Steel Reinforcement: Which one to Choose?

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Presentation Outline

- Why Different Reinforcing Steels?
- Available Reinforcing Steels
- Considerations for Selecting Reinforcement
- Determining Value of Different Reinforcement Types
- Assessing Value of Different Reinforcement Types
- Available Data on Corrosion-resistant Reinforcing Steels
- Summary

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Why Different Reinforcing Steels?

- Structures can be exposed to de-icing salts, salt water, and other salts
- In sufficient quantities, chlorides can result in corrosion of steel reinforcement

- Reinforcing steels can exhibit different corrosion resistance

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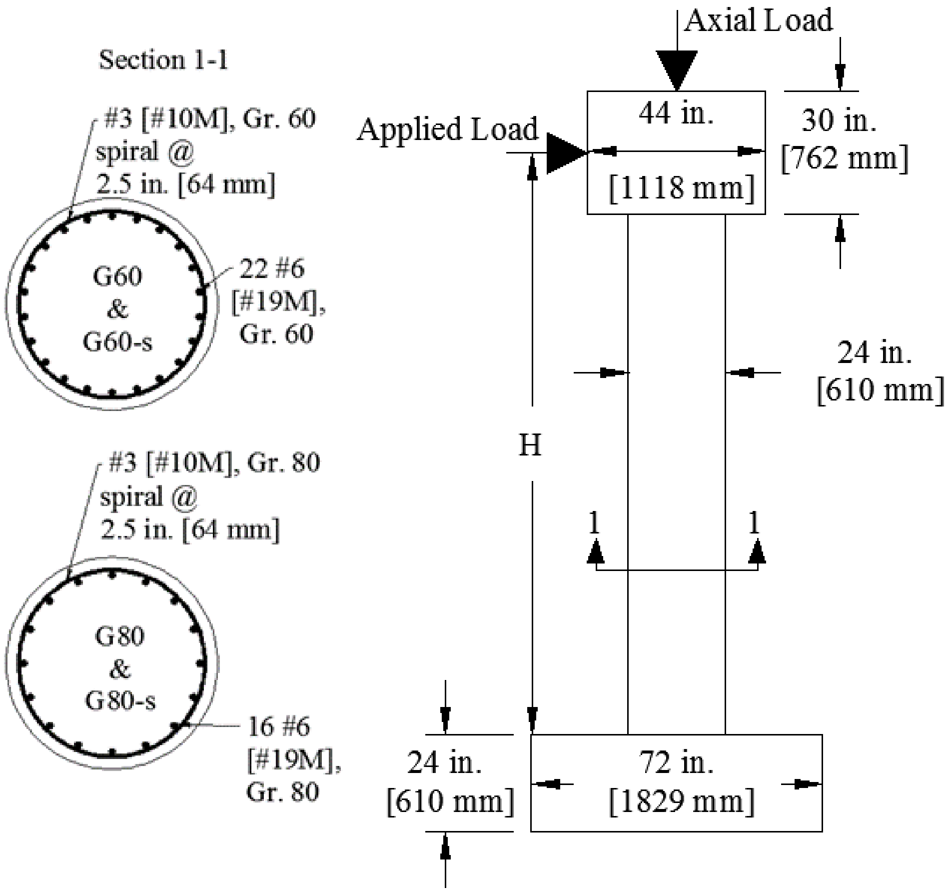
Why Different Reinforcing Steels?

- Different reinforcing steels exhibit different yield and ultimate strengths, and different ductility



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Trejo, D., Barbosa, A., and Link, T., Seismic Performance of Circular Reinforced Concrete Bridge Columns Constructed With Grade 80 Reinforcement, SRS 500-610, 2014

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Available Reinforcing Steels

Bars without surface coatings

ASTM Standard	Specified Grades	General Description	Notes
A615	40 [280], 60 [420], 75 [520], 80 [550], 100 [690]	**carbon** steel bars	Weld with caution; #3 to #20
A706	60 [420] and 80 [550]	**low-alloy** steel bars	Enhanced weldability; #3 to #18; higher ductility rqmts than A615
A996	40 [280], 50 [350], 60 [420]	**rail- and axle**-steel bars	"R" and "RS" steels have lower ductility rqmts than A615; #3 to #11
A1035	100 [690], 120 [830]	**low carbon, chromium,** steel bars (CL, CM, CS)	Weld with caution; #3 to #20
A955	60 [420], 75 [520]	deformed and plain **stainless steel** bars	Suitable welding procedure req'd; #3 to #18 sizes; 6 different chemistry rqmts

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Available Reinforcing Steels

Bars with single epoxy surface coatings

ASTM Standard	Specified Grades	General Description	Notes
A775	Grades meeting A615, A706, or A996 specifications	reinforcing bars with **protective epoxy coating** applied by the electrostatic spray method	Fusion-boned epoxy; #3 to #18 sizes
A934	Grades meeting A615, A706, or A996 specifications	Steel reinforcing bars which prior to surface preparation are **prefabricated and then coated with a protective fusion-bonded epoxy coating**	Fusion-bonded epoxy

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Available Reinforcing Steels

Bars with single metallic surface coatings

ASTM Standard	Specified Grades	General Description	Notes
A767	Grades meeting A615, A706, or A996 specifications	steel reinforcing bars with **protective zinc coatings applied by immersing** the properly prepared reinforcing bars into a molten bath of zinc	#3 to #18 sizes; Two classes for zinc coating thicknesses (1 and 2): Class 1 zinc coating thickness = 150 µm (5.9 mils) and Class 2 zinc coating thickness = 86 µm (3.4 mils)
A1094	Grades meeting A615, A706, or A996 specifications	steel reinforcing bars, with **protective zinc or zinc-alloy coatings applied by the continuous hot-dip process**	Sizes meeting grades in A615, A706, or A996 specifications; Minimum average coating thickness = 50 µm (2 mils)

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Available Reinforcing Steels

Bars with dual coatings

ASTM Standard	Specified Grades	General Description	Notes
A1055	Grades meeting A615, A706, or A996 specifications	Steel reinforcing bars with a **dual coating of zinc-alloy followed by an epoxy coating** applied by the electrostatic spray method.	Suitable welding procedure req'd; #3 to #18 sizes; 6 different chemical requirements

