

**THE EVOLUTION OF BRIDGE DECK REHABILITATION  
STRATEGIES IN ONTARIO**

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## **ABSTRACT**

Rehabilitation of bridge decks is not an exact science; the strategies and selected treatment would depend on a lot of factors including accuracy of the condition survey data, service life requirements, knowledge and expertise of the designer and owner, availability of desired materials and technologies, and to a large extent the fiscal management practices of the agency. This paper describes the historical development of bridge deck rehabilitation strategies in Ontario. Performances of some selected treatments, particularly waterproofing, overlays, cathodic protection systems and the associated concrete removal criteria are discussed in conjunction with the change in policies and practices. Some key changes in construction specifications that were recently implemented to enhance durability of rehabilitations are also discussed. The paper also provides a high-light of the developmental work that are currently underway as part of the ministry's on-going initiative to seek cost effective strategies for managing the bridge inventory.

Key Words: Cathodic protection, concrete removal criteria, corrosion potential, corrosion rate, waterproofing, overlay, tensile bond, shrinkage

## **Introduction**

Rehabilitation of bridge decks is not an exact science; the strategies and selected treatment would depend on a lot of factors including accuracy of the condition survey data, service life requirements, knowledge and expertise of the designer and owner, availability of desired materials and technologies, and to a large extent the fiscal management practices of the agency. The current policies and standards of the Ministry of Transportation of Ontario is the result of many years of development through field applications and monitoring and are contained in the Structure Rehabilitation Manual [1]. Some of the practices have been reverted or changed only after a long period in service when there are enough evidence to justify the change and the Manual will be updated periodically. There is however no single document that describes the historical progression of the deck rehabilitation strategies. This paper therefore attempts to put all the ministry's major deck rehabilitation strategies in chronological order so that it can serve as a convenient reference.

### **Prior to 1965**

Bridge engineers back then did not really have a good understanding of the freeze-thaw effects on concrete and the corrosion of steel reinforcement due to de-icing salt; they also did not have the products or technology that could mitigate these effects successfully. Most bridge decks were not properly air-entrained and though some decks might have been waterproofed, the materials used were ineffective after a few years in service. Consequently, bridge decks deteriorate quite rapidly with a life expectancy of only about 40 years. There was no standard rehabilitation strategies prior to 1965 that would address the on-going corrosion of reinforcement in chloride contaminated concrete; repair work was carried out in a haphazard fashion to maintain the riding surface.

### **1965 – 1980**

The beginning of this era also marked the beginning of major expansion of the transportation network in Ontario. Many major structures were built as part of the Hwy 401, QEW, 427 etc. From 1965 to 1972, the ministry built a lot of exposed decks, including many post-tensioned decks serving as ramp and interchange structures in the greater Toronto area. The reasons for leaving the decks exposed were not well documented, but could include the belief that good quality concrete with post-tensioning would be durable, and that assessment of deterioration of an exposed deck would be much easier than an asphalt covered deck.

Most of the post-tensioned decks with circular voids were originally built without transverse post-tensioning. It was soon discovered that longitudinal cracks occurred at every voids due to stress concentration and possible floating up of the void forming ducts during concreting. Figure 1 shows a close-up view of such cracks on the QEW westbound to Highway 427 southbound ramp structure taken in 1989; the deck was constructed in 1968. At the time of condition survey, there was 14.5% of the deck top surface that had delaminated or spalled and the chloride content at rebar level in the delaminated areas was 3 times the threshold. Figure 2 shows a typical delaminated area with rust staining and spalls.

By 1973, the ministry had realised it was a mistake to build exposed concrete decks in Ontario where the use of de-icing salt on highways was prevalent. Hence, all decks built after 1973 were waterproofed with the hot-applied rubberised asphaltic membrane, except that mastic asphalt was used on some rigid frames until 1976. Furthermore, transverse post-tensioning was introduced after 1974 to prevent longitudinal cracks over circular voids of post-tensioned decks [2].



