Predicting Concrete Permeability for Service Life Models

Bruno Fong-Martinez, PhD
Concrete Engineer, Kiewit (Denver, CO)

ACI Fall 2023 Boston Convention (10.31.23)

BACKGROUND

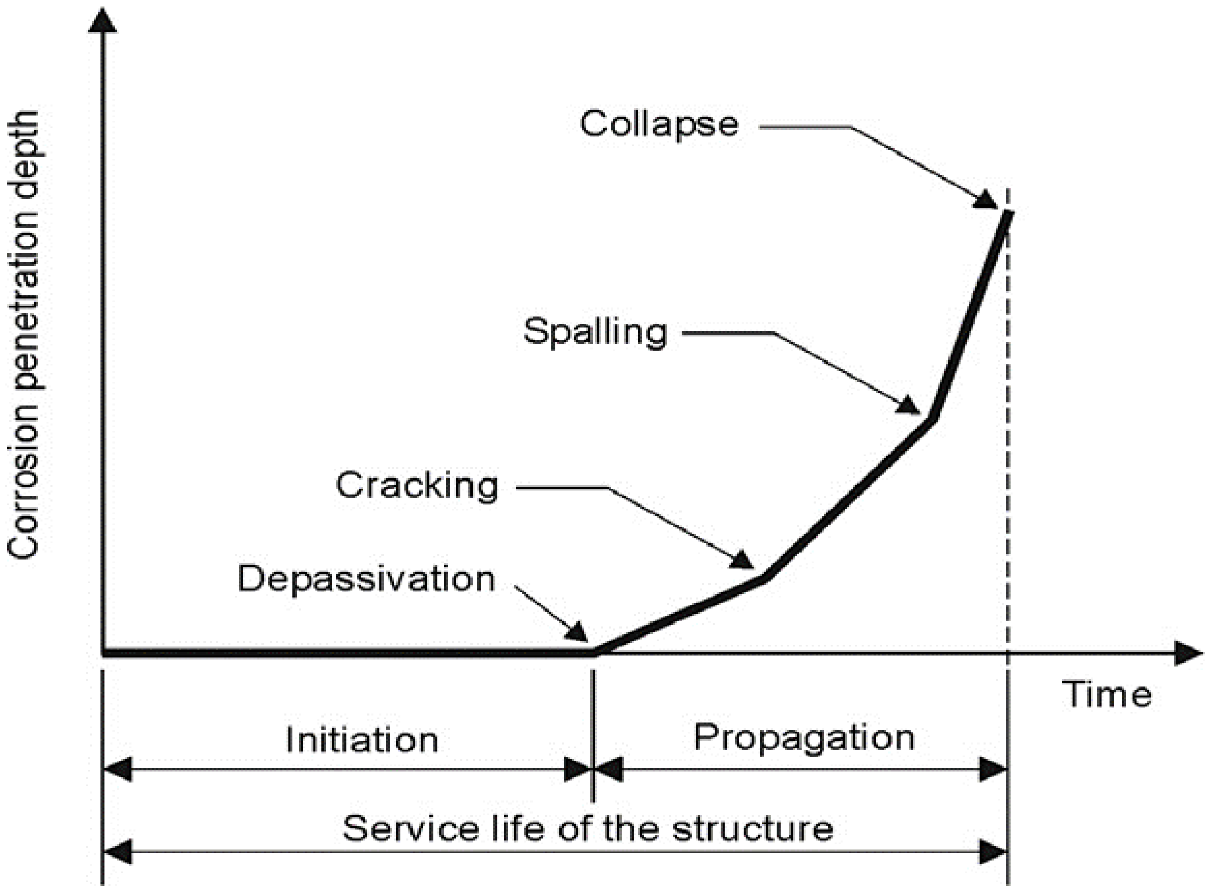
DURABILITY & SERVICE LIFE TODAY

Industry Trends

- 100-year service life (chloride-induced corrosion)
- Sustainability, resiliency, and economic factors
  Total Cost = Construction + Maintenance/Repair

