Building on Our Growth Opportunities
Miser sur nos opportunités de croissance
May 27 – 30, 2015
REGINA, SK

BEST PRACTICES FOR DESIGN AND CONSTRUCTION OF ALUMINUM STRUCTURAL PLATE STRUCTURES

Anna West, MASc, PEng, Atlantic Industries Limited, Canada
Kevin Williams, MEB, PEng, Atlantic Industries Limited, Canada
Phil Carroll, PEng, Atlantic Industries Limited, Canada

Abstract:
Buried bridges constructed of corrugated aluminum structural plate are a lightweight, economical and environmentally friendly solution to traditional bridges in many applications up to spans of 16 m. Aluminum structural plate resists corrosion, impact and scratches as a result of the spontaneously forming oxide layer. This oxide layer, alumina (Al_2O_3), is dense and adheres well to the aluminum alloy substrate when exposed to oxygen carrying environments, such as water or atmosphere. While aluminum structural plate has been on the market for over 50 years, there are many uncertainties in industry regarding appropriate environments, capabilities and durability. The objective of this paper is to address those uncertainties by building on previously published literature with conducted laboratory testing and field inspections of existing structures. Results of the laboratory testing on aluminum structural plate substantiated previously documented claims of resistance against salt spray and abrasion. These results were again reflected during the field inspections in various environments (soft water, brackish water, applications utilizing deicing salts, low to moderate abrasion, etc.). While not appropriate for all applications, aluminum structural plate is suitable for roadways utilizing deicing agents in winter months, soft water, brackish water and moderately abrasive conditions. The outcome of this paper is a best practices guideline for the use of aluminum structural plate. The guideline quantifies appropriate environments for aluminum structural plate as well as design and installation practices for various applications.

1 INTRODUCTION

Aluminum structural plate is used to construct buried bridge structures with spans up to 13 m. Although aluminum structural plate has been in the marketplace for over 50 years, few best practice guidelines exist in the public domain and little detailed information exists in the Canadian Highway Bridge Design Code.

First developed in 1962, aluminum structural plate is made from aluminum alloy 5052-H141. Aluminum is unique in that it protects itself from aggressive environments with a self-healing oxide when exposed to atmosphere or any oxygen carrying environment. The oxide is dense, resists mars and scratches due to its hardness and adheres well to the underlying aluminum. While guidelines exist for aluminum alloy 3004, used for corrugated metal pipe, there are knowledge gaps related to performance in a given environment, resilience in abrasive conditions and differential metal contact pertaining to fasteners in particular.

The Ministry of Transportation of Ontario (MTO) has recently published an update to their Gravity Pipe Study. In this document, a service life of 75 years for various environmental parameters is presented, referencing previously published works by the State of Florida Department of Transportation (FDOT). This paper builds on the MTO document by providing additional durability information on resistance to abrasion, salt, and contact with different materials such as steel fasteners and concrete.

2 OBJECTIVES

- Address users concerns by adding to existing knowledge through literature review, laboratory testing and evaluating the performance of aluminum buried structures in various environments;

- Recommend environments aluminum structural plate performs well in; and
- Recommend fastener materials for various applications and environments.

3 LITERATURE REVIEW

A literature review was conducted on recommended environmental parameters for the use of aluminum structures published by governing agencies throughout North America. The findings are summarized in Table 1. Note that maximum recommended flow velocities and bedload characteristics are based on no metal loss; flow velocity and / or bedload can be greater if abrasion counter measures are considered (i.e. sacrificial thickness added, abrasion plates, invert paving, etc.).