**Figure 1 QEW WB to Highway 427 SB Ramp ( Photo taken 1989)  
- Typical longitudinal crack in deck over voids**



**Figure 2 QEW WB to Highway 427 SB Ramp Deck Top Condition (Photo taken 1989)**

In 1996, the MTO Structural Office undertook an investigation to evaluate the effectiveness of waterproofing membrane on bridge decks where the membrane was installed as part of the original construction [3]. The investigation involved analysing half-cell survey, sawn samples and chloride profile data for a total of 21 decks built in 1973 to 1978. The following is a summary of the findings:

- The thickness of the waterproofing was found to be inadequate in a significant number of locations. Despite this inadequacy, the waterproofing was effective in preventing corrosion of reinforcing steel in the travelled lanes after an average of 16 years in service.

- Only 1% of the total deck area surveyed had corrosion potential  $< -0.35$  volts; 9% of the total deck area surveyed were in the uncertain range of corrosion potential of  $-0.20$  to  $-0.35$  volts.
- 9 out of 121 sawn samples indicated waterproofing failure; all of the failures occurred along the curbs and barrier walls except one which was over a construction joint.
- Chloride penetration was only confined to areas within 1 m from curbs and barrier walls.

In 1974, the ministry installed the first conductive asphalt cathodic protection system on bridge decks based on the work by Stratfull [4] in California. It consisted of primary high-silica cast iron anodes recessed in the concrete surface and covered with a 40mm thick layer of electrically conductive cokebreeze asphalt; the conductive asphalt is then covered with a conventional asphalt surface course. This CP system can only be used on properly air-entrained concrete surfaces as the bridge deck cannot be waterproofed. Later on, from around 1990, this system has been used in conjunction with a normal concrete overlay to overcome the problem for decks where the existing concrete was not properly air-entrained. Figure 3 shows a typical pancake anode recessed in the top surface of a deck.



**Figure 3 Pancake anode recessed into concrete deck**

This CP system had been installed on over 60 decks since 1974, including post-tensioned decks, rigid frames and thin decks. The policy was to use CP where corrosion potential more negative than  $-0.35V$  exceeds 20% of the deck and the majority of the area contains sound concrete. The ministry terminated any new installation of this system in the mid 1990's due to its poor performance and the following associated structural problems:

- (i) Despite the fact that the CP system may be protecting the top reinforcement effectively, the top surface of the concrete continues to suffer moisture and chloride ingress which may lead to freeze thaw damage and salt scaling. By the time the CP system has exhausted its life, the amount of chloride at the rebar level is so high that corrosion could accelerate very rapidly and there is no other effective long term rehabilitation method except replacement of the CP system or replacement of the deck .

- (ii) Due to the lack of waterproofing, moisture and chloride would eventually reach the bottom reinforcement and cause corrosion damage at the soffit of a thin deck. Figure 4 and Figure 5 show the progressive soffit deterioration of the Island Park Overpass Highway 417 where the top had been treated with the conductive asphalt CP system in 1983. The same also applies to shear connectors and stirrups of the girders embedded in the concrete.
- (iii) The post-tensioning cables are not protected against moisture and chloride ingress due to the lack of waterproofing. This is a serious concern since the grouting of the cables carried out in the 1960's might not have been controlled to a very high standard and could have left behind voids at the high points of the cables. Figure 6 shows leaching cracks at the soffit of a post-tensioned deck with circular voids where the top had been treated with the conductive asphalt CP system.
- (iv) The asphalt on top of the anodes would begin to deteriorate in a few years with rust stains bleeding to the surface. Consumption of the coke and acid generation at the anode would soften the asphalt, leading to ravelling and depression of the wearing surface under traffic load ( See Figure 7 and Figure 8). The electrical resistance of the system would then increase due to poor current distribution from the anodes and the cable splices could also corrode.
- (v) Voltage and current output has to be monitored and adjusted on an on-going basis as the system resistance increases. This, in conjunction with the maintenance required for the asphalt and the hardware, has made the system very user unfriendly. The life expectancy is also too short to be worth the cost and effort to install it, particularly when user impact is included in the life-cycle financial analysis.



