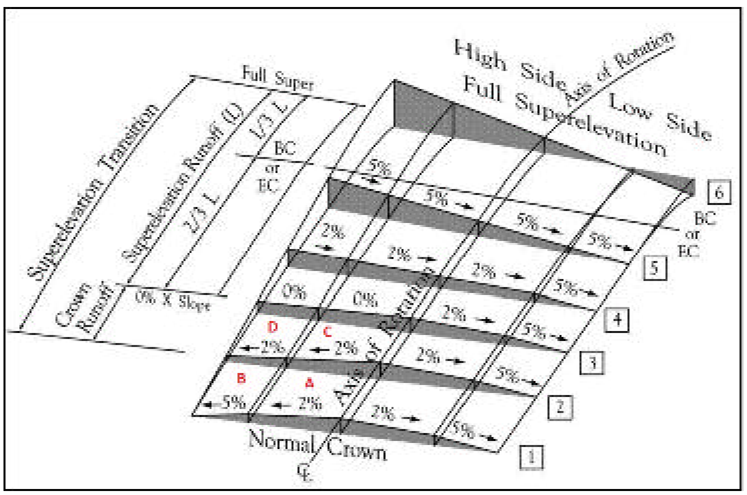
Figure 5

Similarly, the surface of the two adjoining ramps shown in Figure 5 is obviously globally non-planar, but it is difficult, if not impossible, to determine the planarity of specific areas, such as Panels A and B, Figure 5 simply by looking at them with the naked eye. In fact all of the panels installed on these ramps were non-planar as will be discussed in more detail later in this paper.

To aid in recognizing non-planar surfaces, and determining the magnitude of their surface variations, a number of specific roadway features will be shown to illustrate common pavement areas that warrant further examination and more detailed analyses to determine the magnitude of surface planarity.

Super Elevation Transitions

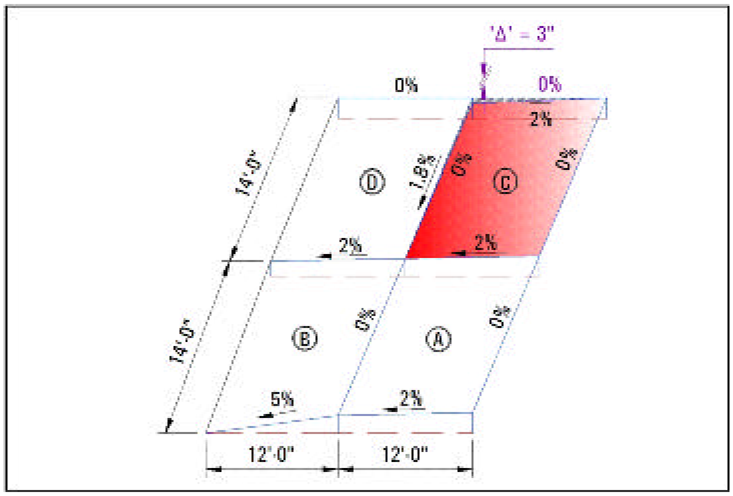
A super elevation or cross slope transition that occurs where the roadway transitions from a straight to a curved horizontal alignment is defined as a change in roadway cross-slope over a given distance along the highway. A sketch of a four-lane-highway super elevation transition, taken from the CALTRANS Highway Design Manual, is shown in Figure 6. The lower left four slabs, identified as slabs A, B, C and D, represent four slabs within the designated super elevation transition.



Elements of a Superelevation Transition (right Curve), [Source, Caltrans]

Figure 6

An enlarged view of slabs A, B, C and D is shown in Figure 7, where dimensions and cross slopes of each panel are indicated. In this example, Panel A is a “flat” single- plane panel, as shown in Figure 1, because the slopes of opposite sides of the panel are equal. Panels B, C and D are non-planar (warped) because the slopes of opposite sides are unequal, as illustrated in Figure 8. Note that the Delta value (the distance that one corner departs from the single plane defined by the other three corners) for panel C is 3 inches in this example. The surface of a single-plane panel, depicted in red, placed in this location, will be out of the plane of the specified roadway surface by 3” which is obviously a magnitude of mismatch that can not be ground away. Panel C **must** be “warped”, as seen in Figure 8, to work in this location.