Table 1: Environmental Parameters and Abrasion Limits

Organization	pH	Resistivity of soil, backfill or effluent Ω-cm	Flow Velocity ft/s (m/s)	Bedload Characteristics & Special Notes
FHWA[1]* & TxDOT[2]*	4 - 9	≥ 500		≥ 25 Ω-cm when backfill is free-draining or saltwater applications
Aluminum Association[3]	4 - 9	≥ 500		Expect good performance in sea water (~ 35 Ω-cm) when surrounding soil is clean
Kaiser Aluminum Corp.[4]*	4 - 9	≥ 1,500	≤ 10 (3.0)	Flows containing large bedload; sandy bedload allows for higher velocities
US Military Specification[3]	4 - 9	--		Even in seawater applications
ODOT[3]*	4.5 - 10	≥ 1,500		
MTO[5]*	4.5 - 9	≥ 200	≤ 5 (1.5)	If buried with free draining backfill material, resistivity is permitted to be as low as 25 Ω-cm; Minor bedloads of sand and gravel
US Army Corps[6,7], Crane Materials Int.[6] & Alcan Inc.[7]	4.5 - 8.5	--		Recommended against use in non-draining clay-organic soils
FDOT[8]*	5 - 9	≥ 1,000	≤ 8 (2.4)	Moderate bedload volumes of sand and gravels; 1.5 in. (3.8 cm) max
Caltrans[9]*	5.5 - 8.5	≥ 1,500	≤ 5 (1.5)	Abrasive channel materials
Highway Design Manual[10]*	5.5 - 8.5	≥ 1,500	≤ 8 (2.4)	Bedloads of sand, silts or clays regardless of volume

Note: *Information pertains to aluminum CMP (AA3004-H32) not aluminum structural plate (AA5052-H141)

3.1 Aluminum Alloys 3004-H32 vs. 5052-H141

Aluminum alloy 3004-H32 (AA3004-H32) is used to manufacture aluminum corrugated metal pipe (CMP) while aluminum alloy 5052-H141 (AA5052-H141) is used to manufacture aluminum structural plate. The majority of information uncovered in the literature review and presented in the above table pertains to aluminum CMP. Industry has traditionally applied these findings to Alloy 5052. While both aluminum alloys, aluminum CMP and aluminum structural plate differ in mechanical properties and chemical composition (Tables 2 and 3):

Table 2: Mechanical Properties of Aluminum Alloys

	Density (g/cm^3)	Hardness (Brinell)	Tensile Strength (MPa)	Yield Strength at 2% Offset (MPa)	Shear Strength (MPa)
AA3004-H32[11]	2.72	52	≥ 190	≥ 145	≥ 120
AA5052-H141[12]	2.68	60	≥ 235	≥ 165	≥ 140

Table 3: Chemical Composition of Aluminum Alloys

	Al	Cr	Cu	Fe	Mg	Mn	Si	Zn
AA3004[13]	95.5 - 98.2	--	≤ 0.25	≤ 0.70	≤ 0.8 - 1.3	≤ 1.0 - 1.5	≤ 0.30	≤ 0.25
AA5052[13]	95.7 - 97.7	0.15 - 0.35	≤ 0.10	≤ 0.40	≤ 2.2 - 2.8	≤ 0.10	≤ 0.25	≤ 0.10

According to Table 2, AA5052-H141 demonstrates mechanical properties superior to AA3004-H32 with regards to hardness and strength. This is due to the chemical composition of the alloys. Aluminum structural plate is a 5xxx series alloy with a greater percentage of magnesium, which increases strength, hardness and workability.[14] Enhanced hardness and strength characteristics allow AA5052-H141 to better resist impact, wear and abrasion. Additionally, the presence of chromium in AA5052 improves the corrosion resistance of the 5xxx series aluminum in comparison to the 3xxx series aluminum alloy. Chromium forms an oxide that is highly resistant to corrosion as well as having high hardness. Chromium acts similarly when it is added to steel to form stainless steel, a highly corrosion resistant group of ferrous material. The addition of magnesium and chromium in AA5052-H141 theoretically improves the performance of aluminum structural plate and industry's practice of applying AA3004 alloy environmental guidelines to AA5052 is in theory, appropriate and conservative. However, laboratory testing and field inspections were conducted to validate the theory.

