Appendix C
Chloride Threshold for Various Reinforcement Steel Types

This appendix summarize chloride threshold values from literature sources for various commonly used reinforcement steel types embedded in concrete. The chloride threshold, also often referred to as the critical chloride content, is the concentration of chloride in concrete required to break down the passive layer (i.e., depassivate) of the reinforcement that may lead to corrosion initiation. Thus, the chloride threshold is crucial for service life predictions of reinforced concrete. Literature shows that many parameters influence chloride threshold values, resulting in scatter of the documented values as there is a lack of stringent definitions and measurement methods [1]. The chloride threshold value depends on several factors including the type and content of cement, concrete-steel interface, pH at steel surface, steel potential, moisture content, etc. It is noted that, due in part to the significance of the concrete-steel interface [2],[3], chloride threshold values determined from steel exposed to solutions meant to simulate the pH of concrete (e.g., synthetic pore solution) are not included in the following tables.

In the following when considering the chloride threshold values, it should be kept in mind that the results are obtained through different testing methods. At present, there is no standardized test method to determine the chloride threshold for steel and therefore extra precaution should be taken when comparing different sources. For this appendix, the chloride threshold values summarized herein consider only the following:

- Chloride threshold for steel in concrete or other cementitious material (e.g., mortar), steels exposed to aqueous solutions are not considered;
- The total chloride content is reported only (free/bound chloride content is not included).

This summary of chloride threshold does not distinguish between:

- Cement type used;
- Water-to-cement(itious material) ratio;
- Method of detection of corrosion onset/critical chloride threshold value;
- Method for exposure to chloride ions;
- Specifics of evaluated exposure conditions (e.g., ponding/submersion, splash/spray in a chloride solution, premixing of chloride, etc.).

Ideally, a comparison of chloride threshold values would distinguish between all of the above parameters; however, this is not possible until a standardized test method is agreed upon.

The unit used to characterize the chloride threshold in the literature is ambiguous. For this appendix, the reported chloride threshold values are documented with the units from the respective reference. To allow for comparison, threshold values are converted to the unit wt-% of cement. In case information on the concrete mix design was not provided, a cement content of 640 lbs/cy (380 kg/m³) and a concrete density of 4050 lbs/cy (2400 kg/m³) were assumed for conversions.

C1.0 Reinforcement Steel Types

Table 1 provides an overview of controlling specifications and compositions of the different steel types considered in the next section, where chloride threshold values for various reinforcement steel types are summarized. In certain cases, requirements to the steel composition are limited in the controlling specification (e.g., ASTM A615 and A706) and in these cases, the composition description is based on published results as explained in the footnotes of Table 1.

Ranges of pitting resistance equivalent (PRE) indices are included in the table for various types of steel. The PRE index indicates the ability of the steel to resist pitting corrosion (in neutral environments), with a higher PRE index generally indicating a higher resistance to pitting. It is noted that, as indicated in the compiled data below and results elsewhere in the literature (see e.g., [58, 63]) the PRE index and chloride threshold value for the steel reinforcement do not always coincide. PRE indices are computed based on the content of chromium (Cr), molybdenum (Mo), and nitrogen (N) in the steel using the following equation [62]:

$$PRE = wt\%Cr + 3.3 \times wt\%Mo + A \times wt\%N \quad (1)$$

The parameter A is set to 16 for computed PRE indices in Table 1 (a value for A of 30 is also cited in the literature, see e.g. [58, 63]).

Table 1: Overview of Specification and Composition Details for Different Steel Types.

Description	Specification	Alloy Type	UNS Designation	Typical Contents / Compositional Requirements (%)			
				Cr	Mo	N	PRE Index
Carbon Steel [1)]	ASTM A615/ ASTM A706/ AASHTO M31	-	-	0.01 - 0.21	0.04 - 0.16	Not reported (Nil) - 0.012	0.14-0.93
Epoxy-coated carbon steel	ASTM A775	-	-	-	-	-	-
Galvanized carbon steel	ASTM A767	-	-	-	-	-	-
Low-carbon chromium steel [2)]	ASTM A1035	CL	K23050	2.0-3.9	1.5 (max)	0.05 (max)	2.0-9.7
		CM	K42050	4.0-7.9			4.0-13.7
		CS	K81550	8.0-10.9			8.0-16.7
Stainless steel-clad carbon steel	AASHTO M329	-	-	-	-	-	-
Austenitic stainless steel [3)]	ASTM A955/ AASHTO M334	XM-29	S24000	17.0-19.0		0.20-0.40	20.2-25.4
		XM-28	S24100	16.5-19.0		0.20-0.45	19.7-26.2
		304	S30400	18.0-20.0		0.10 (max)	18.0-21.6
		304L*	S30403	18.0-20.0		0.10 (max)	18.0-21.6
		316*	S31600	16.0-18.0	2.0-3.0		22.6-27.9
		316L	S31603	16.0-18.0	2.0-3.0	0.10 (max)	22.6-29.5
		316LN	S31653	16.0-18.0	2.0-3.0	0.10-0.16	24.2-30.5
Duplex (austenitic-ferritic) stainless steel [4)]	ASTM A955/ AASHTO M334	2101 LDX	S32101	21.0-22.5	0.10-0.80	0.12-0.25	23.3-29.1
		2304	S32304	21.5-24.5	0.10-0.60	0.10-0.20	23.4-29.7
		2205	S31803	21.0-23.0	2.5-3.5	0.10-0.20	30.8-37.8

