11 years of Performance of

Alberta Transportation's First Bonded Concrete Overlay

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Acknowledgements

This paper documents the efforts of the Southern Region Operations staff of Alberta Transportation to undertake a rut mitigation project to combat a chronic rutting problem. Their efforts as well as those of the Cement Association of Canada and Tetra Tech EBA Inc. were instrumental in the design and construction of this project.

Abstract

In 2004, Alberta Transportation constructed its first bonded concrete overlay in the City of Lethbridge. The bonded concrete overlay was constructed to address a chronic rutting problem in one of the left turn bays at the signalized intersection of highways 3 and 4. Because the rutting was requiring yearly maintenance resources, the department was seeking a more sustainable medium to long term solution and therefore opted to construct its first trial of a bonded concrete overlay.

This paper documents the design and construction of the bonded concrete overlay on existing asphalt pavement, including thickness design, specification development, concrete mix design, site preparation and specific challenges. The paper also reviews the performance since construction and provides an assessment of the long term cost-effectiveness and sustainability of this treatment.

1.0 Introduction

In the early 2000s, the Lethbridge district office of the Southern Region Operations group of Alberta Transportation identified rutting concerns at the intersection of highways 4 and 3 located at the east end of the City of Lethbridge. A need to mitigate the repetitive occurrence of rutting by finding a medium to long term solution was identified. The asphalt concrete pavement (ACP) in the north-to-westbound turning lanes of highway 4 (43rd St. within the city limits) onto highway 3 exhibited ongoing rutting which required yearly maintenance resources.

The solution selected was to place a Portland Cement Concrete (PCC) bonded overlay on the existing asphalt pavement as a trial project for approximately 40 metres (m) of the two left turn lanes of highway 4. The bonded concrete overlay (formerly known as whitetopping) was designed to be placed at a depth of 100 and 125 millimetres (mm). This paper documents the design and construction of this project as well as its performance over the last 11 years.

Initial capital costs of the bonded concrete overlay were higher than the previously used ACP mill and inlay repairs. However, a life-cycle cost analysis completed post-construction suggests that the use of bonded concrete overlay as a means to address rut prone locations was cost-effective.

2.0 Overview of Bonded Concrete Overlays

Concrete overlays are becoming a recognized solution for cost-effective, rapidly constructed, and sustainable pavement preservation. Recommended by the Cement Association of Canada and the American Concrete Pavement Association (ACPA), millions of square meters of concrete overlays have been constructed in recent years [1]. A bonded concrete overlay (BCO) makes use of existing asphalt pavement for additional support, but offers the rutting resistance and longevity of PCC without the thickness required of a full-depth concrete pavement. The design of a BCO can be such to cost-effectively accommodate all combinations of design life and traffic loading [2]. Existing pavement condition and thickness will dictate much of the design and/or success of a BCO. As a rule of thumb, a minimum of 75 mm of ACP should remain after milling off any surface distortions. Additionally, a good bond is essential when the 50 to 150 mm of PCC is overlaid on the asphalt to create a new monolithic pavement.

3.0 Project Background and Pre-Design Investigation

Highway 4 northbound, including the turning and through lanes up to the intersection with highway 3, was identified by Alberta Transportation for rehabilitation in 2004. Based on the low structural requirements, a 50 mm ACP mill and inlay was the preferred treatment for the project. However, this treatment was deemed inadequate to address the recurring rutting in the north-to-westbound turning lanes. A BCO was identified by the Lethbridge district office as a potential method to mitigate the yearly maintenance requirements.

Given that Alberta Transportation had very little experience with concrete at the time and that this was the department’s first BCO, Tetra Tech EBA Inc. was retained to develop specifications for the project including concrete mix design requirements, milled surface preparation, concrete placing, curing and saw cutting provisions. The Technical Standards Branch of the department and the Cement Association of Canada were also contacted for technical assistance.

As part of the pre-design investigation, rut data were collected on the existing asphalt pavement in the turning lanes. Figure 1 presents the measured rut data graphically. Rutting was most severe in the outer turning lane where it ranged from 0 to over 45 mm. In the inner lane, rut depths ranged from 0 to approximately 20 mm. The rut depth data was collected at a one metre interval using the same laser based data collection process used for the department's highway network but with a modified reporting distance.