4 Laboratory Testing

Aluminum alloy 5052 was individually tested for resistance to abrasion and salt spray. Abrasion testing was conducted using a Ministère des Transports du Québec (MTQ) developed testing procedure which has been used internally at MTQ for over 15 years to evaluate abrasion resistance of culvert inverts and asphalt aggregate. During testing, samples are secured at a 45° angle to a jet of water and Ottawa silica sand C-109 (Figure 1), conforming to ASTM C778, at a pressure of 10 MPa and flow of 570 g/min for a duration of four cycles, each cycle lasting 43:20 by computerized controlled steps.[15]

Figure 1: Abrasion testing was completed following internal procedures defined by MTQ using Ottawa silica sand (a) and a controlled abrasion test apparatus (b).

Figure 2 compares the thickness loss of flat 5052 aluminum plate vs. hot dip galvanized (HDG) steel galvanized as per CAN/CSA G164-M92 and ASTM A123 to a thickness of 64 µm (or 915 g/m^2 total both sides outlined in CAN/CSA G401-14 4.5.1). Results indicate the aluminum plate experiences less abrasion loss than galvanized steel. Referencing CSPI Tech. Bulletin Issue 13 02.22.12[16,17], galvanized steel is considered to have appropriate abrasion resistance for water velocities less than 1.5 m/s carrying minor bedloads of sand and gravel. As aluminum experienced less abrasion loss than galvanized steel it is believed aluminum structural plate would be capable of resisting at least this abrasion condition.

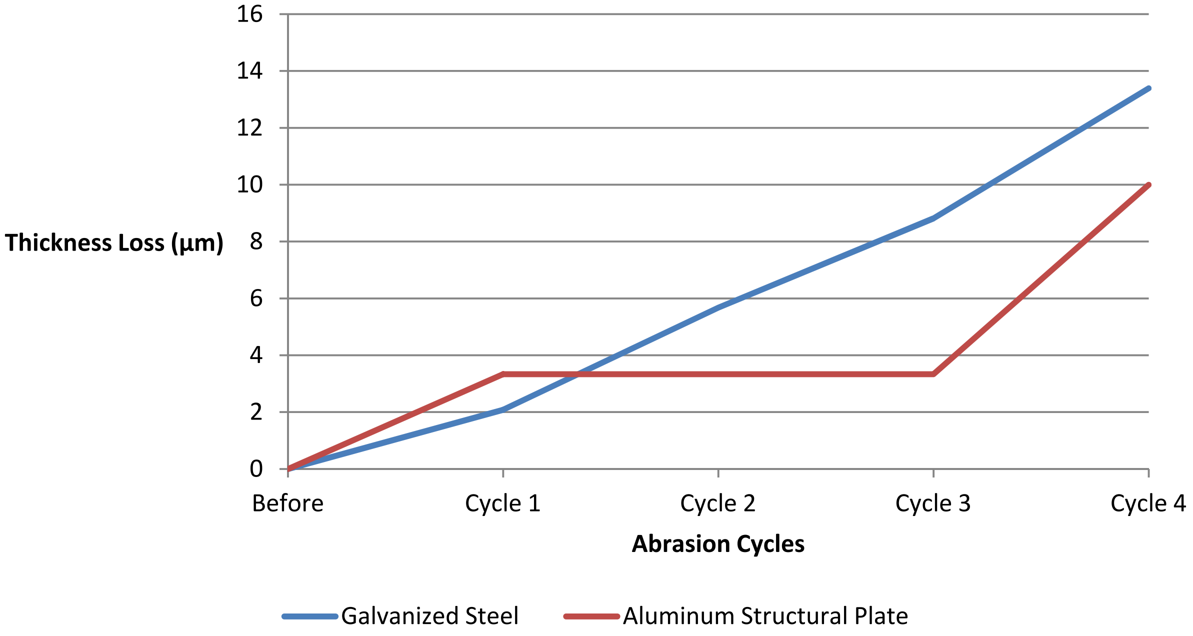


Figure 2: Results of abrasion resistance testing.
Note: Samples were also weighed both prior to and following each abrasion cycle. Mass loss for all samples was less than 1 g.

