

Continuously Reinforced Concrete Pavement Terminal Design

Anna-Carin Brink¹ and Geoff Ayton²

Abstract

In rigid pavement design the word “terminal” is used to describe the termination of a concrete pavement abutting other “structures” such as a flexible pavement, a bridge abutment, or another concrete pavement where structural continuity is impractical or undesirable. A discontinuity in grade caused by the differential settlement between a bridge structure and the adjoining road pavement, typically referred to by the travelling public as the “bump at the end of a bridge”, is well known in the road construction environment. In the United States it is known that this problem affected 25% (approximately 150,000) of all bridges during 2004. Bridge approach slabs are typically used to keep the effects of differential settlement at bridge abutments within tolerable limits. Frequently, however, the magnitude of settlement exceeds the working range of an approach slab, causing substantial maintenance problems. Similarly, differential settlement or movement often occurs where a concrete pavement terminates at a flexible pavement. The provision of anchors (lugs) to prevent horizontal creep due to expansion / contraction of the concrete is considered standard practice in terminal design. The aim of this paper is to compare various worldwide continuously reinforced concrete pavement (CRCP) terminal design methods varying from terminal beams to seamless technology developed to eliminate isolation joints at bridge structures.

Introduction

Over the years Pavement Engineers have asked the question: “What do you do to prevent the bump at the end of the bridge?” Having asked this question and not finding an easy answer has instigated the research that has been done for this paper. The differential settlement that occurs between flexible (asphalt) and rigid (concrete), be it from an asphalt pavement to a concrete pavement, or from a road onto a bridge deck, is quite common. Bridge approach slabs are typically used to keep the effects of differential settlement at bridge abutments within tolerable limits. Frequently, however, the magnitude of settlement exceeds the working range of an approach slab, causing substantial maintenance problems. In the United States it is known that the “bump at the end of a bridge” already affected 25% (approximately 150,000) of all bridges during 2004 (Luna et al. 2004).

In rigid pavement design the word “terminal” is used to describe the termination of a concrete pavement abutting other “structures” such as a flexible pavement, a bridge abutment, or another concrete pavement. While the provision of anchors (lugs) to prevent horizontal creep due to expansion / contraction of the concrete is considered

¹ Anna-Carin Brink, ISCP Director, BEng, MEng, PhD PrEng, Principal Pavement Engineer, AECOM.
anna-carin.brink@aecom.com

² Geoff Ayton, ISCP Honorary Member, BE (Civil), MIEAust, Consulting Engineer.
geoff.ayton@iinet.net.au

standard practice in terminal design, the modes employed to accommodate differential settlement vary throughout the World.

The aim of this paper is to compare various worldwide terminal design methods used in the design and construction of CRCP. Among other things, the terminal beam / jockey slab configuration based on the standard bridge approach slab design is compared with the seamless technology developed to eliminate isolation joints at bridge structures.

CRCP Terminal Design

In designing terminal joints, there are two common options; i.e. either allow free movement by means of a joint capable of absorbing all the movement, or resist the movement wholly or partially by incorporating terminal anchors.

A free-end joint may consist of a large-width single expansion joint, or a series of conventional dowelled expansion joints in a section of jointed pavement adjoining the CRCP. Practice as to the number of joints used and their spacing has varied widely and is a matter for engineering judgement and local knowledge. Experience has shown that the first joint absorbs most of the movement and that, except for cases where extreme movements are anticipated, there is no need for more than three such joints. Other types of free-end joints are:

- Finger-type expansion joints as commonly used on bridges;
- A bellows-type fabricated of steel and rubber; and
- A wide flange steel beam anchored in to a foundation slab.

Where a terminal anchor beam is used, its function is twofold. Firstly it is required to restrain end movement where the CRCP abuts another type of pavement or where movements are in conflict such as at intersections. The active end sections in a CRCP are from 90 m to 150 m long and, if left unrestrained, end movements of up to 50 mm may occur due to thermal expansion and contraction (Perrie and Rossmann 2009). Secondly, the anchor beam is required to induce the tensile stresses which generate the desired transverse shrinkage crack pattern.

Even where terminal anchors are used to restrain movement of the CRCP ends, there remains a risk of residual movement and therefore expansion capacity is commonly provided adjacent to bridges or fixed structures to prevent possible damage to those structures. Numerous terminal designs and configurations have been implemented by various entities as is illustrated in Figure 1 to Figure 4. Variations can be seen in aspects such as the depth, number and spacing of the anchors and in the design of the expansion joint. The construction of a lean-mix concrete subbase (LCS) is standard practice in New South Wales (NSW).

Some of the designs incorporate a subgrade beam below an un-dowelled isolation joint. The beam is used in lieu of a dowelled expansion joint to address concerns over the risks associated with misalignment of dowels. In the case of bridge approaches, the replacement of dowels with a beam serves to address concerns over the stresses imposed on both the dowels and the surrounding concrete if settlement creates a significant deflection angle at this joint.

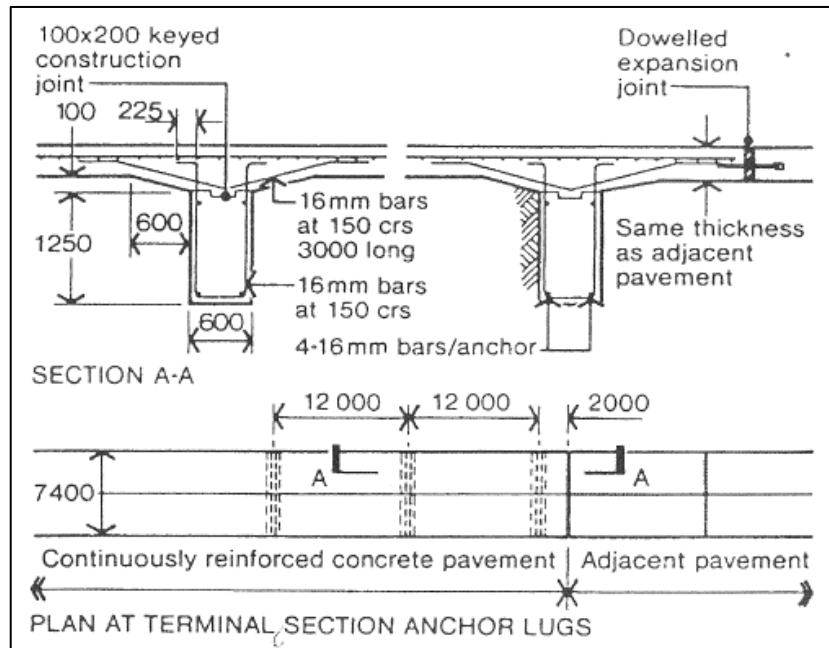


Figure 1: Terminal Anchors – Texas, USA / South Africa (Perrie and Rossmann 2009)