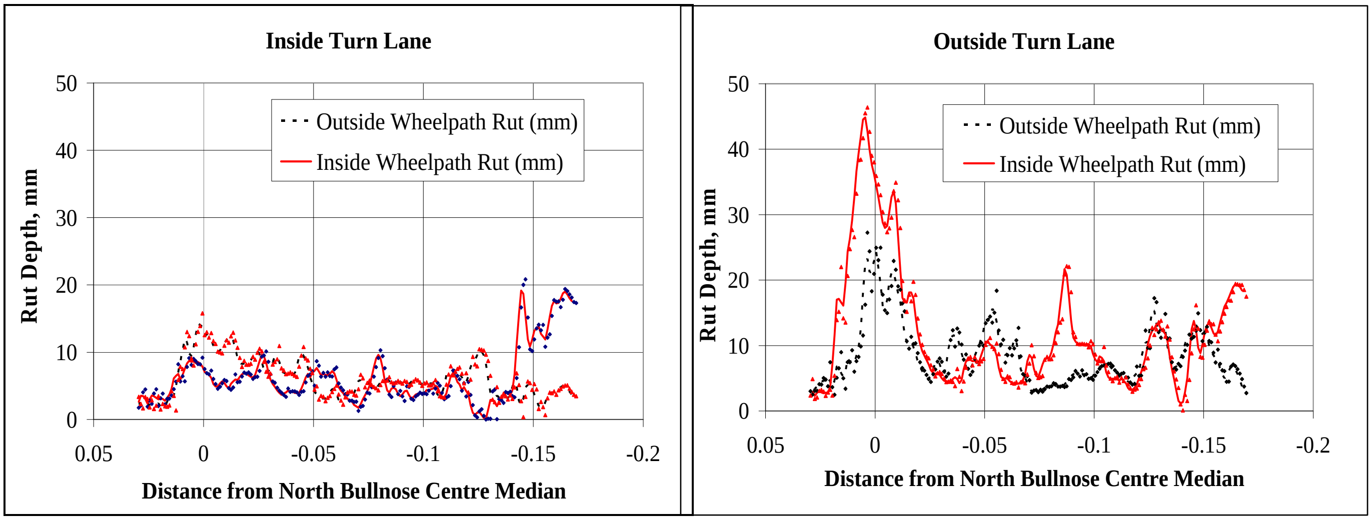


Figure 1 – Rut Depth Measurements in Pre-Existing Asphalt Concrete Pavement

Because neither the department nor the City of Lethbridge had as-built information for the turning lanes, coring was undertaken to confirm the existing ACP thickness in the turning lane and to ensure an adequate post-milling depth given that a minimum of 75 mm of ACP should remain underneath the PCC of a BCO. A plan view of the core locations as well as some of the BCO design details are provided in Figure 2. As reported in Table 1, the cored thickness of the asphalt in the turning lanes was variable, ranging from 175 to 314 mm, with an average of approximately 220 mm. These thicknesses corresponded well to the 225 mm of asphalt from department's as-builts of the through lanes.

Table 1 – Pre-Existing Asphalt Concrete Pavement (ACP) Thickness from Coring

Core	ACP Thickness (mm)	Comment
C1	175	In the rut
C2	314	Out of the rut
C3	210	Out of the rut
C4	180	In the rut
C5	180	In the rut
C6	263	Out of the rut

The final step in the pre-design investigation was to analyse deflection data from Falling Weight Deflectometer (FWD) testing to determine the moduli of the subgrade and pavement layers. Asphalt thicknesses of 175 mm and 225 mm from the coring data along with granular base course thicknesses of 300 mm and 425 mm respectively (the latter from the as-builts of the through lanes) were used to model both a thinner and thicker pavement structure for the turning lanes. Based on these pavement structure inputs, the subgrade modulus was back-calculated to be approximately 55 MPa.

Using the department's 2003 turning movement information, an estimated 780 daily ESALs used the two left turn lanes. These ESALs were input into the department's pavement design methodology, which is based on AASHTO 1993 [3]. Consistent with the project design for the through lanes of highway 4, the

FWD analysis of the turning lanes indicated no structural overlay need for the existing asphalt concrete pavement for a five year design life.

The results of this pre-design investigation showed a strong pavement structure and adequate existing asphalt thickness to support the BCO.

