Alternative Condition Assessment for Concrete Bridge Decks – A Case Study

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ABSTRACT

Concrete bridge decks in Calgary are exposed to de-icing salts leading to deterioration due to chloride induced corrosion of steel reinforcement. Service life predictions for older concrete bridge decks are essential in developing cost-effective repair and rehabilitation strategies. The current methodology to determine the condition of the bridge deck consists of two parts: 1) determination of potential for corrosion by the half-cell potential test and 2) determination of the chloride ion content profile on concrete cores obtained from the deck combined with petrographic examination of the concrete. The standardized ASTM C876 test for corrosion potential was developed for black steel reinforcement. Current construction methodologies for bridges utilize epoxy-coated rebar and galvanized steel reinforcement, polymer modified asphalt overlays, high density concrete, and steel-fibre concrete. These changes to bridge deck construction have rendered the standard method used for corrosion potential prediction unsuitable.

A bridge deck with a steel-fibre concrete overlay in Calgary was surveyed using the ROAD RADAR™ Technology developed by EBA Engineering Consultants Ltd. The thickness of Portland cement concrete (PCC) cover over the rebar and the bridge deck anomalies were mapped. Based on the chloride ion profiles obtained from the cores, the apparent diffusion coefficient was determined. The findings from the non-destructive ROAD RADAR™ survey, the condition of extracted cores, and the chloride ion diffusion profiles formed the basis for the life cycle model developed.

INTRODUCTION

Concrete bridge decks deteriorate upon exposure to severe climatic conditions, followed by the corrosion of steel reinforcement induced by the presence of moisture and de-icing salts. Once deterioration reaches a critical point, the deck must be repaired. Cost-effective management of bridge inventories requires knowledge of the subsurface condition of each bridge deck so that preventative maintenance programs can be employed. Such a preventative maintenance program is intended to do three things:

- Accurately establish the current condition of the bridge structure;
- Slow down the rate of bridge deck deterioration; and
- Prioritize individual bridges so that they are repaired at the most cost-effective time.

The key to an effective preventative maintenance programs is accurate, quantitative, and current information on the subsurface condition of the bridge deck. Once a bridge deck is scheduled for rehabilitation, accurate determination of the type and extent of concrete deterioration is required to tender the work. One currently accepted methodology for bridge deck condition assessment consists of the determination of the copper/copper sulphate ($Cu/CuSO_4$) half-cell corrosion potential, the determination of the chloride ion content profile from extracted concrete cores, and the petrographic examination of these concrete samples. It has also been demonstrated that ground-penetrating radar (GPR) has significant potential in the assessment of deterioration that is occurring beneath the surface of bridge decks.

The City of Calgary commissioned EBA Engineering Consultants Ltd. (EBA) to undertake a condition survey in 2008 of the 16 Avenue Bridge (TransCanada Highway Bridge [TransCanada Bridge]) over University Drive NW. The bridge was constructed in 1959 and was rehabilitated in 2001. At the time of rehabilitation, the deck underwent hydrodemolition to a depth of 90 mm and to a depth of 105 mm at the pier strips. The new deck reinforcing was reportedly galvanized steel, and the concrete deck was covered with a HD concrete overlay with steel fibres. Due to the presence of steel fibres in the overlay and galvanized reinforcing steel, copper-copper sulphate half-cell potential testing was not conducted. Instead, a comprehensive concrete deck coring program was proposed to determine the concrete condition and to determine chloride profiles for life cycle modelling. The program was accepted by The City of Calgary, and the visual condition survey and core extraction from the bridge deck commenced in the summer of 2008. During that time, EBA’s Calgary Materials & Pavement Group had been awarded EBA's internal Applied Technology & Development grant (AT&D) to proceed with the ground-penetrating radar bridge deck analyses to complement and enhance the quality of bridge deck surveys conducted by EBA. Several bridges were selected in communications with The City of Calgary, and the results for the 16 Avenue over University Drive Bridge were combined with the bridge deck survey conducted under the 2008 survey program.

BRIDGE DETAILS

The TransCanada Bridge is a four-lane structure over University Drive NW with individual span lengths of 14.9 m, 18.1 m, and 14.9 m. The bridge dimensions are 66.1 m x 15.2 m, and the total area is 1,000.7 m^2. Pictures of the bridge and the deck are presented in Photo 1 and Photo 2.

Photo 1: General view of the TransCanada Bridge.

Photo 2: General view of the bridge deck.

VISUAL CONDITION SURVEY

The concrete overlay, which contains steel fibres, was constructed in 2001 when the bridge was rehabilitated. The overlay thickness varies from 90 mm to 190 mm. Steel reinforcement was found in the overlay. The concrete surface was tined. Spalling was evident on the deck, as well as small map cracking (Photo 3). Light scaling was noticed throughout the deck (Photo 4). At the time of the inspection, it was noticed that the water from the coring would not drain off of the bridge and would collect on the curbs and in the tined grooves.