**Figure 4 Soffit of Island Park Overpass, Hwy 417, taken in 1993**



**Figure 5 Soffit of Island Park Overpass, Hwy 417, taken in 2000**



**Figure 6 Soffit of Post-Tensioned Deck with leaching cracks**



**Figure 7 Rust staining at anodes of conductive asphalt CP system**



**Figure 8 Asphalt deterioration at anode of conductive asphalt CP System**

In 1979, the ministry implemented the use of epoxy coated rebars for top mat of reinforcement in bridge decks. At the same time, the cover to top reinforcement was increased to  $70 \pm 20$  mm and hot-applied rubberised asphalt waterproofing membrane with protection board continued to be used on all decks. Decks built to this standard were intended to have a minimum service life of 50 years and that no major repair work was expected during the first cycle of rehabilitation after 30 years in service. In 2001, the ministry undertook a study of 12 decks built between 1978 to 1982 to investigate the performance of the epoxy coated rebars and the waterproofing. Dry adhesion tests were conducted on the epoxy coated rebar samples and extensive chloride profile tests were carried out of the core samples [5]. The following is a summary of the test results:

	No. of Samples	Mean	Standard Deviation	Remarks
<b>Adhesion Rating of Epoxy Coating</b>	<b>66</b>	<b>3.0</b>	<b>0.6</b>	<b>5 = poor</b> <b>3 = fair</b> <b>1 = good</b>
<b>Chloride at Deck Surface</b>	<b>67</b>	<b>0.007%</b>	<b>0.024%</b>	
<b>Chloride at Rebar Level</b>	<b>67</b>	<b>0.005%</b>	<b>0.009%</b>	
<b>Concrete cover</b>	<b>68</b>	<b>80mm</b>	<b>15.7mm</b>	<b>Specified</b> <b>= <math>70 \pm 20</math> mm</b>

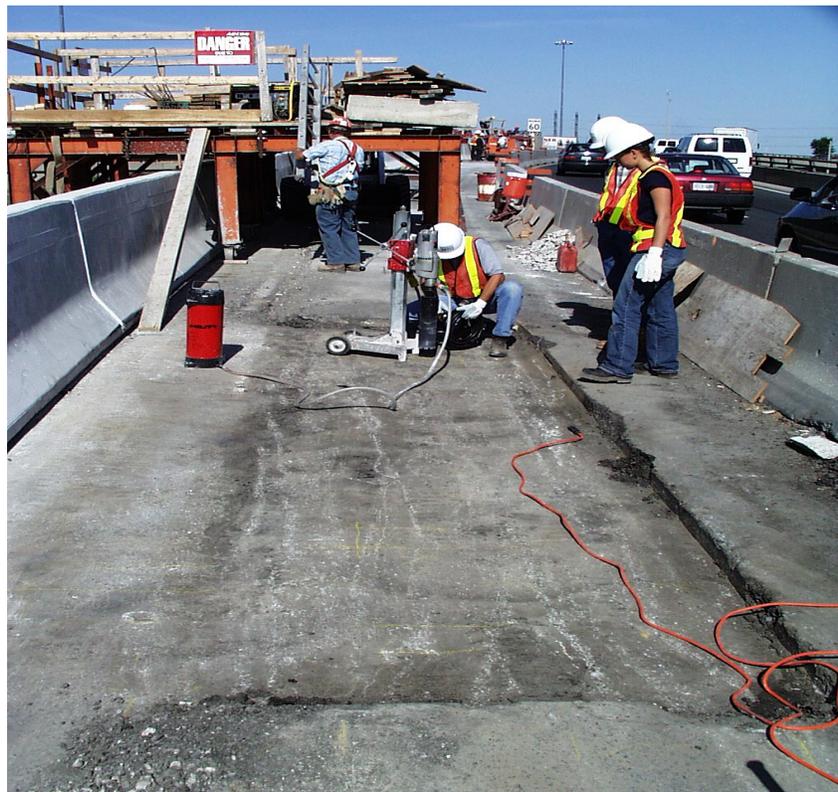
While the mean rating of the epoxy coating is only fair, indicating the knife tip can be inserted under the coating but levering action removes only small chips of coating and not the entire coating, there is however no corrosion of the epoxy coated rebars due to the low chloride content. The waterproofing is effective in mitigation against moisture and chloride and based on extrapolation of the chloride ingress rate, these decks could achieve a 75 years service life provided the waterproofing is replaced every 25 to 30 years.