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Considerations for Selecting Reinforcement

- Mechanical property requirements
- Exposure environment
  - Exposure to moisture
  - Exposure to chlorides and sulfates
- Structure importance/use (incl. traffic)
- Required resistance to corrosion
- Costs
- Value

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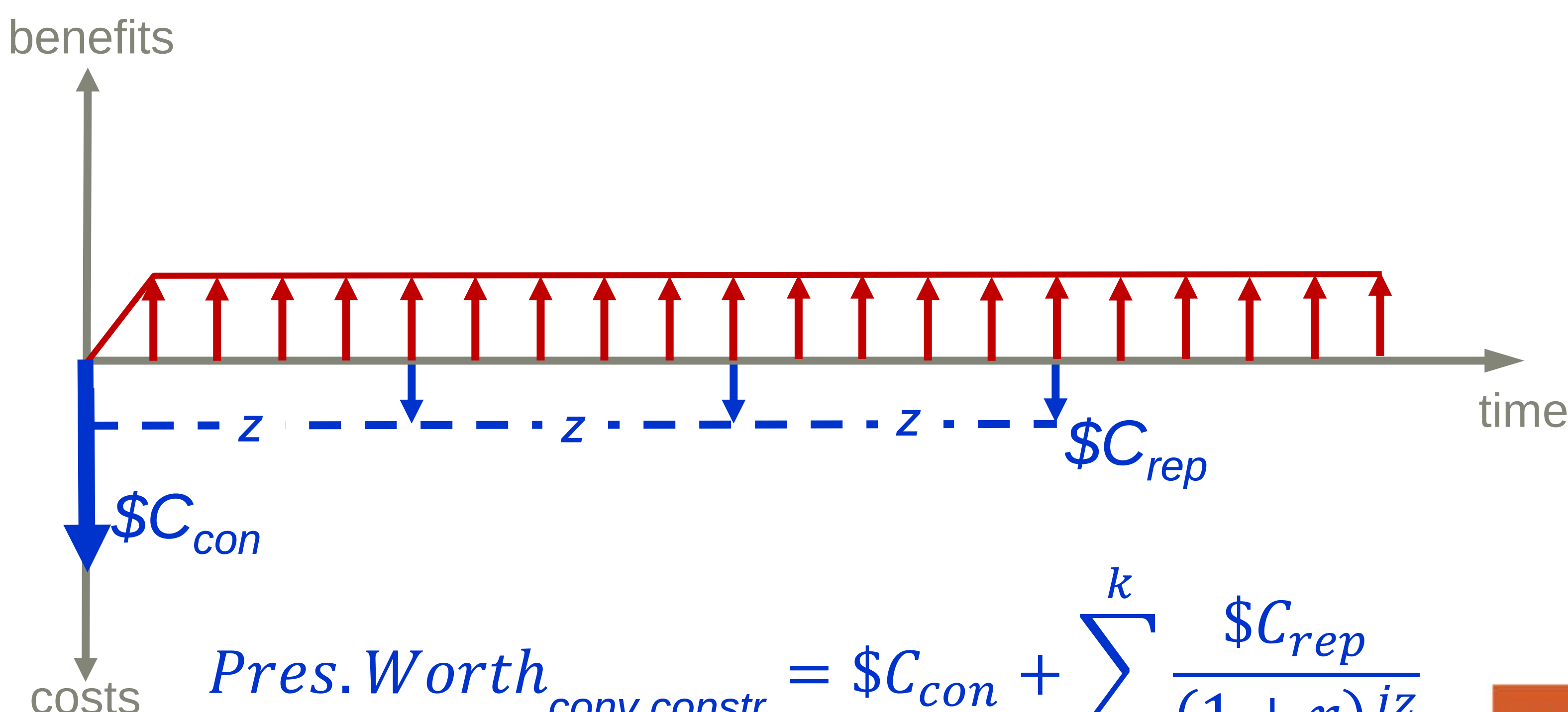
Determining Value

- Is there value for the increased cost of durable materials (i.e., corrosion resisting reinforcement)?



$$Pres.Worth_{conv\ constr} = \$C_{con} + \sum_{j=1}^{k} \frac{\$C_{rep}}{(1+r)^{jz}}$$