Photo 3: Spalling surface of the concrete overlay.

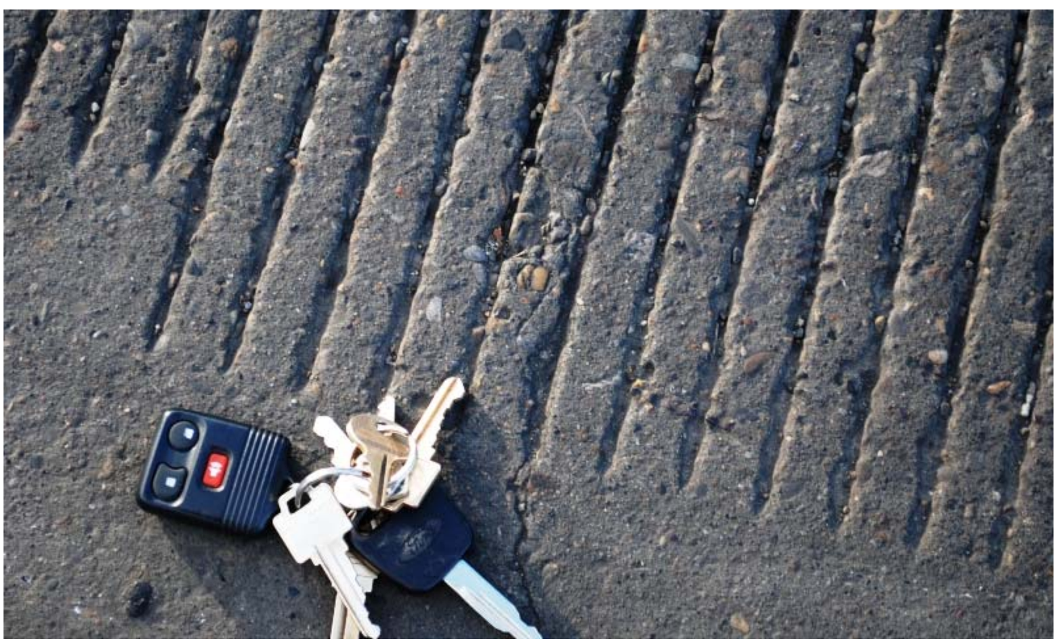

Photo 4: Map cracking and light surface scaling.

The concrete deck was inspected from beneath the deck. Large cracks and rust staining were evident. The underside of the bridge was patched; however, cracks were propagating through the patches. Leaching was also evident from the bottom of the deck (Photo 5).

Photo 5: Leaching and patched areas under the bridge.

The bridge elements consist of a median, curb, and sidewalk on the north side, and curb on the south side of the bridge. The cracking was observed on the median, sidewalks, and curbs. Spalling was noticed on the curb at the southwest edge of the bridge (Photo 6). Light scaling was evident on the median, sidewalks, and curbs. There are two expansion joints on the bridge, one at each end of the bridge. No signs of joint leakage were observed. The expansion joints were filled with sand and gravel that was accumulating in the corners of the deck.

Photo 6: Spalling of concrete curb.

ROAD RADAR™ SURVEY

The ROAD RADAR™ surveys were used to provide comprehensive subsurface structure and condition information for this bridge deck. In addition, to complete structural layer measurements important during rehabilitation, ROAD RADAR™ investigations allow the non-destructive detection of anomalous regions below the surface of the structure. These anomalies include structural and material property variations from the surface to the depth of the top mat of reinforcing steel within the deck structure.

Due to the heavy traffic volumes along the TransCanada Highway, the bridge deck survey was confined to off-peak hours between 10 p.m. and 5 a.m. The total survey time was approximately 12 hours and was conducted with lane closures. The complete coverage survey was accomplished by closing off a single lane of traffic at a time. The survey line layout is presented in Figure 1.

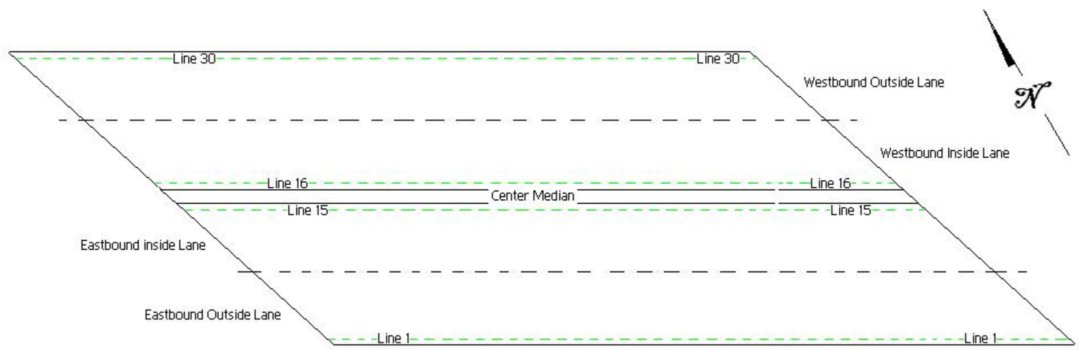

Figure 1: Survey line layout (not to scale).