1) Steel composition is based on typical results published in literature referenced herein and compositions reported in [64] and PRE index is computed considering the reported ranges
2) For low-carbon chromium steel, ranges of chromium content (Cr) are extracted from ASTM A1035. Computed PRE indices consider the allowable ranges of molybdenum (i.e., nil to 1.5) and nitrogen (i.e., nil to 0.05).
3) For austenitic stainless steel, ranges of chromium (Cr), molybdenum (Mo) and nitrogen (N) are generally based on limits in ASTM A955. The alloy types with asterisks (i.e., 304L and 316) are not included in ASTM A955 or AASHTO M334 and details on compositional requirements come from ASTM A666. These steel types are included as associated chloride threshold data is available in the literature. It is noted that higher PRE indices are possible for steel types without specified limits on Mo or N.
4) For duplex stainless steel 2205 (S31803) composition details are taken from ASTM A995, while for 2101 LDX (S32101) and 2304 (S32304) are taken from typical results published in literature referenced herein.

C2.0 Threshold Values from Literature

Chloride threshold values from literature sources are summarized for various steel reinforcement types in Table 2 to Table 8. Chloride thresholds are presented as reported from the cited literature source in these tables together with a ratio of the chloride threshold value of the given reinforcement steel type versus that for carbon steel reinforcement (i.e., $C_{T,x}/C_{T,CS}$-ratio) as reported from the given reference. If no ratio is provided, this means the chloride threshold for carbon steel was not reported in the given reference.

The tables provide the minimum, maximum, and average value of the chloride threshold value reported in the given reference. Where necessary, the reported chloride threshold value is converted to the unit wt-% of cement as described in introduction of this Appendix. Finally, the tables provide a summary of all references including:

1) The average chloride threshold value for the given reinforcement type, and
2) The ratio of this average to the average chloride threshold for carbon steel from Table 2 (i.e., $C_{T,x}/C_{T,CS}$, for 'x' reinforcement steel type).

The ratio of chloride threshold values to the average chloride threshold for carbon steel reinforcement (i.e., $C_{T,x}/C_{T,CS}$) enables easy comparison of the different reinforcement types.

In cases where the reference provides a range for the chloride threshold value (for example 0.30-0.40 wt-% of cement), the mean value of the range is used in the overall average calculation (for example 0.35 wt-% of cement). Similarly, the standard deviation reported in the tables below is computed using the mean value of the range reported from individual references.

C2.1 Carbon Steel

Table 2 summarizes chloride threshold values for carbon steel reinforcement from various literature sources. As summarized in the table, the overall average chloride threshold value from all references was computed as 0.68 wt-% of cement (i.e., $C_{T,CS}$) with an associated standard deviation of 0.47 wt-% of cement.

Table 2: Chloride Threshold Values for Carbon Steel from Literature.

Reference	Chloride threshold, C_T, as reported in reference	Calculated C_T, wt-% cement		
		Minimum	Maximum	Average
[4] Locke and Siman, 1980	0.4-0.8 wt-% cement	0.4	0.8	0.6
[5] Page and Havdahl, 1985	0.4-1.0 wt-% cement	0.4	1.0	0.7
[6] Elsener and Böhni, 1986	0.25-0.5 wt-% cement	0.25	0.5	0.38
[7] Schießl and Schwarzkopf, 1986	0.5 wt-% cement	-	-	0.5
[8]/[9] Pfeifer et al., 1986/1987	0.18-0.26 wt-% cement	0.18	0.26	0.22
[10] Hope and Ip, 1987	0.1-0.19 wt-% cement	0.1	0.19	0.15
[11] Sørensen et al., 1990	<0.5 wt-% cement	-	-	0.5
[12] Hansson and Sørensen, 1990	0.4-1.37 wt-% cement	0.4	1.37	0.89
[13] Schießl and Raupach, 1990	0.5-2.0 wt-% cement	0.5	2.0	1.25
[14] Lambert et al., 1991	1.5-2.5 wt-% cement	1.5	2.5	2.0
[15] Takagi et al., 1991	0.125 wt-% cement	-	-	0.125
[16] Pettersson, 1992	0.5-1.8 wt-% cement	0.5	1.8	1.15
[17] Henriksen and Stoltzner, 1993	0.25-0.4 wt-% cement	0.25	0.4	0.33
[18] Raupach, 1993	0.5-1.0 wt-% cement	0.5	1.0	0.75
[19] Tuutti, 1993	0.5-1.4 wt-% cement	0.5	1.4	0.95
[20] Schießl and Breit, 1994	0.5-2.2 wt-% cement	0.5	2.2	1.35
[21] Sandberg et al., 1995	0.2-2.1 wt-% cement	0.2	2.1	0.21
[22] Schießl and Breit, 1996	0.5-1.0 wt-% cement	0.5	1.0	0.75
[23] Thomas et al., 1996	0.2-0.65 wt-% cement	0.2	0.65	0.43
[24] Breit, 1997	0.25-0.75 wt-% cement	0.25	0.75	0.50
[25] Wiens, 1997	0.22-1.05 wt-% cement	0.22	1.05	0.64
[26] Sandberg, 1998	0.4-1.5 wt-% cement	0.4	1.5	0.95
[27] Alonso et al., 2000	1.24-3.08 wt-% cement	1.24	3.08	2.16
[28] Zimmermann et al., 2000	0.25-1.25 wt-% cement	0.25	1.25	0.75
[29] Breit, 2001	0.25-0.75 wt-% cement	0.25	0.75	0.50
[30] Alonso et al., 2002	0.73 wt-% cement	-	-	0.73
[31] Castellote et al., 2002	0.23 wt-% cement	-	-	0.23
[32] Whiting et al., 2002	0.4 wt-% cement	-	-	0.4
[33] Trejo and Pillai, 2003	0.02-0.24 wt-% cement	0.02	0.24	0.13
[34] Oh et al., 2003	0.68-0.97 wt-% cement	0.68	0.97	0.83
[35] Yeomans, 2004	0.2 wt-% cement	-	-	0.2
[36] Nygaard and Geiker, 2005	0.52-0.75 wt-% cement	0.52	0.75	0.64
[37] AMEC, 2006	460-580 PPM	0.3	0.4	0.35
[38] Manera et al., 2007	1.1-2.0 wt-% cement	1.1	2.0	1.55
[39] Hartt et al., 2007	0.54 wt-% cement	-	-	0.54
[40] WJE, 2008	3.8 lbs/cy	-	-	0.6
[41] Darwin et al., 2009	1.63 lbs/cy	-	-	0.3
[42] Hartt et al., 2009	0.36 wt-% cement	-	-	0.36
[43] NACE, 2012	0.6 wt-% cement	-	-	0.6
[44] Kahl, 2012	1.2 lbs/cy	-	-	0.2
Summary of references		*Average $C_{T,CS}$*		*0.68*
		Standard deviation		*0.47*
		Minimum average		*0.13*
		Maximum average		*2.16*

