Galvanized Rebar:

Lowest Cost of Ownership in Reinforced Concrete Bridges

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Background

The United States initiated a bare pavement policy for roads and highways in the 1950's, which mandated that roads be free of ice and snow during winter months. This policy lead to a significant use of road de-icing salts, namely chlorides, during winter maintenance periods. Since this mandate, states in the Mid-Atlantic, Plains, New England, and Great Lakes regions now average at least 10,000lbs of chloride per lane mile of roadway. The application of significant amounts of road de-icing salts has accelerated deterioration of reinforced concrete bridge structures.

The cause of the concrete degradation is due to the now well-recognized chloride-induced corrosion of the plain (black) reinforcing steel, resulting in deterioration and spalling of the concrete cover. By a process called diffusion, chloride salts on the surface of bridge decks will move through the porous concrete until they reach the depth of the reinforcement. When the concentration of chlorides reaches a critical level, active corrosion of the plain steel rebar will commence.

Region	kg Cl/lane-km	lb Cl/lane-mile
New England (ME, MA, NH, VT)	5,235	18,570
Mid-Atlantic (DE, MD, NJ, NY, VA, WV)	2,791	9,900
Great Lakes (IL, IN, MI, OH, WI)	3,218	11,420
Plains (IA, MN, MO, NE, OK, SD)	2,806	9,953
Mountains and West (AK, CA, ID, NV, NM)	474	1,680

Table I. Average Cl Usage for Deicing in Regions of the USA, from TRB, Special Report 235, Highway Deicing, 1991

The diffusion of chlorides in concrete is a complex process. Factors that influence the movement of chlorides include the type and properties of the concrete. Also important are the surface chloride concentrations, depth of concrete cover over the rebar, and the chloride concentration levels. As well, physical deformities in the concrete, such as cracks, will significantly accelerate the movement of chlorides through the concrete to the rebar, where corrosion can start.

One way to mitigate the onset of corrosion is to use corrosion-resistant rebar rather than plain black steel. Common choices are fusion bonded epoxy, galvanized steel, and stainless steel rebar. Each type of rebar has benefits and limitations, from corrosion resistance to cost. An optimum mix of the properties of the concrete and the type of reinforcement is needed to reduce the impact of chloride-induced corrosion and provide the lowest cost of ownership for reinforced concrete bridges.

To study the impact of reinforcing steel deterioration on total cost of ownership of a reinforced concrete bridge, computer modeling using a Monte Carlo probability analysis was performed based on the de-icing salt use and condition of the reinforced concrete bridge decks from the State of Virginia. Data from 27 bridges were used to develop models for chloride induced corrosion initiation and propagation. Diffusion models that incorporate Monte Carlo calculations are better able to simulate the probabilistic nature of the input variables, as the input parameters are random variables with their own statistical distribution. Using known inputs from existing bridges limited the number of variables.

The diffusion of chloride into concrete decks and its effects on service life were calculated for epoxy-coated rebar, batch galvanized steel rebar, and 316LN stainless steel rebar. The total present cost (TPC) and life-cycle cost (LCC) figures show that galvanized steel rebar provides the most cost-effective protection for reinforced bridge decks with a 100-year life.

The state of Virginia is composed of six climactic zones. The amount of road de-icing salt used varies considerably in the state from zone to zone, from a low of about 800 lbs per lane mile in the Tidewater zone to a high of 15,500 lbs per lane mile in the Northern zone. Road de-icing salt usage in the Northern zone compares with other heavy salt using states in the Mid-Atlantic, Great Lakes, and Northeast regions.

Climate Zone	kg Cl per lane-km (lb-Cl per lane-mile)
Southern Mountain (SM)	688 (2,441)
Central Mountain (CM)	671 (2,381)
Western Piedmont (WP)	220 (781)
Northern (N)	4,369 (15,501)
Eastern Piedmont (EP)	530 (1,880)
Tidewater (TW)	225 (798)

Table II. Average Chloride Usage in the Six Virginia Climate Zones, Three-Year Average, from Virginia Department of Transportation

The modeling parameters, such as chloride loading, were obtained directly from VDOT, while the properties of the concrete used for bridge deck construction, the depth of concrete cover, and chloride concentration distributions were measured directly from core samples obtained in 2005 from bridges representative of the construction era of 1984 to 1991.

Therefore, the modeling parameters for bridge construction were constant. The variable parameters were the salt loading by climate zone, the initial surface crack densities of the deck area, and the type of rebar.