### **1981 – 1990**

By the early 1980's, many of the exposed concrete decks that were built in the 1960's were already suffering extensive corrosion damage and condition surveys indicated significant chloride penetration and corrosion potential more negative than  $-0.35V$  in large areas. The ministry realised that the service lives of these decks could be extended if further ingress of chloride and moisture could be prevented. Hence, waterproofing was installed during the first cycle of rehabilitation of many of these decks in the early 1980's and since the existing concrete surface was too rough in most cases to receive the waterproofing, most of them also received an overlay. Latex modified overlay was typically used during this period because of its low permeability and good bonding characteristics. Delaminated and unsound concrete were removed but areas with corrosion potential  $<-0.35V$  but otherwise sound concrete would have been left in place. The policy also allowed the use of exposed latex modified overlay for secondary highways where the existing structure could not carry the extra load of the overlay, waterproofing and paving. Recent condition surveys conducted on many of these decks in preparation for a second cycle rehabilitation have shown that in general the first rehabilitation treatment has been effective; the corrosion potentials in the previously active areas have shifted into the passive and uncertain range, despite the fact that chloride content at the rebar level has exceeded threshold. The latex overlay is also performing very well with minimal disbondment after 20 years. Figure 9 shows a localized area of removal of the latex modified overlay on a post-tensioned deck during condition survey and Figure 10 shows the core taken from the same area. The

only area that could perform poorly is localized over the voids where a pre-existing wide crack might have allowed excessive amount of chloride and moisture ingress and the steel would continue to corrode at a significant rate after the rehabilitation. Figure 11 shows the localized corrosion of transverse rebars over the voids.

The hot-applied rubberised asphalt waterproofing system consisting of a form-in-place membrane,  $5 \pm 1$  mm thick, covered by a 4 mm thick protection board, has gradually become one of the key components in the rehabilitation of existing decks as well as the corrosion protection strategy for new decks. However, by 1983, it became evident that the quality of the end product frequently did not meet the specified requirements due to contractors skimping on the membrane thickness. In 1986, the ministry implemented a full statistical end-result specification for membrane thickness; payment reduction is applied whenever the mean thickness is less than 5 mm and the percent defective is from 0.1% to 5.0%. The lot is rejectable when the mean thickness is less than 4.0mm or when the percent defective is more than 5%. In 1987, the end-result specification was further enhanced by adding a material quality component with payment reduction for substandard material used. The quality and workmanship of waterproofing installed after the implementation of end-result specification has improved greatly and has been very consistent since then [6].



**Figure 9 Condition Survey on Latex Modified Concrete Overlay 2002  
(QEW/Hwy 427 Bridge No. 7)**



**Figure 10 Core taken from deck with latex modified overlay**



**Figure 11 Localized corrosion of rebar over circular voids of PT deck**

Prior to 1988, removal of concrete from the top surface of decks as part of rehabilitation treatment was based on delamination only; area with corrosion potential more negative than  $-0.35$  volt but otherwise sound concrete was not removed. In 1988, the ministry conducted an investigation to evaluate the reliability of half-cell surveys and the implication of its use as criteria for concrete removal [7]. It was found that in general, delaminated concrete corresponded very well to areas of high corrosion potential and the total estimated increase in area of removal for the 11 structures investigated was 6%. It was believed that removing the area with corrosion potential  $< -0.35$  volt would also correspond to removing chloride contaminated concrete and would maximize the life expectancy of the rehabilitation treatment. Hence, the policy of concrete removal by half-cell potential criteria as given in ASTM C876 was implemented in 1989 for all deck rehabilitation. This has been the most influential factor in the selection of rehabilitation treatment since the recommended treatment depends on the extent of concrete removal:

Delamination + HCP area  $< 10\%$  of deck : Patch / waterproof / pave

Delamination + HCP area  $> 10\%$  of deck : Overlay / waterproof / pave

Concrete would be removed to 25mm behind the first layer of rebars and locally to 25mm around the second layer; and the concrete surface and rebars are abrasive blast cleaned before new concrete is placed.

It was also recognised that the extent of delamination and severe scaling of an asphalt covered deck could not be assessed accurately by the cores and sawn samples, which only represent a very small percentage of the deck statistically. During this period, the ministry also acquired the deck assessment radar technology (DART) to pre-screen about 50 decks a year. The results of the DART survey (delaminations, severe scaling, cover to rebar) were co-ordinated with the half-cell survey to arrive at the appropriate rehabilitation treatment. Figure 12 shows the DART antenna with an operational frequency of 1 GHz, mounted on an MTO cube van ready to carry out survey of a deck.

