FHWA/FDOT Corrosion-Resistant Reinforcing Bar Seminar
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SERVICE LIFE PROJECTION FOR METALLIC CORROSION RESISTANT REINFORCEMENTS – The Role of Chloride Concentration Threshold

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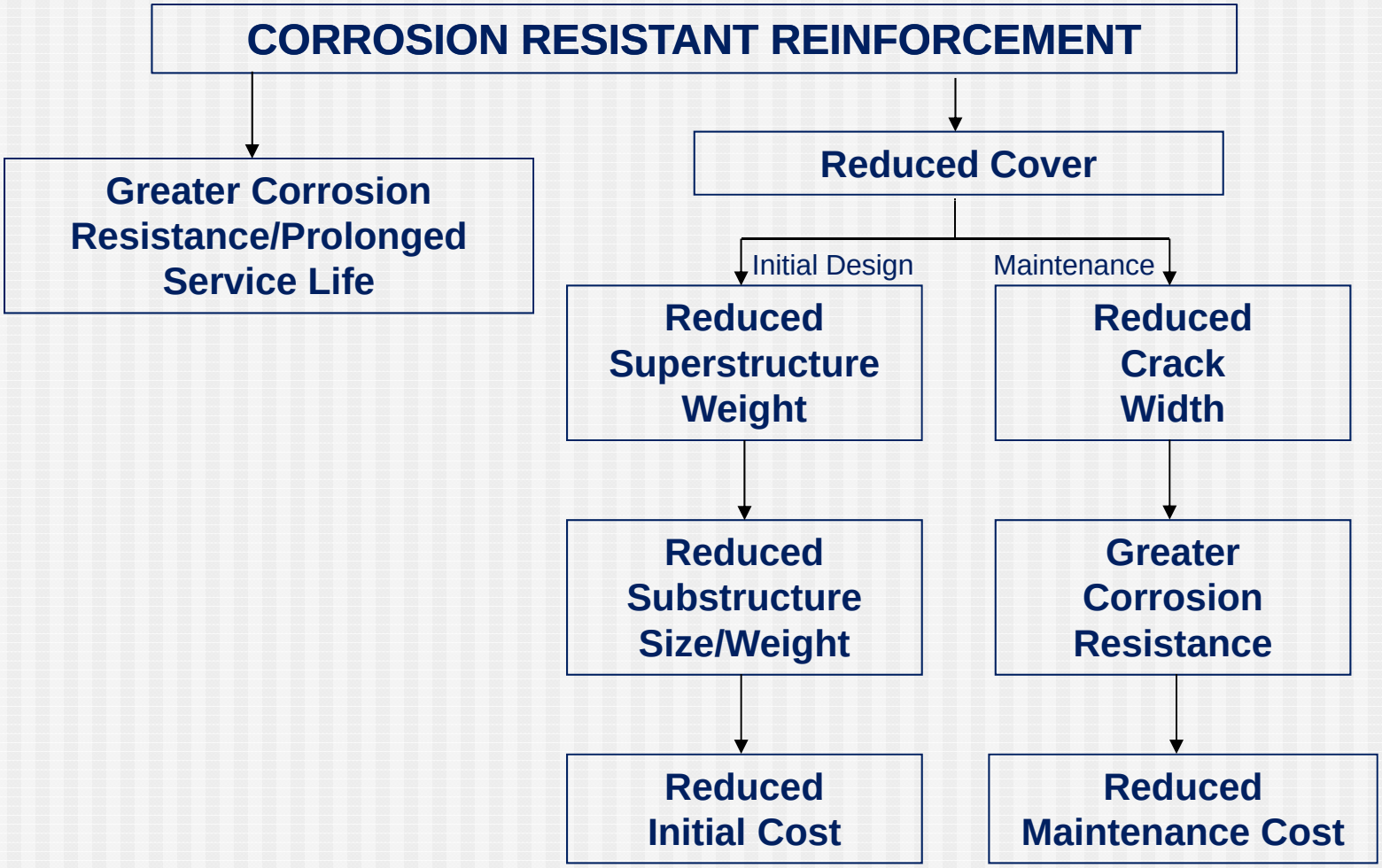
Background

It is generally recognized that reinforcing steel in concrete remains passive until a critical [Cl^-], C_T, is achieved at the steel depth. Consequently, determination of C_T and means by which this parameter can be enhanced are important considerations in alloy development, design, and materials selection for infrastructure systems and components.

Largely because of disclosure of premature corrosion of epoxy-coated reinforcement in Florida Key's bridges in the mid-1980's, increased attention has focused during the past 20-plus years upon utility of corrosion resistant reinforcements (CRR), stainless steels in particular.

A complicating aspect of selecting CRRs is the relatively large number of alloys that are available. However, the fact that there are multiple choices facilitates selection of the least expensive alloy that will provide a relatively maintenance free service life. This requires though that an accurate methodology for performing comparisons be available.

Perspective Approach to CRR Utility – The Potential Utility of CRRs for Concrete Construction Extends Beyond Corrosion Resistance Per Se



Objective

The objective of this presentation is to describe experiments and report results for concrete specimens with select CRR that were exposed to chlorides as part of a research program sponsored jointly by the FHWA and FDOT.

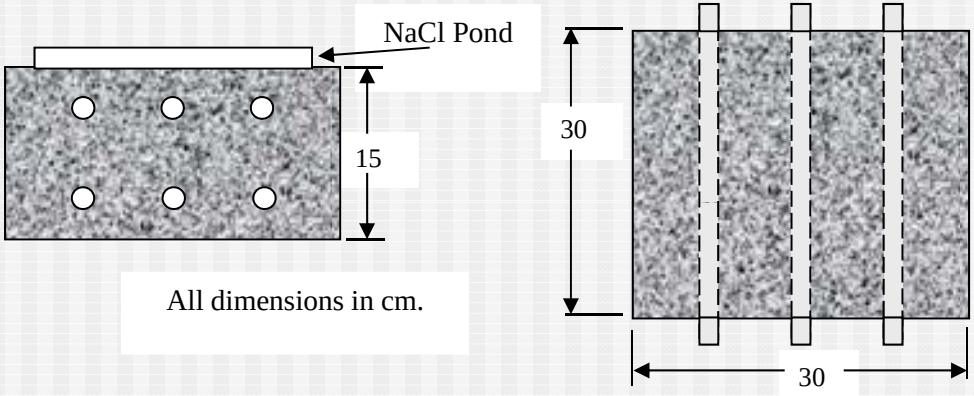
Particularly relevant are, first, development of threshold chloride concentration data for CRR and, second, application of an analytical methodology whereby service life can be projected.