Salt spray testing was conducted in a chamber following the standard practices of ASTM B117. Samples were exposed to the salt fog at a controlled temperature of 35°C and angle of 15°. Samples were cleaned with deionized water, evaluated and photographed at 500 hour intervals for a total of 3,000 hours of exposure. Upon final removal from the chamber, samples were cleaned with deionized water and a light abrasive to remove scale and corrosion products for accurate measurement of coating degradation.

Figure 3 below depicts images of the samples following 3,000 hours of exposure. The HDG steel suffered extensive corrosion across the entire face of the sample. However, the aluminum sample looks unscathed and in the same condition as it had been prior to entering the salt spray chamber.

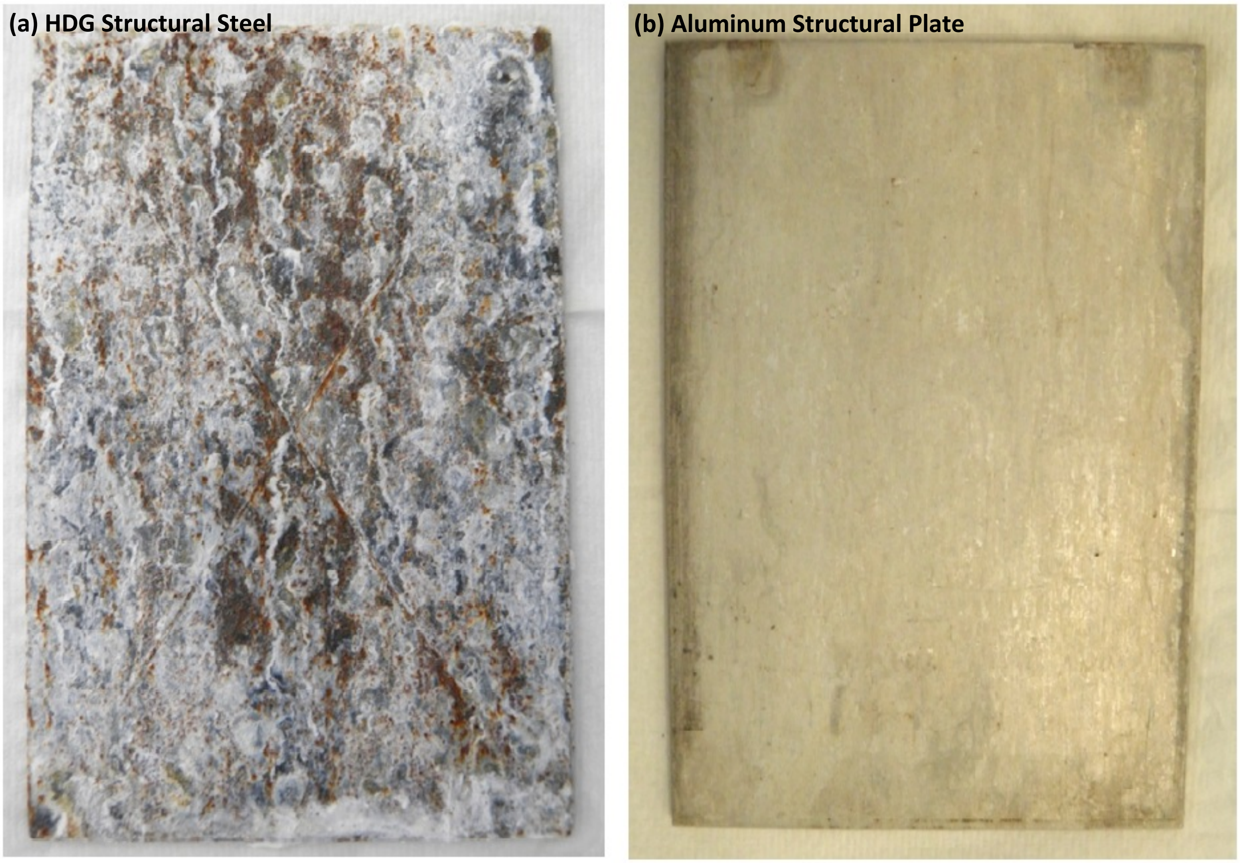


Figure 3: Samples following 3,000 hrs of exposure to salt spray in accordance to ASTM B117: (a) HDG steel and (b) aluminum structural plate.