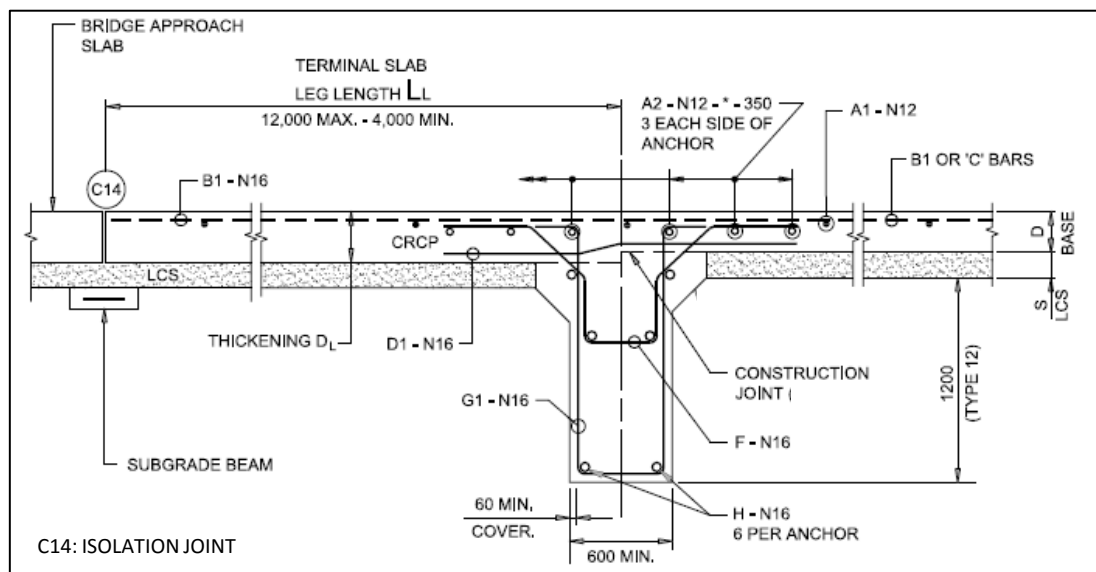


Figure 2: Terminal Anchor – NSW, Australia (RMS MD.R83.CC 2010) (Terminal anchors No 2 & 3 not shown)

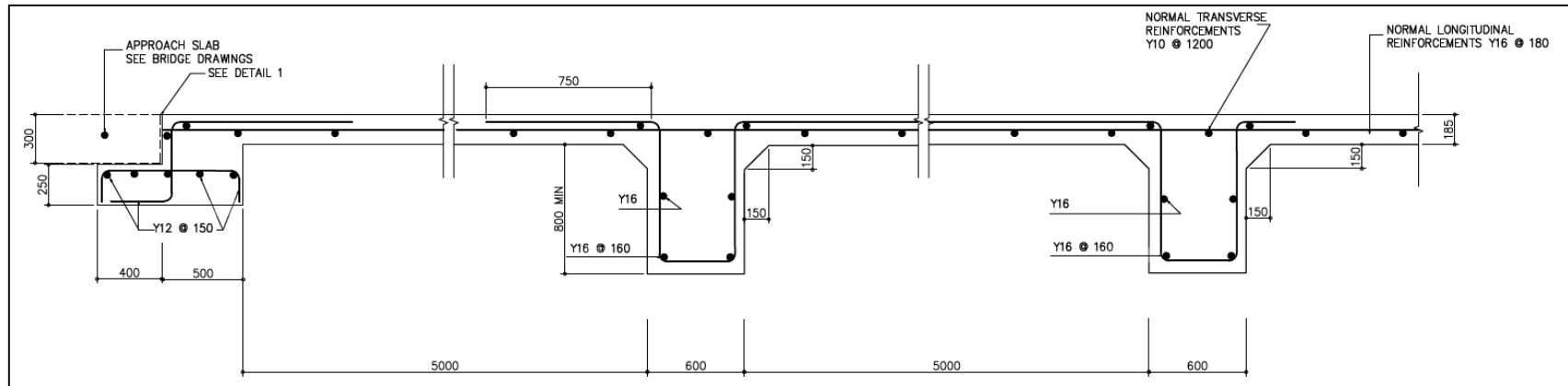


Figure 3: Terminal Anchors – Gauteng, South Africa (Kromhout 2015)

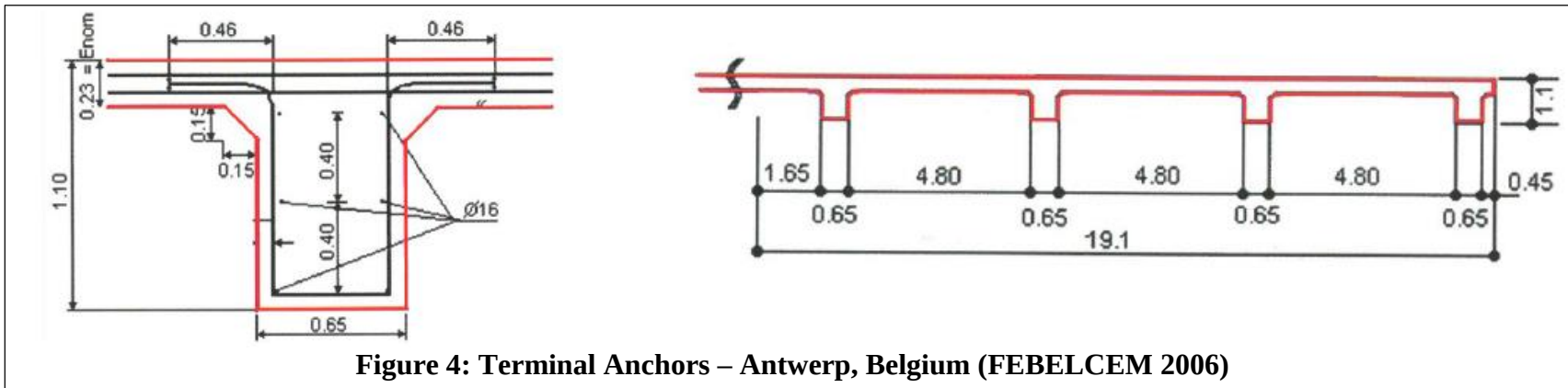


Figure 4: Terminal Anchors – Antwerp, Belgium (FEBELCEM 2006)

A further variation in design is the use of a wide flange beam to accommodate the end movement. Some authorities use the beam in lieu of terminal anchors but others use it to supplement the anchors. Figure 5 shows an example of a beam that was constructed in 1975 on the Pacific Highway at Clybucca, 14 km north of Kempsey.

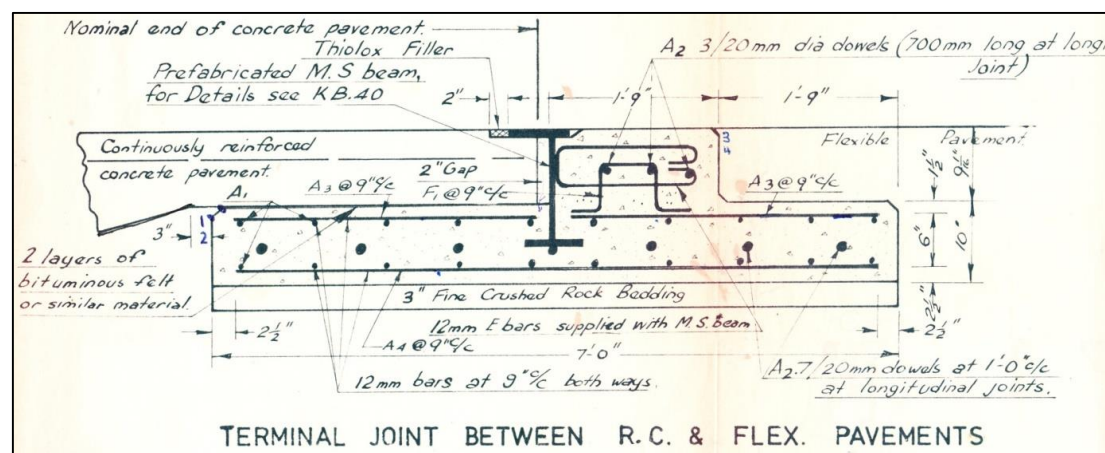


Figure 5: Wide-Flange Beam – Clybucca NSW, Australia 1975 (RMS 0010.275.RC.6311) (Terminal anchors not shown)

Observations taken in the years following construction indicated that there was no appreciable movement in the 50 mm (2 inch) expansion cavity. It was therefore concluded that the three anchors were successful in arresting all end movements and that the wide-flange beam was superfluous. On that basis, the beam was omitted from all subsequent CRCP projects in NSW. However, during a site inspection in late 2014 (and to the surprise of the authors) it was noted that the expansion cavity is now substantially narrower than the specified 50 mm. Further observations of movement (if any) would be interesting, and this will be simplified when highway traffic is removed from the pavement during 2015 after the completion of a bypass.