Lane closures were accomplished by flaggers setting up barricades on either end of the bridge for the appropriate survey lane, with traffic redirected to the corresponding lane. Traffic control was provided by The City of Calgary. At the time of the survey, the weather was clear with an ambient air temperature ranging from 10°C to 15°C.

The bridge was surveyed using a complete coverage methodology, consisting of multiple parallel lines across the entire length of the deck. All distances were measured using a commercial distance-measuring device integrated into the survey vehicle. The longitudinal sampling resolution for the onboard radar systems was approximately 15 mm (or 67 samples per metre) resulting in approximately 5,660 measurements per survey line with a total of 30 survey lines collected.

Bridge deck expansion joints on either side of the structure and visible in the radar data were used as survey start and endpoint references. The survey line offsets were established by placing grid marks at 0.5 m spacing across the expansion joints at each end of the structure. Each survey line was started with the vehicle positioned with the radar antenna systems centred over the corresponding grid mark on the structure's surface. The vehicle maintained a fixed lateral offset while travelling down the deck by utilizing a curb edge, guardrail, or longitudinal joint as the survey frame of reference. In this fashion, the lateral position was maintained with a practical variation of less than ±0.1 m.

Following collection, the survey data was transferred from the radar vehicle to EBA's office-based workstations for processing. EBA's proprietary software was used to automatically interpret and report the data.

BRIDGE SURVEY PRESENTATION FORMATS

The full coverage survey methodology of the ROAD RADAR™ system allows the rendering of all measured parameters using a contoured plan map format. A north arrow is included to aid in plan map and figure orientation. Dimensions are given in metres for both the longitudinal and transverse axes. An appropriate legend is provided for each map. The descriptions of the reported parameters and any corresponding rendering details are discussed below.

PCC Cover Plan Map (physical parameter) reports the total measured PCC cover over the uppermost layer of the reinforcing steel. For decks with an undetectable overlay/deck boundary, the contour map presents the PCC cover from the deck surface to the top mat of reinforcing steel. For this structure, a distinct delineation between the HD overlay and the original PCC deck was not detected. The accuracy of the measured cover parameter is 6 mm or 5%, whichever is greater.

Deck Anomaly Plan Map (interfered parameter) presents a measure of the location and areal extent (as well as total affected area and percentage of the total surveyed area) of subsurface anomalies as detected by radar at or above the top mat of rebar boundary. Figure 2 shows a section of ROAD RADAR™ data with no subsurface anomalies. For this figure, the black line near 0.0 nS (vertical time axis) represents the surface of the structure, and the apex of each inverted hyperbola represents the location of each transverse rebar in the top mat of reinforcing steel.

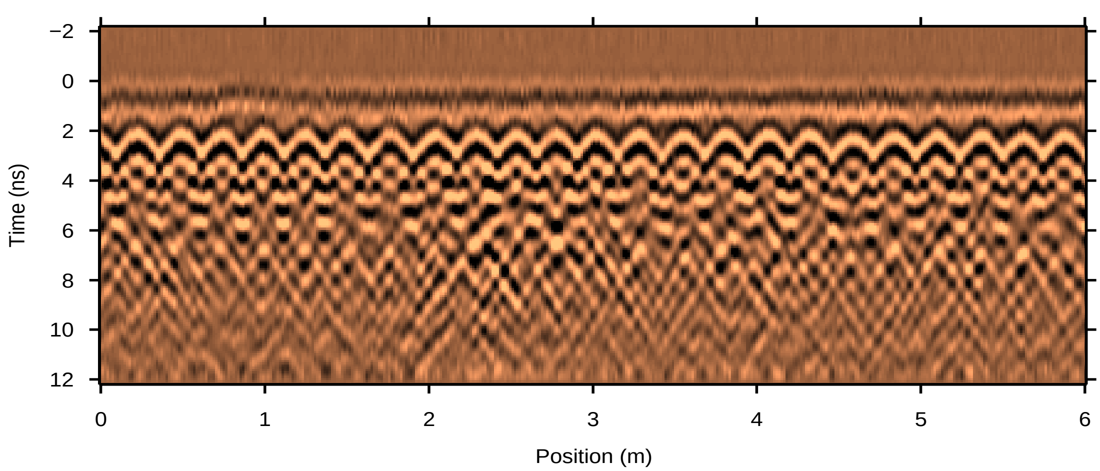

Figure 2: Typical section of bridge deck data without distresses.