Reinforcements

Designation./Spec.	Common Design.	As-Rec'd. Cond.	PREN
UNS-S31603	Type 316LSS	Pickled	26.4
UNS-S30400	Type 304SS	Pickled	19.6
UNS-S32304	Type 2304SS	Pickled	24.9
ASTM A955-98	Type 2101LDXSS	As-Rolled	25.1
ASTM A1035	MMFX 2	As-Rolled	9.4
AASHTO MP 13M/MP 13-04	Nouvinox	Pickled	-
	SMI	Pickled	-
UNS-S41003	Type 3Cr12SS	Pickled	12
ASTM A615	Black Bar	As-Rolled	0.3

PREN (Pitting Resistance Equivalent Number) where PREN = %Cr + 3.3·%Mo + 16·%N

Reinforced Concrete Slab Specimens



Specimens and Experimental Procedure

Triplicate specimens for each type of reinforcement.

One week wet – one week dry cyclic ponding with 15 wt% NaCl.

Potential and macro-cell current monitoring.

The three top bars were connected through a 10 Ω resistor to the three bottom bars and voltage drop periodically measured. Upon detection of corrosion activity, the top bars were disconnected and individually reconnected to the bottom bars and potential and voltage drop remeasured. By this, the top bar that was active was identified and was disconnected from the bottom bars for the remainder of the exposure.

Categorization of Reinforcements According to Performance

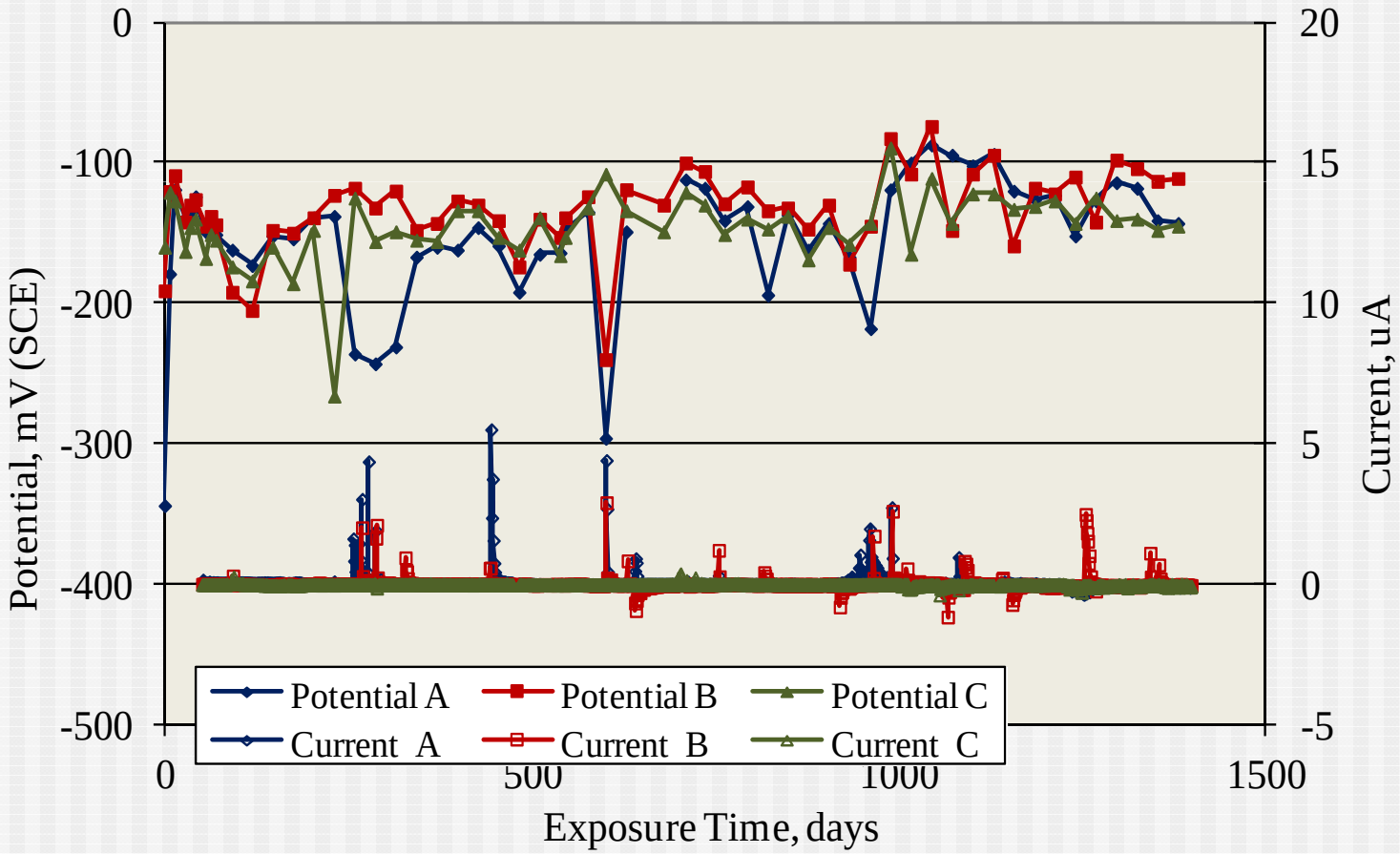
1. **Black Bar (reference for comparison).**
2. **Improved Performance Reinforcements (corrosion initiated but at times greater than for BB).**