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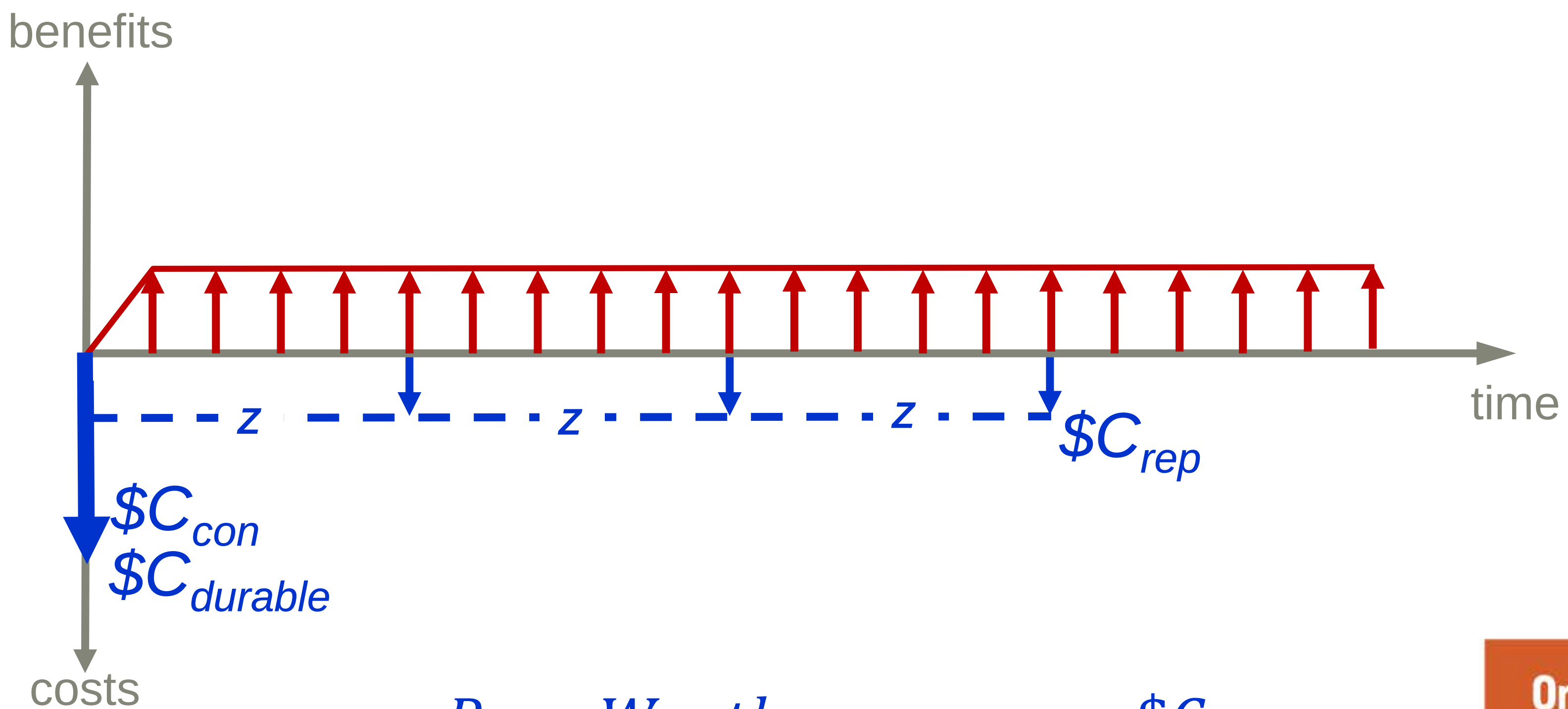
Trejo, D. and Reinschmidt, K., "Justifying Materials Selection for Reinforced Concrete Structures. II: – Economic Analysis," *Journal of Bridge Engineering*, January/February 2007, Vol. 12, No. 1, pp. 38-44.

Determining Value

$$\text{Present Worth}_{\textit{durable construction}} \leq \text{Present Worth}_{\textit{conventional construction}}$$



$$Pres.Worth_{\text{durable constr}} = \$C_{durable}$$

Determining Value

$$\boldsymbol{Present\ Worth_{durable\ constr}} \leq \boldsymbol{Present\ Worth_{conv\ constr}}$$

$$\$\boldsymbol{C_{durable}} \leq \$\boldsymbol{C_{con}} + \sum_{j=1}^{k} \frac{\$C_{repair}}{(1+r)^{jz}}$$

$$\frac{\$\boldsymbol{C_{durable}}}{\$\boldsymbol{C_{con}}} \leq 1 + \frac{\$C_{repair}}{\$\boldsymbol{C_{con}}} \times \sum_{j=1}^{k} \frac{1}{(1+r)^{jz}}$$

Using expansion of a binomial series, where:

$$\sum_{j=1}^{k} x^{j} = \frac{x - x^{k+1}}{1-x}$$

we get:

$$\frac{\$\boldsymbol{C_{durable}}}{\$\boldsymbol{C_{con}}} \leq 1 + \frac{\$C_{repair}}{\$\boldsymbol{C_{con}}} \times \frac{1-(1+r)^{-kz}}{(1+r)^{z}-1}$$

Determining Value

Is there value for the increased cost of durable materials (i.e., corrosion resisting reinforcement)?

$$\frac{\$\boldsymbol{C_{durable}}}{\$\boldsymbol{C_{con}}} \leq 1 + \frac{\$C_{repair}}{\$\boldsymbol{C_{con}}} \times \frac{1-(1+r)^{-kz}}{(1+r)^{z}-1}$$

Base case: $\frac{\$C_{repair}}{\$C_{con}} = 0.2$; SL=90; r=0.07; k= 6; z = 15 years

$$\frac{\$\boldsymbol{C_{durable}}}{\$\boldsymbol{C_{con}}} \leq 1 + \mathbf{0.2} \times \frac{1-(1.07)^{-90}}{(1.07)^{15}-1} = 1.113$$

$$\$\boldsymbol{C_{durable}} = 1.113 \times \$\boldsymbol{C_{con}}$$

The durable materials can cost up to 11.3% of the overall project cost when using conventional material to add value