Detailed View of Panels A, B, C and D From Figure 6

Figure 7

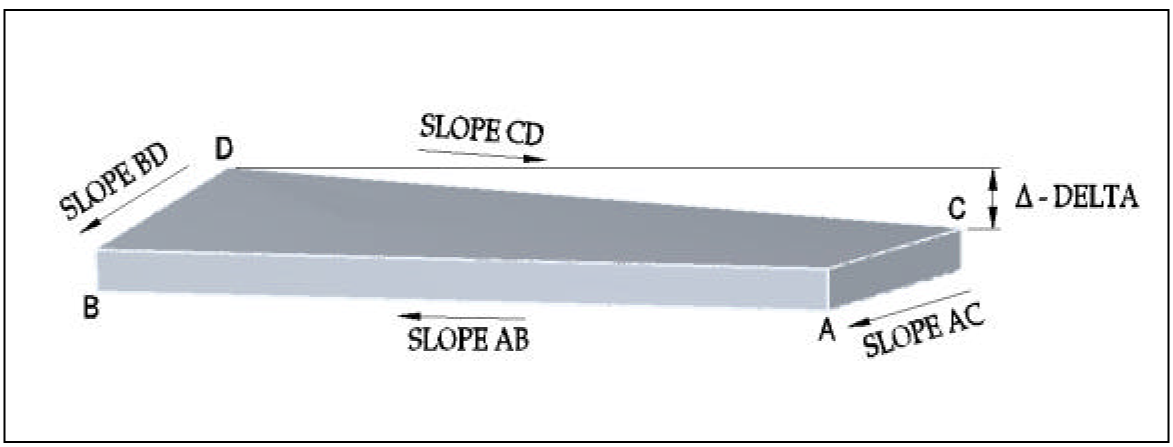


Illustration of a Warped Panel With Differing Slopes on Opposite Sides

Figure 8

This example illustrates how individual panel geometry is determined in a super elevation transition. It should be pointed out the slope values in this example are somewhat exaggerated for demonstration purposes. It not uncommon, however, to encounter delta values of ½ to 2 inches and even more on interstate mainline and access ramp super elevation transitions. It is obvious that deltas of this magnitude are much larger than the commonly-accepted ¼” mismatch discussed previously.

Where super elevation and super elevation transition data is provided, as it was on the project shown in Figure 5, the surface geometry of the global surface and of each panel is easily calculated and depicted with a digital surface model. Where such data are not given, as they are usually not on intermittent repair projects, surface geometry in the form of a digital surface model of the global pavement surface and of individual panels must be developed from survey information taken of the surrounding pavement that is to remain intact, since a visual examination of the surrounding pavement is not a reliable indicator of the **magnitude** of surface warp within a given panel.

The project plans and specification should clearly specify how such detailed field data is to be collected, in terms of frequency of the survey shots, and who is responsible for designing the surface geometry of the new panels once the surface field data has been collected.

Horizontally-Curved Roadways on Straight Grades

Warped surfaces may also be encountered on ordinary horizontally curved and super elevated roadways even when the cross slope within the curve is constant. A plan view of Panel B, Figure 5 is shown in Figure 9. It is obvious in Figure 5 that Panel B resides in a horizontally-curved profile grade that is greater than zero. The cross slope at A is the same as the cross slope at B since this panel resides in the fully super elevated portion of the curve. The difference in elevation between A and B is the same as the difference between C and D. Since this identical difference in elevation occurs along two chords of unequal lengths, the slopes of the two opposite sides, AB and CD are unequal, making this a warped slab as shown in Figure 8.

It should also be pointed out the magnitudes of the deltas of warped panels on horizontally-curved highways are radii and grade dependent. The smaller the radius in Figure 9, the greater the difference in chord lengths. The greater the profile grade, the greater the difference in slopes of opposite sides. It may not be necessary to warp panels that are used in large radius curves especially when the profile grade is very small.

When the warped panel shown in Figure 9 is placed in the field, it is placed upon a previously-graded subgraded surface such that points A and B are placed at the proper profile grade and ends AC and BD are placed at the specified cross-slope, each along their respective radial lines. Relative to each other, ends AC and BD are sloped differently because they radiate from two different points on the curve even though the design cross slopes at A and B are equal. .

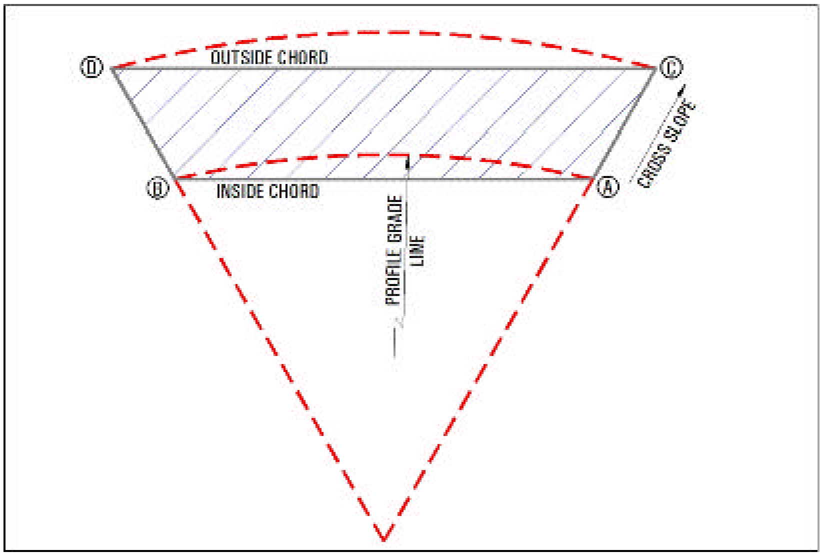


Illustration of Panel B, Figure 5 (Exaggerated)
In the Middle of a Horizontal Curve

Figure 9

Example Calculation

The warp of the 12 foot wide x 18 foot long (nominally) Panel B, Figure 5 and Figure 9 will be calculated. The contract plans for the project specified the radius of the control line (the arc connecting AB in Figure 8) to be 75 meters or 246 feet and the profile grade of the control line be - 4%, B to A.