   Stainless steels 3Cr12 and 2101 and A1035 (MMFX2)

3. **High Performance Reinforcements (no sustained corrosion initiation).**

   Stainless steels 304, 316, 2304, and stainless steel clad bars

Potential and Macro-Cell Current Response of 316L SS Reinforced Specimens

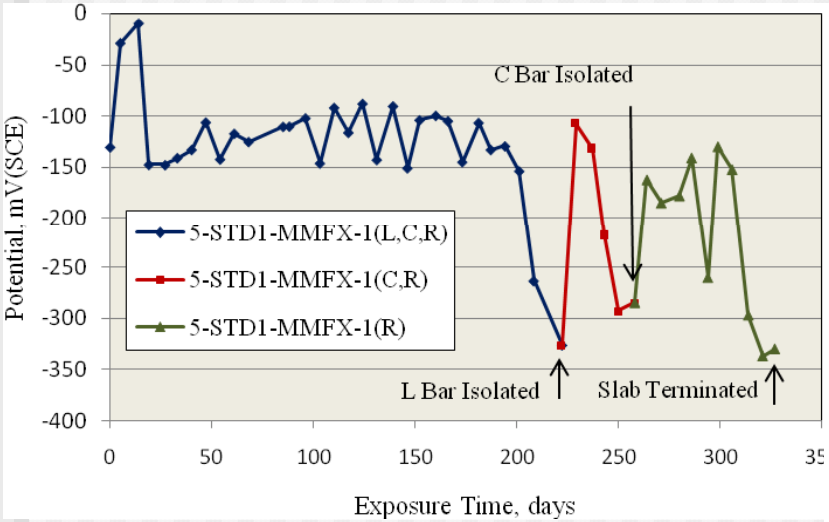


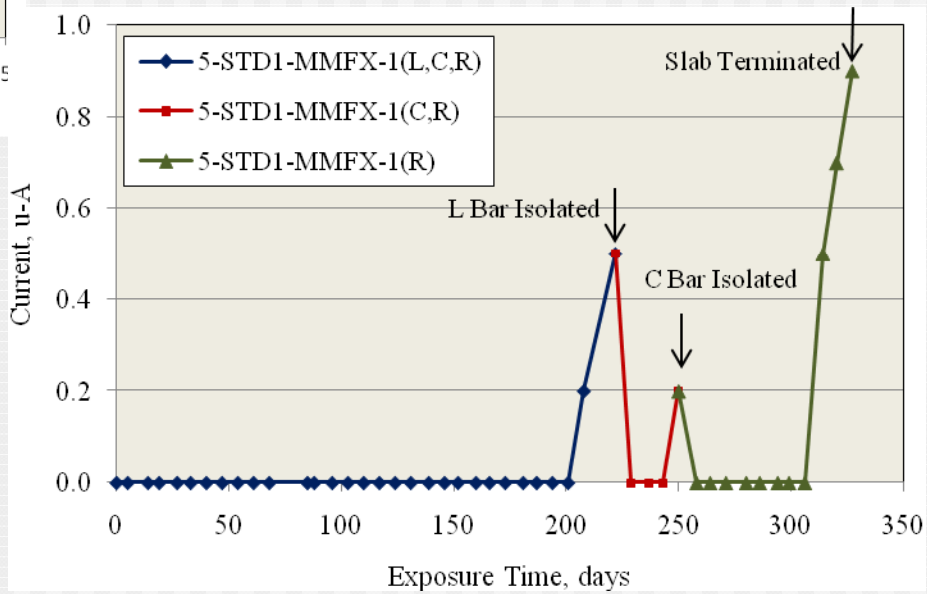
Chloride Concentration for High Performance Reinforcements

Reinforcement Type	Exposure Time, days	$[Cl^-]$, kg/m^3
316	1,726	13.9
304	440	10.2
2304	929	12.5
Stelax	1,726	13.9
SMI	944	12.5

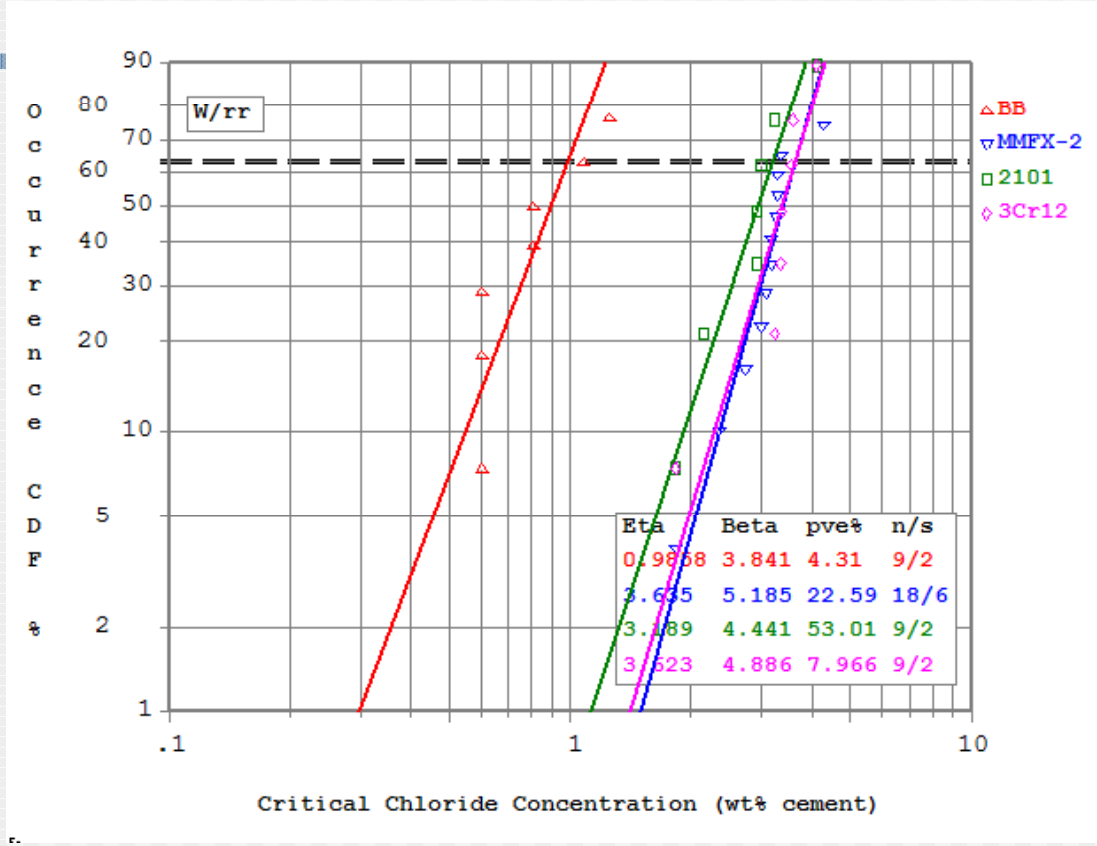
The indicated $[Cl^-]$ was measured at the bar depth at the indicated times with no corrosion being noted for any of these CRR. Consequently, C_T exceeded the listed chloride concentrations.