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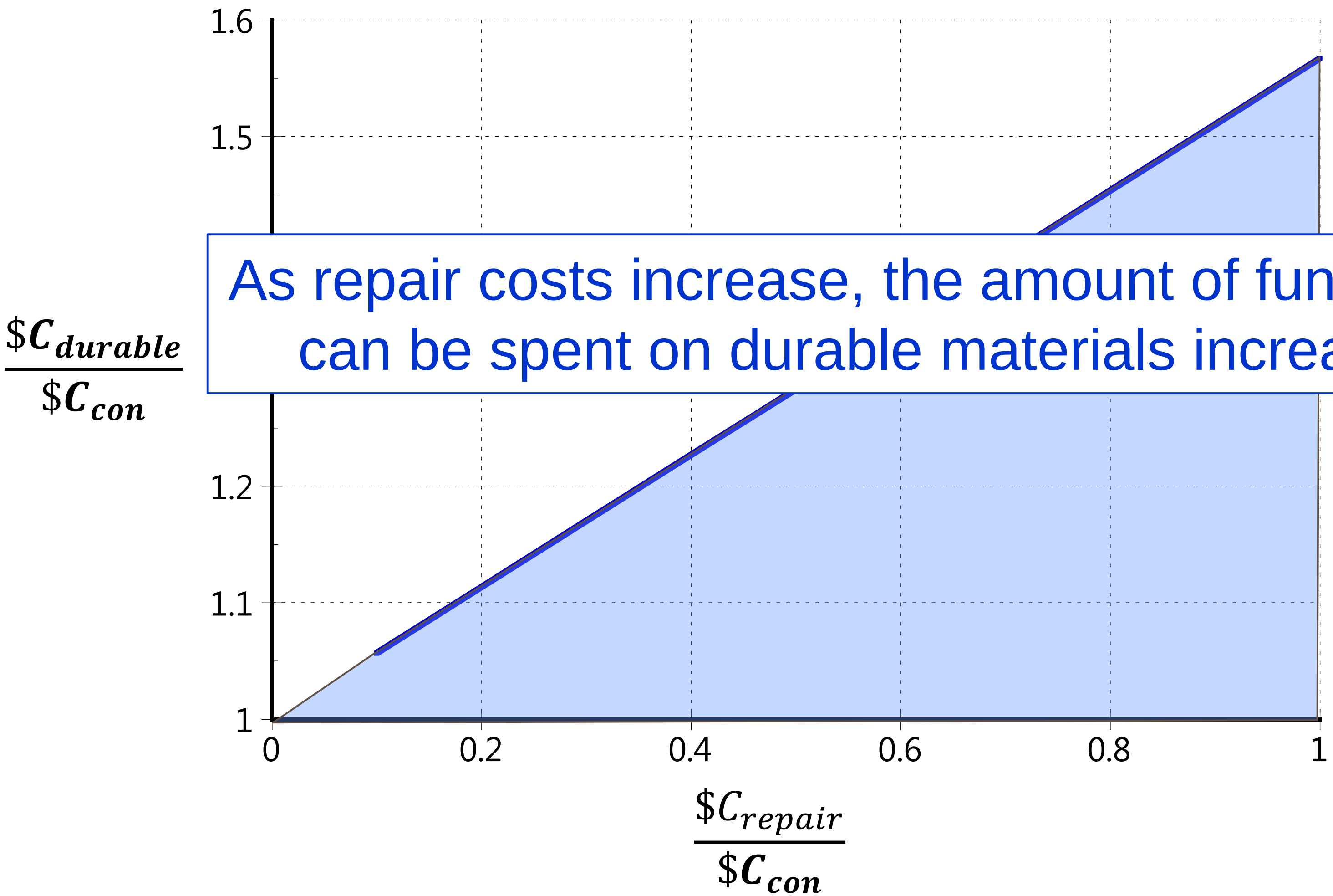
Determining Value

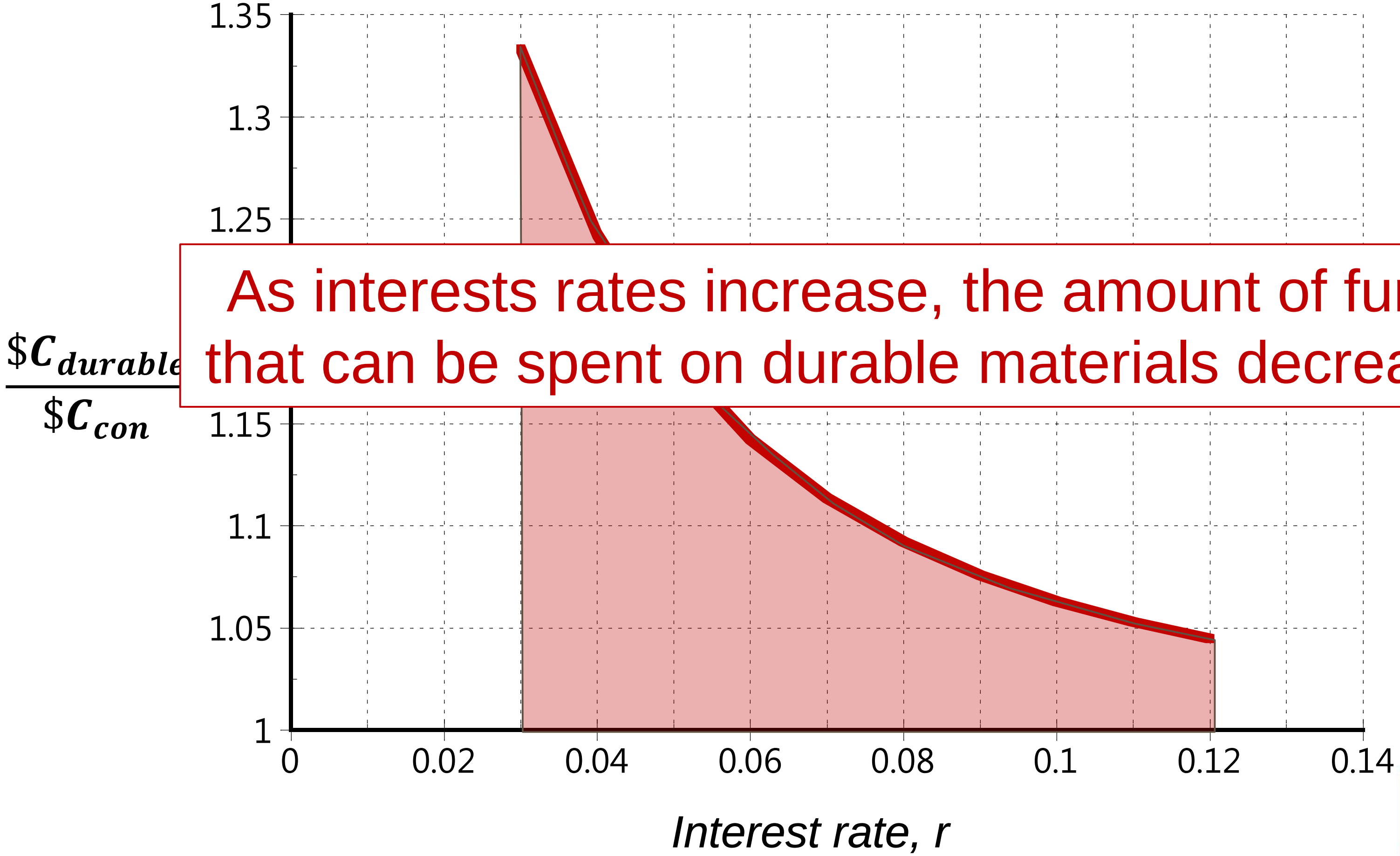
Is there value?