CRCP Anchor Design

The number of terminal anchors required is considered to be largely a function of the length of the CRCP section, the subgrade soil properties, and the depth and spacing of anchors. Several design models are available (McCullough 1966) to estimate the number of anchors that will be required to limit end movements to a nominated magnitude. Mainly because of load reversals and restrictions imposed on total anchor movement due to thrust and soil cohesion, calculations indicate that a terminal design with 3 anchors, spaced at 5 m centres, is sufficient to limit end movement to an acceptable range in most soil types (Tinni and Stubbs 1994). On the Gateway WA project, however, a number of the CRCP transitions between flexible pavements and concrete bath structures are relatively short and the number of anchors per terminal anchor was therefore reduced for different CRCP lengths as detailed in Table 1.

Table 1: Terminal Anchor Configurations (GWA 2014)

Slab Length	CRCP / Flexible Pavement Terminal Anchors	CRCP / Bath Structure Terminal Anchors
$L \leq 100 \text{ m}$	Terminal anchor and jockey slab*	One standard anchor
$100 \text{ m} < L \leq 150 \text{ m}$	Terminal anchor and jockey slab, plus one standard anchor	Two standard anchors
$L > 150 \text{ m}$	Terminal anchor and jockey slab, plus two standard anchors	Three standard anchors

* Jockey slabs described below.

Bridge Approach Slabs

Bridge approaches typically experience two types of settlement, global and local. A consolidation of the underlying natural foundation soils which is evidence of long-term differential settlement between the bridge structure and the bridge abutment is considered to be global settlement. Compression of fill materials underneath the approach pavement; evidence of embankment consolidation in the upper 3 to 6 m of the bridge embankment, is seen as local settlement. The different components of a bridge approach system are illustrated in Figure 6.

The presence of an approach slab has no effect on the magnitude of the differential settlement that will ultimately develop between the embankment fill and the bridge abutment. The primary function of a bridge approach slab is to provide a transition, or a ramp, between the superstructure and the settling embankment.

Various detailed studies of the performance of bridge approach slabs have been conducted over the years. While the use of approach slabs is promoted, it is recommended that a geotechnical engineer be responsible for assessing the need on a site-specific basis. Select granular fill placed and compacted with stringent control is imperative as the main causes of bridge approach distress have been traced to consolidation of approach foundation soils, compression of embankment fill and localised soil settlement due to inadequate compaction.

Studies also show that the type of abutment also affects the magnitude of approach settlement. Spill-through or shelf abutments generally result in larger settlements than the cantilever-type. One study (Hoppe 1999) showed that traffic volume had no influence.

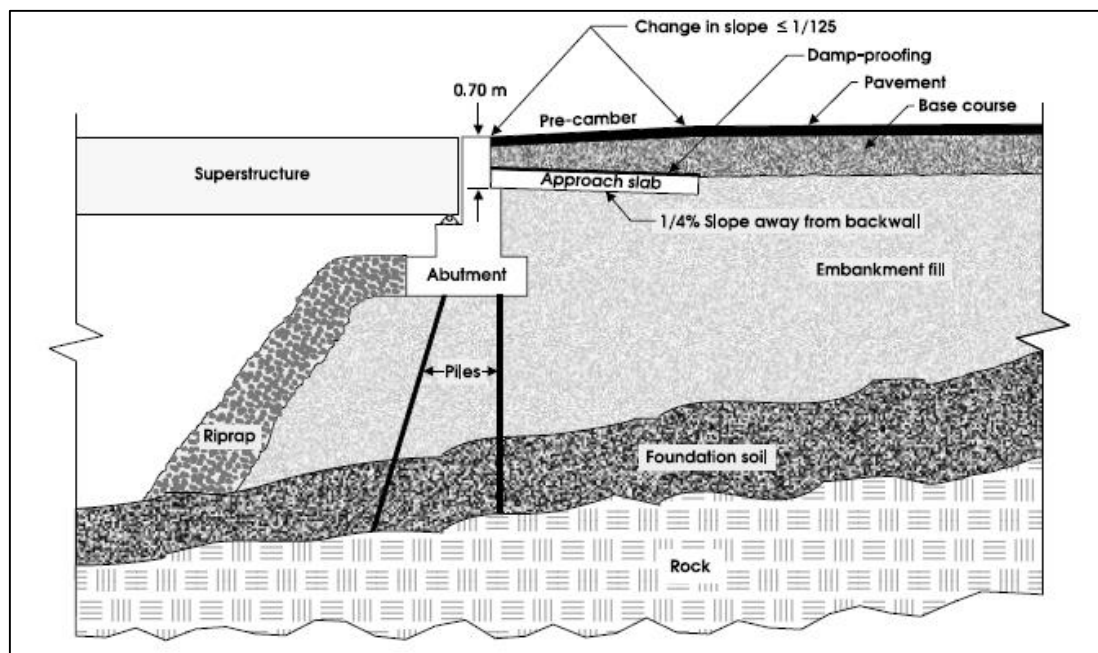


Figure 6: Bridge Approach Slab Detail (Hoppe 1999)

In the United States the most common approach slab length is 6.1 m with thicknesses varying between 230 and 380 mm. However, slab lengths varying from 3 m to 12.2 m have been reported, with thicknesses varying from 200 mm for a slab 4.6 m long to 430 mm for a 9.1 m long slab. Although there is not a consensus about the use of dowelled or tied connections, dowelled connections are commonly used at integral bridges (Hoppe 1999).

The practice in South Africa is that the bridge approach slab is typically 3 m long and 300 mm thick for normal fill heights of 6 to 8 m, and 5 m long with a thickness of between 300 and 500 mm for higher fills. The jockey slab is designed to bridge across an, approximately 500 mm width from the back of the slab that is supported by the fill. The underside of the slab at the abutment is 800 mm beneath the road surface and is inclined backwards at 10% for the fill / layer works to gradually become thinner from back to front resulting in a gradual transition from fill to bridge structure. The slab rests on a 300 mm wide corbel at the abutment with rotation of the slab facilitated through 2 layers of Malthoid acting as bearings during consolidation of the fill. The approach slab is also anchored into the back of the abutment with mild steel bars to allow rotation, with a wrapping of Malthoid to protect it against rusting.

In some instances the approach slab is used to anchor the bridge abutment. A cut-off wall is then provided at the back of the slab to anchor into the fill (Kromhout 2015). This is illustrated in Figure 7.