Potential and Current Acquisition for Specimens with Improved Performance Reinforcements





Cumulative Distribution Function Plot of C_T



Percent Active	BB	2101	MMFX-2	3Cr12	C_T(alloy)/C_T(BB)		
					2101	MMFX-2	3Cr12
10	0.43	1.73	2.10	2.34	4.02	4.88	5.44
20	0.58	2.12	2.56	2.69	3.66	4.41	4.64
50	0.89	2.88	3.46	3.31	3.24	3.89	3.72

An Analytical Method for Projecting Time-to-Corrosion Initiation, T_i

Modeling techniques to project T_i are commonly based on a Cl^- diffusion analysis employing a situation specific solution to Fick's second law, normally one-dimensional:

$$C(x,T) = C_s \cdot \left(1 - ERF\left(\frac{x}{2 \cdot \sqrt{D \cdot T}}\right)\right)$$

$$C_T = C_s \cdot \left(1 - ERF\left(\frac{x}{2 \cdot \sqrt{D \cdot T_i}}\right)\right)$$

Methodology

An equation attributed to Sagüés was modified to accommodate all four variables (D, C_s, x, and C_T) as distributed. Thus,

$$\frac{dN(T)}{N} = \frac{1}{\sum_i N_i} \sum_i N_i \int_{D_{li}}^{D_{hi}} \int_{Cs_{li}}^{Cs_{hi}} \int_{C_{T_{li}}}^{C_{T_{hi}}} P_{cumxi} \left[2 \cdot \sqrt{D \cdot (T - T_p)} \cdot ERF^{-1}\left(1 - \frac{C_T}{C_s}\right) \right]$$

$$P_{C_{Ti}}(C_T) \cdot P_{Csi}(C_s) \cdot P_{Di}(D) dC_T dC_s dD$$

The evolution of corrosion initiation $dN(T_i)/N$ was solved for by 1) setting $T_p = 0$, whereby T becomes T_i, 2) assuming various mean and standard deviation values for D, C_s, x, and C_T and that these are normally distributed, and 3) numerically integrating the above expression with a) limits $\pm 3\sigma$ from the mean and b) the condition that $C_s > C_T$. By doing this for a range of T, a CDF plot of T_i was constructed.

Methodology (continued)

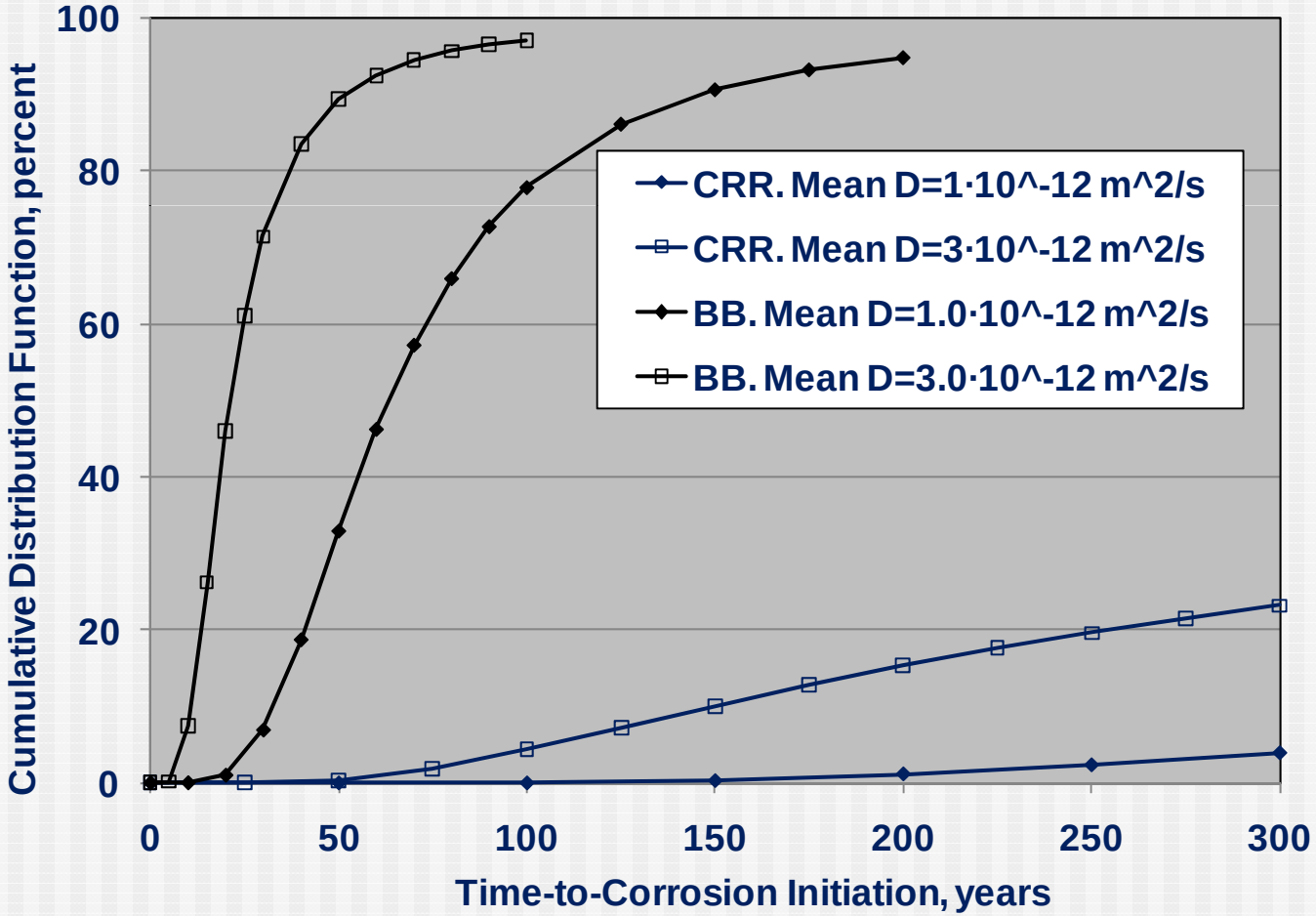
The previous governing equation was employed to evaluate the cumulative distribution behavior of T_i for CRR that were classified as intermediate performers and for which $\mu(C_T)$ and $\sigma(C_T)$ data are available relative to black bar (BB).