Challenges

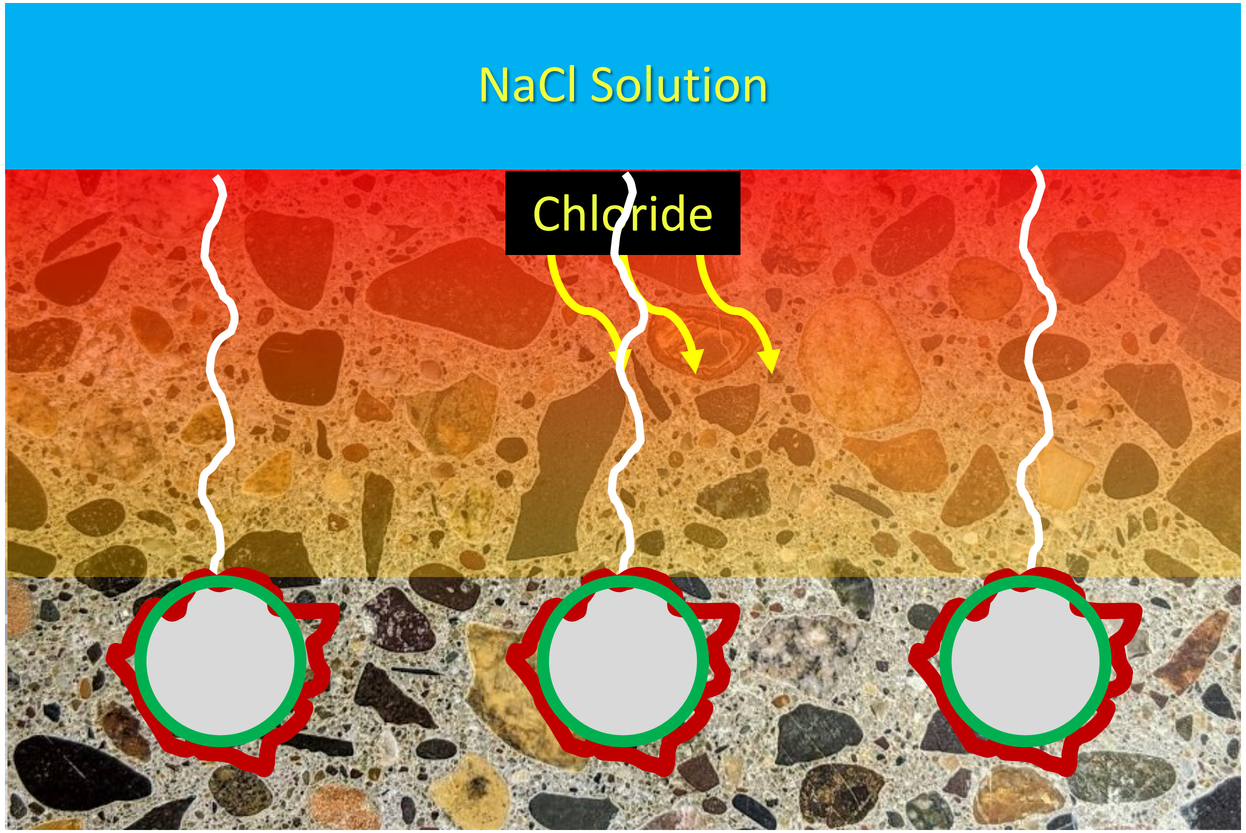
- Design code deficiencies
  Focus on chloride-induced corrosion
  ***Lack of standardization for service life design**
- Multiple variables and factors
  Durability mechanisms
  Exposure conditions
  ***Available materials**



(Bertolini et al., 2013)

CORROSION MECHANISM

(Chloride-Induced)



Permeability

Chloride Threshold

SERVICE LIFE MODEL INPUTS

Property	Purpose	Testing	
		Duration	Methods
Permeability	Quantifies resistance to fluid penetration	~1-3 months	Diffusion ASTM C1556
			Migration NT Build 492