Subsurface rebar anomalies identify radar signatures for distresses existing within the deck structure. Significant subsurface (deck) anomalies of interest for monolithic structures typically occur between the PCC deck surface and the top layer of reinforcing steel, with the most significant occurring at the level of the rebar. Deck anomalies are further categorized as low, medium, and high severity. The anomalies are distinguishable by their abnormal radar signatures in comparison with the normal hyperbolic signature for transverse reinforcing steel bars (highlighted on Figure 3).

A low severity classification is consistent with areas in the initial stages of concrete deterioration/delamination at the rebar level. Medium and high severity deck anomaly signatures are indicative of areas exhibiting characteristics for delamination, debonding of concrete overlay from the deck, and/or significant spalling of the upper portion of the deck structure. Deck anomalies were classified in the context of potentially complicated or unusual rebar placement schedules and steel corrosion or pitting. In such cases, sophisticated post-processing techniques were used to interpret the effects of atypically placed longitudinal bars, which can complicate consistent transverse rebar layer condition assessment.

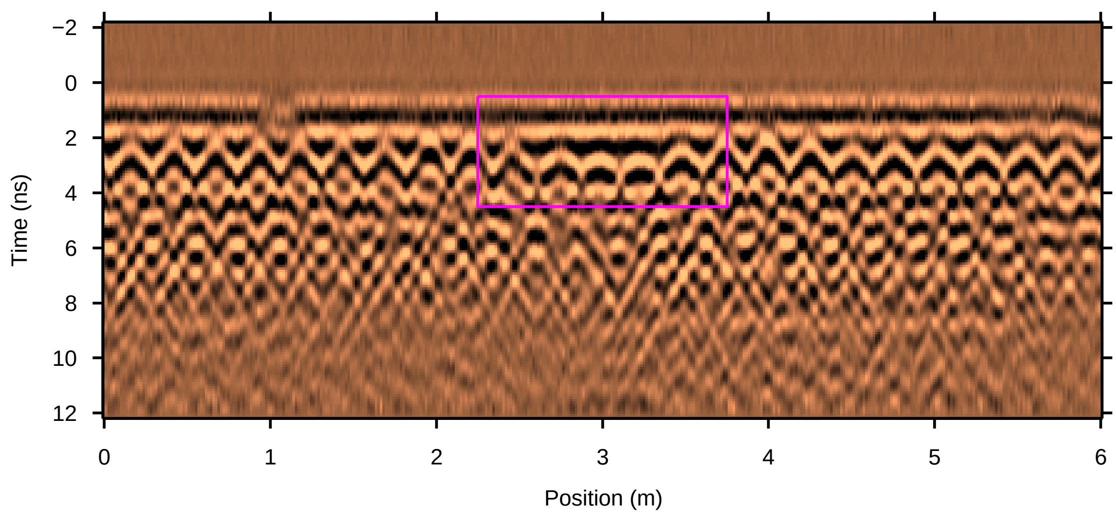

Figure 3: Bridge deck radar data showing an area with rebar distress signatures.

Structural Anomaly Plan Map (interferred parameter) is a measure of the location and a real extent (as well as total affected area and percentage of the total surveyed area) of radar signatures that are considered anomalous by the interpretation software, but which can be attributed to normal bridge deck structural entities such as joints (both construction and expansion joints.) Although anomalous from a radar signature perspective, these are not anomalies from a bridge structure viewpoint.

ROAD RADAR™ SYSTEM SUMMARY OF RESULTS

The longitudinal resolution for all surveys in this study was programmed to acquire a sample every 15 mm. This resolution represents approximately 67 structural samples per metre of survey line. This level of survey completeness and detail, available during the radar data post-processing and interpretation, allows the system to detect and identify structural deviations and anomalies that are far smaller than events detectable through conventional testing (such as coring or audible chain drag.) The effect of this capability is the measurement of structural variations and radar signature anomalies indicative of the current level of structural deterioration.

The origin for the plan maps was established at the northwest curb edge of the inside east bound lane. Plan maps for the TransCanada Bridge are included on Figures 4 to 6.

On July 17, 2008, EBA extracted 16 cores from this bridge deck. Visual observations and chloride tests were conducted on each of these cores. The core locations have been annotated on Figures 4 to 6 for reference. Results of the core examination are reported in the subsequent sections of this paper.

Figure 4 presents the thickness of the concrete cover (total concrete cover above the top mat of rebar, including the steel-fibre reinforced HD concrete overlay) for this bridge. This plan map shows a variable thickness PCC cover ranging from less than 60 mm to more than 140 mm, with an average thickness of 100 mm across the bridge deck. A sample of the radar data with a line marking the location of the rebar interface is included on the plan map. In general, the thickness measurements from the total concrete cover correlated to the 16 extracted cores.