The radius of the arc DC is calculated to be:

246 ft. + 12 ft. = 258 ft.

The panel chord length along the control line AB was selected to be 18 feet during the shop drawing process. Since the chord lengths of concentric curves are proportional to the radii, chord length CD is:

$$CD = \frac{258}{246} \times 18 = 18.878 \text{ ft.}$$

The difference in elevation from B to A equals the difference in elevation from D to C and is calculated as follows:

-.04 (4% grade) x 18 ft. = - .72 ft.

$$\text{Slope AB} = -\frac{.72\text{ ft.}}{18\text{ ft.}} = -.04\text{ ft./ft.} \qquad \text{Slope DC} = -\frac{.72\text{ ft.}}{18.878\text{ ft.}} = -.0381396\text{ ft./ft.}$$

The difference in the two slopes is:

$$-.04 - .0381396 = .0018604\text{ ft./ft.}$$

This may be better visualized if the slab is rotated such that chords DC and BD are level. The elevation of corner A with respect to the level elevations of corners B, C and D is calculated by multiplying the difference in the two slopes by the 18 foot chord length, AB as follows:

$$-.0018604\text{ ft./ft.} \times 18\text{ft.} = -.033\text{ ft.}$$

The difference in elevation between corner A and corners B, C and D is defined as the delta of the slab.

As a matter of record, all of the 12 foot wide x 18 foot long (nominally) precast panels for the inside lane of the ramp shown in Figure 5 were cast with a .03 foot (3/8 inch) delta. Each warped panel was placed on a chorded subgrade surface that was graded to the exact same delta. All of the panels on the ramp matched within the specified placement tolerance of ¼ inch and no grinding of the ramp was required. The 3/8 inch warp built into each panel in this case prevented a mismatch of 3/8 inch that would have had to have been ground off if flat single-plane panels were used.

Warped Surfaces on Perfectly Straight Roadways

Significantly non-planar (warped) surfaces are frequently encountered on interstate roadways that are perfectly straight. To illustrate this, a sketch of a three- lane Interstate roadway, presumed to have been built 40 years ago, is shown in Figure 10 as it was originally built to a 0% grade (level) and a uniform cross slope of 2%.

Over the 40 year period, it is assumed the pavement moved or settled as a result of increasingly heavy truck traffic, failed load transfer devices and ravages of climatic elements, such as temperature swings and heavy rains. A sketch of what this same pavement might look like 40 years later is shown in Figure 11. The settlement values shown in the sketch are somewhat exaggerated in this example, for illustration purposes, but are not far from what has often been encountered on many of the Interstate precast pavement projects completed to date.

In this example the right-hand lane, relative to traffic, is to be replaced with new precast panels. Note that settlement of 1" at the lower right corner of Panel S-54 changes the vertical profile of the right edge of that panel to 0.8%. If the right edge of New Panel NS-7 is designed to the original 0% profile, as good practice demands, and the left edge is designed to a 0.8% profile, to match the right edge of S-54, also as good practice demands, NS-7 becomes a warped panel because the slopes of opposite sides are unequal.