C2.2 Epoxy-Coated Carbon Steel

Chloride threshold values for epoxy-coated carbon steel reinforcement (ECR) are available in the literature, as summarized in Table 3. However, corrosion initiation of ECR is strongly influenced by the condition and type of the epoxy coating and concrete properties, and literature sources indicate or directly state that the chloride threshold for ECR will vary on a project-to-project basis [46,66,69]. The corrosion performance of ECR is affected by coating defects (which are difficult to avoid in the field), time of wetness, adhesion loss, temperature, single mat versus double mat; and concrete properties. As shown in Table 3, results are split between a chloride threshold similar to or less than uncoated carbon steel to values significantly higher than that of carbon steel. It is noted that ECR appears to not provide significant additional protection against chloride induced reinforcement corrosion when poor quality (i.e., highly chloride permeable) concrete is used [67].

The performance of ECR in major structures with design lives of 75 years to 100 years is still uncertain [42] with examples of satisfactory [68] and poor [67] field performance of ECR available in the literature. Additional discuss on the impact of epoxy coating on the corrosion performance of carbon steel is available in the literature (see e.g., [66], [42]).

Table 3: Chloride Threshold Values for Epoxy-Coated Carbon Steel from Literature.

Reference	Chloride threshold, C_T, as reported in reference	Ratio of C_T to carbon steel, $C_{T,CS}$, as reported in reference	Calculated C_T, wt-% cement		
			Minimum	Maximum	Average
[45] Keβler et al., 2015	0.9 wt-% cement	1.5	-	-	0.9
[68] Lee and Krauss, 2005*	300-1,875 ppm	-	0.19	1.18	0.69
[47] Tourney, 2016	500 PPM	1	-	-	0.32
Summary of references			*Average $C_{T,ECR}$*		*0.63*
			Ratio of averages ($C_{T,ECR}/C_{T,CS}$)		*0.93*
			Standard deviation		*0.24*
			Minimum average		*0.32*
			Maximum average		*0.9*

* Multiple references included in this reference and the range of reported results is given.

C2.3 Galvanized Carbon Steel

Table 4: Chloride Threshold Values for Galvanized Carbon Steel from Literature.

Reference	Chloride threshold, C_T, as reported in reference	Ratio of C_T to carbon steel, $C_{T,CS}$, as reported in reference	Calculated C_T, wt-% cement		
			Minimum	Maximum	Average
[35] Yeomans, 2004	1250 PPM	2.5	-	-	0.79
[41] Darwin et al., 2009	2.57 lbs/cy	1.58	-	-	0.40
[48] Shimida and Nishi, 1983	-	1	-	-	0.68
[49] Treadeway and Davis, 1989	-	< 1	-	-	< 0.68*
[50] Swamy, 1990	-	4-5	2.7	3.4	3.06
[51] Clemeña and Virmani, 2004	-	1	-	-	0.68
[52] Allan, 2004	1.0-2.0 wt-% cement	-	1.0	2.0	1.5
[53] Pianca and Schell, 2005	-	~1	-	-	0.68
[54] Broomfield, 2007	1.0-2.0 wt-% cement	2-5	1.0	2.0	1.5
[55] Matthews, 2014	1.0 wt-% cement	1.67	-	-	1.0
Summary of references			*Average $C_{T,GSR}$*		*1.14*
			Ratio of averages ($C_{T,GSR}/C_{T,CS}$)		*1.68*
			Standard deviation		*0.77*
			Minimum average		*0.40*
			Maximum average		*3.06*

* Not included in the calculation of Average C_T

C2.4 Low-Carbon Chromium Steel

Table 5: Chloride Threshold Values for Low-Carbon Chromium Steel from Literature.