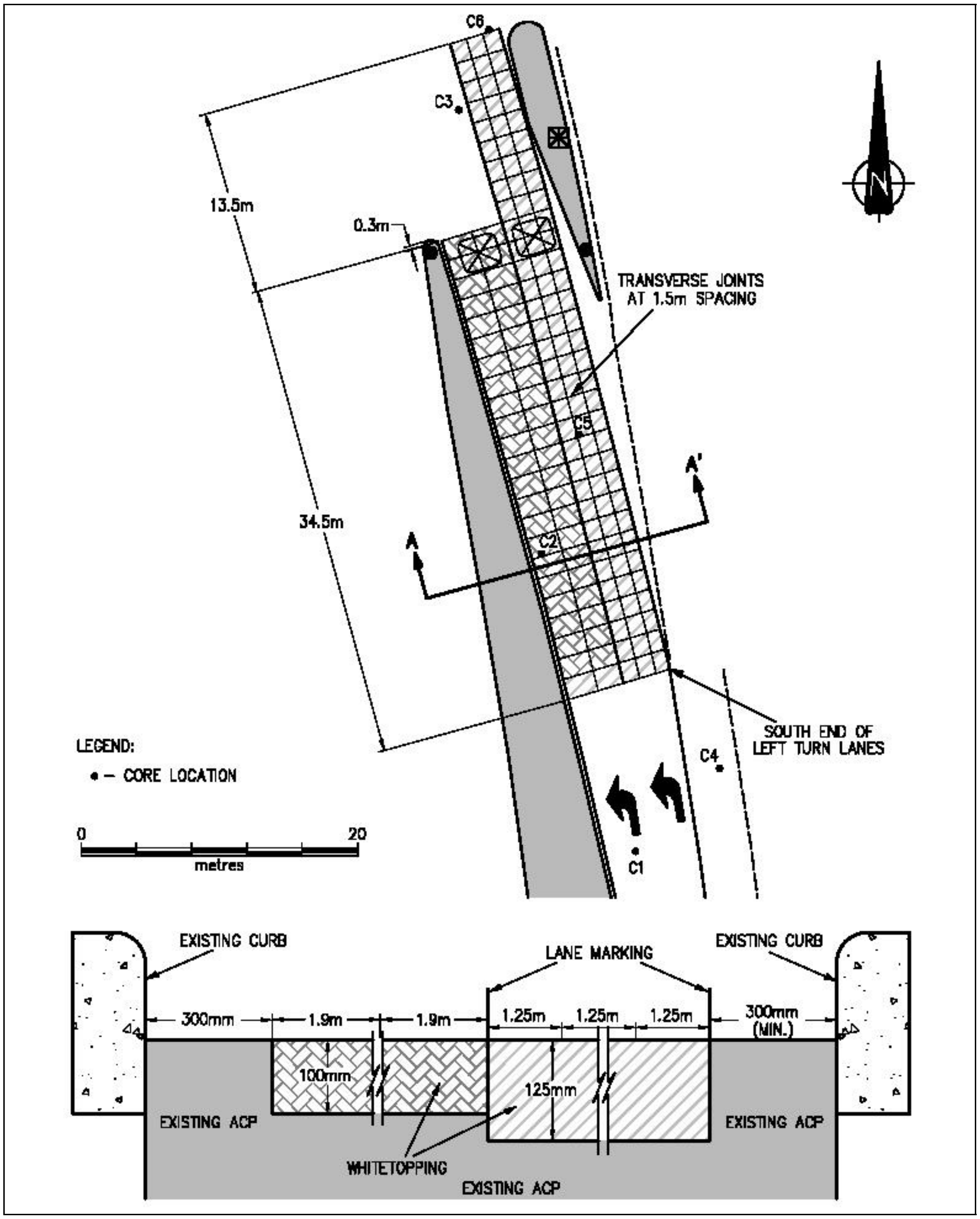


Figure 2 – Bonded Concrete Overlay Initial Core Locations and Design Details

4.0 Bonded Concrete Overlay Design Considerations and Methodologies

The overall process for designing a BCO consists of analysing a number of interdependent factors. A successful BCO will be the optimized balance of considering:

- the existing pavement characterization,
- the costs of the project and rehabilitation,
- the design life and traffic load, and
- the thickness design of the overlay.

Each of these factors incorporates a number of individual considerations relevant to the design methodology and the project itself. For example, the condition of the existing asphalt pavement will determine the extent of milling to remove surface deteriorations. The amount of material remaining has an impact on the thickness of the PCC overlay for the desired service life and loading: too thin of an underlying asphalt layer will require additional support from the PCC layer; an overly thick asphalt layer (200+ mm) will impact the PCC thickness design as the asphalt layer may be stiffer than the PCC layer.

A number of design methodologies have been developed and improved upon since BCO applications have become more mainstream with each design method using the above factors as well as other considerations. These methods include AASHTO 1993 [3], the Mechanistic-Empirical Pavement Design Guide [4], and the bonded concrete on asphalt (BCOA) design procedure [5, 6]. The BCOA thickness design method was developed by the ACPA in 1998 for relatively thin (50 to 100 mm) concrete overlays on asphalt with smaller panel sizes (typically a maximum of 1.8 m by 1.8 m). The iterative, mechanistic procedure is based on calculating the fatigue damage in the slab for corner loading and on limiting the fatigue damage at the bottom of the existing asphalt. The design method was revised in 2011 and 2012 and current input requirements are [2, 6]:

- ESALs,
- percentage of allowable cracked slabs,
- reliability,
- design location (to determine effective temperature gradient),
- existing asphalt thickness and modulus,
- composite subgrade/base/subbase k-value,
- concrete flexural strength, modulus elasticity, and coefficient of thermal expansion,
- fibre usage, and
- slab size and surface preparation.

Many past design methodologies for BCOs were based on limited information available at the time of their development. However, by 2013, a number of BCOs had been in service for a significant period of time. This allowed for the re-evaluation of modes of failure for these overlays. This resulted in the development of the bonded concrete overlay of asphalt mechanistic-empirical design procedure (BCOA-ME) [7]. The BCOA-ME procedure is accessible through an online interface [8] and is the most up-to-date and accurate method for designing a BCO. It incorporates the ACPA BCOA performance prediction model as well as a number of updated models for transverse, longitudinal, and reflective cracking. The primary enhancements in the BCOA-ME model are:

- the predominant failure modes are redefined as a function of slab size as opposed overlay thickness;
- all modes of failure are addressed in one procedure;
- the variability of the asphalt stiffness with temperature is considered;
- the equivalent temperature gradient is defined based on local conditions;
- the prediction models have been calibrated with actual performance data;
- the effects of fiber on the performance of the overlay are more accurately quantified; and
- the effects of deboning are considered [2].