While test results cannot be exclusively relied upon to relate directly to expected field service, the test results support the chloride and resistivity boundaries stated by various organizations outlined in the literature review. In addition, testing was completed side by side hot-dip galvanized steel, which served as a qualitative benchmark.

5 Field Inspections

Field inspections were completed on aluminum structural plate structures across New Brunswick. Applications varied from steam crossings in residential neighbourhoods, to highway accesses with concrete baffles to facilitate fish passage, to structures transmitting tidal waters under the TransCanada Highway. The age of the structures ranged from 10 to 22 years old with no indications of degradation caused by abrasion or corrosive environments on any of the structures. The structures were rated according to Item 62 – Culverts of the FHWA's *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges (1995)*[18] on a scale of 0 to 9, 9 being the best score (no deficiencies) and 0 being the worst (bridge closed; replacement necessary). All structures were rated with a score of 8 (no noticeable or noteworthy deficiencies which affect the condition of the culvert; insignificant scrape marks caused by drift) or 9, as indicated in Table 4.

Table 4: Summary of Field Inspections

Description	Yr Install	Water Properties					Rating Code
		SO_4^{2-} (ppm)	Cl^- (ppm)	$CaCO_3$ (ppm)	pH	ρ (Ω·cm)	
DAS Crossing w/ Fish Baffles	2003	< 200	< 29	25 - 50	6.82	26,738	9
DAS Crossing w/ Fish Baffles	2004	< 200	< 29	25 - 50	7.13	29,851	9
DAS Box Culvert	2003	< 200	~ 53	~ 120	6.64	5,945	8
DAS Round (with Invert)	1992	200 - 400	> 643	~ 425	7.22	111	8
DAS Arch (not submerged; concrete base)	2010	< 200	~ 0	0 - 25	6.83	34,483	9
DAS Round w/ Fish Baffles	2004	<200	~ 0	0 - 25	6.73	41,494	8

Though some of the structures inspected contained an invert, many of the structures inspected contain concrete fish baffles or are open bottom structures supported on concrete (or aluminum) footings. While structures with inverts are lower cost and useful in high cover applications as they eliminate footings, open bottom structures offer a great deal of security to abrasion as energy is lost on the natural streambed rather than the invert of the crossing; there is negligible abrasion on the aluminum structural plate itself as it is removed from the flowing waters. Additionally, photos taken of various successful aluminum structures are shown in Figure 4.

Figure 4: Aluminum structural plate structures in service.

6 Best Practices

Analyzing the literature review in conjunction with the laboratory testing and field inspections, best practices for design and construction aluminum structural plate structures have been summarized in the following sub-sections under the headers of *Environmental Parameters*, *Service Life*, *Fasteners* and *Contact with Concrete*.

6.1 Environmental Parameters

Aluminum structural plate performs well in soft water as it does in hard. Additionally, aluminum structural plate is not affected by chlorides and sulphates individually, but their combined effect on resistivity. As laboratory testing and in-service performance in a variety of environments was strong, aluminum structural plate is deemed suitable for use in environments summarized in Table 5.