Pictured: The Varina-Enon Bridge, Henrico, Virginia. Photo courtesy of Virginia Department of Transportation.

Analysis

The computer simulation for each of the six climate zones determined the time needed for chlorides to build up to the critical corrosion threshold to cause corrosion of the rebar. The service life of the bridge was then calculated based on the speed of corrosion of the rebar and the resulting degradation of the concrete. From the service life calculations the total cost of ownership was determined for an 8,000 sq ft bridge deck [744 m2].

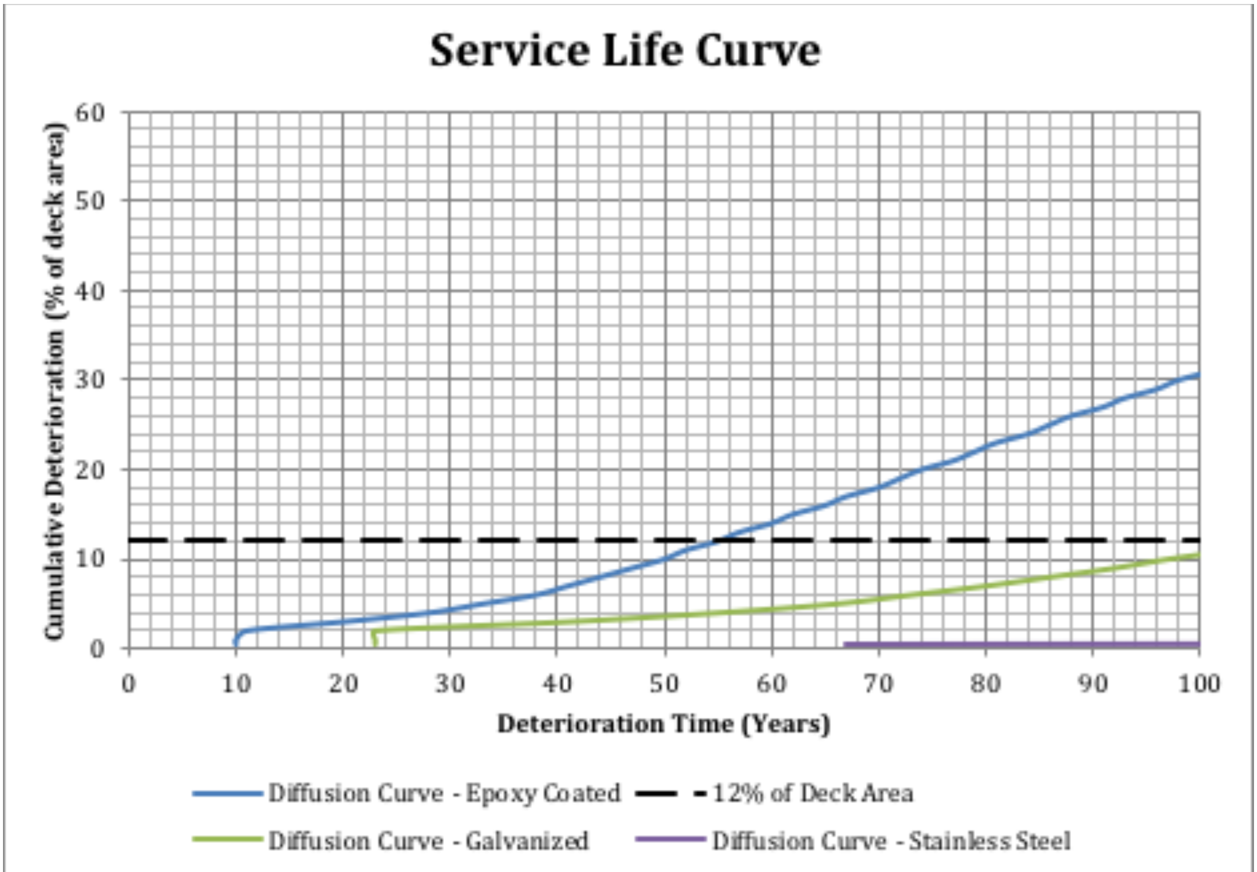
This Monte Carlo simulation determined the most probable results by considering thousands of possible input scenarios and their outcomes. The other key variables that were included in this study were:

- The depth of concrete cover on the roadway;
- The speed of chloride diffusion into the concrete;
- The chloride concentration threshold to initiate corrosion in each of the three types of rebars.