Although the 1998 BCOA design procedure was referenced, the design recommended by Tetra Tech EBA Inc. for the repair of the intersection rutting was ultimately based on the physical constraints of the site. Based on the minimum depth of asphalt required and the existing asphalt thickness from the coring, and constrained by the need to match to the existing curb and gutter, a 100 mm BCO was chosen as the design repair. However, because of the relatively high percentage of truck traffic, and because the majority of the trucks use the outer turning lane, a 125 mm thickness was designed for the outer turning lane.

5.0 PCC Mix Design

A summary of the PCC mix specification and submitted design is provided in Table 2. Of note was the requirement for polypropylene fibres.

Table 2 – PCC Mix Requirements

Specification Requirements	**Design Submitted**
CSA A23.1-00 Class C1 Exposure • Air content: 5 – 8 % • Maximum Water/cementing materials ratio: 0.40	 • See specific air content requirements • 0.38
Aggregate Requirements (ironstone and deleterious material content): 0.8% max in coarse aggregate; 1.5% max in fine aggregate	0.6% in coarse aggregate
Type 10 Portland Cement	Type 10 Portland Cement
Minimum Portland cement content: 335 kg/m³	335 kg/m³
Fly Ash: max 10% of cement content	8.2% of cementitious
Air Content: 6.0 +/- 1%	4 – 7%
Slump: 80 +/- 20mm	Maximum 100 mm
Minimum Compressive Strength • 20 MPa at 3-days based on the average of 2 cylinders • 30 MPa at 28-days based on the average of 3 cylinders	30 MPa 28 day strength
Synthetic Structural Fiber (Grace Canada Inc. "Strux 9040", Forta "Ferro" or approved equivalent)	Grace Canada Inc. "Strux 9040" (4.6 kg/m³)
Fiber residual strength: 0.6 MPa min	Fiber dosage based on City of Edmonton 118th Ave. project
Minimum toughness Performance Level lll at 7-days to ASTM C1018	Unknown

6.0 Construction

Construction of the BCO was done in July 2004 through the regional highway maintenance contractor. Milling of the asphalt in both lanes was done two days prior to the concrete pour. An extra 25 mm key was milled along the north edge for the placement of the first set of electrical conduits for the advanced green signalization. Because of hot weather, with daytime temperatures near 30°C, it was decided to pour the turning lanes on separate days to maximize curing during the cooler mornings. Formwork was installed to separate the pours of the inner and outer turning lanes.

Inner Lane

Pouring of the inner lane began on July 6th at 07:10. Contrary to the specifications, the formwork did not appear to have a release agent applied to it and no bond breaker appeared to have been applied to the adjacent concrete curbing along the median. Also contrary to the specifications, the milled surface had not been cleaned by air and water blasting.

The air test on the first truckload of concrete was 7.5% (above specification requirements of 6% ± 1%) with a slump of 45 mm (below specification requirements of 80 mm ± 20 mm). Cylinders for strength measurement were cast from the first truckload. The second truckload was only tested for air and slump and did not have cylinders cast. The air content was 9.0% and the slump was 50 mm. The third truckload, with an air content of 6.5% and a slump of 35 mm, had cylinders cast. The fourth and final truckload was not tested. The last of the concrete was poured at 09:30.

A hand operated vibrating screed was used to consolidate the concrete; however, no pencil vibrator was used for initial consolidation, which was contrary to the specifications. The surface was finished with a float. Approximately 30 minutes after float finishing, the surface was tined using a tined float. A curing compound was applied to the concrete surface. A wetted filter cloth was also applied approximately 6 hours after the completion of the pouring. Joint saw cutting began at approximately 17:00 and took about two hours. The saw cuts were flushed with water. After saw cutting, the filter cloth was re-laid and re-soaked.

Due to a verbal miscommunication, the jointing was done incorrectly. Because the poured inner lane was 4.5 m wide, it was decided to cut three panels across instead of the two as shown in the design drawing (Figure 2). However, instead of three panels of approximately 1.5 by 1.5 metres, four panels of approximately 1.1 metres wide and 1.5 metres long were saw cut across the lane resulting in longitudinal joints near the wheel paths.

Once the formwork was been removed, the depths of the saw cuts were measured at 20 to 30 mm along the exposed edge of the inner lane. The saw cut joints were specified to be the greater of 30% of the PCC depth, or 30 mm; therefore, the saw cut depths did not appear to be fully compliant with the contract specifications.

Outer Lane

After pouring the inner lane, a string line was used to measure the milled depth in the outer lane. Depths of as little as 85 mm were measured. Given the 45 mm thickness of the second set of electrical conduits, an 85 mm depth allowed little room for error in saw cutting depth. As well, because most of the truck traffic uses the outer turning lane, it was considered imperative that the design depth of 125 mm be met. The outer lane was re-milled with a bobcat mounted miller on July 6th. An extra 25 mm deep key was also milled along the south edge of the inlay to provide a thicker transition between the asphalt and concrete. The re-milled surface was measured at 120 to 125 mm deep.