As repair costs increase, the amount of funds that can be spent on durable materials increases

Determining Value

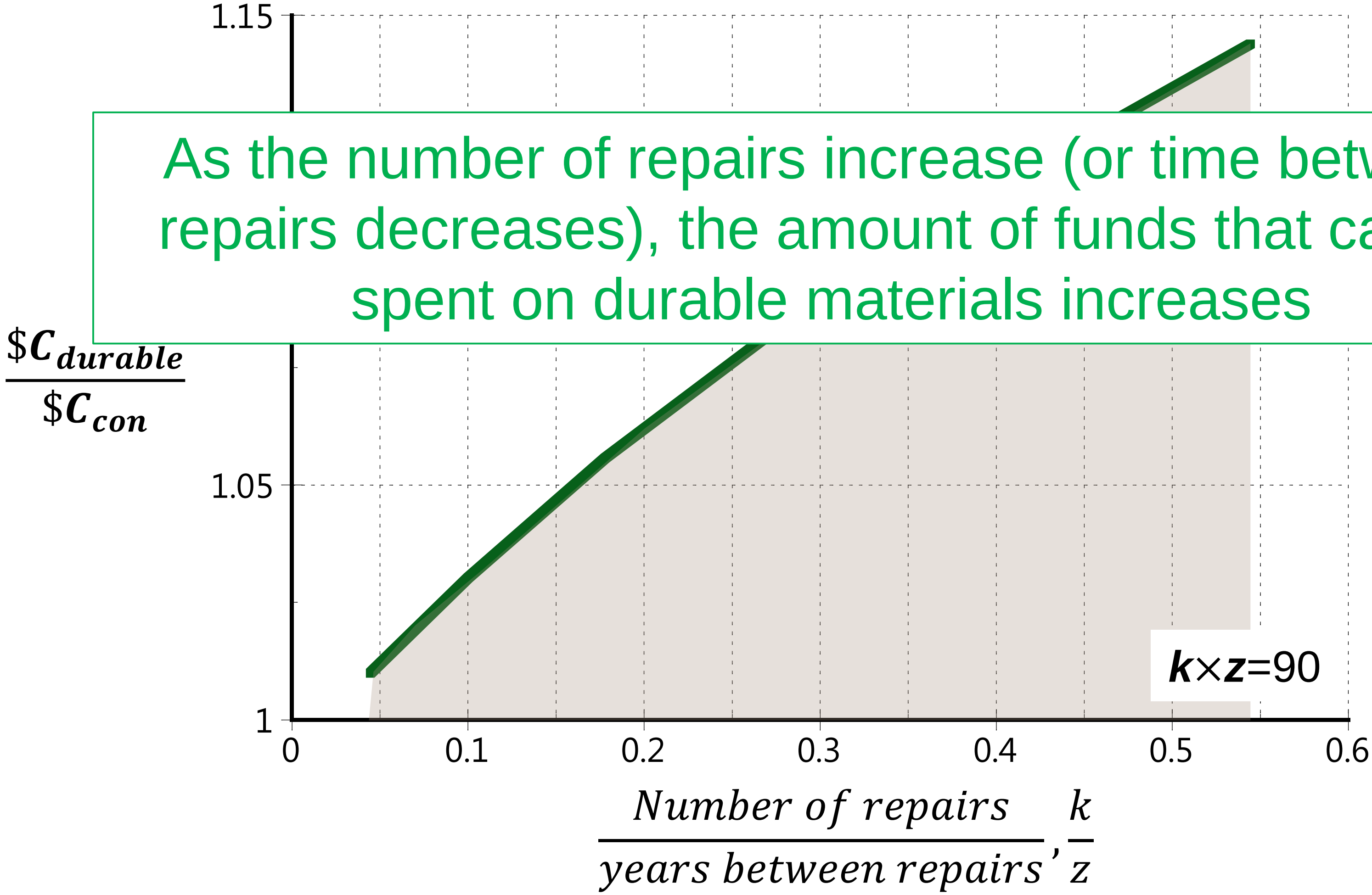
Is there value?



As interests rates increase, the amount of funds that can be spent on durable materials decreases

Determining Value

Is there value?



As the number of repairs increase (or time between repairs decreases), the amount of funds that can be spent on durable materials increases