Alloy	Reference	Chloride threshold, C_T, as reported in reference	Ratio of C_T to carbon steel, $C_{T,CS}$, as reported in reference	Calculated C_T, wt-% cement		
				Minimum	Maximum	Average
CM	[47] Tourney, 2016	1000 PPM	2	-	-	0.63
CS	[37] AMEC, 2006	2700-2730 PPM	4.7-5.9	1.71	1.72	1.71
	[39] Hartt et al., 2007	1.1 wt-% cement	3.38	-	-	1.1
	[40] WJE, 2008	11.5 lbs/cy	3	-	-	1.8
	[56] Moruza et al., 2010	-	4.6-6.4	3.1	4.3	3.7
	[41] Darwin et al., 2009	6.34 lbs/cy	3.89	-	-	1.0
	[42] Hartt et al., 2009	1.44 wt-% cement	4	-	-	1.44
	Summary of references			*Average $C_{T,LCC}$*		*1.80*
				Ratio of averages ($C_{T,LCC}/C_{T,CS}$)		*2.64*
				Standard deviation		*0.92*
				Minimum average		*1.0*
				Maximum average		*3.7*

C2.5 Stainless-Steel-Clad Carbon Steel

Stainless-steel-clad carbon steel reinforcement consists of an ordinary carbon steel core with a stainless steel outer layer approximately 0.02” – 0.04” (0.5-1.0 mm) thick. The outer cladding layer can be made from various grades of stainless steel. When bending and cutting individual bars, the cut ends of the bars expose the carbon steel core and becomes a weak link for corrosion protection. Producers recommend that bar ends be capped, which complicates fabrication and can be a significant drawback to the technology [55].

Table 6: Chloride Threshold Values for Stainless Steel-Clad Carbon Steel from Literature.

Reference	Chloride threshold, C_T, as reported in reference	Ratio of C_T to carbon steel, $C_{T,CS}$, as reported in reference	Calculated C_T, wt-% cement		
			Minimum	Maximum	Average
[56] Moruza et al., 2010	-	6.5-8.8	4.42	5.99	5.20

C2.6 Austenitic Stainless Steel

Table 7: Chloride Threshold Values for Austenitic Steel from Literature.

Alloy	Reference	Chloride threshold, C_T, as reported in reference	Ratio of C_T to carbon steel, $C_{T,CS}$, as reported in reference	Calculated C_T, wt-% cement		
				Minimum	Maximum	Average
XM-28	[44] Kahl, 2012	19 lbs/cy	15.8	-	-	2.97
304	[11] Sørensen et al., 1990	3.5-5.0 wt-% cement	7-10	3.5	5.0	4.3
	[37] AMEC, 2006	>5630 PPM	9.7-12.2	-	-	>3.6
	[40] WJE, 2008	>20.8 lbs/cy	>5.4	-	-	>3.2
	[44] Kahl, 2012	19 lbs/cy	15.8	-	-	3.0
	[51] Clemeña and Virmani, 2004	>3.7 wt-% cement	-	-	-	>3.7
	[57] Treadaway et al., 2010	>3.2 wt-% cement	-	-	-	>3.2
	[58] Nurnberger et al., 1993	>2.5 wt-% cement	-	-	-	>2.5
	[42] Harrt et al., 2009	>4.8 wt-% cement	-	-	-	>4.8
	Summary of references			*Average $C_{T,304}$*		*3.53*
				Ratio of averages ($C_{T,304}/C_{T,CS}$)		*5.19*
				Standard deviation		*0.68*
				Minimum average		*2.5*
				Maximum average		*4.8*
304L	[43] NACE, 2012	6.5 wt-% cement	10.8	-	-	6.5
	[59] Bertolini et al., 2000	>6.0 wt-% cement	-	-	-	>6.0
	[60] Randström et al., 2010	>2.6 wt-% cement	-	-	-	>2.6
	[62] Schönning et al., 2011	>4.0 wt-% cement	-	-	-	>4.0
	Summary of references			*Average $C_{T,304L}$*		*4.78*
				Ratio of averages ($C_{T,304L}/C_{T,CS}$)		*7.02*
				Standard deviation		*1.6*
				Minimum average		*2.6*
				Maximum average		*6.5*
316	[11] Sørensen et al., 1990	3.5-5.0 wt-% cement	7-10	3.5	5.0	4.3
	[57] Treadaway et al., 2010	>3.2 wt-% cement	-	-	-	>3.2
	[58] Nurnberger et al., 1993	>2.5 wt-% cement	-	-	-	>2.5
	Summary of references			*Average $C_{T,316}$*		*3.32*
				Ratio of averages ($C_{T,316}/C_{T,CS}$)		*4.88*
				Standard deviation		*0.72*
				Minimum average		*2.5*
				Maximum average		*4.3*