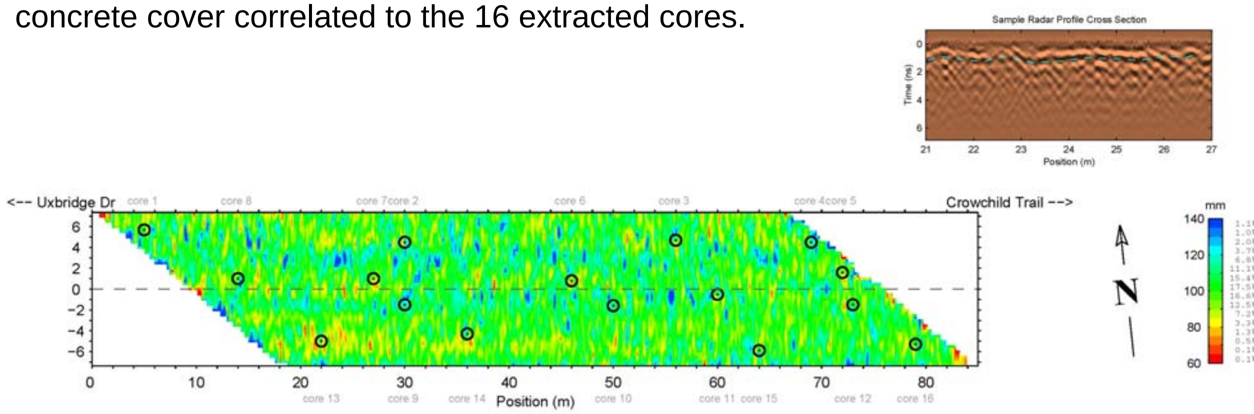

Figure 4: Steel-fibre PCC cover plan map.

Figure 5 presents deck anomalies detected at the surface of the structure. The medium and high severity anomalies on this bridge cover 44.7% of the area of the bridge. These anomalies indicate planar variations in the bridge structure at or above the level of the top mat of reinforcing steel. In most cases, high severity anomalies were identified along the south curb along the eastbound outside lane. The locations of these anomalies are consistent with low-lying drainage areas for the deck. Low and medium severity anomalies identify radar signatures characteristic of areas in the initial stages of distress, such as concrete durability failure or a delamination of overlay concrete.

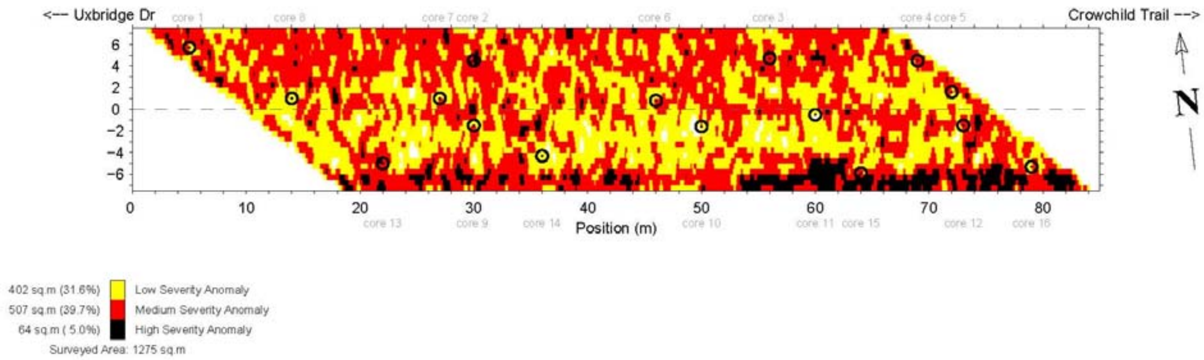

Figure 5: Deck anomaly plan map.

Figure 6 presents the structural anomalies for the structure. The structural anomalies are anomalous from a radar perspective, but are typically associated with normal structural discontinuities (construction or expansion joints) from a bridge structure viewpoint. This plan map identifies the locations of expansion joints along the bridge deck.

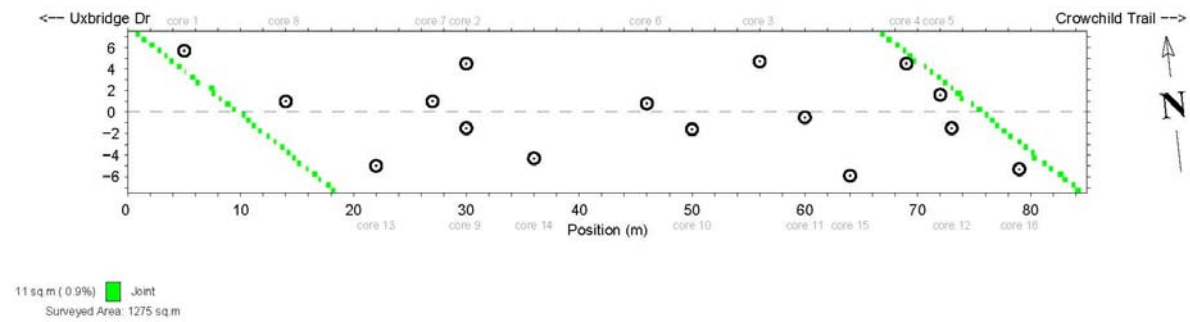

Figure 6: Structural anomaly plan map.