SERVICE LIFE MODEL INPUTS

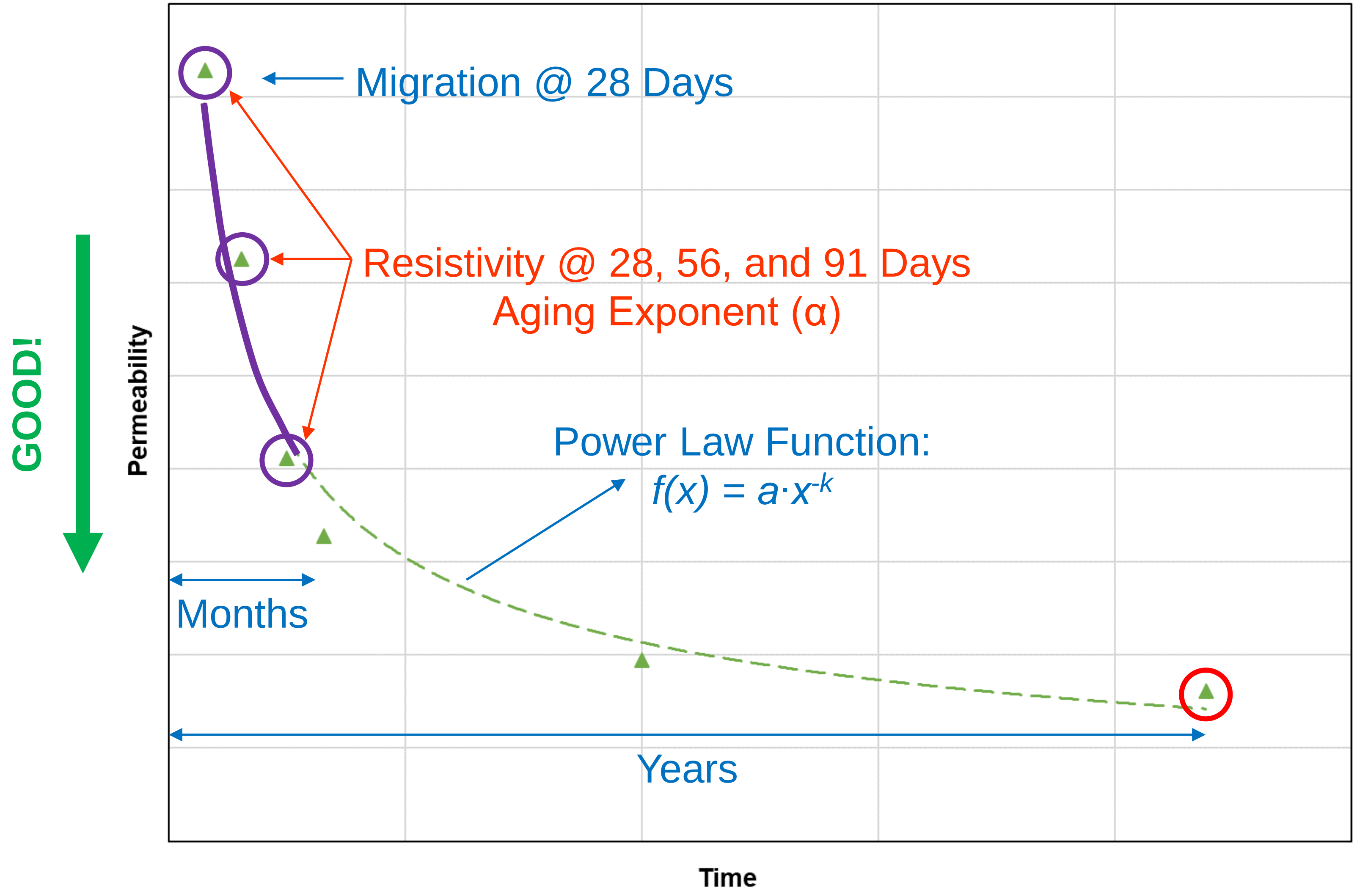
Property	**Purpose**	**Testing**	
		Duration	Methods
Permeability	Quantifies resistance to fluid penetration	~1-3 months	Diffusion ASTM C1556
			Migration NT Build 492
Aging Exponent (α)	Models drop in permeability with time	~ 3 months	Bulk Resistivity ASTM C1876
			RCPT ASTM C1202