**Figure 12 DART survey on decks**



## 1991 – 2000

By the early 1990's, it was evident that the conductive asphalt CP system was performing poorly and had fallen well below expectation. However, it did not deter the ministry from exploring other forms of cathodic protection systems. It was recognised that corrosion of steel in concrete is an electrochemical process and can be stopped by electrochemical treatments such as cathodic protection (CP). In 1981, the Federal Highway Administration (FHWA) issued a statement describing CP as the only rehabilitation technique proven to stop corrosion in chloride contaminated structures, regardless of chloride content in the concrete. With the use of cathodic protection, chloride contaminated but otherwise sound concrete does not have to be removed. This is especially advantageous when the structural component has large area of active corrosion (corrosion potential  $< -0.35V$ ) but the delaminated area is relatively small; structural integrity could be preserved since no extensive concrete removal would be required. In 1990, the ministry implemented the second generation CP system consisting of a continuous titanium mesh anode embedded in a normal concrete overlay. The bridge decks were then waterproofed and paved. Presently the ministry has approximately 9 bridges protected with this second generation CP system. Generally, the second generation systems are performing well and a 20-30 year service life is expected. The presence of waterproofing membrane for the second generation system is a big advantage since further ingress of chloride and moisture can be minimized. Figure 13 shows the placing of titanium anode mesh on the existing deck surface prior to placing of normal concrete overlay. Currently, this system would still be considered for new installation whenever the need arises, and if the life-cycle cost is justified. However, the system voltage and current output still needs to be monitored and periodic maintenance and repair of the power supply hardware is required.



**Figure 13 Titanium Mesh Anode Cathodic Protection System**

In the mid 1990's, a lot of the ministry's deck rehabilitation contracts were experiencing massive overruns. The ministry conducted an overrun study and found the following are some of the major causes of the overruns:

- (i) Failure of the condition survey to reveal accurate condition of the deck surface, particularly shallow delaminations and small cover to reinforcement, which may lead to scope change during construction.
- (ii) Variability of the half-cell survey and migration of uncertain corrosion activity into active corrosion area between the time of condition survey and the time of construction.
- (iii) Difficulty in enforcing specification requirements for concrete removal (eg. hammer sizes, depth of removals etc.) due to inexperienced field staff or aggressive contractor.
- (iv) Inaccurate interpretation of condition survey data and quantity estimates calculated by inexperienced consultants leading to inappropriate rehabilitation treatments and scope change.
- (v) Poor condition of soffits of thin decks leading to full depth removal when combined with removal at top surface.

In order to mitigate against future overruns, the ministry adopted some major changes to the policies and practices in 1999, including the following:

- 1) For exposed concrete components, delamination survey should be carried out within a year of construction for correct design quantity estimation.
- 2) Where significant deterioration of the deck soffit is evident visually (>10%), a detailed soffit condition survey is recommended to investigate and determine the extent of full depth removals required.
- 3) The estimating procedure in the Structure Rehabilitation Manual should be revised to include areas with corrosion potential between  $-0.31$  to  $-0.35$  volts to adjust quantities when surveys are out of date. The growth rate of 10% per year used in previous estimates had been found to be inadequate when there is a big percentage in the transitional range.
- 4) Where the excessive field removal is particularly due to the removal of sound concrete with high corrosion potential ( $<-0.35$  volts), consideration should be given to increasing the criteria to  $<-0.45$  volts provided this is appropriate for the intended remaining service life of the structure. This should only be considered for secondary highways and if concrete cover is greater than 60 mm and reinforcing steel does not show signs of severe corrosion.
- 5) If a large overrun is encountered, the Contract Administrator should inform the Regional Structural Section and Construction Office before proceeding with the removal, as in some cases excessive concrete removal might affect the load carrying capacity and the behavior of the structure. The Regional Structural Sections should evaluate the large removal overruns (actual quantity > 115% of tender) that is being identified during construction to avoid excessive removals and to preserve the overall integrity and behavior of the structure. The Contract Administrator and Construction office monitoring staff should also make sure that the Contractor is not causing new delaminations by using oversized hammers and improper removal procedures.
- 6) Sliding scale payment for overrun quantity has been introduced in some Regions. There are insufficient data to assess the effectiveness of this approach. Further investigation would be required in the future to determine the benefits of this payment method.