VISUAL OBSERVATION OF CONCRETE CORES

A total of 16 cores were extracted from the bridge deck; four cores from each lane. A summary of the core analysis is presented in Table 1.

Table 1: Core summary.

Station (m)	Offset (m)	Overlay Thickness/ Core Length (mm)	Depth to Rebar (mm)	Surface Condition	Consolidation	Rebar/ Rebar Imprint	Comments
5 Core 1	5.7	125; core broke at overlay/deck bond		Surface hard, light loss of surface	Good		
30 Core 2	4.5	115; core broke at overlay/deck bond	60	Surface hard, light loss of surface	Good	Rebar is dirty	
56 Core 3	4.7	105; core broke at overlay/deck bond	90	Surface hard, light loss of surface	Good	Imprint contains some old concrete	
69 Core 4	4.5	125; core broke at overlay/deck bond	90	Surface hard, light loss of surface	Good	Clean	Sand was located at the bottom of the core
72 Core 5	1.6	100 to 120/ 115 to 170		Surface hard, light loss of surface	Good		Loose material at concrete bond (sand and wood)
46 Core 6	0.8	110; core broke at overlay/deck bond		Surface hard, light loss of surface	Good		
27 Core 7	1	+105; no deck concrete	45, 65, 95	Surface hard, light loss of surface	Good	Rebar is dirty; imprint is clean	No deck concrete encountered
14 Core 8	1	90-95; core broke at overlay/deck bond	90	Surface hard, light loss of surface	Good	Clean	
30 Core 9	-1.5	65 to 100/ 100	40	Surface hard, light loss of surface	Good	Clean	Overlay/deck bond very uneven
50 Core 10	-1.6	75 to 110/ 110	40, 105	Surface hard, light loss of surface	Good	Rebar dirty at 40; rust specs on imprint at 105	
60 Core 11	-0.5	75+	50	Surface hard, light loss of surface	Good	Rebar is dirty and has rust specs	No deck concrete encountered
73 Core 12	-1.5	115 to 150/ 170 to 190	130	Surface hard, light loss of surface	Good, large voids in old concrete	Clean rebar	Bond uneven
22 Core 13	-5	95+	N/A	Surface hard, light loss of surface	Good	N/A	No deck concrete encountered
36 Core 14	-4.3	85+	80	Surface hard, light loss of surface	Good	Clean imprint	
64 Core 15	-5.9	115 to 190	90	Surface hard, light loss of surface	Good	dirty	Sand found at bottom of core
79 Core 16	-5.3	125+	100	Surface hard, light loss of surface	Good	dirty	No deck concrete encountered

The overall condition of the cores ranged from good to fair. However, the bond between the new and old concrete is compromised. Loose material, such as sand and construction debris (including wood), was encountered, and all but one core failed at the bond during coring. Rebar was found to be dirty with some construction debris cemented to its surface.

The drawings for 2001 rehabilitation work indicated galvanized steel to be used for reinforcing. All rebar encountered in the cores indicated that black steel was used. The overlay depth varies depending on the location on the deck. The depth of rebar varied in the concrete overlay from 40 mm to 130 mm.

WATER SOLUBLE CHLORIDE ION DETERMINATION

The 16 cores obtained from the bridge deck were tested for their chloride ion content at different depths. The overall condition of the HD concrete overlay as well as the total depth to the concrete deck surface plays a role in the penetration of chloride ions into the concrete from de-icing salts. Therefore, minimal cracking of the wearing surface as well as a thicker overlay layer is expected to reduce the amount of chloride ions that may actually penetrate to the reinforcing steel.

Water-soluble chloride ion content of hardened concrete, as determined by ASTM C1218 procedure, expresses the amount of chloride ions by mass of concrete. The water-soluble chloride ion contents vary from 0.001% to 0.105% by mass of concrete at rebar depth. It should be noted that the chloride ion concentration generally decreases with an increase in depth towards the rebar. The deck cores 1, 4, 5, 6, 12, and 15 do not follow this pattern. Each one of these cores has high chloride ion concentration at the bottom of the overlay or in the old concrete deck below. This is the result of a high level of chlorides being left in the concrete deck during rehab. High chloride concentration at the bottom of the rehabilitated overlay is due to diffusion in the upward direction from a higher concentration (old concrete deck) to a lower concentration (concrete overlay).