Permeability and Aging Exponent are mostly influenced by w/cm ratio, SCM type, and % replacement

Used for **fib 34** model

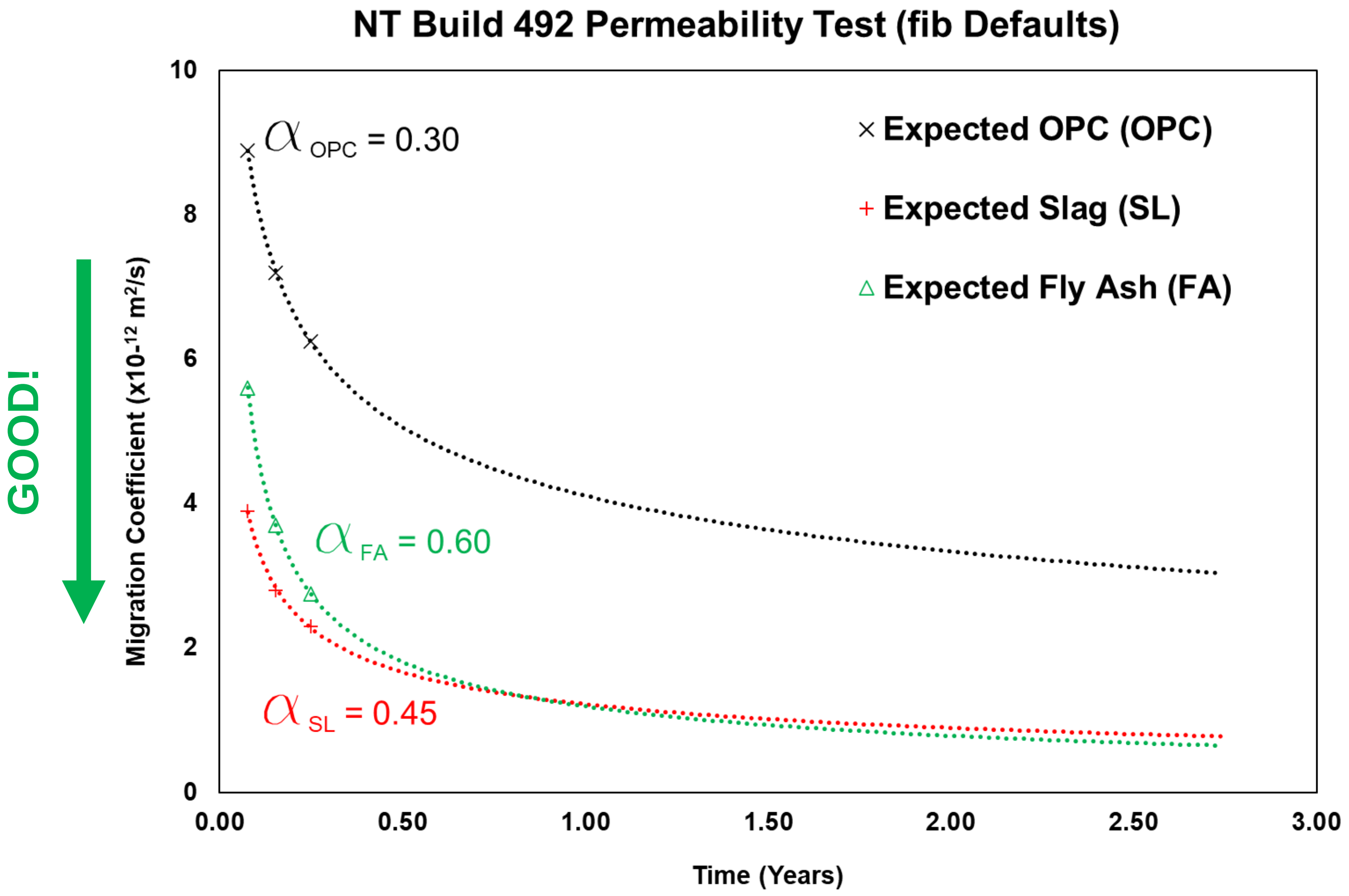
$$Conductivity = \frac{1}{Resistivity}$$