According to one study involving UNS-S41003 (3Cr12) and three independent investigations using ASTM A1035 (MMFX2), $\mu(C_T)$ for these alloys is conservatively ~4x that for BB.

Analysis Parameters

Parameter	Value
μ(D), m^2/s	$3.0 \cdot 10^{-12}/1.0 \cdot 10^{-12}$
σ(D), m^2/s	$1.0 \cdot 10^{-12}/0.3 \cdot 10^{-12}$
$\mu(C_s)$, wt% cem	4.00
$\sigma(C_s)$, wt% cem	1.00
μ(x), cm	7.50
σ(x), cm	0.75
BB: $\mu(C_T)$, wt% cem	0.896
BB: $\sigma(C_T)$, wt% cem	0.260
CRR: $\mu(C_T)$, wt% cem	3.580
CRR: $\sigma(C_T)$, wt% cem	0.346

BB and CRR CDF(T_i) Comparison at Two μ(D) Values

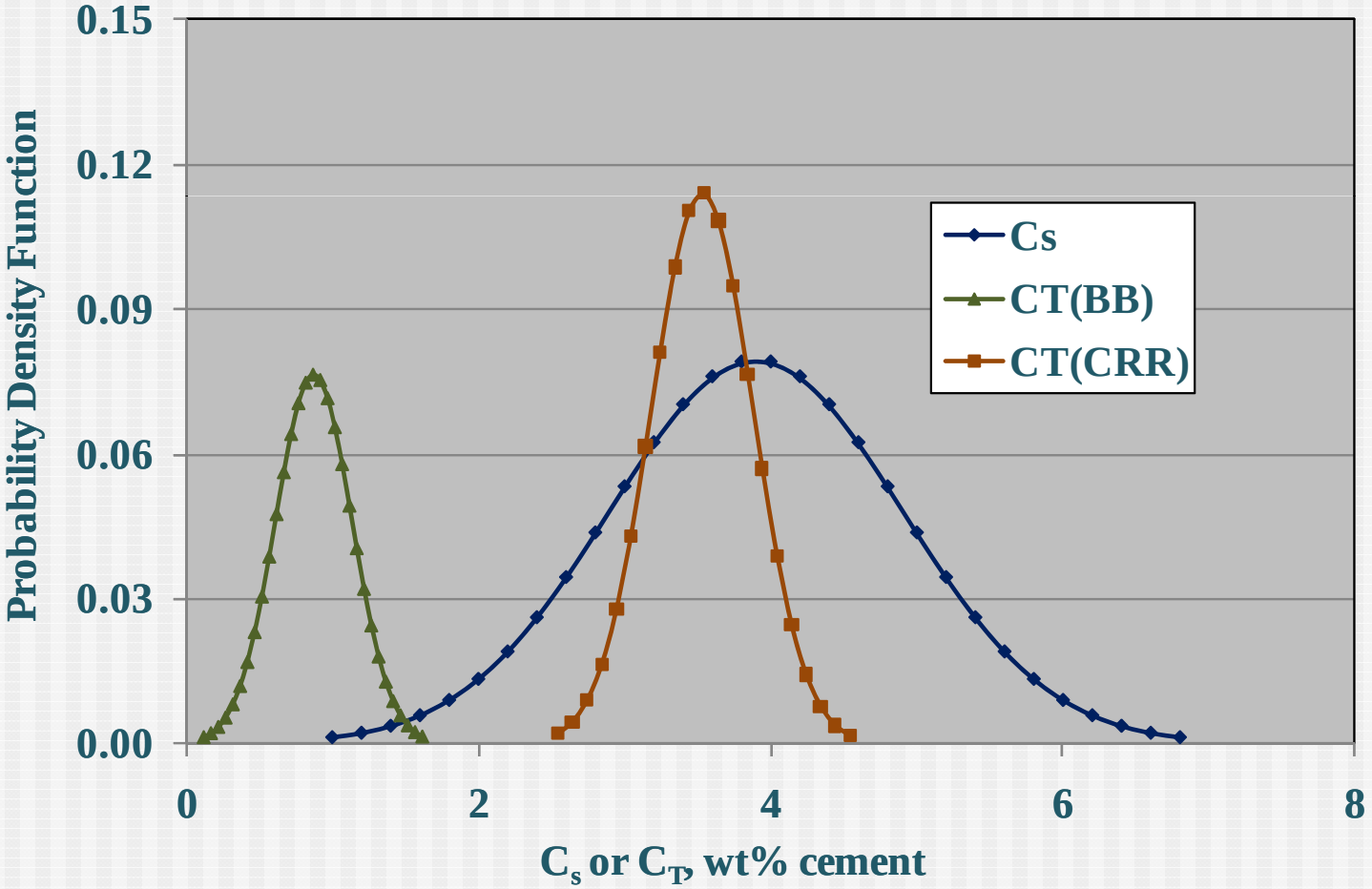


BB and CRR CDF(T_i) Comparison