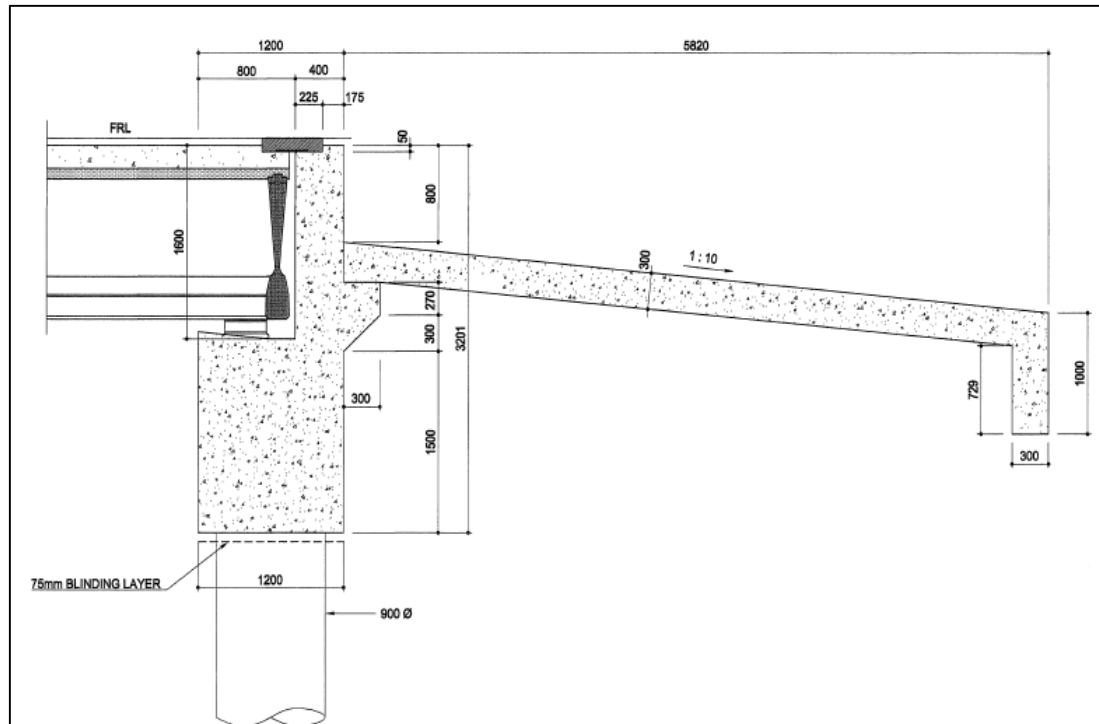


Figure 7: Bridge Approach Slab with Cut-Off Wall (Kromhout 2015)

There are two common scenarios for the design and construction of CRCP terminal ends, one between CRCP and rigid structures/pavements and the other between CRCP and a flexible pavement. Both scenarios require design to cater for potential differential settlement as well as horizontal movement. Good design also needs to take account of the logistics of field construction.

The following paragraphs describe some of the designs constructed in different parts of the world.

CRCP / Rigid Structure Terminal Design

Figure 7 shows the current RMS standard CRCP / bridge transition design for small bridge abutment skew angles (not more than 6 degrees). The main features are as follows:

- (a) The minimum leg length (L_L) of 4 m seeks to keep the anchor out of the zone of the most severe settlement, in order to minimise the risk of anchor settlement and rotation. Though not shown here, RMS approach slabs are now typically 6 m long, meaning that the anchor will be no closer than 10 m from the abutment.
- (b) The 12 m maximum leg length seeks to limit the magnitude of movement in the C14 isolation joint with consideration for ride quality and sealant life.
- (c) The Base within the terminal length is thickened to match the thickness of the approach slab and to improve its durability in the event of embankment settlement.
- (d) The C14 isolation joint with subgrade beam is used in lieu of a dowelled joint, because of the likelihood of rotation within this joint, which would cause dowel lock-up and possibly also concrete fracture.
- (e) The approach slab is restrained on the abutment by vertical dowels with an expansion wrapping to cater for slab rotation.

Though not shown here, design variations are available to cater for large abutment skews, including the following features:

- (f) Large skews create acute-cornered slabs (typically above the C14 joint) and NSW experience has shown that the high corner stresses are best addressed with a combination of steel mesh and steel-fibre reinforcement.
- (g) Large skews often also result in the need to increase the allowable leg length L_L beyond 12 m and to depart from conventional joint layouts.

Some of these features present challenges to the construction team, but the main priority must be the pursuit of good long-term structural performance together with optimal ride quality at highway speeds.

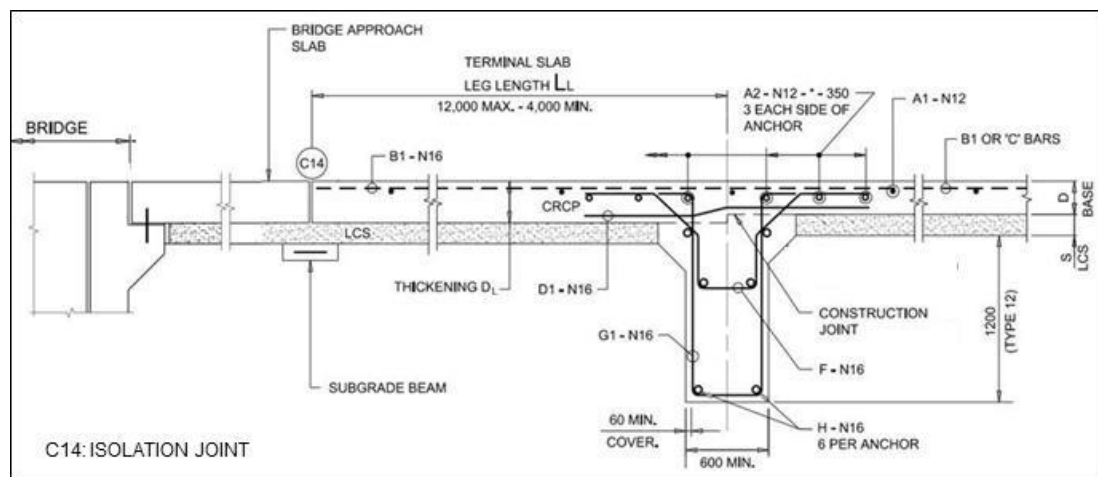


Figure 8: CRCP Terminal Design at Bridges (RMS MD.R83.CC 2010)

In the USA, efforts have been devoted to the refinement of approach designs which eliminate all transverse joints in bridge structures and their approaches. This seems to have been largely motivated by the difficulty of managing the runoff of winter de-icing salts and the corrosion caused to bearings and substructures. A further motivation seems to be the difficulty of designing and maintaining bridge expansion joints for large movements.

As far back as 1963 Prof Frank McCullough, having recognised this problem across many structures in the United States, motivated the need for the construction of an experimental section to investigate the feasibility of a seamless joint between a CRCP and a continuous slab bridge. Two identical bridge structures at the Irving Lee Street Overpass where it passes under the main lanes of Interstate Highway 35 were chosen. A control unit (Figure 9) and an experimental unit were constructed (Figure 10).