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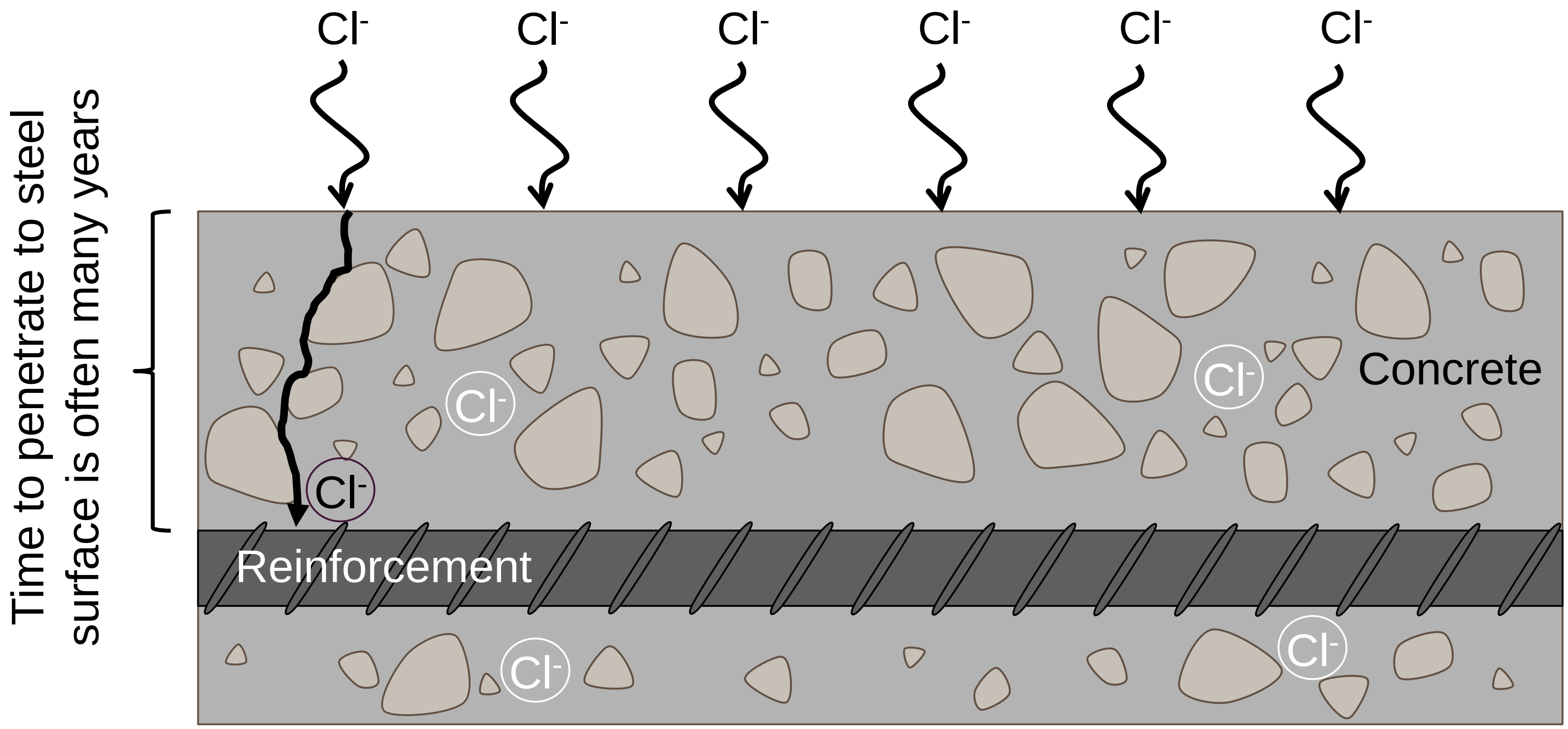
Assessing Value



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Assessing Value

- Time to Corrosion

$$D_a \nabla^2 c = \frac{\partial c}{\partial t}$$ (Simplified; constant D_a; 1D)

$$C(x,t) = C_s - (C_s - C_i) \cdot erf\left(\frac{x}{\sqrt{4 \cdot D_a \cdot t}}\right)$$

C_s = concentration of chlorides at surface of concrete (mass %)
C_i = concentration of chlorides in fresh concrete, aka background chlorides, (mass %)
x = depth below concrete surface, *m*
D_a = apparent diffusion coefficient, m^2/s
t = exposure time, *s*

If we force the chloride concentration at time *t* and depth *x* to be the chloride concentration at time *t* that initiates active corrosion (critical chloride threshold, C_T), the time to corrosion can be determined as follows:

$$t_{corr} = \frac{\left[\frac{x}{inverf\left[\frac{C_S - C_T}{C_S - C_i}\right]}\right]^2}{4D_a}$$

Assessing Value

- Determining Time to Corrosion

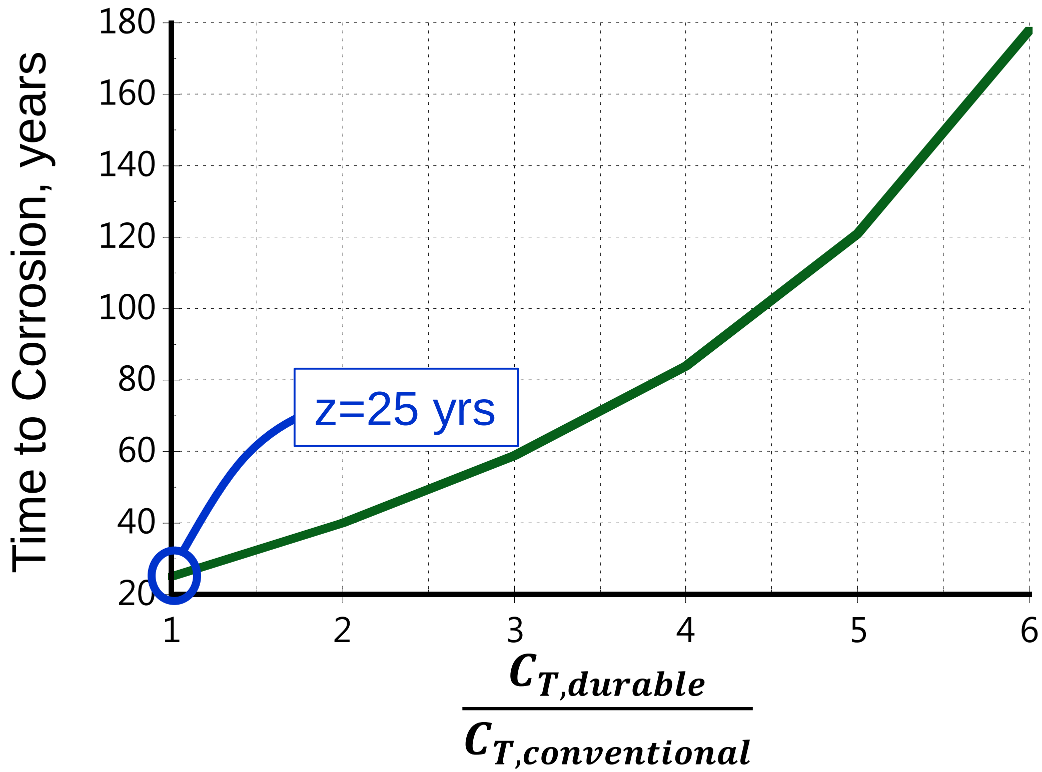
$$t_{corr} = \frac{\left[\dfrac{x}{inverf\left[\dfrac{C_S - C_T}{C_S - C_i}\right]}\right]^2}{4D_a}$$