PERMEABILITY



FIB 34 DEFAULT AGING EXPONENTS (α)

0.40 w/cm | 50% Slag | 25% Fly Ash



TAKEAWAYS

- α: 0.30 – 0.60
- FA > SL > OPC
- Exponent → Rapid decay
- Full behavior takes year(s)
- 91-day results very preliminary (0.25% of 100-year life!)

CASE STUDIES

OUTLINE

Project	Location	Cement	SCM
I	West Coast	Type I/II	Fly Ash Class F 20-45%
II	East Coast	Type I/II	Slag Grade 120 50-60%
III	East Coast	Type I/II	Slag Grade 120 50-60%

NOTES

Recent Mega Projects ($ Billions)

- Data within last two years
- Extraordinary level of oversight and resources

Data Collection and Analysis

- Reputable labs involved and facilities inspected
- Sampling and storage procedures inspected onsite
- Checked for outliers in data
- Unusual results validated by multiple labs

SAMPLE TEST MATRIX

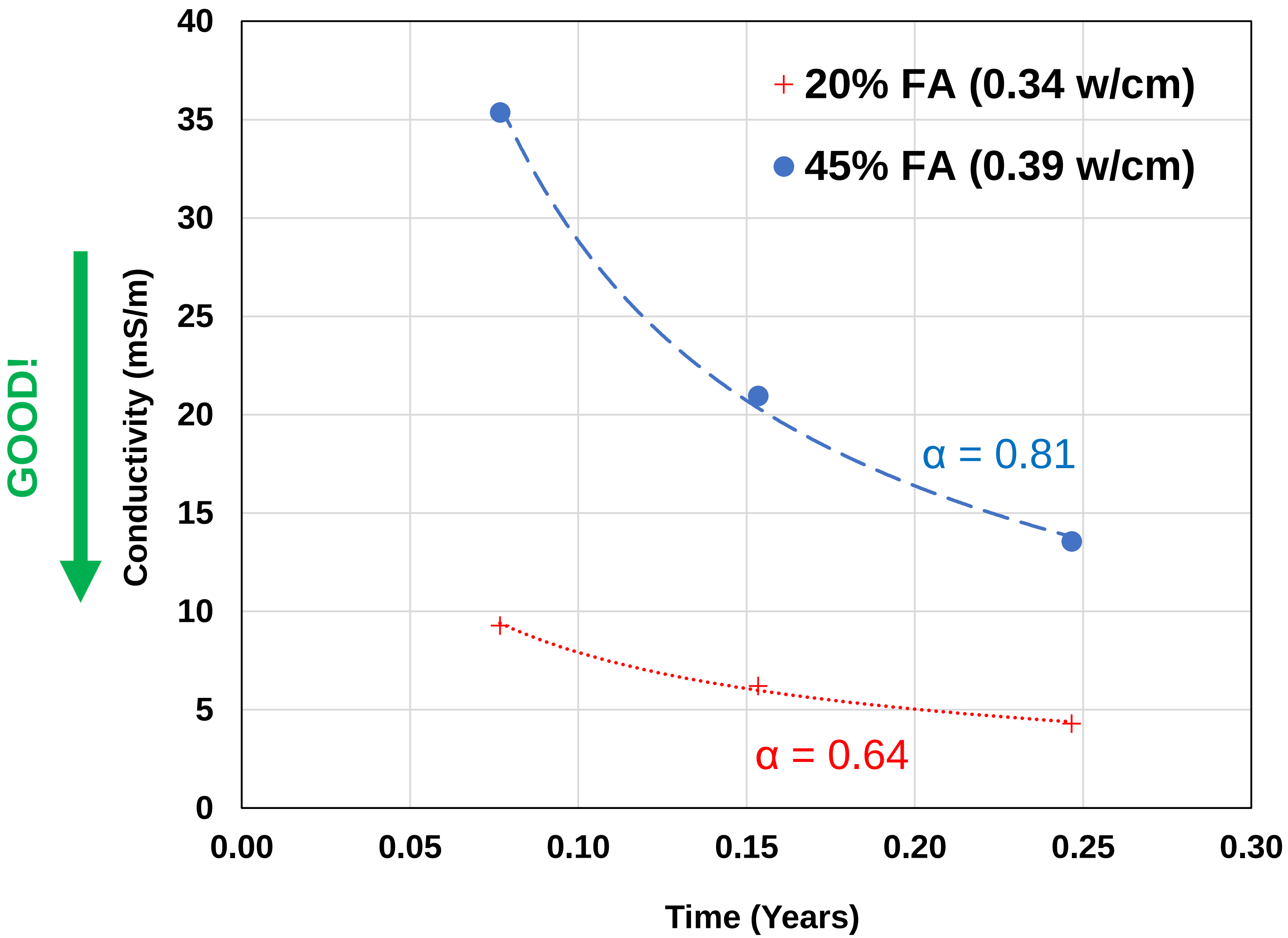
Mix - Marine and Mass Concrete Samples					
Laboratory	Test	Standard	Sample Type	Details	# Samples
A	Compression	ASTM C39	4x8 Cylinders	Test at 1, 3, 7, 14, 21, 28, 56, and 91 days. Three cylinders per test age.	24
	Maturity	ASTM C1074	4x8 Cylinders	2 cylinders with temperature sensors	2