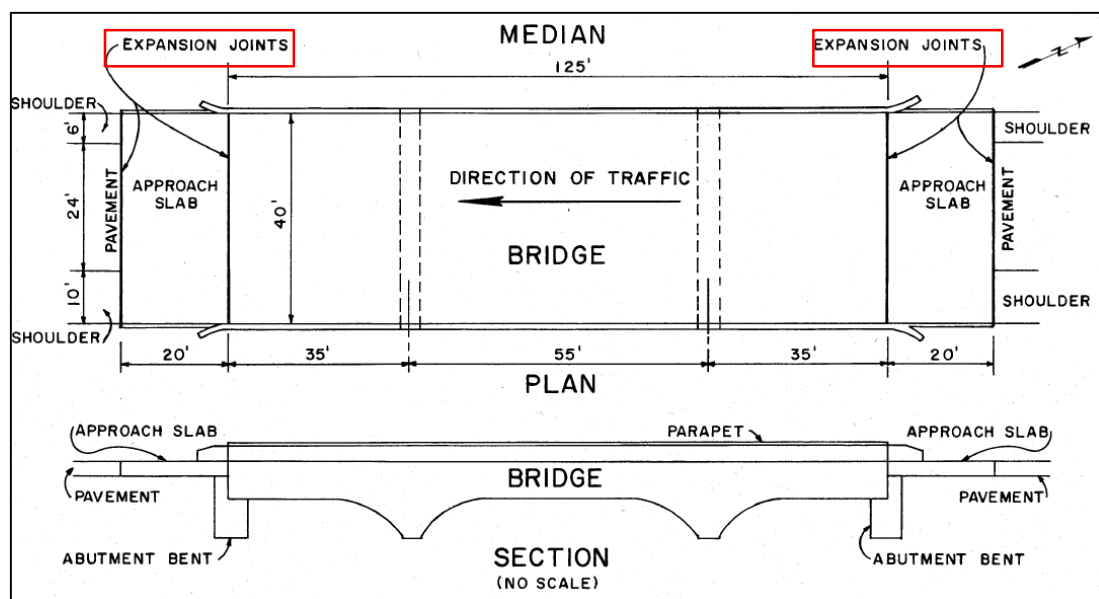


Figure 9: Layout of Control Unit (McCullough and Herber 1966)

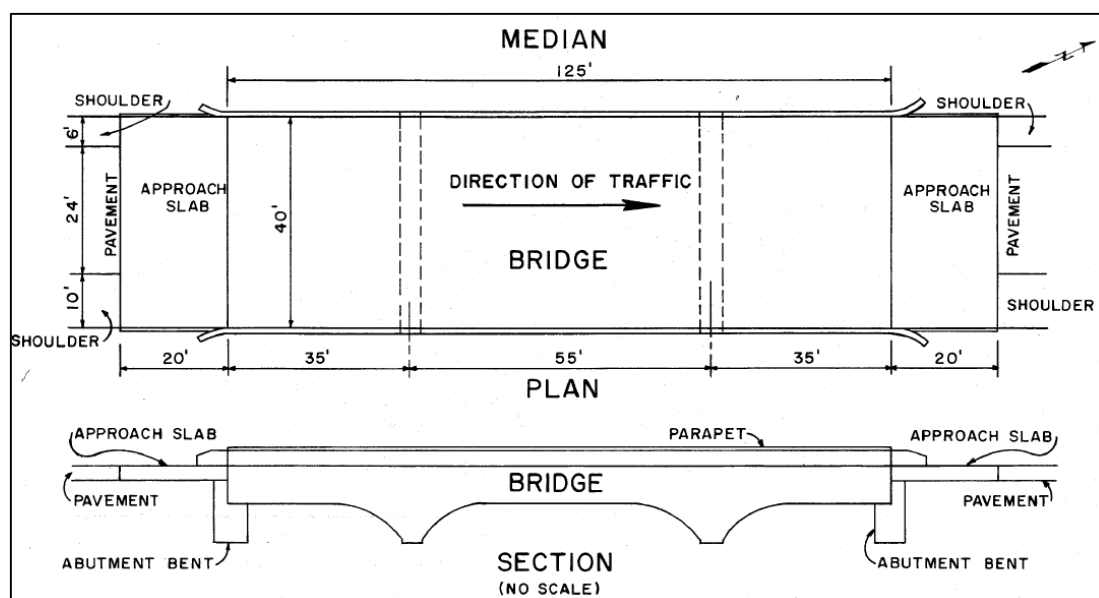


Figure 10: Layout of Experimental Unit (McCullough and Herber 1966)

The control unit was constructed in the usual manner with a five-anchor terminal anchorage system to anchor the CRCP and a structure approach slab at each end of the structure. In the experimental unit, the terminal anchorage was eliminated and the CRCP, approach slab and structure were all tied together. Both units were monitored over a period of two years.

One of the major conclusions of the study was that the expensive approach slab should be eliminated, which meant that subgrade beams and the two expansion joints were also unnecessary (McCullough and Herber 1966). This was confirmed in the subsequent publication in which it was stated that although problems were experienced with the experimental installation, it was felt that proper design along with good construction procedures would reveal the feasibility of the concept (McCullough and Sewell 1966).

During the design of the Westlink M7, connecting the M5 motorway at Prestons to the M2 Motorway at Baulkham Hills in Sydney, Australia, it was decided to implement the seamless pavement concept. The 40 km long two-lane dual-carriageway Motorway includes 68 bridges but the seamless design was used only for those with total length less than 120 m. The seamless pavement concept minimizing the overall number of joints was seen as a natural extension of the long-term trend in multi-span bridge construction to reduce the number of deck joints. Continuity was achieved by connecting the CRCP longitudinal reinforcement directly into the bridge decks with additional pavement reinforcement provided in the vicinity of the bridge to resist induced forces.

This simple concept in which the bridge and pavement are assessed as a seamless continuum is illustrated schematically in Figure 11.

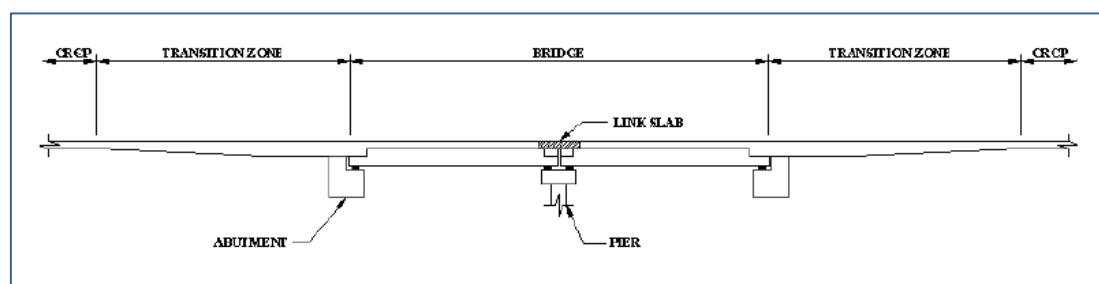


Figure 11: Seamless Pavement Concept (Griffiths et al. 2006)

For completeness, it should be noted that consideration should be given to possible future maintenance needs in the transition zone or the adjacent CRCP. The seamless design can reportedly be used to reduce bridge substructure costs by designing for horizontal loads in the bridge to be carried by the pavement. This raises the issue of the possible impact of a significant pavement failure within the approach area.

Towards the end of the detailed design stage of the Gateway WA project, the implementation of the seamless technology was investigated to eliminate transverse joints between the concrete bath structures and the CRCP transition pavements (see Figure 12). If the seamless technology was applied, the connection between the bath structure and the CRCP would have had to accommodate the stresses induced by shrinkage, creep, thermal strain, possible settlement and traffic loads.

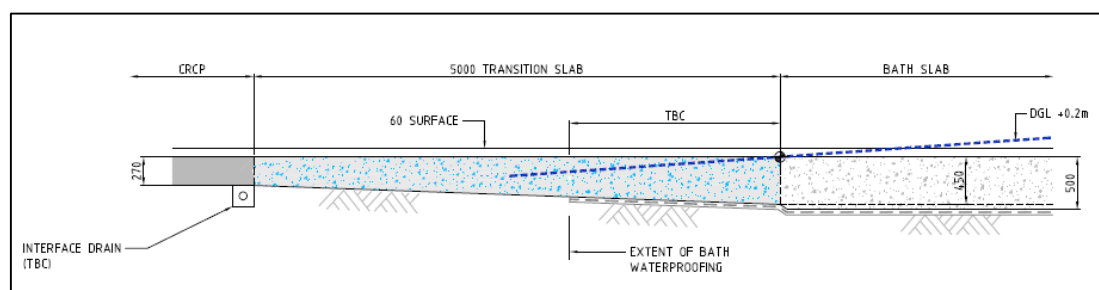


Figure 12 – Seamless CRCP / Bath Structure Transition

The design loadings for the longitudinal behaviour of the pavement arise from temperature change, concrete shrinkage and concrete creep. The typical strains induced in a bridge structure due to environmental loadings are $200 \mu\epsilon$ in expansion and $650 \mu\epsilon$ in contraction.