The chloride ion content versus depth is presented in Figure 7. Included in the graphs are suggested threshold limits (Cady, P.D. and Weyers, R.E. (1992): Predicting Service Life of Concrete Bridge Decks Subject to Reinforcement Corrosion, Corrosion Forms and Control for Infrastructure, ASTM STP 1137, American Society for Testing and Materials, Philadelphia). Chloride ion contents present in amounts greater than 0.025% to 0.05% by mass of concrete depassivate the steel and promote corrosion activity.

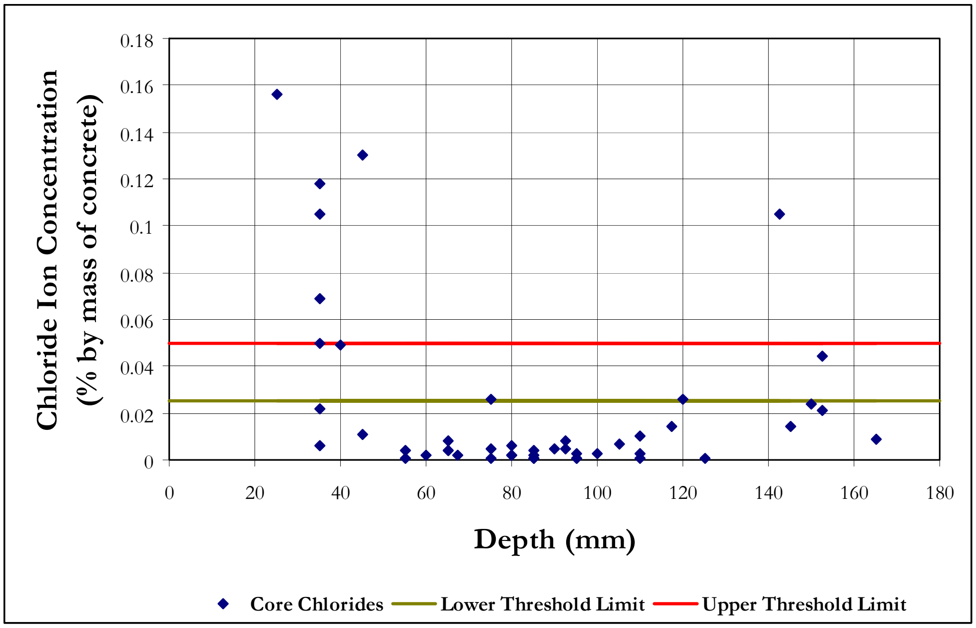

Figure 7: Chloride ion concentrations vs. depth.

The chloride concentrations presented in Figure 7 indicate that the chloride ion content is rising closer to the surface and closer to the overlay/deck bond. There is no good correlation between the concentrations and the depth of concrete mainly due to chlorides left in old concrete and the upward transport of chlorides within the old/new concrete interface. The range of chlorides at about 40 mm below surface is large (0.006% to 0.130%) and can only be explained by concrete uniformity/construction issues at the time of the rehabilitation work.

CARBONATION DETERMINATION

Calcium hydroxide, sodium ions, and potassium ions are found in pores of sound concrete. These basic substances tend to elevate pH levels into the range of 11 to 13. In the concrete carbonation process, the calcium hydroxide is converted to calcium carbonate, resulting in a lowering of the pH in the pore solution. Carbonation does not attack the concrete reinforcements; however, it contributes to lowering the pH level and subsequently altering the passive layer on steel. The presence of the passive layer on steel in a highly alkaline environment prevents the creation of corrosion cells and steel corrosion.

Samples were taken in order to determine the extent of carbonation in the bridge. The results indicate that pH values range from 11.6 to 12.2 in the bridge deck. The pH levels tend to remain constant with an increase in depth. Variations in pH levels are statistically insignificant and the extent of carbonation is minimal, if any.

SERVICE LIFE PREDICTIONS

Corrosion of reinforcing steel is a major cause of concrete deterioration and consequently of loss of serviceability of concrete structures. Penetration of chlorides from de-icing salts contributes to premature deterioration. Service life is defined as the time required for transport processes to raise the chloride content at the depth of the steel to the threshold level (corrosion initiation) and the time for corrosion damage to the end of functional service life (corrosion propagation). Therefore, the rate of chloride transport in concrete will determine the extent of the service life of the concrete structure.

The transport of chloride ions in concrete is described by Fick's Second Law for non-steady conditions, under which the ion concentrations are changing with time. Based on the data from the bridge deck survey, the apparent diffusion coefficient was estimated analytically using the error function equation from the solution to Fick's Second Law of diffusion for each measured point. The constant chloride diffusion coefficient was also determined from the chloride profile by fitting the solution of Fick's Second Law to the measured chloride ion profile in non-linear regression analysis.

The range of depth-dependent diffusion coefficients is large, and there is no evidence that the diffusion coefficient becomes constant at any depth. Largely scattered diffusion coefficients on the top 10 mm depth are influenced by sorption and desorption on the surface, and therefore, the top 10 mm of concrete will not be considered in the life prediction model. The top surface was also affected by tinning and some shallow surface cracking noted during visual inspection. The correlation between the chloride ion diffusion coefficient and depth is presented in Figure 8.