CDF(T_i), percent	T_i, years			
	BB		CRR	
	$\mu(D) = 3\cdot10^{-12}$ m^2/s	$\mu(D) = 1\cdot10^{-12}$ m^2/s	$\mu(D) = 3\cdot10^{-12}$ m^2/s	$\mu(D) = 1\cdot10^{-12}$ m^2/s
1	6.5	20.1	63	191
10	10.9	33.1	149	-
20	13.5	40.9	255	-
30	15.9	48.0	-	-

CDF(T_i), percent	T_i(CRR)/T_i(BB)	
	$\mu(D) = 3\cdot10^{-12}$ m^2/s	$\mu(D) = 1\cdot10^{-12}$ m^2/s
1	9.7	9.5
10	13.7	-
20	18.9	-
30	-	-

Comparison of C_s and C_T Distributions for BB and CRR



Reported $\mu(C_s)$ Values – Asian and European Marine

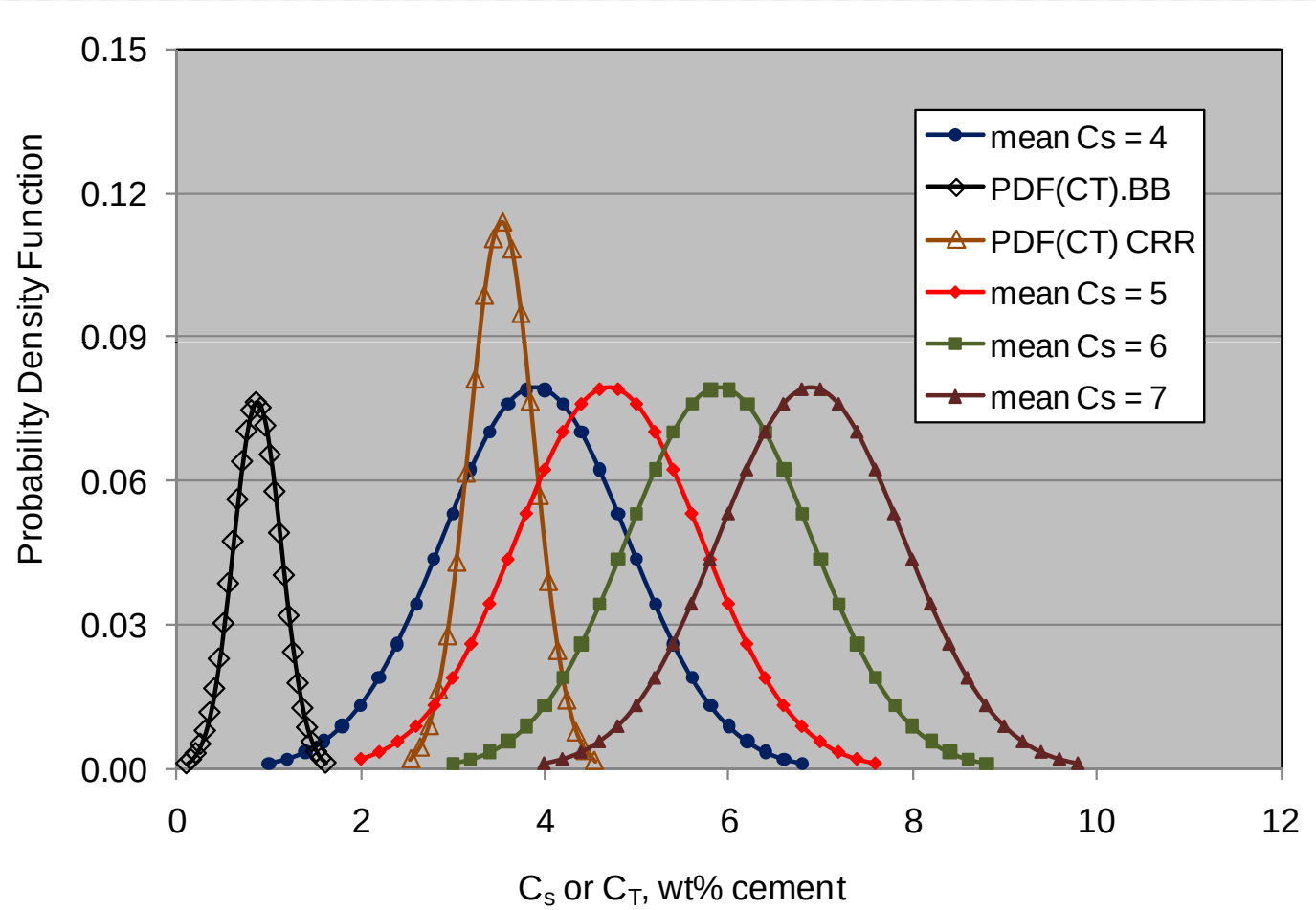
Gjørv

Classification	$\mu(C_s)$, wt% cement	$\sigma(C_s)$, wt% cement
High	5.5	1.3
Average	3.5	0.8
Moderate	1.5	0.5