Alloy	Reference	Chloride threshold, C_T, as reported in reference	Ratio of C_T to carbon steel, $C_{T,CS}$, as reported in reference	Calculated C_T, wt-% cement		
				Minimum	Maximum	Average
316L	[43] NACE, 2012	6.9 wt-% cement	11.5	-	-	6.9
	[59] Bertolini et al., 2000	>6.0 wt-% cement	-	-	-	6.0
	[60] Randström et al., 2010	>2.6 wt-% cement	-	-	-	>2.6
	[62] Schönning et al., 2011	>4.0 wt-% cement	-	-	-	4.0
	Summary of references			*Average $C_{T,316L}$*		*4.88*
				Ratio of averages ($C_{T,316L}/C_{T,CS}$)		*7.17*
				Standard deviation		*1.68*
				Minimum average		*2.6*
				Maximum average		*6.9*
316LN	[37] AMEC, 2006	>5630 PPM	9.7-12.2	-	-	>3.6
	[44] Kahl, 2012	31 lbs/cy	25.8	-	-	4.8
	[51] Clemeña and Virmani, 2004	>3.7 wt-% cement	-	-	-	>3.7
	[56] Moruza et al., 2010	-	>10.4	-	-	>7.1
	[42] Harrt et al., 2009	>6.5 wt-% cement	-	-	-	>6.5
	[61] Islam et al., 2013	>3.0 wt-% cement	-	-	-	>3.0
	Summary of references			*Average $C_{T,316LN}$*		*4.79*
				Ratio of averages ($C_{T,316LN}/C_{T,CS}$)		*7.04*
				Standard deviation		*1.53*
				Minimum average		*3.0*
				Maximum average		*7.1*

C2.7 Duplex (Austenitic-Ferritic) Stainless Steel

Table 8: Chloride Threshold Values for Duplex (Austenitic-Ferritic) Stainless Steel from Literature.

<table>
<tr><th rowspan="2">Alloy</th><th rowspan="2">Reference</th><th rowspan="2">Chloride threshold, C_T, as reported in reference</th><th rowspan="2">Ratio of C_T to carbon steel, $C_{T,CS}$, as reported in reference</th><th colspan="3">Calculated C_T, wt-% cement</th></tr>
<tr><th>Minimum</th><th>Maximum</th><th>Average</th></tr>
<tr><td rowspan="12">2101 LDX</td><td>[37] AMEC, 2006</td><td>1550-1560 PPM</td><td>2.7-3.4</td><td>0.98</td><td>0.99</td><td>0.99</td></tr>
<tr><td>[51] Clemeña and Virmani, 2004</td><td>0.88-0.90 wt-% cement</td><td>-</td><td>0.88</td><td>0.90</td><td>0.9</td></tr>
<tr><td>[56] Moruza et al., 2010</td><td>-</td><td>2.6-3.7</td><td>1.8</td><td>2.5</td><td>2.1</td></tr>
<tr><td>[42] Harrt et al., 2009</td><td>1.83-4.12 wt-% cement</td><td>-</td><td>1.83</td><td>4.12</td><td>3.0</td></tr>
<tr><td>[60] Randström et al., 2010</td><td>>2.6 wt-% cement</td><td>-</td><td>-</td><td>-</td><td>>2.6</td></tr>
<tr><td>[61] Islam et al., 2013</td><td>>3.0 wt-% cement</td><td>-</td><td>-</td><td>-</td><td>>3.0</td></tr>
<tr><td>[62] Schönning et al., 2011</td><td>>4.0 wt-% cement</td><td>-</td><td>-</td><td>-</td><td>>4.0</td></tr>
<tr><td colspan="3" rowspan="5">Summary of references</td><td colspan="2">Average. C_T</td><td>2.37</td></tr>
<tr><td colspan="2">Ratio of averages ($C_{T,2101}/C_{T,CS}$)</td><td>3.48</td></tr>
<tr><td colspan="2">Standard deviation</td><td>1.04</td></tr>
<tr><td colspan="2">Minimum average</td><td>0.9</td></tr>
<tr><td colspan="2">Maximum average</td><td>4.0</td></tr>
<tr><td rowspan="10">2304</td><td>[47] Tourney, 2016</td><td>>5000 PPM</td><td>>10</td><td>-</td><td>-</td><td>>3.2</td></tr>
<tr><td>[42] Harrt et al., 2009</td><td>>5.9 wt-% cement</td><td>-</td><td>-</td><td>-</td><td>>5.9</td></tr>
<tr><td>[60] Randström et al., 2010</td><td>>2.6 wt-% cement</td><td>-</td><td>-</td><td>-</td><td>>2.6</td></tr>
<tr><td>[61] Islam et al., 2013</td><td>>3 wt-% cement</td><td>-</td><td>-</td><td>-</td><td>>3</td></tr>
<tr><td>[62] Schönning et al., 2011</td><td>>4.0 wt-% cement</td><td>-</td><td>-</td><td>-</td><td>>4.0</td></tr>
<tr><td colspan="3" rowspan="5">Summary of references</td><td colspan="2">Average C_T</td><td>3.7</td></tr>
<tr><td colspan="2">Ratio of averages ($C_{T,2304}/C_{T,CS}$)</td><td>5.5</td></tr>
<tr><td colspan="2">Standard deviation</td><td>1.2</td></tr>
<tr><td colspan="2">Minimum average</td><td>2.6</td></tr>
<tr><td colspan="2">Maximum average</td><td>5.9</td></tr>
<tr><td rowspan="7">2205</td><td>[37] AMEC, 2006</td><td>>5630 PPM</td><td>9.7-12.2</td><td>-</td><td>-</td><td>>3.6</td></tr>
<tr><td>[44] Kahl, 2012</td><td>>22 lbs/cy</td><td>18.3</td><td>-</td><td>-</td><td>>3.4</td></tr>
<tr><td colspan="3" rowspan="5">Summary of references</td><td colspan="2">Average C_T</td><td>3.5</td></tr>
<tr><td colspan="2">Ratio of averages ($C_{T,2205}/C_{T,CS}$)</td><td>5.14</td></tr>
<tr><td colspan="2">Standard deviation</td><td>0.06</td></tr>
<tr><td colspan="2">Minimum average</td><td>3.4</td></tr>
<tr><td colspan="2">Maximum average</td><td>3.6</td></tr>
</table>