Results

The most aggressive conditions were found in the Northern zone, which had the highest salt loading. Considering the initial condition of 6% surface crack density, the critical corrosion threshold for corrosion is reached almost immediately with epoxy coated rebar, while for galvanized steel rebar the corrosion threshold takes 15 years. Corrosion initiation only begins in the stainless steel rebar after 50 years in the Northern climate zone.

A bridge in Virginia is considered to have reached its maximum service life when 12% of the surface needs patching or repairing. The calculated service life curve for the Northern zone, again for a bridge deck where 6% of the surface area had initial surface cracks, showed that deck replacement is required after 54 years for the epoxy-coated rebar, 109 years for the galvanized rebar, and outside of the 100-year specified life for the stainless steel rebar.



Bridge maintenance is undertaken when 2% of the bridge surface area needs patching or repairing. As an example for the epoxy-coated bar, corrosion initiation with a deck with 6% initial surface cracks begins in the first year. The surface damage of the deck increases to a total of 2% after 11 years, after which the first deck patching will be required. Additional re-patching is required until the end of service life when the deck requires replacement after 54 years.

For galvanized steel, however, 15 years are needed before corrosion of the steel begins so that a 2% damaged area on the surface of the deck is not reached until 23 years. For stainless steel, the time to corrosion initiation is well beyond the design life of the deck, but because of the very high chloride concentration, corrosion begins quickly; however, the time for any repairs is also well beyond the 100-year design life of the bridge.

Initial Damage and Maintenance Patching	**Epoxy-Coated**	**Galvanized**	**316L**
No Surface Cracking	**Years When Patching Required**		
2% patch	33	63	>100
4% patch	39	76	
8% patch	48	95	
12%, End of Service Life	59	>100	
3% Surface Cracking	**Years When Patching Required**		
2% patch	29	55	>100
4% patch	37	71	
8% patch	49	96	
12%, End of Service Life	59	>100	
6% Surface Cracking	**Years When Patching Required**		
2% patch	11	23	>100
4% patch	28	55	
8% patch	44	86	
12%, End of Service Life	54	>100	
12% Surface Cracking	**Years When Patching Required**		
2% patch	11	23	>100
4% patch	15	31	
8% patch	30	62	
12%, End of Service Life	46	89	

Table III. Corrosion performance service life of Virginia bridge decks in the Northern Climate Zones for 0%, 3%, 6%, and 12% initial surface cracking conditions using epoxy-coated, hot dip galvanized or stainless rebar.

Pricing and costs

The cost of rebar, the material purchase, and the cost of patching for maintenance were then used to determine the total cost of ownership. User costs and traffic control costs were not included because these can vary with individual construction sites. However, an estimate of uniform traffic control cost is included in the patching and overlay prices. The prices used in this study are from 2016.

Using the example of the most severe condition, the Northern zone, the cash flow values for cost of ownership of a bridge with an initial 6% surface cracking density show epoxy-coated rebar to be the most expensive. The significant repairs required drive the high cost of ownership for the epoxy-coated rebar.

The reduced maintenance and upkeep costs associated with galvanized rebar equate it with the lowest cost of ownership. Stainless steel rebar has no maintenance costs in the model, but the high initial cost of the rebar makes it the most expensive option.

Percent Deterioration	At Year	Activity	Cost $	Factor 3.5%	LCC $
Epoxy Coated Rebar, Initial Construction					239,670
2%	11	Patch	9,120	0.6849	6,250
4%	28	Patch	9,120	0.3816	3,480
8%	44	Patch	18,240	0.2201	4,010
12%	54	Overlay	145,600	0.156	22,720
2%	64	Patch	9,120	0.1106	1,010
4%	66	Patch	9,120	0.1032	940
6%	68	Patch	9,120	0.0963	880
8%	70	Patch	9,120	0.0899	820
10%	72	Patch	9,120	0.084	770
12%	74	Patch	9,120	0.0784	720
Total Costs			467,350		281,270
Galvanized Rebar, Initial Construction					243,220
2%	23	Patch	9,120	0.4533	4,130
4%	55	Patch	9,120	0.1508	1,370
6%	75	Patch	9,120	0.0757	690
Total Costs			270,580		249,410
Class III Stainless Rebar, Initial Construction			331,080		331,080

Table IV. Cash Flow Requirements, Northern Zone, 6% deck initial surface cracking. No inflation is assumed, and a real interest rate of 3.5% is used to calculate present value costs.