- 7) For certain sites, if the combined information from the detailed deck condition survey and DART survey still could not provide a clear representation of the condition of the deck top surface, then removing a large 1 m x 6 m strip of asphalt to expose the concrete surface during condition survey could be considered. This option should be exercised with judgment due to the extra cost involved to remove and replace asphalt and waterproofing, extra time required to do the work, potential damage to the deck surface and quality control of waterproofing. If the contract is delayed, it could have an adverse effect to the deck. It could be used in high-risk projects where a small increase in percentage of concrete removal could result in a significant increase in cost and scope.

By this time, the good performance of waterproofing has been well established and consequently the need to use latex modified overlay for its low permeability gradually diminished. The majority of the overlays placed in the 1990's were normal concrete overlay with the exception where the existing structure could not carry the extra weight of the overlay and asphalt, an exposed low permeability overlay could be used. With the development of high performance concrete in the mid 1990's, silica fume became more widely used in concrete to improve durability. The ministry adopted silica fume overlay as an alternative low permeability overlay with a maximum chloride permeability of 1000 coulombs and the minimum compressive strength of 40 MPa. However, the use of silica fume overlay has not gained favor even today due to the potential cracking and the extra time required for wet curing (7 days versus 1 day for latex modified).

### **Hydrodemolition**

One of the findings of the overrun study was that the use of jack hammers for partial depth removal of concrete was difficult to control and could often lead to excessive removal, further propagation of cracks and delamination, and damage of the reinforcement. There was therefore a revived interest in hydrodemolition as a systematic approach to concrete removal. The ministry first tried the technology in the late 1980's but it was not very successful due to frequent break down of the equipment. In 1998, the ministry implemented another trial project using hydrodemolition to remove a uniform thickness of concrete over the entire deck top surface. Figure 14 shows the top surface of the deck after hydrodemolition.



**Figure 14** Top surface of deck after hydrodemolition, Hwy 25 over Hwy 401

From a technical point of view for concrete removal, the trial could be considered a success. The performance of the hydrodemolition equipment was good with little down time and the quality of the resulting concrete surface was good. The only dissatisfaction was that the reinforcement was not as clean as we had expected and that laitance remaining on the steel could harden up if not pressure washed promptly (see Figure 15). However, it was unfortunate that the ministry also wanted to test the capability of the industry to treat the affluent on-site so that it could be discharged back to the environment. This has proven to be quite a hurdle with approval requirements from MOEE and time-consuming testing. The ministry has not used hydrodemolition again since that time due to the apprehension in people's mind regarding the stringent environmental requirements. However, this is a mis-conception, and despite this setback, the ministry still considers hydrodemolition a viable option, particularly for second generation rehabilitation of thick decks that were overlaid previously. In future applications, the contractor would likely be given the option to transport the affluent and dispose of it as liquid industrial waste rather than mandatory on-site treatment.



**Figure 15 Condition of reinforcing steel after hydrodemolition**

## **2000 to Present**

In 2001, the ministry implemented a major change to the rehabilitation policy for post-tensioned decks based on the following information:

### **Hwy 401/427 Bridges, Condition surveys conducted in year 2000.**

Site No.	Year Constructed	Year Rehab / Treatment	Chloride %	% < -0.35V
37-812	1969	xxxx, Overlay, WP, P	0.03%	0
37-814	1969	1983, Overlay, WP, P	0.044%	0
37-815/1	1969	1981, Overlay, WP, P	0.033%	0
37-815/2	1969	1981, Overlay, WP, P	0.047%	0
37-816	1968	1981, Overlay, WP, P	0.041%	0
37-817	1968	1980, Overlay, WP, P	0.025%	0
37-829	1969	1984, Patch, WP, P	0.034%	0