C3.0 Comparing PRE Index and Chloride Threshold Values

Figure 1 plots the calculated average chloride threshold values from Sections C2.1-C2.7 above against the associated median PRE index for the given alloy type from Table 1. As the figure shows, generally reinforcement steel types with higher PRE indices have an increased chloride threshold value. However, a clear relationship between the median PRE index of the steel type and its chloride threshold in concrete is not apparent. A linear fitting of the compiled data in Figure 1 yielded an R-squared value of 0.57.

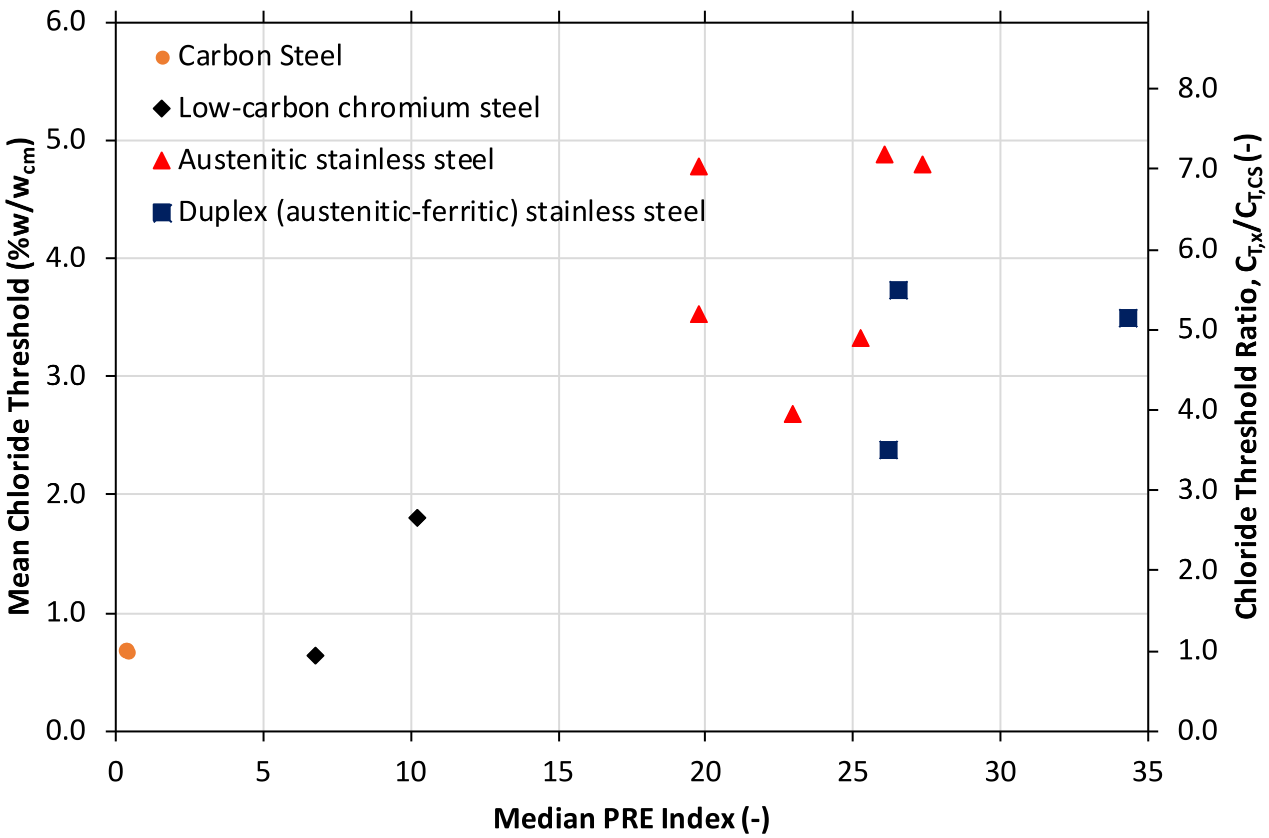

Figure 1 – Plot of mean chloride threshold, CT for various reinforcement steel types versus the median PRE index from Table 1.