The corresponding stresses in the CRCP are 100 $\mu\epsilon$ in expansion and 300 $\mu\epsilon$ in contraction. The bridge structure, being elevated and exposed to atmospheric conditions at all faces, has the ability to expand and contract to a far greater extent than the bath structure, which will be exposed to environmental conditions mostly on the pavement surface.

In the CRCP, the percentage steel was chosen to limit the crack width to 0.25 mm, and in the bath structure to 0.2 mm, as the latter has to be waterproof. The question therefore arose whether the construction of a seamless joint puts the bath structure at risk of exhibiting larger crack widths. This was considered unlikely, as the cross-section of the CRCP is smaller than the cross-section of the bath structure, which means that the bath will act as a continuous anchor. The other implication of this is that, with the bath structure being the anchor, terminal anchors are not required in the CRCP.

Another factor that plays a role in the seamless joint design is the subgrade restraint, or coefficient of friction, μ , between the base and subbase layers. With little to no settlement of the bath structure expected, the CRCP should be in full contact with the subbase and the latter with the selected material zone (SMZ) and subgrade.

The maximum restraint tension force that previously existed in the bath structure decreased from 972 kN/m width in the centre down to zero at the free end. When the pavement is attached to the concrete bath structure, the maximum tension force remains at 972 kN/m width and the force at the pavement interface is estimated at around 400 kN/m width. The CRCP has been designed for a maximum tension force of 520 kN/m width. The tension forces distributed through the bath and the CRCP by constructing a transition slab, rather than an isolation joint are less than what they have been designed for and should not have caused any detrimental effects.

Seamless pavement technology has major advantages. The removal of joints potentially means reduced maintenance and improved rideability. It also eliminates the noise of vehicle wheels striking pavement and bridge joints, bridge open deck joint drainage and the labour-intensive construction of the triple anchor system.

Unfortunately, the GWA Alliance voted for the construction of a more conventional joint with concrete joint nosing upstands and steel nosings with a compression seal at the pavement surface (see Figure 13). Note that there is not a separate approach slab to the concrete bath structure as the CRCP fulfils this function.

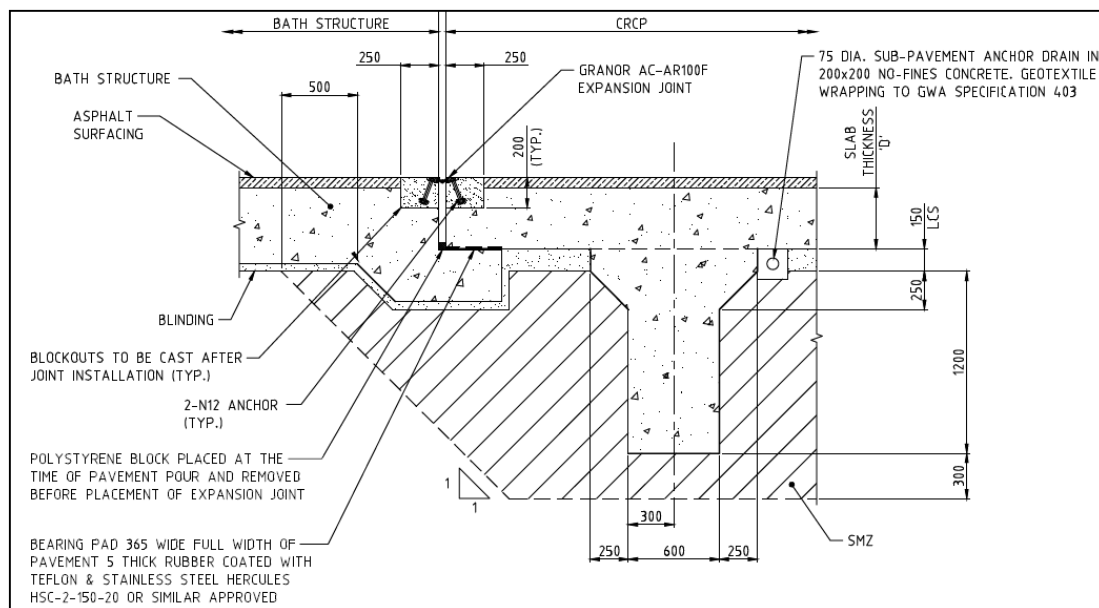


Figure 13 - CRCP / Bath Structure Joint (GWA 2014)
(Anchors 2 and 3 not shown)

CRCP / Plain Concrete Pavement Terminal Design

The transverse interface between a CRCP and a plain (jointed) concrete pavement (PCP) has commonly been designed as either an expansion or an isolation joint. By contrast, it has become common practice in NSW to use a simpler tied construction joint as shown in Figure 14.

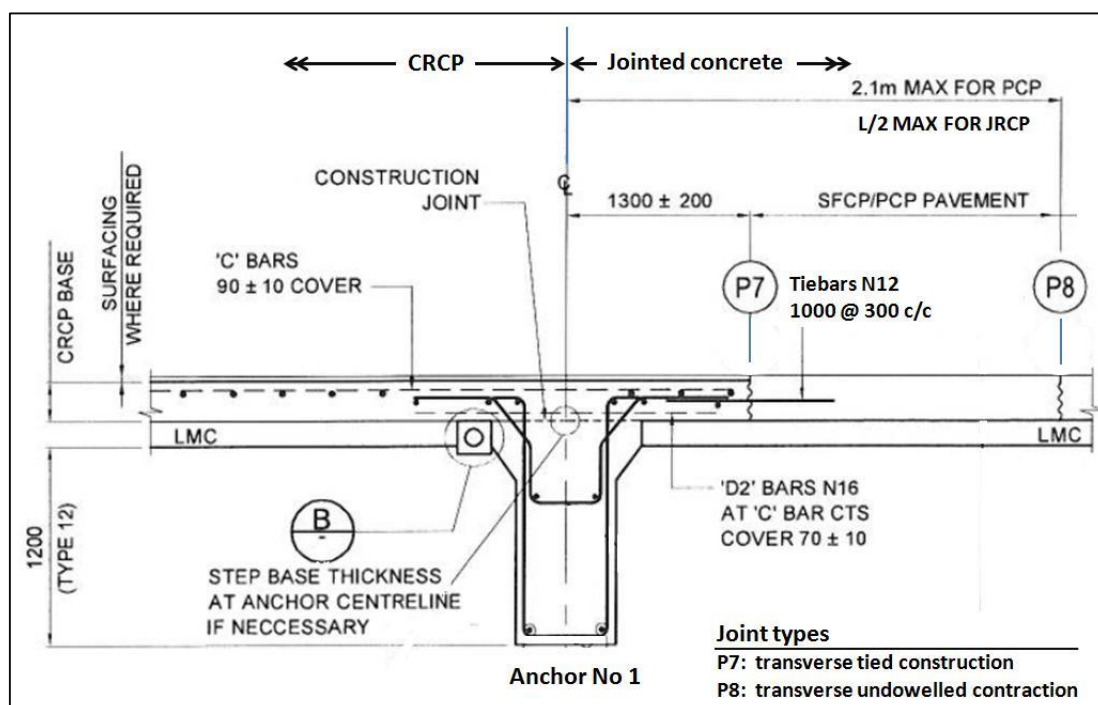


Figure 14: CRCP / Plain Concrete Pavement Joint (RMS MD.R83.CP 2010)
(Anchors 2 and 3 not shown)

It is assumed that there will be negligible movement at the final anchor (No. 1). The key feature is that the limiting distance from the anchor centreline to the nearest contraction joint (P8) is set so that the magnitude of cyclic movement in the P8 is consistent with all adjacent P8s. For PCP, the specified 2.1 m is half of the standard PCP slab length of 4.2 m. For JRCp, a similar guideline applies so that where a standard JRCp slab length of (say) 8.0 m is used, the separation distance would be 4.0 m maximum.