On July 7th, at the department's direction and prior to placing the concrete in the outer lane, the surface was air blown to remove debris. This resulted in a cleaner surface than what had been observed in the inner lane.

The concrete pour started at 06:20. The concrete air content appeared more controlled on the second day of pouring, with the first truckload having an air content of 6.0% and the second truckload having an air content of 5.2%. The slumps were 70 mm and 55 mm respectively. A few fibre balls were noted in the mix. A total of five truckloads were used to complete the pour of the outer lane with cylinders being cast from two of these truckloads.

At the department's request, a pencil vibrator was used for initial consolidation of the concrete. Saw cutting of the outer lane resulted in three panels across the lane with dimensions of about 1.2 metres wide by 1.5 metres long, as per the design. It was realized afterwards that the inner turning lane was made wider (4.5 m) than the outer turning lane (3.6 m). In hindsight, and as per the specification drawing, more emphasis should have been placed on making the two turning lanes the same width, or even with the outer lane slightly wider, to accommodate the more frequent outer lane truck traffic and truck tracking while turning.

In keeping with BCO applications, the saw cut joints were not sealed because of the close joint spacing and narrowness of the saw cuts (approximately 3 mm wide). Sealing of the joints would require re-cutting of the joints with a wider saw blade and installing backer rod and sealant. This is a substantial effort for joints that were not expected to experience much movement due to their tight spacing.

7.0 Post-Construction

To maximize curing and strength development, the concrete was not opened to traffic until July 11th. Concrete strength test results are summarized in Table 3. No individual strength test was below the specified requirements of 20 MPa at 3 days and 30 MPa at 28 days. Based on an average 28 day compressive strength of 36 MPa, the flexural strength of the concrete was estimated at 4.5 MPa [9].

Table 3 – Summary of Concrete Compressive Strengths

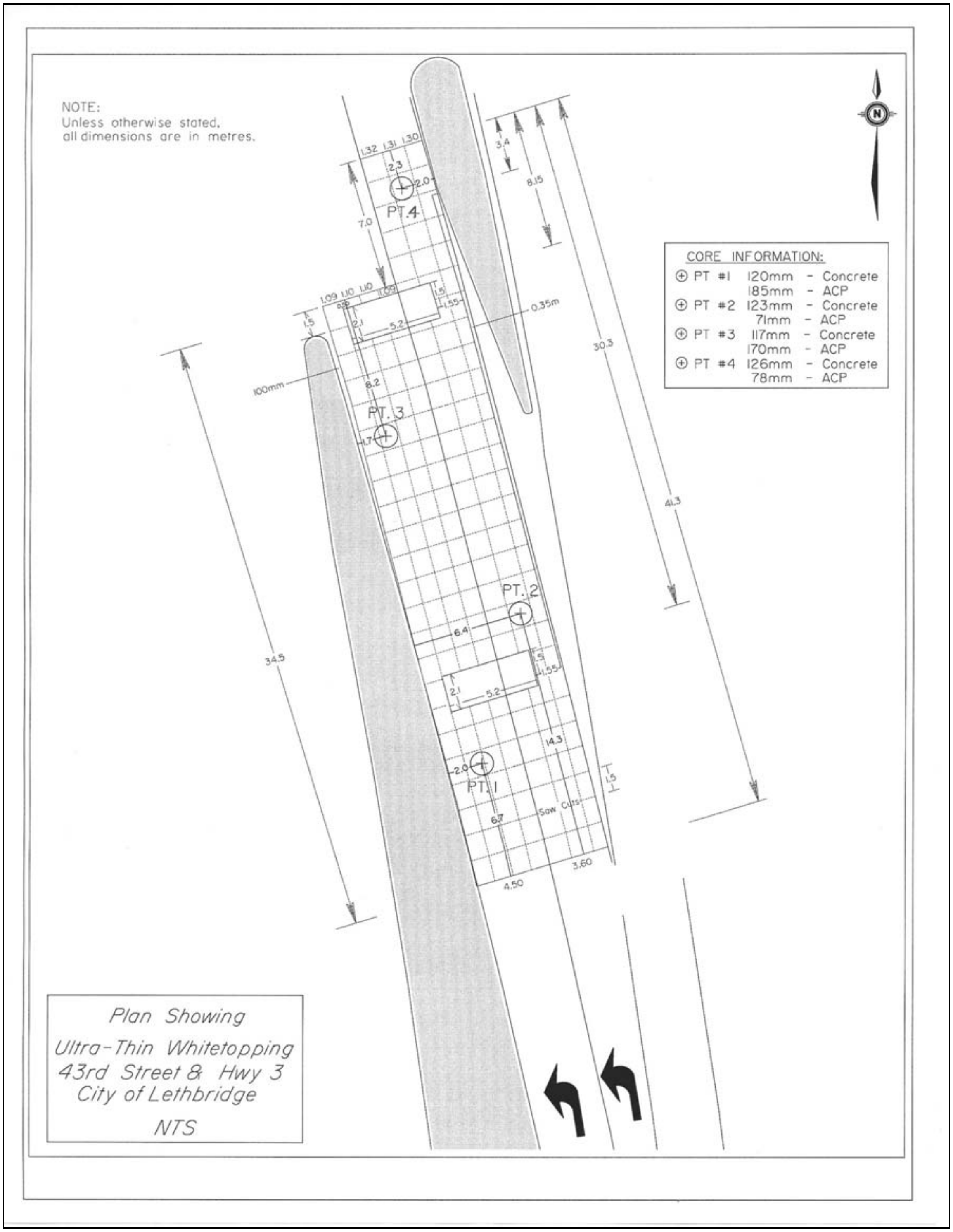
Test No.	Truck #	Date /Time	Compressive Strength (MPa)		
			3 Day	7 Day	28 Day
1	465	July 6/04 – 07:30	26.9	30.2	36.1
2	462	July 6/04 – 09:00	27.5	31.0	36.0
3	465	July 7/05 – 06:30	26.4	31.2	35.3
4	465[1]	July 7/05 – 06:30	26.2	29.1	36.8
		Average	**26.8**	**30.4**	**36.0**
		Specification Requirements	20	n/a	30