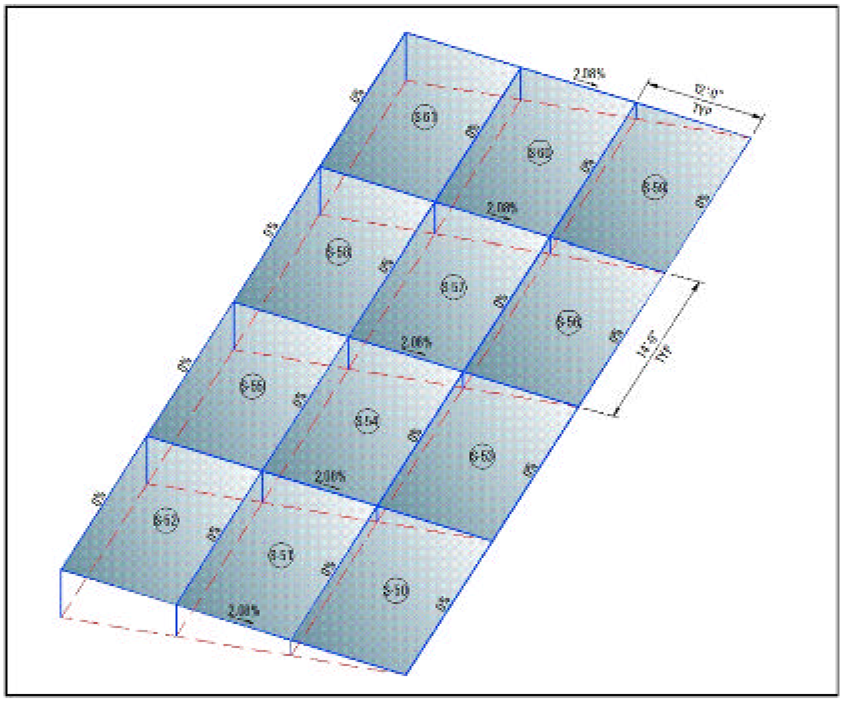


Illustration of Panels In A Three-Lane Highway In As-Built Condition

Figure 10

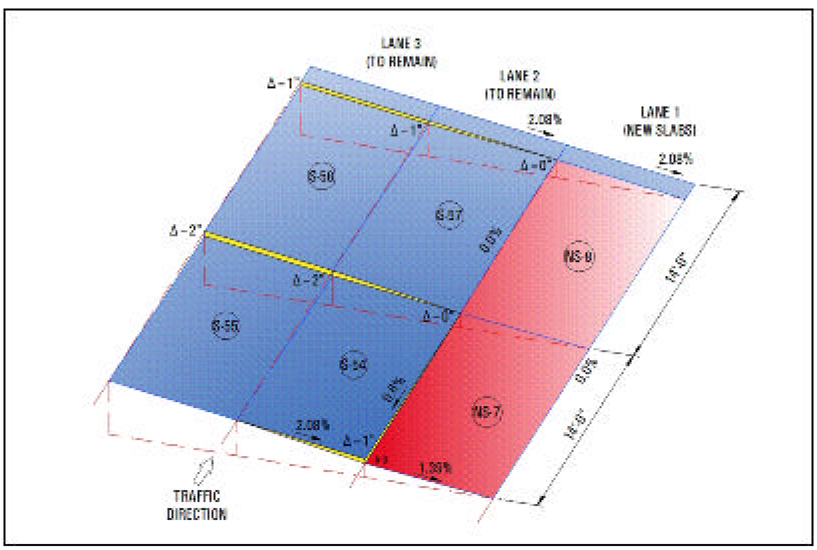


Illustration Of Selected Panels From Figure 9 After Many Years Of Service

Figure 11

As a matter of reference to an actual project, the right-hand lane of the Interstate shown in Figure 4 was replaced with new precast panels. The profile along the line of the left-hand edges of the new panels was designed to match the undulating edge of the existing pavement, while the profile of the line along the line of the right-hand edges of the new panels was "smoothed out" from the existing condition. As a result of this design procedure, approximately 25% of new precast panels were warped, some as much as 2", even though the roadway was perfectly straight. Clearly it would have been cost prohibitive and structurally inadvisable to grind 2 inches away from the top surface of flat single-plane panels had they been used on this roadway.

When new precast panels are installed adjacent to existing Interstate lanes, as shown in this example, it is advisable to develop a profile of the abutting edge of the new panels from data gathered from an accurate "x-y-z" survey of the edge to be matched. The profile of the new panels should then be **developed**, to closely match the profile of the existing edge to minimize water dam drainage issues and to avoid duplicating "humps" that may exist along the existing edge. The humps in the existing pavement can be smoothed out by profile grinding.

This example shows that large deltas can be encountered on perfectly straight roadways. Contract plans and specifications for precast pavement used on such projects should point out the likelihood of the occurrence of such deltas and specify how they should be dealt with. They should specifically detail how surface data of the existing roadway are to be taken, if such information is not already included in the contract documents and how it is to be used in the geometric design procedure.

Contoured Intersection Pavement

Significantly warped surfaces are also frequently encountered in intersections where surface geometries are often too complex to define with conventional profiles and superelevation data, especially where vertical curves and skewed intersection alignments are present. In such cases, contour drawings or digital surface models may be used as more accurate depictions of the pavement surface.

The non-planar surface geometry of the intersection shown in Figure 12 is obvious by visual observation. If this intersection were to be replaced with precast panels (it was not), an accurate "x-y-z" survey of the intersection would need to be taken as a first step toward developing the digital surface model if such a model of the new surface in not provided. The survey should include locations of all man holes, catch basins and other utilities, as well as exact locations of curb lines and other boundaries.

Example Intersection With Complex Geometry and Obvious Non-Planarity
Figure 12

The New York State intersection shown in Figures 13 and 14 was replaced with new precast panels in 2006. In this case, the precast designer used data taken from a NYS DOT aerial survey to develop a surface model of the existing intersection pavement. From that model it was deemed necessary to modify the grades of the new intersection to include improvements in drainage and super elevations. A new design surface model was developed accordingly.

The aerial view shown in Figure 14 shows the heavy skews of the intersecting highways and the street-level view, shown in Figure 13, shows the vertical profile and the heavy cross slope of the main intersection highway. Even though it is difficult to detect non-planarity of panel-size-portions of the intersection from the photos, 34% of the 180 precast panels used in this intersection were warped, ranging from ¼ inches to 2-5/8 inches. Clearly the surface of this intersection could not have been successfully built with flat single-plane panels.