CRCP / Flexible Pavement Terminal Design

At the other end of the spectrum is the very challenging CRCP / flexible pavement joint. There are several potential distress mechanisms including the deterioration of jointing material, the ingress of water with subsequent pumping of fines, and differential settlement. A good example of all the above occurring is shown in Figure 15. The CRCP inlay in this instance was constructed in a dedicated truck lane on National Route 3 in KwaZulu Natal, South Africa. There was no joint sealant, water was pumping out adjacent to the flexible shoulder and pavement failure is obvious. The discomfort experienced by heavy vehicles at this point caused truck drivers to avoid this area, dangerously cross into the centre, light vehicle lane and veer back into the truck lane.



Figure 15: CRCP / Flexible Pavement Joint (N3/3, km 6.5 Southbound)

In an attempt to repair the joint and at the same time reinstate end-anchorage to the CRCP, the so-called anchor beam jockey slab (similar to the bridge approach/jockey slab) was developed (see Figure 16). The main purpose of the minimum 40 mm thick asphalt surfacing was in an attempt to create a self-healing joint that does not necessarily need a sealant. Although the beam itself was constructed perpendicular to the traffic lane the approach slab section varied in length from 1.5 m minimum to 3 m and depending on site conditions and as shown in Figure 17, the joint angle was skewed in some instances.

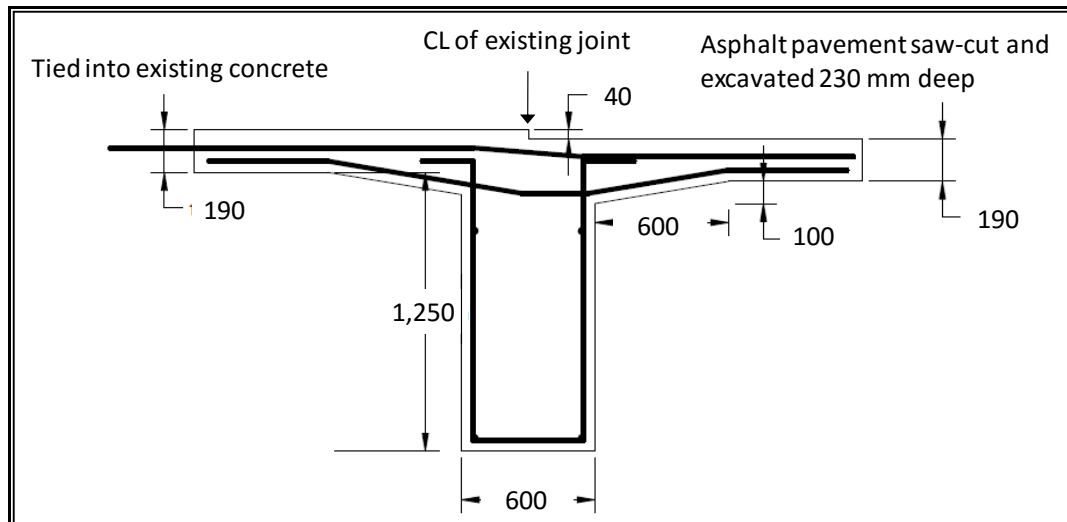


Figure 16 – Anchor Beam Jockey Slab (Brink 2012)



Figure 17: Anchor Beam Jockey Slab (N3/3, km 20.0 Northbound)

The current RMS CRCP / flexible pavement terminal design is illustrated in Figure 18. Its main features are as follows:

- (a) The length of the terminal leg is a compromise between providing adequate resistance against anchor rotation whilst minimising the distance between the anchor centreline and the flexible interface in order to minimise the cyclic movement of the concrete edge;
- (b) The use of a granular material against the concrete which can tolerate water ingress (deep asphaltic concrete is an option);
- (c) A subsurface drain is provided at the interface in recognition that water ingress is unlikely to be completely eliminated; and

- (d) The CRCP terminal leg is thickened to resist the “cantilever” stresses and to sustain traffic impact loads if settlement and/or failure of the flexible pavement isn’t quickly addressed.

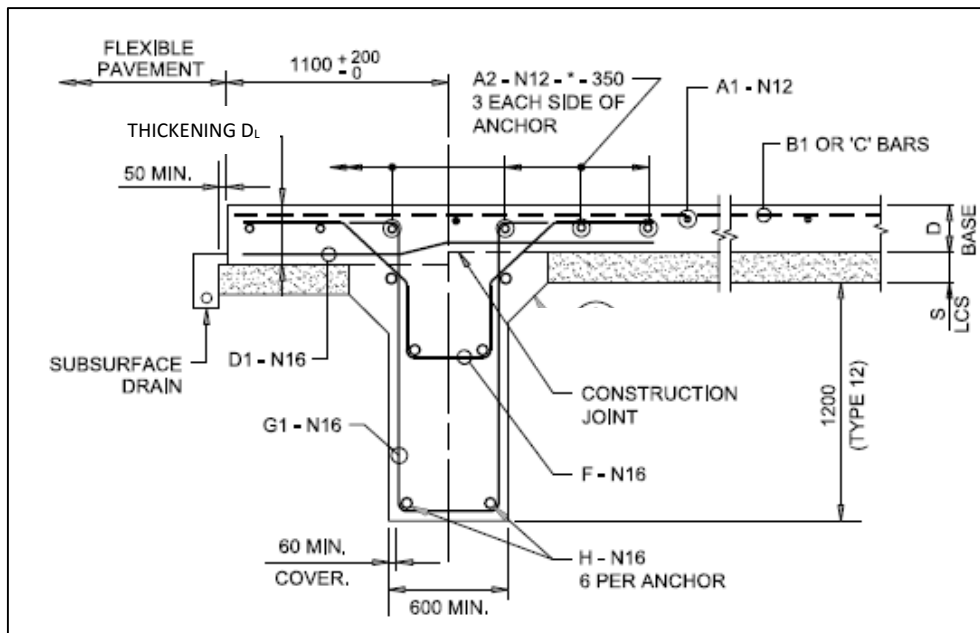


Figure 18: CRCP Terminal Anchor at Flexible Pavement (RMS MD.R83.CC 2010)

When designing the CRCP transition pavements for the Gateway WA project, a combination of the anchor beam jockey slab and the RMS terminal anchor at flexible pavements was developed (see Figure 19). The major difference between the detail in Figure 16 and this detail is that the jockey slab section is tapered down to provide a thicker overlay at the actual joint between the CRCP and the flexible pavement. The minimum asphalt thickness on top of the slab at the centreline of the anchor is 60 mm. It is also important to note that the subsurface drain is located underneath the concrete slab as opposed to underneath the flexible pavement; detailed in Figure 18. The logic behind the location of the subsurface drain is that in the event of water entering the pavement structure, the concrete slab is less likely to settle than the adjacent flexible pavement structure.