[1] Presumed error in truck number

Before opening to traffic, the pavement was cored to verify the concrete thickness, to take extra measurements of the asphalt thickness, and to verify the bond between the asphalt and concrete. Two cores per lane were taken and Figure 3 shows the core locations and measured thicknesses. Despite the different thicknesses designed for the inner and outer lane, the cores indicated the concrete thickness was consistent and averaged 122 mm in both turning lanes. The remaining asphalt thickness averaged 178 mm in the inner lane but only 75 mm in the outer lane.

8.0 Long-term Performance

The performance of the BCO has been monitored regularly since construction in 2004. Despite the initial appearance of one panel edge cracking shortly after construction, the long term performance of the BCO has exceeded expectations with no other cracking issues until just recently. In April 2015, a site inspection noted one failed panel and a handful of other panel cracks. Figures 4 to 7 document some of the performance since 2004 and Figure 8 provides a schematic of the cracking from the 2015 site inspection.



CORE INFORMATION:

⊕ PT #1	120mm	-	Concrete
	185mm	-	ACP
⊕ PT #2	123mm	-	Concrete
	71mm	-	ACP
⊕ PT #3	117mm	-	Concrete
	170mm	-	ACP
⊕ PT #4	126mm	-	Concrete
	78mm	-	ACP

Figure 3 – As-built Ultra-Thin Whitetopping, 43rd St. and Hwy. 3 in Lethbridge

Figure 4 – June 2007 photo of BCO

Figure 5 – June 2008 photo of BCO

Figure 6 – April 2015 photo of BCO failed panel in outer turning lane

Figure 7 – April 2015 photo of BCO in outer turning lane

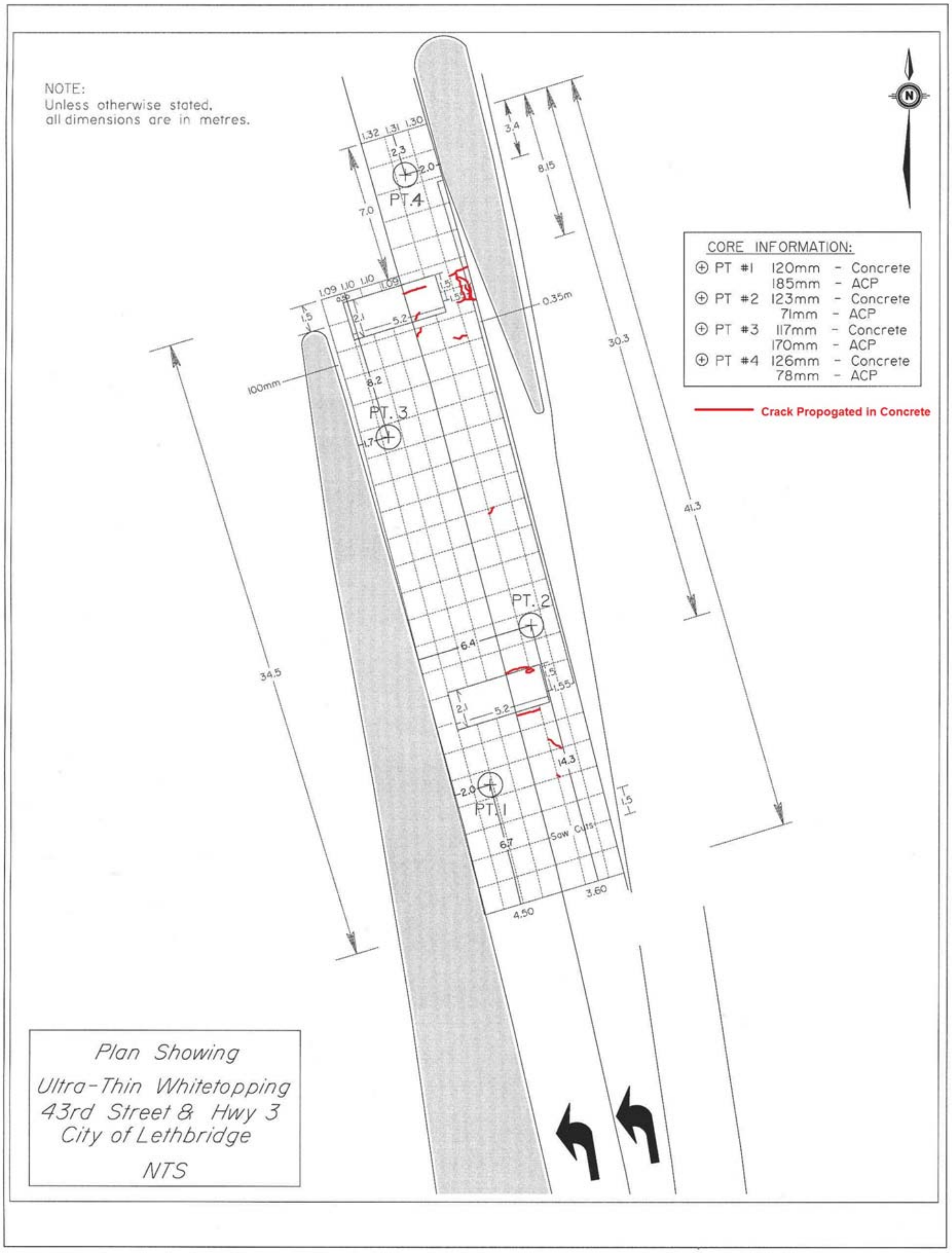
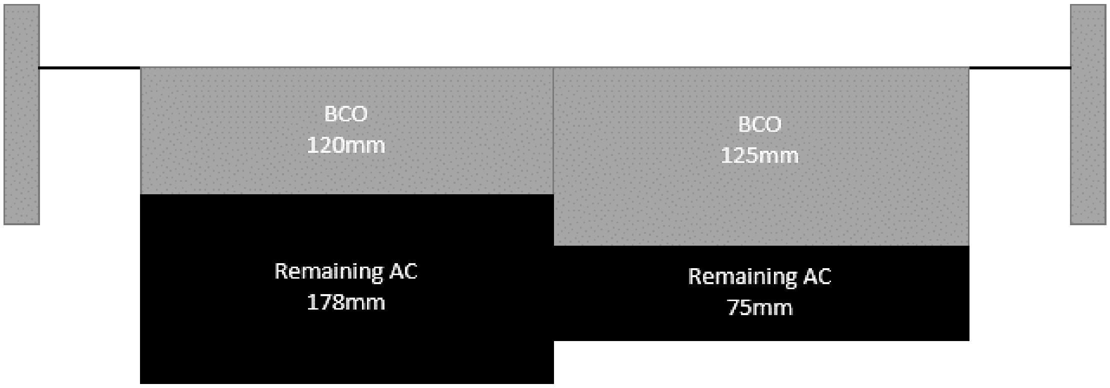


Figure 8 – Schematic of April 2015 Cracking

9.0 Estimated Service Life