	Drying Shrinkage	ASTM C157	3x3x11.25 Prism	Start drying exposure after 28 days of curing	3
	Freeze Thaw	ASTM C666	3x4x16 Prism	Start freeze-thaw cycles after 28 days of curing	3
	Tensile	ASTM C39	4x8 Cylinders	Test at 3, 7, 14, 28, and 91 days. Two cylinders per test age.	10
	Elastic Modulus	ASTM C469	4x8 Cylinders	Test at 3, 7, 14, 28, and 91 days. Two cylinders per test age.	10
	Chloride	ASTM C1152	4x8 Cylinders	One sample	1
	Extra	N/A	4x8 Cylinders	N/A	3
B	CoTE	COE CRD-C 39	3x3x11.25 Prism	Test at earliest convenience	3
	RCPT	ASTM C1202	4x8 Cylinders	Room temp. Test at 28, 56, and 91 days. Two cylinders per test age.	6
	Migration Coefficient	NT Build 492	4x8 Cylinders	Test at 28, 56, and 91 days. Three cylinders per test age.	9
	Resistivity	ASTM C1876	4x8 Cylinders	Room temp. Test at 28, 56, and 91 days. Same specimens tested at various ages.	3
	Hardened Air	ASTM C457	4x8 Cylinders	Test at earliest convenience	3
	Extra	N/A	4x8 Cylinders	N/A	3

INVOLVEMENT (1 MIX)

- 3-6 months
- ~100 samples
- ~$50k testing alone
- Lab and Field settings
- Multiple labs (shipping)

PART I – MAKES SENSE

RESISTIVITY VALUES (90 DAYS)