Street Level View of Intersection That Was Reconstructed With Precast Panels

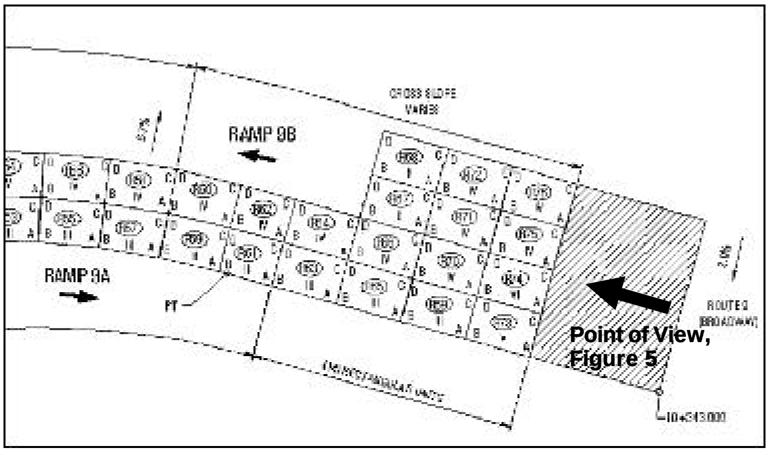
Figure 13

Aerial View of Figure 10 Intersection

Figure 14

Ramp Termini Pavement

The terminus of the Ramp 9A shown in Figure 5 is another example of heavily-contoured pavement that is not readily visible to the naked eye. A slab layout drawing of the terminus of that ramp is shown in Figure 15. All of the rectangular panels were designed to be 12 feet wide x 18 feet long (nominally).



Slab Layout Drawing of the Ramp Terminus Shown in Figure 4

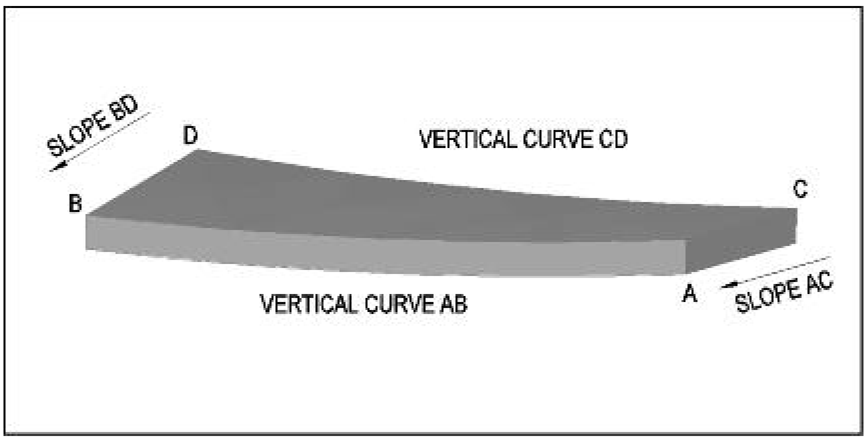
Figure 15

What is not shown in Figure 15 is that the cross-slope of Ramp 9A changed from 5.7 % up left at the end of the curve to 2% down left at the end of the ramp, over a distance of approximately 143 feet. This rapid change in cross-slope resulted in panels that were heavily warped. Panel R71, for example, was warped 2.25 inches yet that significant warp is not discernable by looking at the Panel outlined as “A” in Figure 5. Most of the other panels labeled as “Rectangular Units” in Figure 15 were also significantly warped. It is remarkable that this series of panels, each cast to a specific warp and placed upon a similarly-warped subgrade surface, created the obviously smooth pavement surface seen in Figure 5. It is also worth noting the panels were never ground to make them smoother since they matched within the required surface tolerance of +/- 1/4 inch. .

Precast Panels in Superelevation Transitions in Vertical Curves

Pavement surface geometry becomes even more complex when the roadway resides in a horizontal **and** vertical curve **and** in a superelevation transition, as was the case of the 9A Ramp shown in Figure 5. In such a case, the surface between any two given points, such as Points “A” and “B” and Points “C” and “D”, Figure 16, is theoretically arced or vertically curved as opposed to being straight as shown in the warped panel in Figure 8. While it is customary to cast concrete pavement in place in such a configuration it is difficult to design and fabricate precast panels that are vertically curved in this fashion.

The Super-Slab precast pavement system, a proprietary precast pavement system solves this problem by designing and casting panels that are vertically and horizontally straight on all fours sides as shown in Figure 8 (Smith et al. 2005). In this system, the coordinates of corners “A”, “B”, “C: and “D” are determined from a digital surface model and are used to define the **vertically-straight-sided** warped panels and the subgrade surface that supports them. The straight-sided warped slabs are used as a substitute for the arced panel shown in Figure 16. The “global pavement” shown in Figure 5 was made up of a series of such vertically-straight-sided precast panels.