At the time of construction, the ACPA's Engineering Bulletin "Whitetopping – State of the Practice" [10], which tabularizes the 1998 ACPA BCOA methodology, was used to estimate the service life of the BCO. The subgrade modulus calculated from the FWD analysis was used as input to estimate an effective k-value (Westergaard modulus of subgrade support). For this project, a back-calculated resilient modulus of 55 MPa translates empirically to a California Bearing Ratio (CBR) value of approximately 7.5. Using the table and nomograph provided in the Engineering Bulletin, the k-value of the subgrade was estimated at 45 MPa/m and the value of k_t (k-value on top of the existing pavement) was estimated at 110 MPa/m. Given the subgrade strength, heavy truck traffic, average asphalt thickness of 75 mm, joint spacing and estimated concrete flexural strength, the service life of the outer turning lane, based on extrapolation of the BCO design charts, was estimated at 4.5 years.

As noted previously, because of the advancements in BCO design methods, BCOA-ME was also used to re-evaluate the service life for both the inner and outer lanes. As shown in Figure 9, the results from this analysis indicate that the outer lane is at the end of its service life while the inner lane has remaining service life. This correlates well to the in-field performance observations that show the outer lane is starting to experience some failures and is nearing the end of its service life at 11 years whereas the inner lane remains in excellent condition.



Assuming 15% ESALs in inner lane	**Assuming 85% ESALs in outer lane**
38,352 ESALs / year	217,175 ESALs / year
BCOA ME = 75mm	BCOA ME = 121mm
421,872 ESALs / 11 years	217,175 ESALs / 11 years
BCOA ME recommends = 75mm	BCOA ME = 131mm
Assuming 100% ESALs in inner lane	**Assuming 100% ESALs in outer lane**
255,527 ESALs / year	255,527 ESALs / year
BCOA ME = 75mm	BCOA ME = 122mm
2,810,797 ESALs / 11 years	2,810,797 ESALs / 11 years
BCOA ME = 85mm	BCOA ME = 132mm
Service Life Remaining	**Service Life Complete**