The epoxy-coated rebar deck requires significantly more patching than the galvanized steel deck and also requires an overlay after 54 years of service. The galvanized steel rebar deck only requires patching during the 100-year life. The stainless steel rebar deck will be maintenance-free beyond 100 years. The total cost and life cycle analysis for the 3, 6 and 12% deck surface cracking initial levels for the Northern, Southern Mountain and Tidewater climate zones are shown in Tables V-VII.

Rebar Type	Present Cost $	Difference		LCC $	Difference	
		$	%		$	%
3% Deck Initial Surface Cracking						
Epoxy-Coated Rebar	458,230	--	--	271,170	--	--
Galvanized Rebar	261,684	-196,500	-43	245,400	-25,770	-10
316L Stainless Rebar	331,080	-127,150	-28	331,080	+59,910	+22
6% Deck Initial Surface Cracking						
Epoxy-Coated Rebar	467,350	--	--	281,270	--	--
Galvanized Rebar	270,580	-196,890	-42	249,410	-31,860	-11
316L Stainless Rebar	331,080	-136,390	-29	331,080	+49,810	+17
12% Deck Initial Surface Cracking						
Epoxy-Coated Rebar	502,300	--	--	296,920	--	--
Galvanized Rebar	288,820	-213,480	-42	253,340	-43,580	-15
316L Stainless Rebar	331,080	-171,220	-34	331,080	+34,160	+12

Table V. Present (Non-Discounted) Cost and Life Cycle Cost (LCC) for Northern climate zone.

Rebar Type	Present Cost $	Difference		LCC $	Difference	
		$	%		$	%
3% Deck Initial Surface Cracking						
Epoxy-Coated Rebar	294,390	--	--	248,080	--	--
Galvanized Rebar	252,340	-42,050	-14	244,095	-3,980	-2
316L Stainless Rebar	331,080	+36,690	+12	331,080	+83,000	+33
6% Deck Initial Surface Cracking						
Epoxy-Coated Rebar	312,630	--	--	258,180	--	--
Galvanized Rebar	263,740	-48,890	-16	248,100	-10,080	-4
316L Stainless Rebar	331,080	+18,450	+6	331,080	+72,900	+28
12% Deck Initial Surface Cracking						
Epoxy-Coated Rebar	476,480	--	--	287,330	--	--
Galvanized Rebar	275,140	-201,340	-42	249,240	-38,090	-13
316L Stainless Rebar	331,080	-145,400	-30	331,080	+47,750	+15

Table VI. Present (Non-Discounted) Cost and Life Cycle Cost (LCC) for Southern Mountain climate zone.

Rebar Type	Present Cost $	Difference		LCC $	Difference	
		$	%		$	%
3% Deck Initial Surface Cracking						
Epoxy-Coated Rebar	267,030	--	--	244,620	--	--
Galvanized Rebar	243,220	-23,810	-9	243,220	-1,440	-1
316L Stainless Rebar	331,080	+64,050	+24	331,080	+85,720	+35
6% Deck Initial Surface Cracking						
Epoxy-Coated Rebar	276,150	--	--	258,180	--	--
Galvanized Rebar	252,340	-23,810	-9	246,360	-4,190	-2
316L Stainless Rebar	331,080	+54,930	+20	331,080	+80,530	+32
12% Deck Initial Surface Cracking						
Epoxy-Coated Rebar	294,390	--	--	257,330	--	--
Galvanized Rebar	261,570	-32,820	-11	248,790	-8,540	-3
316L Stainless Rebar	331,080	+36,690	+12	331,080	+73,750	+29

Table VII. Present (Non-Discounted) Cost and Life Cycle Cost (LCC) for Tidewater climate zone.

Conclusions

For the bridge type considered in this study, with low-permeability concrete, a design cover depth of 2.5 inches (6.4 centimeters) and the ranges of chloride surface concentrations, hot dip galvanized reinforcing steel has the lowest cost of ownership for all combinations of deck cracking and environmental climate zones. The stainless steel is the most expensive choice based on life-cycle costs but does present a maintenance-free condition for service lives greater than the design life of a 100-year bridge. Epoxy-coated steel requires the greatest amount of maintenance over this service period and always has a higher life cycle cost (total cost of ownership) than galvanized rebar.

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