Bamforth

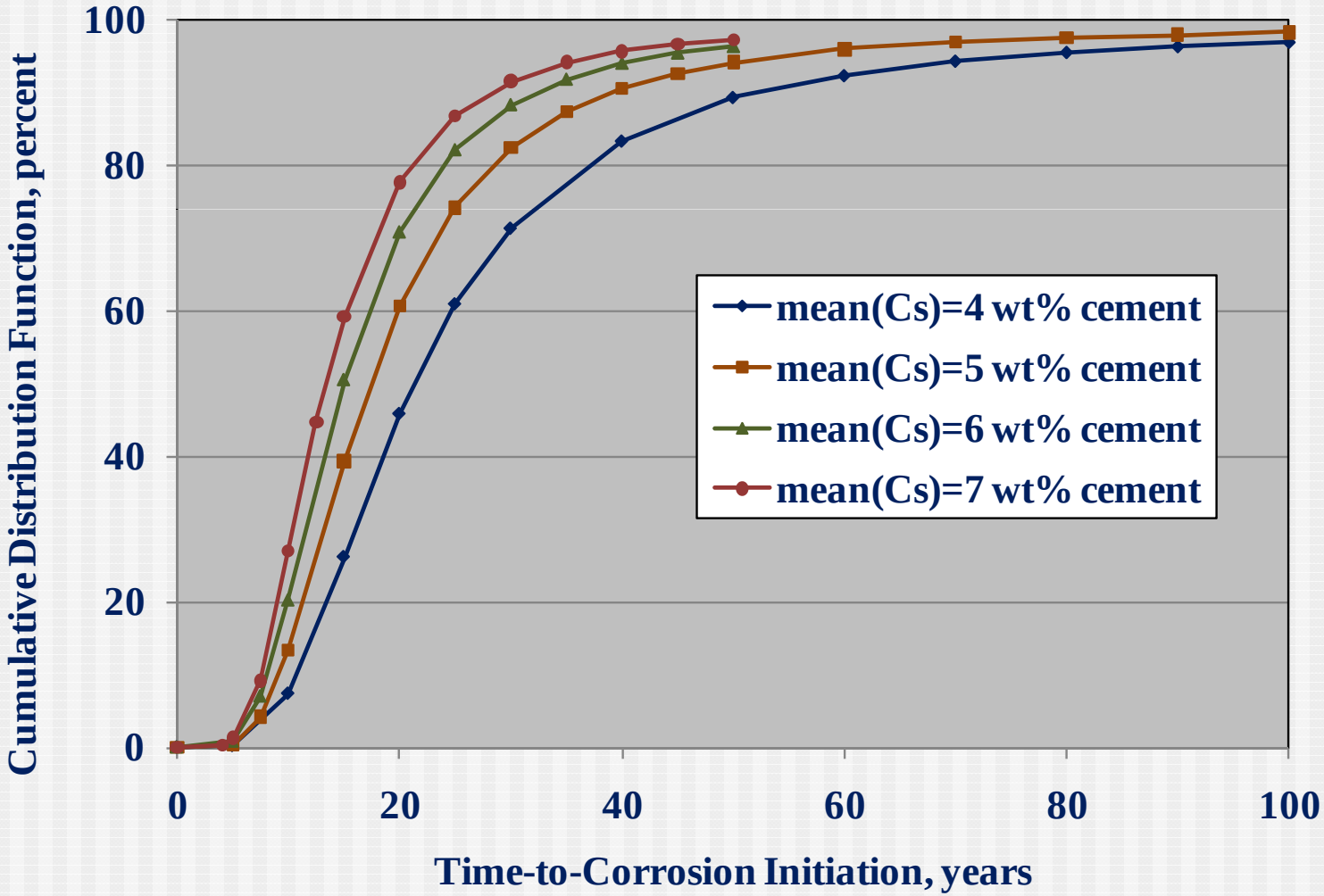
Classification	$\mu(C_s)$, wt% cement
Extreme	>5.6
Severe	3.8-5.6
Moderate	1.9-3.8
Mild	<1.9