Arced Warped Slab

Figure 16

Casting and Placing Warped Panels

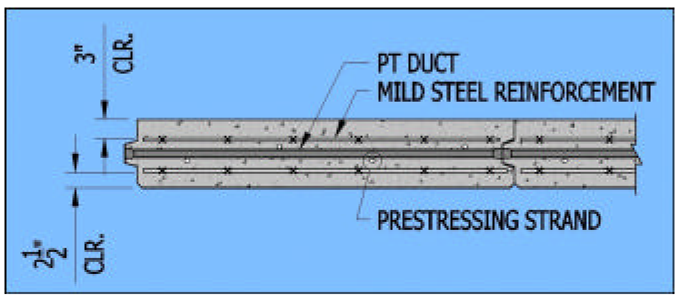
The proprietary steel form used to manufacture warped panels as shown in Figure 8 is capable of fabricating panels with warps in excess of 2.5 inches (Smith 2006). The form is very accurate and is simple to use, requiring only one vertical adjustment at one corner of the form. The labor associated with this adjustment amounts to less that 5% **additional labor** than that required for fabricating a flat panel. Since labor constitutes approximately 15% of the total panel price the additional cost associated with fabricating warped panels is a very small percentage of the total.

Warped panels are placed upon a precisely-graded subgrade surface, the same as flat single-plane panels. The additional costs associated with placing warped panels upon a similarly-warped subgrade surface comes only from extra field surveying required to lay out grade control rails, since the grading process itself is the same as that required for flat single-plane panels. The surveying portion of a typical project is usually performed in a matter of a few man hours that make up a very small portion of the total man hours needed to install the panels.

Surface Geometry Planarity May Affect Joint Design

It has already been established that flat (single plane) panels may be used on subgrade surfaces that are slightly non-planar or warped as long as the surface differential between panels does not exceed ¼ inches. This cost saving approach can only happen if the edges of the panels are fabricated to allow panels to move vertically, relative to each other, at joints, as shown in Figure 3.

The keyed or tongue and groove (T&G) joint design shown in Figure 17 will not allow vertical movement between panels. This joint design, adopted for use for Precast Prestressed Concrete Pavement (PPCP) panels (FHWA Tech Brief 2009) is used to aid load transfer at joints and in vertically aligning panels, one to the other, such that top surfaces match each other (Merritt et al 2006).



Tongue-and-Groove PPCP Joint

Figure 17

When flat single-plane T&G panels are placed on a warped surface, such as on a super elevation transition, the plane of the panel assembly will be determined by the T&G joints and the highest part of the subgrade surface, not just by the subgrade surface.

To illustrate this, consider the assembly of the three 12 feet wide x 12 feet long tongue-and-groove panels, shown in Figure 18, placed on a superelevated surface. Note that the profile of the subgrade at the B-B end of the panels is level (in this example) and that the profile at the A-A end is sloped. It should be apparent the surface between the two ends warps accordingly. Assume the slope at the A-A end is 1.5% and that the first slab placed, Slab 1, is placed level such that the B-B and the A-A ends are level. In this position, there are no voids under the B-B end and the right corner of the A-A end, but there is a void of 2-3/16 inches under the left corner of the A-A end.

When Slab 2 is installed next to Slab 1, its left edge is restrained in a level position (assuming Slab 1 remains level) by virtue of the T&G joint. The right edge of Slab 2 comes to rest on the 1.5% subgrade surface leaving a 2-3/16 inches void under the right B corner. When the tongue of Slab 3 is inserted in the groove of Slab 2, its left edge is also level (at a higher elevation than the left edge of Slab 2) and it comes to rest on the 1.5% subgrade surface leaving a 4-5/16 inch void under the right B-B corner. Although the difference in grades in this example is somewhat exaggerated for illustration purposes, it clearly shows the void under the B-B side of the panels increases as more panels are added.

This example assumes the T&G joints are perfectly engaged and the panels do not deflect under their own dead load. In practice, T&G joints between precast panels are not match-cast and are not, therefore, perfectly engaged so slight vertical mismatches at the joints **may** occur. Similarly some very slight flexing of the panels may also occur but hardly of the magnitudes illustrated previously in this paper. This example demonstrates single-plane tongue-and-groove panels will not theoretically work in superelevation transitions. T&G panels placed on transitioning superelevated subgrade surfaces must be warped to match the surface upon which they are placed if the joints are to be fully engaged and if the panels are to fully contact the warped subgrade surface.