Table 5: Environmental Parameters and Abrasion Limitations for Aluminum

pH	Resistivity (Ω-cm)	Organic Content (%)	Total Hardness ($CaCO_3$ ppm)	Chlorides (Cl^- ppm)	Sulphates (SO_4^{2-} ppm)	Flow Velocity (m/s)	Bed Load Characteristics
4.5 - 9	≥ 500*	≤ 1%	NL	NL	NL	≤ 1.5	Low Abrasive: minor bed loads of sand and gravel

In cases where the resistivity is less than 500 Ω-cm, aluminum can still be used provided particular attention is paid to pH and the backfill material used during construction. Looking back to Table 1, the FHWA, TxDOT, MTO, Aluminum Association all state aluminum can be used to resistivities in the 25 to 35 Ω-cm range, provided “clean” (free-draining gravel with little to no sands) backfill is used. Field inspections of aluminum structures in tidal applications, one with a resistivity of 111 Ω-cm (Table 4) and a second structure shown in Figure 4 (c) (resistivity estimated to be between 25 Ω-cm and 250 Ω cm), demonstrate excellent performance for upwards of 50 years with a durability performance rating of 8.

6.2 Service Life

Service life of aluminum structural plate is dependent on the environment – primarily pH, resistivity and abrasion. FDOT developed an equation (Equation 1) for determining the service life of an aluminum structure based on a first perforation corrosion model:

[1][5,8] $SL = \frac{T_p}{R_{pH} + R_r}$

Where:

SL = service life; time to first perforation (yrs)

T_p = thickness of plate (in.)

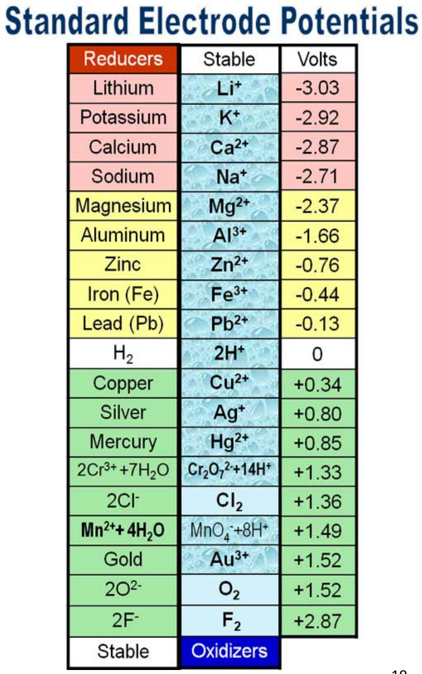
R_{pH} = Corrosion rate for pH (in./yr)

R_r = Corrosion rate for resistivity (in./yr)

Aluminum corrodes by localized pitting. The above equation implies that provided localized corrosion does not penetrate the entire thickness of an aluminum structural plate, the strength and structural integrity of a structure is unaffected.[17] Tables for R_{pH} and R_r values can be found in the publically available FDOT’s *Drainage Culvert Service Life Performance and Estimation (1993)*[8].

6.3 Fasteners

Aluminum structural plate offers superior durability over that of HDG steel in waters with high chloride concentration, brackish and soft water applications. However, HDG fasteners are still acceptable, and in many cases preferred due to superior strength and installation ease, in many of these environments deemed unsuitable for structural steel plate. The justification for this is based on the electrode potentials (Figure 5), rules of galvanic corrosion and area effect.


Standard Electrode Potentials

Reducers	Stable	Volts
Lithium	Li^+	-3.03
Potassium	K^+	-2.92
Calcium	Ca^{2+}	-2.87
Sodium	Na^+	-2.71
Magnesium	Mg^{2+}	-2.37
Aluminum	Al^{3+}	-1.66
Zinc	Zn^{2+}	-0.76
Iron (Fe)	Fe^{3+}	-0.44
Lead (Pb)	Pb^{2+}	-0.13
H_2	$2H^+$	0
Copper	Cu^{2+}	+0.34
Silver	Ag^+	+0.80
Mercury	Hg^{2+}	+0.85
$2Cr^{3+} + 7H_2O$	$Cr_2O_7^{2-} + 14H^+$	+1.33
$2Cl^-$	Cl_2	+1.36
$Mn^{2+} + 4H_2O$	$MnO_4^- + 8H^+$	+1.49
Gold	Au^{3+}	+1.52
$2O^{2-}$	O_2	+1.52
$2F^-$	F_2	+2.87
Stable	Oxidizers	