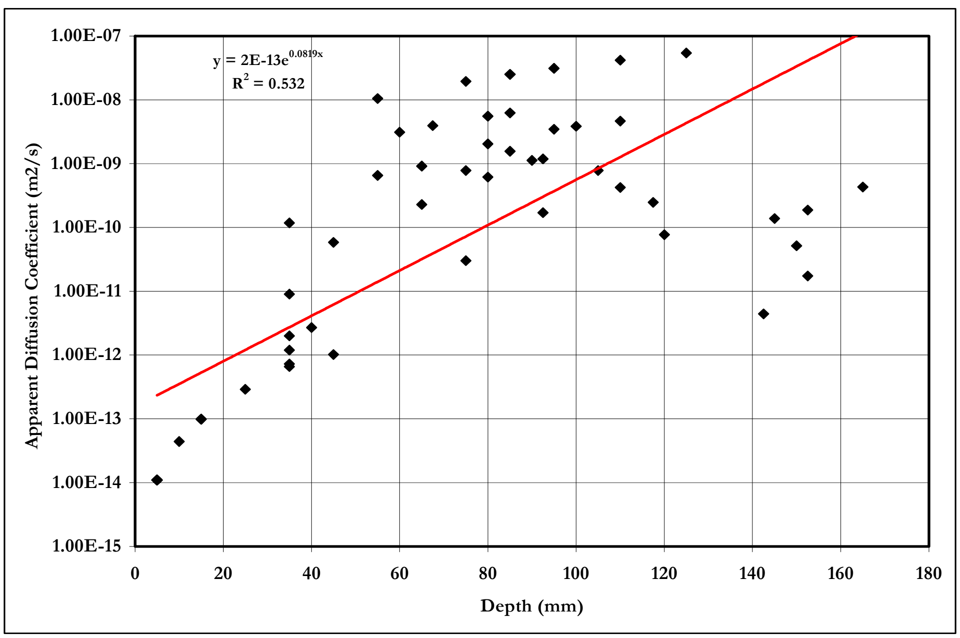

Figure 8: Correlation between diffusion coefficient and depth from surface (diffusion coefficient in log scale).

The coefficient of determination R^2 indicates that over 53% of the samples have the diffusion coefficient dependent on the depth from surface. The outliers are likely due to the sorption and desorption within the top 10 mm, surface cracking and tanning, and possibly something other than diffusion transport mechanisms. In addition, chloride transport patterns on the new/old concrete interface affect the correlation with depth. The wide range of chloride concentrations at the 40 mm depth also contributed to the poor correlation.

The constant diffusion coefficient was calculated from the composite chloride profile and non-linear regression analysis and was determined to be 1.46×10^{-12} m^2/s. Based on this rate of chloride ion transport in concrete, it is determined that the threshold concentration at the depth of the rebar will be reached at about seven years. A threshold limit of 0.2% by mass of cement or 0.03% by mass of concrete (ACI 222 Corrosion of Metals in Concrete) was assumed in the model.

DISCUSSION

The results of the core survey in conjunction with the ROAD RADAR™ survey indicate that in general the quality of concrete in the rehabilitated deck is good. Several issues were identified with the reconstruction work. The reinforcement is placed somewhat randomly with the concrete cover ranging from 40 mm to 130 mm. The condition of the rebar indicates that old rebar was partially dirty in some locations. Galvanized steel was specified for the rehabilitation work; however, black steel was used for the deck reinforcement. Core analysis indicated that the bond between the new overlay and old concrete was not always achieved. There was evidence that the surface of the old concrete was not cleaned properly and loose sand and construction debris was identified on the concrete interfaces. A comparison of high potential for corrosion areas identified in a 1992 survey with the deck anomaly plan map generated by the ROAD RADAR™ survey indicated that the westbound lanes of the bridge with high corrosion potential (1992) remained predominantly within medium severity anomalies in 2008 survey. The east curb of the eastbound lane identified as high potential for corrosion in 1992 remained as a high severity anomaly in the 2008 survey. Total area of medium and high severity anomalies determined in 2008 is about 45% compared to about 40% of high potential for corrosion areas in 1992.

The chloride profiles indicated largely scattered Cl ion concentrations. The scatter is likely due to non-homogenous concrete (often associated with steel-fibre additions), chloride mass transport at the old/new concrete interface, and possibly the influence of the bridge underside being within the splash zone from the traffic on University Drive below.

The life cycle analysis confirmed that the rehabilitation work completed in 2001 extended the life span of the deck by 15 years. This comprehensive study confirms that the ROAD RADAR™ survey combined with a detailed core examination allow for an analysis of rehabilitation work and its impact on prolonging the service life of bridge structures.