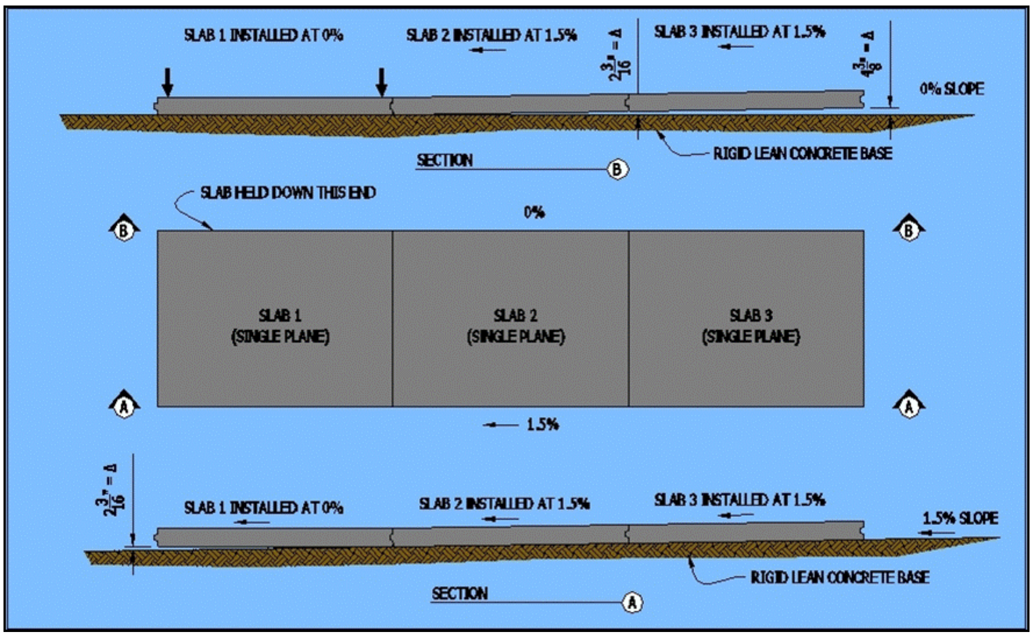
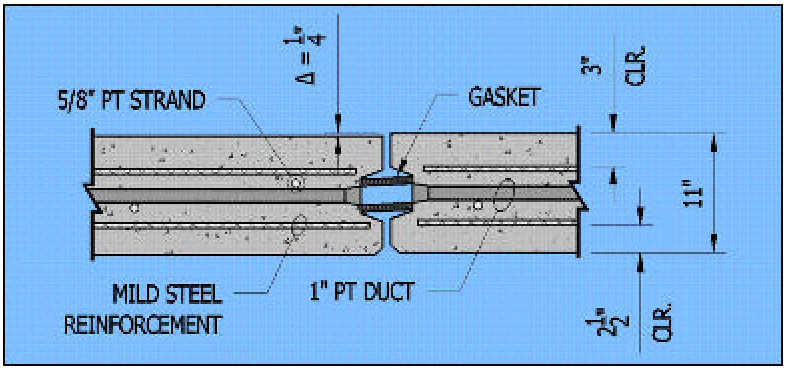


Illustration of Placing T&G Panels on a Superelevated Subgrade Surface

Figure 18

Effect of Non-Planar Geometry on Post Tensioning Duct Alignment

An alternate joint design that does allow PPCP panels to vertically mismatch as shown in Figure 3 is shown in Figure 19. The ¼ inch mismatch shown in Figure 19 may be acceptable from a surface match point of view but ¼ inch is twice as much as the maximum allowable mismatch between post tensioning ducts allowed in most specifications. It should be clear that duct alignment requirements alone will prohibit the use of single plane panels in cases where non-planar surfaces result in panel mismatches of greater than ¼ inch. Best practice demands PPCP panels utilizing this joint design also be warped in order for ducts to line up properly and to match the surface upon which they are placed.



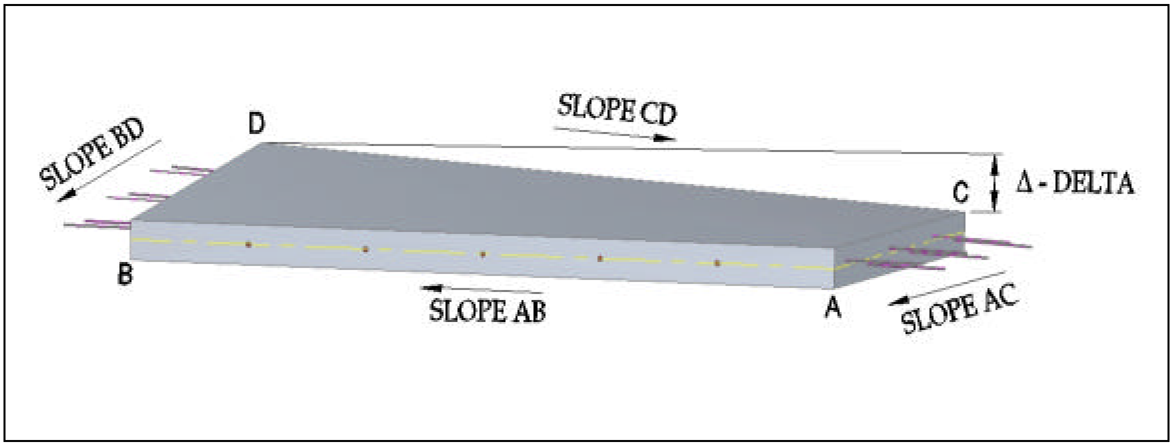
Double-Groove Joint in PPCP Panel Mismatched ¼-in.

Figure 19

Fabricating Warped Prestressed Panels

It is difficult to fabricate PPCP panels in traditional long line single-plane beds. All warped panels, including warped PPCP panels must be fabricated in "warpable" beds as it is necessary to keep strands parallel to the top and bottom surface of the panels to keep prestress loads concentric to the panel ends. The plane of the strands must be warped, the same as the panel, as seen in Figure 20.