Figure 5: Standard Electrode Potentials[19]

According to the standard electrode potentials, aluminum will corrode preferentially to zinc (HDG) and zinc preferentially to steel (iron). This same premise governs hot-dip galvanizing steel – a sacrificial zinc coating is added to steel offering galvanic protection by corroding preferentially. While the electrode potential indicates that a reaction will initiate, the surrounding conditions or environment dictate the speed of the reaction. Suitable environments for aluminum structural plate have been recommended in which the rate of reaction, and resulting metal loss, is estimated in section *Service Life*. In the case of HDG fasteners used with aluminum structural plate, the area effect (large surface area of the anode and small surface area of the cathode) lessens the impact of differential metals in environments that extend beyond those recommended for structural steel plate (i.e. non-aggressive waters (sulphates < 600 ppm) and some softer waters).

In summary:

- Hot-dip galvanized fasteners are more desirable than aluminum fasteners in many environments as they offer superior strength and installation benefits;
- Aluminum fasteners may be preferred by the owner to eliminate any dissimilar metal reactions in applications that are particularly damning to HDG steel (i.e. extremely soft water, brackish, or salt water); and
- Austenitic stainless steel is an alternative to aluminum in aggressive applications requiring high strength fasteners.[20]

6.4 Contact with Concrete

Aluminum can be paired with concrete (i.e. collars, fish baffles, footings, etc.), provided none of the following criteria are met or have the potential to be satisfied during the service life of the structure:[21,22]

- Steel or rebar is embedded in the concrete, electrically connected or not;
- Deicing salts are or will be applied in the vicinity;
- Calcium chloride is contained in the concrete mix; or
- Structure is in or near salt water.

If any of the above criteria have been satisfied, aluminum must be isolated (i.e. with a bond breaker) from contact with the concrete by one of the following two means:[5]

- Coat rebar with paint of bitumastic material to isolate the dissimilar metals preventing galvanic corrosion and prolonging the service life of the components; or
- Separate aluminum (including fasteners) from concrete to prevent chemical corrosion using nylon, neoprene or bitumastic material.

Following the above criteria, a typical solution with aluminum structural plate has concrete reinforced with traditional steel rebar using aluminum anchor bolts as fasteners. Connection between concrete collars, headwalls and fish baffles to aluminum structural plate or fasteners (i.e. anchor bolts) requires a bond breaker. However, a bond breaker is not required between base channel and concrete footings as the primary purpose of base channel is non-structural but to hold structures in place during construction. The need for bond breakers will be evaluated as per the project's design engineer.

7 Conclusions

Aluminum is a viable solution for lightweight buried metal structures in many environments, including those that have:

- Low abrasion conditions containing minor bedloads of sand and gravel with flow velocities of 1.5 m/s or less;
- Soft or hard water (no minimum or maximum requirements for $CaCO_3$); and / or
- Low resistivity and / or high soluble salts (chlorides and sulphates) including applications where deicing sales are used on road surfaces in winter months.

The service life for aluminum structural plate structures can be determined using Equation 1, based on the estimated rate of corrosion for both pH and resistivity. To achieve a greater design service life, simply add additional sacrificial thickness to the structural plate. When estimating remaining service life or designing a new structure, it is important to consider both side of the structure; corrosive conditions may be present on the inside, outside or both sides. The calculations are to be adjusted accordingly.

Aluminum structural plate can be paired with concrete without concern for premature degradation, provided a barrier is used to isolate the aluminum in cases where high concentrations of chlorides are present or steel rebar is embedded for additional strength. Isolation methods include nylon, neoprene or bitumastic material placed between the aluminum and concrete as per the direction of the project's design engineer.

8 Acknowledgements

I would like to acknowledge Donald Villeneuve and Marjorie Ramirez with Ministère des Transports du Québec (MTQ) for conducting the in-house abrasion testing as well as resistance to salt spray in accordance with ASTM B117 and Pete Ault for fielding questions via email and phone.