Comparison of C_s and C_T Distributions for BB and CRR

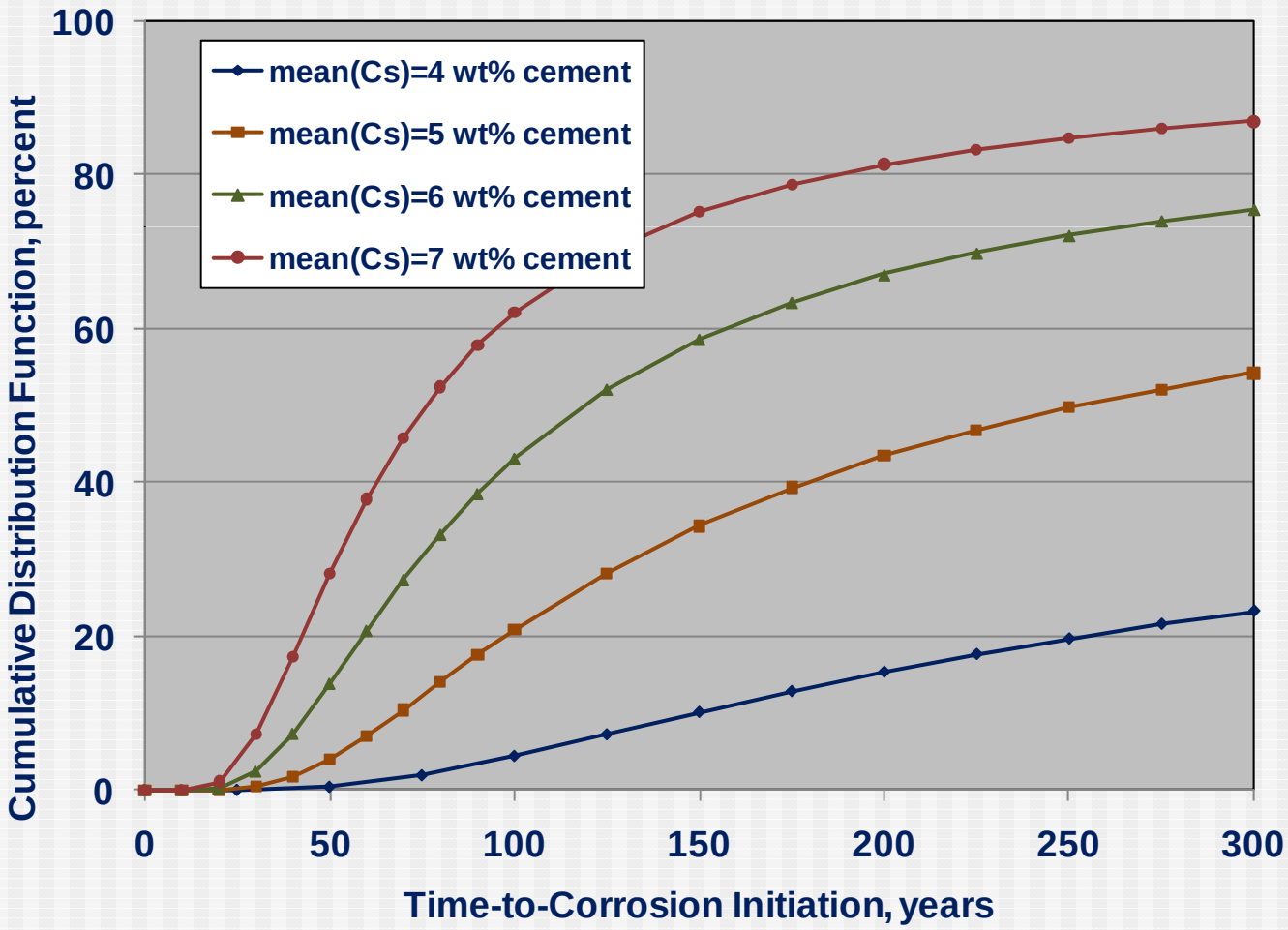


Because of C_s-C_T distribution overlap, the choice of $\mu(C_s)$ can have a significant impact upon CDF(T_i).

CDF(T_i) Distributions for BB with Different $\mu(C_s)$



CDF(T_i) Distributions for CRR with Different $\mu(C_s)$



T_i(CRR)/$T_{i(}$BB) Summary for Different $\mu(C_s)$

$\mu(C_s)$ = 7.00 wt% cement

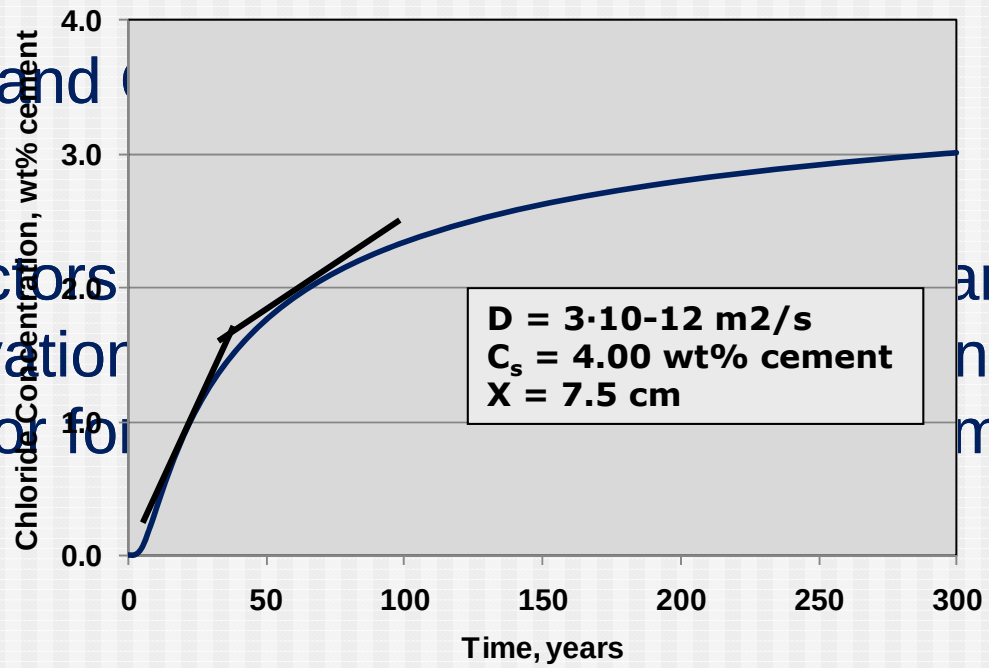
CDF(T_i), percent	T_i(CRR)/T_i(BB)	
	$D=3\cdot10^{-12}$ m^2/s	$D=1\cdot10^{-12}$ m^2/s
1	4.4	4.3
10	4.6	4.6
20	4.9	4.9
30	5.1	5.1

$\mu(C_s)$ = 4.00 wt% cement

CDF(T_i), percent	T_i(CRR)/T_i(BB)	
	$\mu(D) = 3\cdot10^{-12}$ m^2/s	$\mu(D) = 1\cdot10^{-12}$ m^2/s
1	9.7	9.5
10	13.7	-
20	18.9	-
30	-	-

Summary of Factors Contributing to T_i Extension of These CRR Compared to BB

- There is an inherent time increase to initiate active corrosion due to higher alloy content and perhaps microstructural issues (factor of 4-5 enhancement).
- The greater the initial T_i, the more gradual the subsequent rate of corrosion initiation for still passive elements.
- Overlap of the C_T and (of CRR.
- Together these factors ancement of T_i for initial activatior ng T_i enhancement factor for ments.



Conclusions

1. Corrosion resistant alloys are a viable alternative to both black bar and ECR.

2. Because there are a variety of corrosion resistant reinforcement alternatives, materials selection can be tailored to the anticipated exposure severity. Reinforcements 2101, 3Cr12, and MMFX2, termed improved performers, initiated corrosion during the course of this study, albeit at times greater than for BB, whereas 2304, 304, 316, and 316-clad bars did not.

Conclusions (continued)

3. The C_T and macro-cell current data indicate that the intended service life of major reinforced concrete bridge structures (75-100 years) can confidently be achieved with the solid high performance reinforcements that were investigated. This same service life is projected to result also with the improved performance bars provided a) design and construction quality control are good, b) concrete cracks remain narrow, and c) surface [Cl^-] is not extreme.