Characteristic of reinforcing bar

$$\frac{C_{T,durable\,rebar}}{C_{T,conventional\,rebar}}$$

Assessing Value

- Time to Corrosion for Different Durable Reinforcing Steels



$$\boldsymbol{k} = Roundup\left\{\frac{TTC_x}{TTC_1}\right\} - 1$$

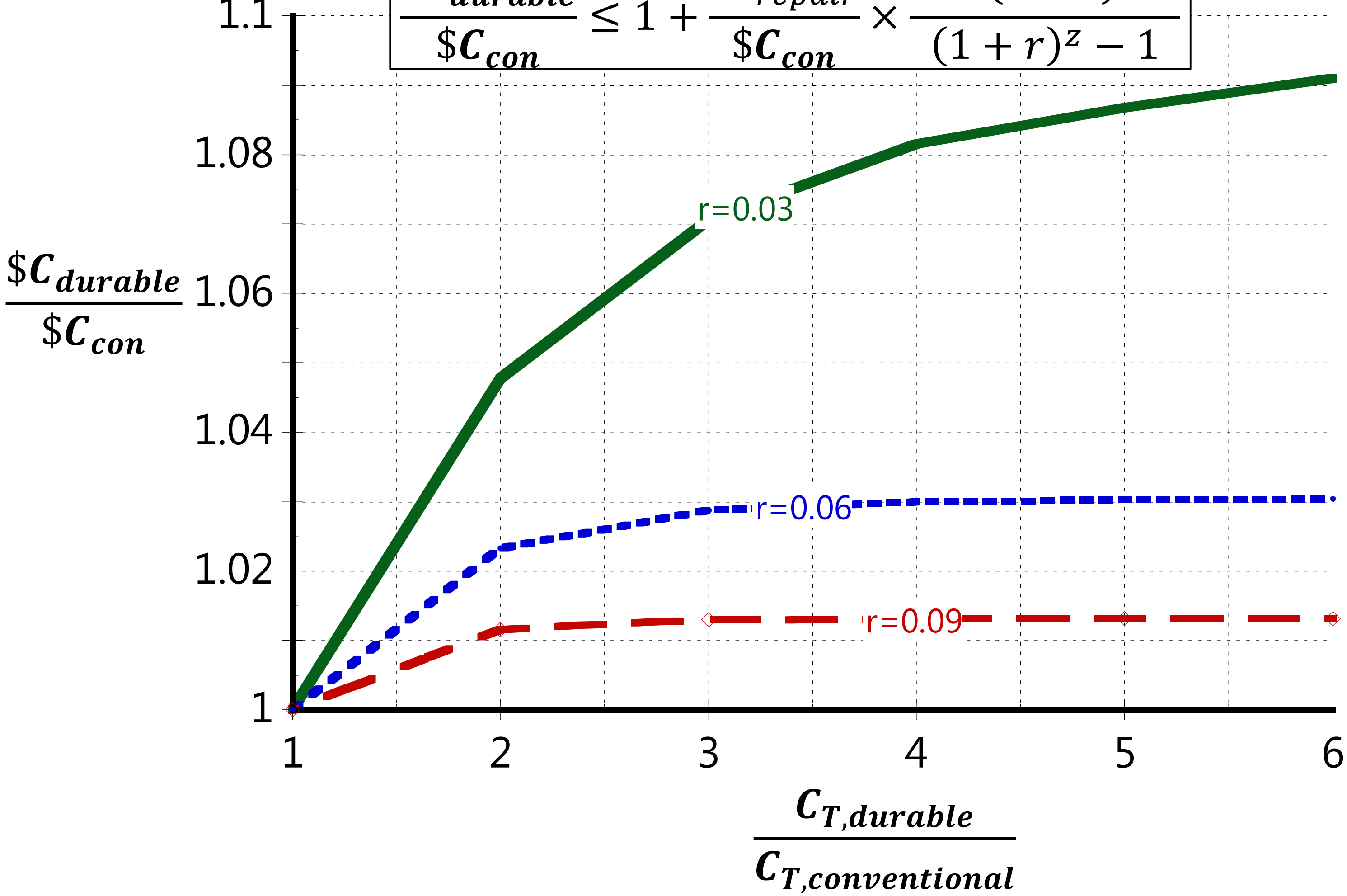
$$TTC = time\ to\ corrosion$$

$$\frac{\$\boldsymbol{C}_{\boldsymbol{durable}}}{\$\boldsymbol{C}_{\boldsymbol{con}}} \leq 1 + \frac{\$C_{repair}}{\$\boldsymbol{C}_{\boldsymbol{con}}} \times \frac{1-(1+r)^{-kz}}{(1+r)^{z}-1}$$

Assessing Value

- Determining maximum value of using durable reinforcement

$$\frac{\$C_{durable}}{\$C_{con}} \leq 1 + \frac{\$C_{repair}}{\$C_{con}} \times \frac{1-(1+r)^{-kz}}{(1+r)^{z}-1}$$



Assessing Value

EXAMPLE

- RC structure using conventional steel to be constructed for $10M.
- A corrosion-resistant reinforcement is available with $\frac{C_{T,durable}}{C_{T,conventional}}$ =3;
- r=3%;

Which reinforcement to chose?

This method determines the maximum that should be spent on the corrosion-resistant reinforcement assuming the properties of that reinforcement; this process can be used for different reinforcement and results can be compared.

$\frac{C_{T,durable}}{C_{T,conventional}}$	Time to Corrosion, yrs	$\frac{\$C_{durable}}{\$C_{con}}$		
		r=0.03	r=0.06	r=0.09
1	25	1	1	1
2	40	1.0478	1.0233	1.0116
3	59	1.0706	[illegible]	[illegible]
4	84	1.0815	[illegible]	[illegible]
5	[illegible]	[illegible]	[illegible]	[illegible]
6	[illegible]	[illegible]	[illegible]	[illegible]

$\frac{\$C_{durable}}{\$C_{con}} = 1.0706$

$\$C_{durable} = 1.0706 \times \$C_{con} = 1.0706 \times \$10M =$ **$10.71M**

Up to $710,000 can be spent on the corrosion-resistant steel reinforcement

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Some Data on CT for Steel Reinforcing Bars