9 References

1. FHWA. 1979. *Corrugated Metal Pipe Durability Guidelines*. U.S. Department of Transportation: Federal Highway Administration. FHWA Technical Advisory: T 5040.12
2. TxDOT. 2004. *Hydraulic Design Manual*. Texas Department of Transportation.
3. The Aluminum Association. 1983. *Aluminum drainage products manual*.
4. Lowe, T.A. & Koepf, A.H. *Corrosion Performance of Aluminum Culvert*. Kaiser Aluminum and Chemical Corporation.

5. Ontario Ministry of Transportation. 2014. *MTO Gravity Pipe Guidelines*. Ministry of Transportation Ontario: Highway Design Office.
6. Brown, B. 2011. *Corrosion Resistance of Aluminum*. Crane Materials International.
7. Mak, A. 2002. *Corrosion of Steel, Aluminum and Copper in Electrical Applications*. Alcan Cable Inc.
8. Cerlanek, W.D. & Powers, R.G. 1993. *Drainage Culvert Service Life Performance and Estimation*. State of Florida Department of Transportation: State Materials Office – Corrosion Research Laboratory.
9. Caltrans. 2012. *Corrosion Guidelines: Version 2.0*. California Department of Transportation: Division of Engineering Services – Materials Engineering and Testing Services: Corrosion and Structural Concrete Field Investigation Branch.
10. 2011. *Highway Design Manual*
11. ASTM. 2007. ASTM B209/B209 M-06: Standard Specification for Aluminum and Aluminum-Alloy Sheet and Plate. *Annual Book of ASTM Standards 2007*. Section Two: Nonferrous Metal Products. Volume 02.02: Aluminum and Magnesium Alloys. ASTM International.
12. ASTM. 2007. ASTM B746/B746 M-02: Standard Specification for Corrugated Aluminum Alloy Structural Plate for Field-Bolted Pipe, Pipe-Arches, and Arches. *Annual Book of ASTM Standards 2007*. Section Two: Nonferrous Metal Products. Volume 02.02: Aluminum and Magnesium Alloys. ASTM International.
13. MatWeb. 2014. Aluminum 5052 / Aluminum 3004. *MatWeb Material Property Data*. Accessed August 8, 2014 from: http://www.matweb.com
14. ESAB. 2014. How and why alloying elements are added to aluminum. *ESAB Knowledge Center*. Accessed August 8, 2014 from: http://www.esabna.com/us/en/education/blog/how-and-why-alloying-elements-are-added-to-aluminum.cfm
15. Ramirez, M., Larouche, P. & Giguere, M. 2013. *Evaluation de la Performance a l'Abrasion de l'Acier Galvanise, de l'Acier Revetu avec un Polymere Thermoplastique et de l'Aluminum*. Ministere des Transports du Quebec: Dossier 13-020.
16. CSPI. 2012. Canadian Performance Guideline for Buried Steel Structures. *Technical Bulletin Issue Thirteen: 02.22.12*. Corrugated Steel Pipe Institute of Canada.
17. Ault, P. 2012. *White Paper: Performance Guideline for Buried Steel Structures*. Corrugated Steel Pipe Institute of Canada.
18. FHWA. 1995. *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges*. U.S. Department of Transportation: Federal Highway Administration – Office of Engineering: Bridge Division. Report No. FHWA-PD-96-001.
19. 2011. Activity Series of Metals (Also called Reactivity Series). *Chemistry Land*. Accessed March 6, 2014 from: http://www.chemistryland.com/CHM130FieldLab/Lab8/Lab8.html
20. CSA Standards. 2014. *Canadian Highway Bridge Design Code: Commentary on CAN/CSA-26-06*.
21. Woods, H. 1966. *Corrosion of Embedded Material Other than Reinforcing Steel*. Portland Cement Association: Research and Development Laboratories.
22. Jana, D. & Tepke, D.G. *Corrosion of Aluminum Metal in Concrete – A Case Study*. Construction Materials Consultants & Sutton-Kennerly & Associates.