This warped strand arrangement presents two problems. First, constant thickness warped prestressed panels need to be cast, one at a time, in beds that can be adjusted to each specific panel warp, rather than in multiples in flat, single-plane, long-line beds since each panel may need to be warped to a unique plane. Secondly, the prestressing dead heads must be designed to accommodate variably-positioned (warped) strands. Casting panels in single-panel beds is obviously more costly than casting them in long-line beds but it does enable manufacture of geometrically-correct PPCP panels that fit correctly in the field.



Strand and PT Duct Positioning in Warped PPCP Panels

Figure 20

Post tensioning ducts are typically sandwiched around the strands so if the strands are warped, the ducts will also be warped such that they exit the edge of the panel at the correct vertical position. This ensures ducts will line up accurately from panel to panel.

"Self-Warping" Precast Panels

Some engineers maintain it is not necessary to cast warped PPCP panels because prestressed precast panels "flex" to "conform" to warped subgrade surfaces. While it is true that prestressed panels do deflect or flex under certain support conditions it is also true that the deflections are typically fractions of an inch which are not even close to the warp magnitudes of 2 inches or more pointed out in this paper. It is also important to recognize it is impossible to count upon any particular specific support condition when the panels are placed in the field, hence, it is impossible to predict the amount of "flex" that will occur. The magnitudes of warps indicated in previous sections are unlikely to be achieved by letting precast panels flex under their own dead load.

Practicality of Fabricating Non-Planar Panels

Design and fabrication of warped non-planar precast panels has become a routine straight-forward process that only incrementally adds to the cost of the panels (Smith 2006). All of the survey, design and installation expertise required to design and install warped panels is readily available and has been implemented in the installation of over 20% of the 10,000 Super-Slab® panels installed to date. The cost of those panels was only slightly higher, less than 5% higher, than flat panels constituting the remainder of the installations. Because of this, warped non-planar panels should be used in every situation where flat panels are even marginally-problematic.

Plans and Specifications Should Address Pavement Surface Planarity

The previous sections have demonstrated non-planar pavement surfaces are common place and that the magnitudes of non-planarity demonstrated in the previous examples can not be ignored when plans and specifications are developed for precast pavement projects. Plans and specification should clearly indicate whether or not non-planar surfaces are expected to be present on the project and should address the following issues:

1. Maximum allowable surface mismatch from new panel surface to adjacent new or existing pavement surface. Most current specifications already limit this to ¼";
2. The maximum allowable amount of profile grinding that may be performed to achieve smoothness specifications;
3. Specific portions of the project where significant non-planar surfaces may exist;
4. How existing pavement surface planarity is to be determined if that information is not provided in the contract plans;
5. Who is responsible for evaluating the planarity of the existing pavement, collecting existing surface plane data and how that data is to be used to designed the new panels;
6. Procedure for installing non-planar panels as it relates to subgrade preparation;

The use of precast pavement is still relatively new in the concrete pavement industry and many of the design, fabrication and installation techniques are still relatively unknown to concrete pavement professionals. It is imperative that developers of plans and specification recognize and address all details of precast pavement technology, including those associated with surface geometry in order to ensure successful installations.

Summary

Precast pavement is typically used to repair or replace only parts of existing concrete pavement. While some of these areas may be contoured gradually-enough to be replaced with flat single-plane panels that may be diamond ground to meet specified smoothness requirements, other areas may be significantly-contoured such that they can only be properly replaced with warped non-planar panels. The geometry of each warped panel must be designed to fit the overall global surface geometry of the pavement surrounding it.

It is difficult to determine the planarity of an existing pavement surface by looking at it with the naked eye. If designers suspect the surface may be non-planar, they should conduct or require a detailed field survey to determine the magnitude of non-planarity within given precast panels. Relatively large warps, in the order of one to two inches, commonly occur in specific pavement configurations such as in superelevation transitions, horizontally-curved roadways, ramp termini and roadway intersections.

Precast Prestressed Concrete Pavement (PPCP) panels are particularly affected by the incidence of non-planar surfaces, as such surfaces may affect joint design, and placement of prestressing strand and post-tensioning ducts. Strands in warped PPCP panels must also be warped to ensure alignment of post tensioning ducts from panel to panel. Because of this, they may need to be cast one panel at a time, on adjustable beds instead of on single-plane, long line beds traditionally used in the fabrication of such panels.

The conventional practice of defining pavement surfaces by specifying profile grades, horizontal and vertical curvature and roadway cross slopes may be inadequate for some precast pavement installations especially where precast panels must match adjacent existing pavement. The plans and specification should clearly indicate how the design surface of the new panels is to be determined and how the panels are to be placed to ensure a proper surface match with adjacent pavement.

Highway owners, precast pavement designers and installers should recognize technology to design, manufacture and install non-planar precast pavement has been reduced to practice and has become a routine and straight-forward practice. They should therefore embrace, rather than avoid, the use of warped non-planar panels as a better, more accurate way to address undulating surface geometry common to many roadways. There should be no reason why any concrete pavement, no matter how complex the surface geometry might be, can not be repaired or replaced with precast concrete panels.

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