C4.0 Considerations when Selecting Alternative Reinforcement Types

This section provides an indicative, simplified analysis of selected chloride threshold values in Section C2.0 with the aim of highlighting that the use of an alternative reinforcement type as a singular measure may not eliminate the risk for chloride-induced reinforcement corrosion. The selection of an alternative reinforcement type and, particularly, possible relaxation of other design parameters (e.g., concrete cover thickness, chloride migration coefficient, etc.) should carefully consider the severity of the prevailing exposure conditions. While the following section focuses on chloride-induced reinforcement corrosion, other deterioration mechanisms influencing reinforcement including carbonation-induced corrosion should also be subject to appropriate consideration as described in Table 4-6 of the Main Body of this Summary Guide.

To illustrate the potential impact of the selected alternative reinforcement type, the average critical chloride values for select steel types assembled in Section C2.0 are used to develop assumed statistical distributions of chloride threshold values based on the compiled references. The assumed distributions are then used in two example full probabilistic calculations representing two exposure situations. The distributions presented herein are assumed based on the compiled data alone and were not subject to further verification. As such these distributions are not appropriate for actual input parameters as described below. The aim of this section is exclusively to indicate that the selection of alternative reinforcements should carefully consider the severity of the exposure conditions and other influential design parameters (e.g., concrete cover thickness, chloride migration coefficient, etc.).

As described in Table 4-7 in the main body of this Summary Guide, when completing full probabilistic modeling of chloride-induced reinforcement corrosion, the *fib* Bulletin 34 recommends using a beta distribution for the critical chloride content of uncoated carbon steel reinforcement, with a mean value of 0.6% by mass of cementitious materials, a standard deviation of 0.15, a lower bound of 0.2, and an upper bound of 2.0. The commentary to the *fib* Bulletin 34 states regarding to the use of different steel types "*If another steel quality is used (e.g. stainless steel), mean value, standard deviation, lower and upper boundary of C_{crit} usually are on a higher level*." However, more detailed instruction on the development of the C_{crit}-distribution is not provided in the fib Bulletin 34.

The fib Bulletin 34 recommended beta distribution is used to model the compiled critical chloride contents for select steel types. The upper and lower bound values for each steel type considered are taken as the highest and lowest reported values, respectively. A best-fit approach, whereby the R-squared value is maximized to as close to a value of 1 as achievable, is then used to establish a mean and standard deviation for the beta distribution. Figure 2 plots the cumulative distribution of the reported chloride threshold values for the various steel types. Data points compiled from the literature are shown as the different colored symbols, while the achieved best-fit beta distribution is shown in the corresponding color curves. Table 9 summarizes the beta distribution parameters for the different steel types along with the achieved R-squared values. It must be noted that the values compiled in Table 3 to Table 8, used to develop the beta distributions, are from individual experimental investigations. These investigations vary in terms of experimental approaches, measurement techniques, exposure method, compositions of the steel and concrete or mortar, among other variables. The C_{crit}-distributions can therefore vary significantly when additional data is considered or if a different analysis or experimental approach is used. The beta distribution parameters in Table 9 are therefore strictly informative in this illustrative example and are not appropriate for design as a more robust verification is necessary to justify the distributions. The parameters are applied in the examples below to provide a general indication of the impact the selected steel type may have on chloride-induced reinforcement corrosion.

The average values from individual reference were utilized and values reported as greater than (>) a particular level are considered simply as the reported value. The various grades of 304 steel (304 and 304L) are analyzed together. Similarly, the various grades of 316 steel (316, 316L and 316LN) are analyzed together. The steel types considered in this analysis include ASTM A1035 Type CS, 304, and 316. Other steel types were not included in this analysis due to the limited number of data points or due to the limited difference in chloride threshold values compared to that of carbon steel.

Table 9: Best-fit beta distribution parameters for the curves shown in Figure 2 with the achieved R-squared value.

Beta distribution parameter	Steel Type			
	Carbon Steel [1)]	ASTM A1035 – CS	304	316
Mean	0.60	1.49	3.66	4.29
Standard Deviation	0.15	0.53	1.03	1.49
Lower boundary	0.20	0.9	2.5	2.5
Upper boundary	2.0	3.8	6.6	7.2
Achieved R^2 value	-	0.980	0.975	0.971