**QEW/427 Bridges, Condition surveys conducted in year 1999.**

Site No.	Year Constructed	Year Rehab / Treatment	Chloride %	% < -0.35V
37-236	1968	1993, Anode Mesh CP	0.09%	NA
37-713	1968	1993, Latex O'lay, WP, P	0.13%	1.3%
37-714	1968	1985, Patch, WP, P	0.022%	0.7%
37-715	1968	1981, Latex O'lay, WP, P	0.159%	0
37-717	1968	1985, Patch, WP, P	0.07%	0
37-718	1968	1985, Patch, WP, P	0.065%	0.5%
37-719	1968	1984, Latex O'lay, WP, P	0.16%	0.4%
37-721	1968	1985, Patch, WP, P	0.033%	1.7%
37-722	1968	1984, Latex O'lay, WP, P	0.09%	0
37-724	1968	1992, Patch, WP, P	0.054%	4%

As can be seen from the above summaries for the two groups of bridges, the half-cell readings taken according to the standard 1.5 m grids are very passive indicating that there is little corrosion activity, despite the fact that these decks had been exposed to chloride for over ten years prior to the first generation rehabilitation and the chloride content generally exceeds threshold at the rebar level. This apparent passification is particularly evident for those decks that were treated with latex overlay plus waterproofing where most corrosion potential readings between  $-0.25V$  to  $-0.35V$  prior to the overlay treatment are now more passive than  $-0.15V$ . However, a significant number of cores in the recent surveys did show rusting of rebars to varying degree; it could not be determined whether the rusting was pre-existing before the rehabilitation or whether corrosion is continuing.

During the second generation rehabilitation of the Hwy 401/427 bridges in year 2000, it was observed that there was longitudinal crack over almost every one of the voids. Half-cell readings taken directly over the voids and in the vicinity of the cracks are more negative than the areas between the voids with some readings  $< -0.35V$ , indicating some very localised corrosion activity. The half-cell survey conducted during the deck condition survey according to the standard 1.5 m grids had missed most of these localised areas of higher corrosion potential. After deteriorated concrete is removed over the voids, the transverse reinforcing is exhibiting significant rusting, though not very much section loss. This rusting phenomenon is only confined to an area of about 150 mm on either side of the cracks. It could not be determined whether the rusting was pre-existing or on-going. The transverse top reinforcement at the solid section over the piers exhibited medium to severe rusting with some section loss over an extensive area. Since the half-cell readings at the solid sections were all very passive, it is believed that much of the corrosion occurred prior to the first generation rehabilitation. During removal of deteriorated concrete over the voids, which could be either delamination or debonding of the overlay, a significant percentage of the areas had punched through exposing the void form below. Quite often, the top mat of rebars were actually resting on the void form with little or no cover from below. These areas which were only meant to be partial depth removal had turned into full depth removal and extra forming is required to pour back the new concrete. At many locations where concrete removal was identified by chain drag, the rebars were in very good condition with no rust. It could be inferred that at these locations, the overlay has debonded from the original concrete surface rather than corrosion initiated delamination. Therefore, removal of concrete to 25 mm below rebars according to OPSS 928 is inappropriate. A research study conducted by Professor M. Bartlett and Christopher Scollard [8] also confirmed that partial depth concrete removal from a post-tensioned deck could have detrimental structural effects to the extent that the secondary prestressing could reverse in direction; the rehabilitation treatment should therefore minimize the amount of concrete removal. Figure 16 shows excessive concrete removal of a post-tensioned deck with circular voids when corrosion potential was used as criteria for removal.



Figure 16 Excessive concrete removal of a post-tensioned deck with circular voids

**New rehabilitation policy for post-tensioned decks implemented in 2001**

- I) Decks that have never been rehabilitated
  - If the chloride content exceeds threshold ( 0.03% by mass of concrete for post-tensioned decks ) at the rebar level,
    - HCP + Delam < 5% of deck : Latex overlay, waterproof and pave
    - HCP + Delam > 5% of deck : Titanium mesh cathodic protection system + Normal concrete overlay, waterproof and pave
  - If chloride content is less than threshold,
    - HCP + Delam < 5% of deck : Patch, waterproof and pave
    - HCP + Delam > 5% of deck : Latex overlay, waterproof and pave
- II) Decks that were previously rehabilitated with overlay
  - HCP + Delam < 5% of deck : Patch, waterproof and pave
  - HCP + Delam > 5% of deck : Remove overlay, install titanium mesh cathodic protection system + Normal concrete overlay, waterproof and pave
- III) Decks that were previously rehabilitated with patch, waterproof and pave: Same as (I).
- IV) Decks that were previously rehabilitated with conductive asphalt CP system
 