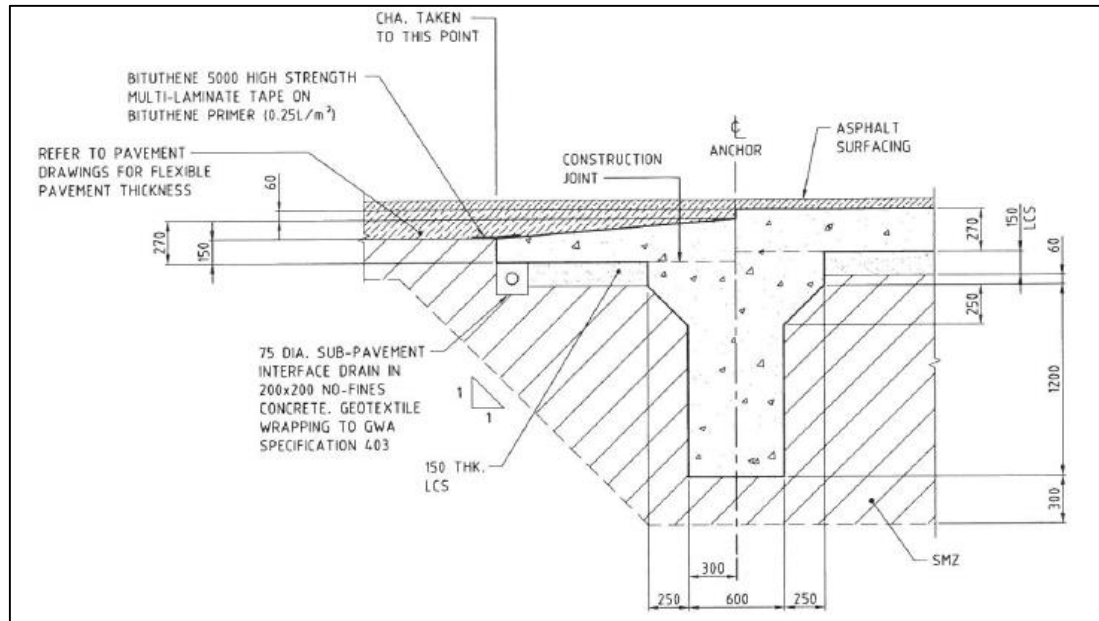


Figure 19: Anchor Beam Jockey Slab Joint at Flexible Pavement (GWA 2014)

Another example of a CRCP / flexible pavement joint is shown in Figure 20. During the recent upgrade and widening of the Ben Schoeman Freeway as part of the Gauteng Freeway Project in South Africa, 1.5 m wide (measured longitudinally) asphalt base plugs were constructed between the CRCP and adjacent flexible pavements. The performance of these joints is being monitored and to date no settlement has been reported.

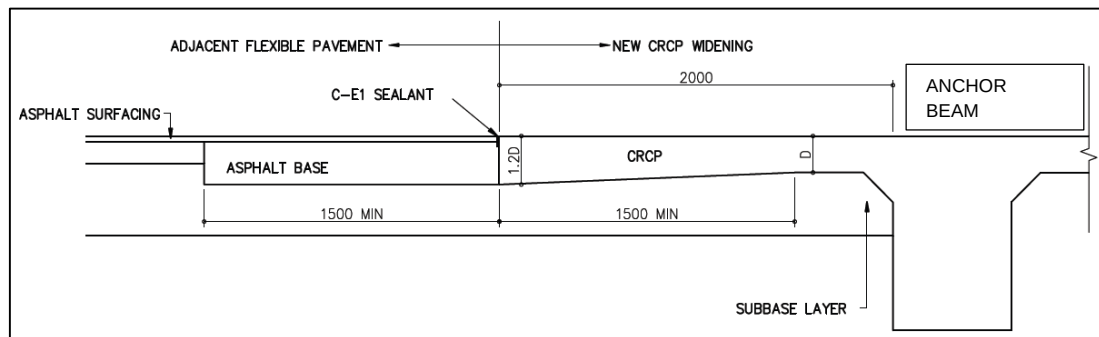


Figure 20: CRCP / Flexible Transverse Pavement Joint (Drawing No. J00068/4Pd 2008)

During the construction of the Antwerp Ring Road in Belgium end anchorage was generally provided by anchors as shown in Figure 4 above. In some instances, however, reportedly “*mainly because of the substantially lower price*”, it was decided to use the design shown in Figure 21 which incorporated a bridge-type expansion joint with steel piles and ground beams to allow free movement of the end of the concrete and prevent damage to the adjacent flexible pavement.

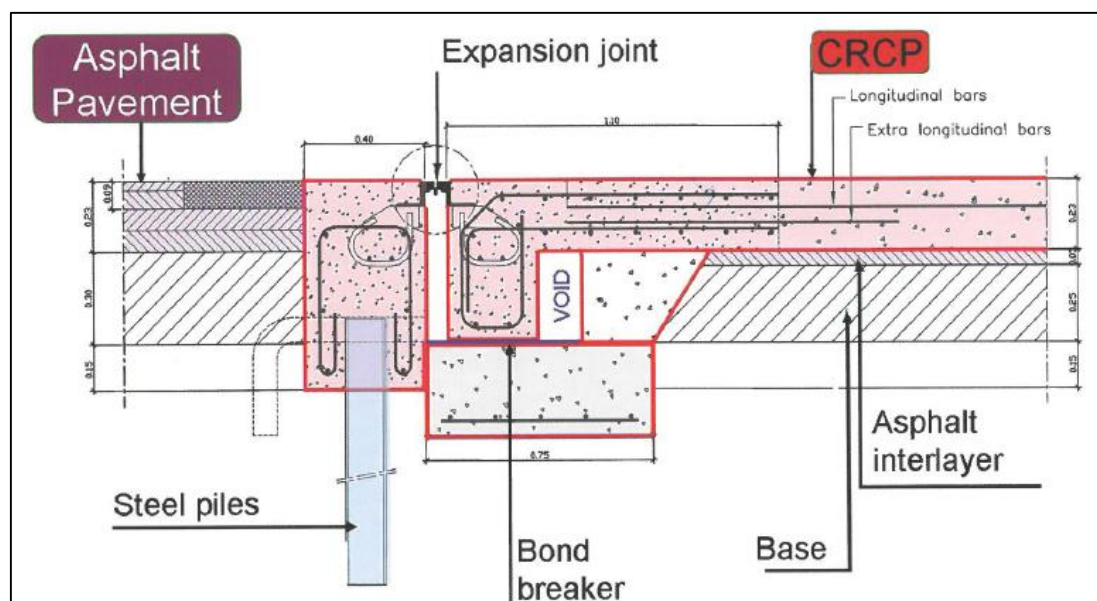


Figure 21: CRCP / Flexible Pavement Joint (FEBELCEM 2006)

Summary

This paper seeks to detail the challenges involved in the design of CRCP terminal joints abutting structures, jointed concrete pavements and flexible pavements. A discussion has been provided of the potential distress modes, and a range of solutions has been provided from various worldwide authorities with explanations of how the features of those designs seek to address the various distresses.

One consensus is that there is always room for further improvement and so it is important that we continue to monitor the performance of terminal joints and to assess the potential for refinements.

Research Significance

As long as there are discontinuities between a CRCP and any other type of pavement and/or structure, terminal design will be involved. Sometimes only time will tell if that which has been designed and constructed is serving the purpose.

Projects listed in this paper that can be revisited to investigate whether the designs have been successful, are:

- (a) Antwerp Ring Road, Belgium
- (b) Ben Schoeman Freeway, South Africa
- (c) The M7, NSW, Australia
- (d) Gateway WA, Australia

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This paper is largely based on the following presentation made to a select audience:
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