Figure 9 – BCOA-ME Service Life Predictions

10.0 Life Cycle Cost Assessment

Based on construction costs, the cost of the BCO was approximately four times the price of an asphalt mill and inlay excluding ancillary work. Including all ancillary work, of which the most significant was traffic loop installation and traffic control, the BCO was only one and a half times the price of an asphalt repair. As such, if the service life of the BCO were to be two years it would have been a more cost-effective treatment than asphalt based on initial construction costs. Based on actual performance, the service life of the BCO appears to be at least 11 years. Asphalt was requiring yearly maintenance repairs. A cost comparison is provided in Table 4 and shows that the BCO was more cost-effective than the future anticipated asphalt repair costs based on the actual maintenance activities that had been occurring at the site. However, it is important to note that this cost comparison does not include the BCO repair costs that will be incurred over the next few years nor does it reflect the costs associated with a better designed non-maintenance type asphalt repair.

Table 4 – 11 Year Cost Comparison of Bonded Concrete Overlay to Asphalt Mill and Inlay

Year	Bonded Concrete Overlay	Asphalt Mill & Inlay
2004	$78,000	$52,000
2005		$3,000[1]
2006		$8,000[2]
2007		$3,000
2008		$52,000
2009		$3,000
2010		$8,000
2011		$3,000
2012		$52,000
2013		$3,000
2014		$8,000
2015		$3,000
TOTAL	**$78,000**	**$198,000**

[1] Hand patching of rutting

[2] Minor milling or rutting

The future BCO repairs are expected to entail full BCO panel removal (PCC and asphalt layer) and replacement with full depth PCC. Despite the anticipated repair costs, long-lasting pavements such as this BCO demonstrate economic advantages in terms of life-cycle costs and also contribute to a pavement's sustainability in several ways. This BCO reduced the requirement for yearly maintenance thereby consuming fewer raw materials over the pavement's life-cycle. Although not specifically quantified, there were also savings through the elimination of yearly constructions zones which impede traffic, create congestion, generate additional vehicle emissions and delay users. Additionally, the reduction in the number of construction zones may have increased roadway safety. These environmental and social benefits yield additional long-term economic benefits to the public.

11.0 Conclusions and Recommendations

This project provided Alberta Transportation with an opportunity to evaluate an alternative treatment to the standard asphalt mill and inlay for severely rutted intersections. Based on this trial project and the associated background work, the following conclusions and recommendations are provided:

1. The service life of this bonded concrete overlay appears to be approximately 11 years in the outer lane. This exceeded expectations and was a more cost-effective treatment than an asphalt mill and inlay. As such, the department should continue to consider the use of bonded concrete overlays to address intersection rutting problems.

2. Because the bonded concrete overlay is reaching the end of its service life, repairs will be required soon. The cost of these repairs, which may involve full depth panel replacement, has not been factored into the life-cycle accounting to date. Another life cycle cost analysis is recommended post-repair.

3. A number of deviations from the specifications were noted during the construction of this trial section. It is recommended that any future projects of this nature utilize on-site inspection and enforcement to ensure the intent of the specifications is met. Key elements for compliance are:
   - obtaining proper milling depths,
   - proper post-milling surface preparation including air and water blasting, and
   - proper consolidation of the concrete using a pencil vibrator.

12.0 References

1. American Concrete Pavements Association, The National Concrete Overlay Explorer. http://overlays.acpa.org (accessed May 11, 2015)

2. National Concrete Pavement Technology Centre, Guide to Concrete Overlays, 3rd Edition. ACPA publication TB021.03P, Washington, DC (2014). http://www.cptechcenter.org/technical-library/documents/Overlays_3rd_edition.pdf (accessed May 11, 2015)

3. American Association of State Highway and Transportation Officials (AASHTO), AASHTO Guide for Design of Pavement Structures, AASHTO, Washington, DC (1993).

4. American Association of State Highway and Transportation Officials (AASHTO), Mechanistic-Empirical Pavement Design Guide, A Manual of Practice, AASHTO, Washington, DC (2008).

5. Wu C-L, Tarr S, Refai T, Nagai M, Sheehan M, Development of Ultra-Thin Whitetopping Design Procedure. Report RD 2124, Portland Cement Association, Skokie, IL (1998).

6. American Concrete Pavements Association, Concrete Overlay on Asphalt (BCOA) Thickness Designer. http://apps.acpa.org/applibrary/BCOA (accessed May 11, 2015)

7. Vandenbossche J, Mu F, Dufalla N, Li Z, Bonded Concrete Overlay of Asphalt Pavements Mechanistic-Empirical Design Guide (BCOA-ME) Theory Manual, University of Pittsburgh, Pittsburgh, PA (2013).

8. http://www.engineering.pitt.edu/Vandenbossche/BCOA-ME/ (accessed May 11, 2015)

9. Canadian Portland Cement Association, Thickness Design for Concrete Highways and Steet Pavements, Engineering Bulletin EB209.03P, Ottawa, ON (undated).

10. American Concrete Pavement Association, *Whitetopping State of the Practice* Engineering Bulletin EB210.02P, Skokie, IL (1998).