Since there is no waterproofing on the deck, the chloride content would undoubtedly exceed threshold greatly. The only long term solution to stop further corrosion on the rebars would be the titanium mesh cathodic protection system, plus normal concrete overlay, waterproof and pave. In order to mitigate further exposure of the post-tensioning cables to moisture and de-icing salt, these decks should be programmed for second generation rehabilitation immediately.
- V) Half-cell criteria shall not be used for concrete removal.
- VI) Only chipping hammers shall be used for Partial Depth Concrete Removal. For decks with existing overlay, debonded areas of the overlay shall only be removed to sound concrete. This would necessitate inspection of the original concrete surface of all removal areas identified by chain drag before removal should proceed any deeper.

### New Concrete Removal Policy

In 2002, due to fiscal constraint, the ministry undertook a review of its bridge rehabilitation policies to see how the existing inventory could be managed effectively with the available funding. As for decks, the policy of removing concrete by half-cell potential was under scrutiny since this practice has often led to expensive treatments, overruns and scope change during construction. Recent research investigations on some MTO bridges have shown that while removal by delamination alone does reduce the service life of the rehabilitation; this reduction may not be as significant as expected. The waterproofing membrane (with or without overlay) can prevent moisture, oxygen and further ingress of chloride, thus slowing the corrosion rate and would make the corrosion potential more passive afterwards. The following examples show clearly the corrosion potentials passify after rehabilitation even though chloride contamination concrete was not removed, and that a reasonable service life could still be achieved.

	<b>Bennett Rd/Hwy 401</b>	<b>Bridge No.5 QEW/Hwy 427</b>	<b>Dundas St. Overpass Hwy 427</b>
Year of construction	1966	1968	1969
Type of structure	Slab on girders	PT voided slab	Slab on PC box beams
Condition survey prior to rehab	In 1994, condition survey showed 76% < -0.35 V and 25 % delamination. Chloride at rebar is 4X to 6X threshold	In 1979, span 7 had 13% < -0.35V; delamination unknown.	Year 1983 > - 0.20V 14% - 0.20 to -0.35V 84% <- 0.35V 2% Average -0.25V
Rehab treatment	In 1998, deck was rehabilitated with normal concrete overlay, waterproof and pave. Concrete removal was by delamination only	In 1981, deck was rehabilitated with latex overlay, waterproof and paved	In 1985, deck was rehabilitated with latex overlay, waterproof and paved.
Condition survey after rehab	In 2003, only 6% < -0.35 V in main deck area, average corrosion potential -0.29V. No delam was detected	In 2002, span 7 had 0% < -0.35V, 7% in- 0.2 to -0.35V, 93% > -0.2V Chloride at rebar 2X threshold	Year 2003 > -0.20V 97% -0.20 to -0.35V 3% < -0.35V 0% Average -0.13V Chloride 4X to 6X threshold
Service life prediction by LP3	15 years	35 years	30 years

Literature search on the definition of chloride threshold reveals a range of values, from 0.025% to 0.05% by mass of concrete. It would depend on cement content, resistivity of concrete, availability of oxygen, moisture etc. The threshold value of 0.025% used in the past therefore represents a conservative lower bound. A revised concrete removal policy was then implemented in 2004 as follows:

- Ave Chloride < 0.05% Delamination only
- Ave Chloride > 0.05% Delamination & Half- Cell
- Average chloride content at average cover of rebar should be used

- Decks with less than 10% area  $< -0.35V$ 
  - Use all cores for chloride test
- Decks with more than 10% area  $< -0.35V$ 
  - Use only the cores taken at the HCP areas
- This policy does not apply to post-tensioned decks, which removal would only be by delamination
- Only chipping hammers (max 9 kg and 100mm stroke) are allowed for partial depth concrete removal on decks

### **On-going research and development**

The following deck rehabilitation treatments are being investigated by the ministry and they show good potential for future use:

- sacrificial anode cathodic protection systems
- solar powered titanium mesh cathodic protection system

### **References**

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