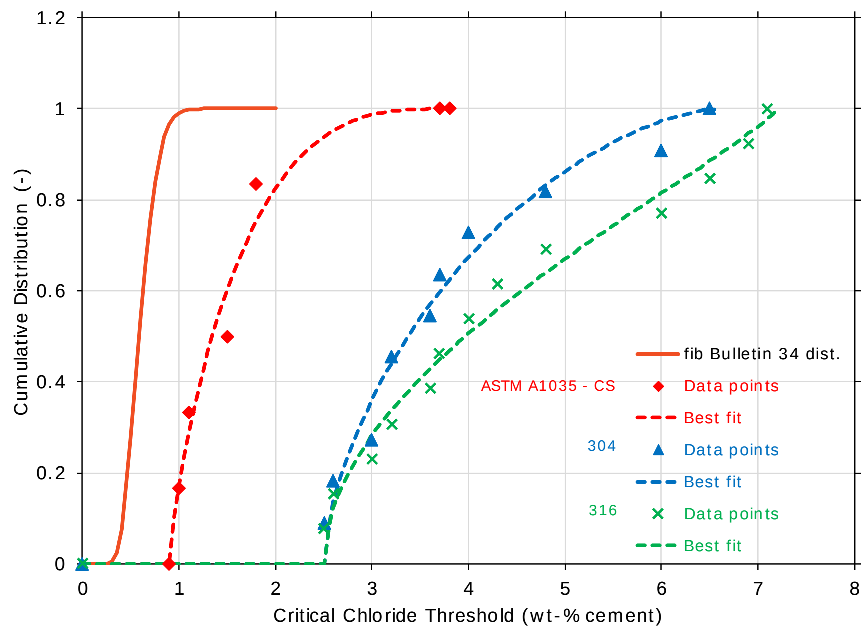

Figure 2 – Plot of assumed cumulative distribution of critical chloride threshold (C_{Crit}) values for alternative reinforcement types, with data points given as symbols, best fit curves as broken lines, and the fib Bulletin distribution for carbon steel given as a solid orange line.

Two basic exposure situations are used to assess the impact that the above derived distribution to describe C_{Crit} for the various steel types are described in Table 10. It is noted that exposure condition 1 are taken from the example Birth Certificate provided in Appendix F, while exposure condition 2 are taken from the Service Life Design Example 3 in Appendix D and complete input parameters are found in these locations.

Table 10: Summary of input data for full probabilistic calculations to assess impact of C_{crit}-values from Table 9.

Input parameter	Exposure Condition 1	Exposure Condition 2	
		Case A	Case B
Critical chloride content, C_{Crit}	See Table 9		
Cement type	PC + 30% Slag	OPC + 20-35% FA	OPC + 20-35% FA
Chloride migration coefficient, $D_{RCM,0}$ (average/standard deviation)	0.596/0.238 in²/y	4.9/0.98 x 10^{-12} m²/s	15.0/3.0 x 10^{-12} m²/s
Surface chloride concentration, $C_{s,\Delta x}$ (average/standard deviation, % wt./wt cem)	0.70/0.35	3.5/1.75	3.5/1.75
Cover thickness (average/standard deviation, in.)	2.5/0.35	2.5/0.3	2.5/0.3
Δx (average/standard deviation, in.)	0.35/0.22	0.35/0.22	0.35/0.22
Service life (years)	100	50 (100) 1)	50 (100) 1)

1) In the original example, a 50-year service life was considered. 100 years is also computed in these calculations.

For exposure condition 1, the 'As-constructed' chloride migration coefficients and age factor from Appendix F were used. For exposure condition 2, the concrete parameters were varied. In Case A, the original chloride migration coefficient requirement concluded in the Service Life Design

Example 3 in Appendix D was used. In Case B, a higher (i.e., less strict) chloride migration coefficient requirement was investigated. Case B is intended to simulate the impact of relaxing requirements to the concrete properties on the achieved reliability index with the various steel types. It is noted that the two exposure conditions used in this illustrative example consider only a limited range of potential exposure conditions, among other input parameters.

Table 11 provides approximate reliability indices computed after 50 and 100 years from the different exposure conditions, concrete cases, and assumed C_{crit}-distributions for the various steel types. The table shows that the alternative reinforcement types increase the computed reliability index compared to carbon steel at the same service life and exposure condition. As noted in the table, Exposure Condition 1 has a limited surface chloride concentration, resulting in the C_{Crit} distribution range being higher than the exposure. In these cases, a reliability index was not determined as calculations using the SHRP2 R19A spreadsheet tool typically resulted in zero (0) failures after several run. It is also pointed out that the relaxation in the concrete's chloride migration coefficient demonstrated in Exposure Condition 2 – Case B (with a relaxed chloride migration coefficient) resulted in computed reliability indices less than 1.30 (i.e,. target reliability index per fib Bulletin 34) in some cases.

While the values in Table 11 are strictly indicative (as calculations are based on unverified C_{crit}-distributions, a limited consideration of exposure conditions, concrete cover thickness), the values emphasize the importance of considering the severity of the exposure conditions in the selection of alternative reinforcement steel types and/or durability requirements for the concrete. This illustrative example therefore indicates that the use or specification of an alternative reinforcement type, as a singular measure, may not eliminate the risk for chloride-induced reinforcement corrosion. Further, any relaxation of other durability-related requirements (e.g., concrete cover thickness, chloride migration coefficient, etc.) based on the use of an alternative reinforcement should be carefully considered.

Table 11: Computed reliability indices after 50 and 100 years for the varying assumed C_{Crit} beta distribution values for the different steel types compiled in Table 9.

Steel type	Exposure Condition 1		Exposure Condition 2			
			Case A		Case B	
	50 years	100 years	50 years	100 years	50 years	100 years
Carbon Steel	1.566	1.303	1.3	1.0	0.38	0.14
ASTM A1035 - CS	ND	ND	≈2.0	≈1.7	≈1.2	≈0.9
304	ND	ND	≈3.1	≈2.8	≈2.3	≈2.1
316	ND	ND	≈3.2	≈2.9	≈2.4	≈2.2

ND – Not determined – It is noted that in these cases the reliability index was not computed as the surface chloride concentration is less than the C_{Crit} distribution in most or all circumstances and typically calculations in the SHRP2 R19A spreadsheet tool showed zero (0) failures after several runs.

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