Published Critical Chloride Threshold Values

System	Binder	w/b	Steel Type	Steel surface condition	Measured C_T (% wt. binder)	Ref.
concrete	100% OPC	0.4	ribbed	cleaned	0.6 – 1.2	(Locke & Siman, 1980)
concrete	100% OPC	0.45	smooth	cleaned	0.2 – 0.4	(Hope & Ip, 1987)
concrete	100% OPC	0.5	ribbed	as received*	0.5-1	(Schießl & Breit, 1996)
concrete	50% OPC + 50% GGBS	0.5	ribbed	as received*	1.0 – 1.5	(Schießl & Breit, 1996)
concrete	76% OPC + 24% FA	0.5	ribbed	as received*	1.0 – 1.5	(Schießl & Breit, 1996)
concrete	85% OPC + 15% FA	0.52	ribbed	as received*	0.54-0.74	(Thomas, 1996)
concrete	70% OPC + 30% FA	0.46	ribbed	as received*	0.42-0.58	(Thomas, 1996)
concrete	50% OPC + 50% FA	0.37	ribbed	as received*	0.18-0.22	(Thomas, 1996)
concrete	85% OPC + 15% FA	0.45	smooth	as received*	0.85-0.95	(Oh et al., 2003)
concrete	70% OPC + 30% FA	0.45	smooth	as received*	0.63-0.74	(Oh et al., 2003)
concrete	100% OPC	0.45	smooth	cleaned	0.52 – 0.74	(Nygaard & Geiker, 2005)
concrete	90% OPC +10% SF	0.6	smooth	cleaned	0.6 – 1.2	(Manera et al., 2008)

* Assumed because the surface condition was not reported

Shakouri, M. and Trejo, D., “Estimating the Critical Chloride Threshold for Conventional Reinforcing Steel in Concrete Using a Hierarchical Bayesian Model,” Journal of Sustainable and Resilient Infrastructure, Dec 2017

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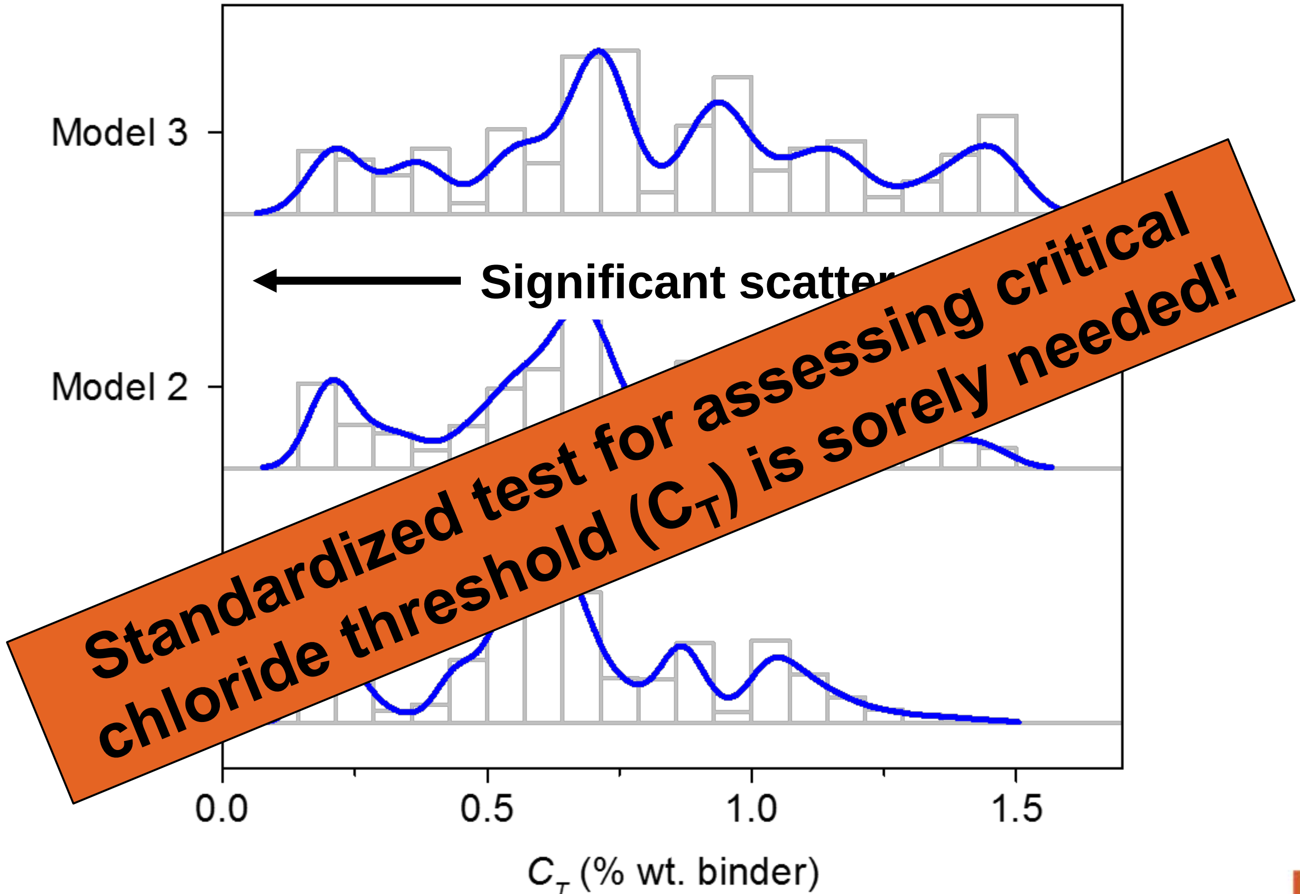

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Summary

- Determining whether a durable reinforcing steel should be used or not will depend on the value that that reinforcement provides
- A economic assessment method is available to determine the maximum increase in cost when considering a durable reinforcing steel
- Standard service-life models can be used to generate data such that the maximum cost increase can be determined; if reinforcement costs exceed this maximum cost, there is limited value for using such reinforcement
- One key need for predicting added-value of corrosion-resistant reinforcement is standardized testing for assessing the critical chloride threshold

Thank you!

Questions?