TAKEAWAYS

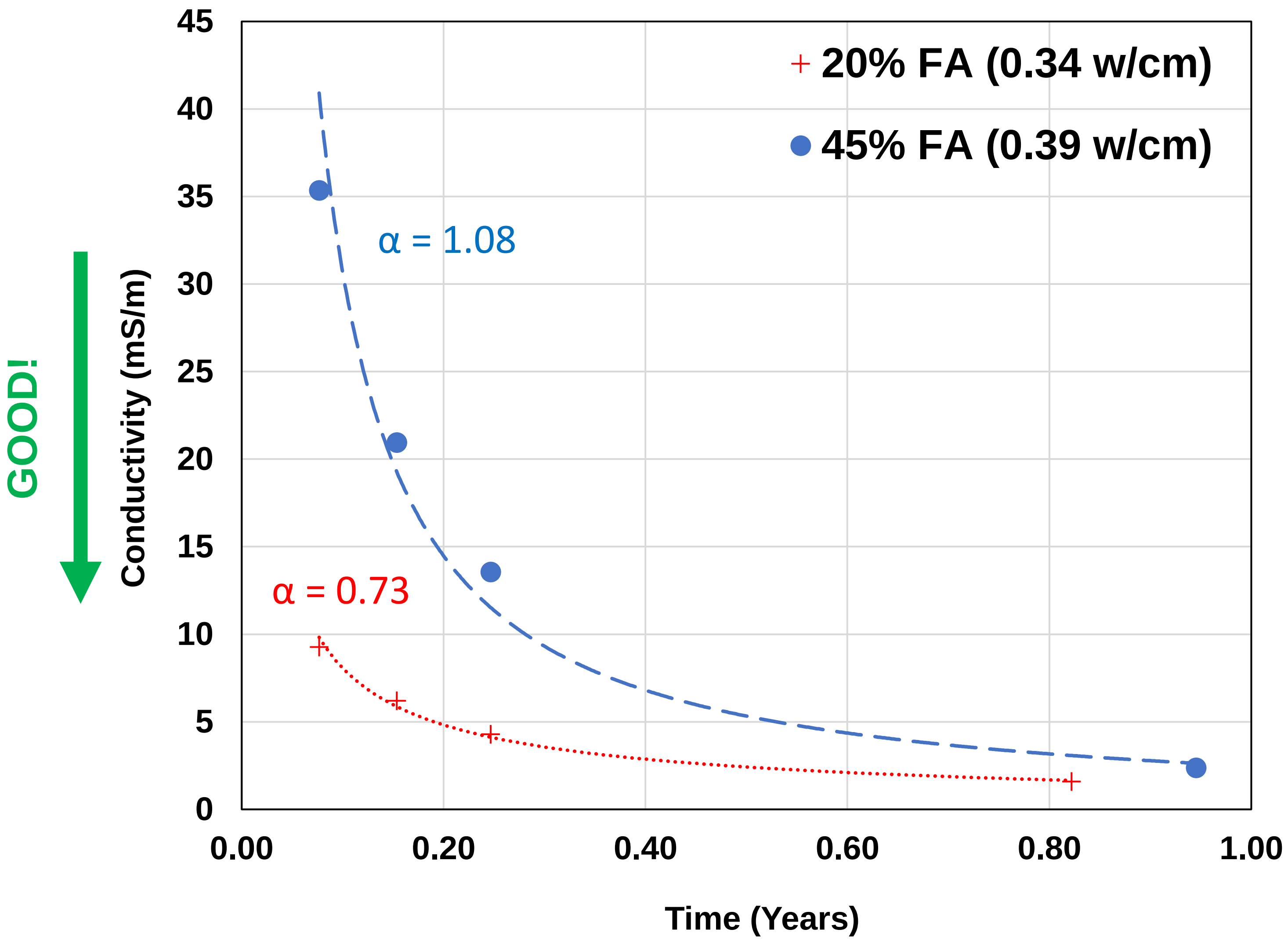
- Higher FA% → Higher α
- w/cm affects early permeability
- High α values (>0.60)

QUESTIONS

1. Should α be capped?

   <u>Are values artificially high because of 'early-age' measurements?</u>

RESISTIVITY VALUES (~1 YEAR)



QUESTIONS

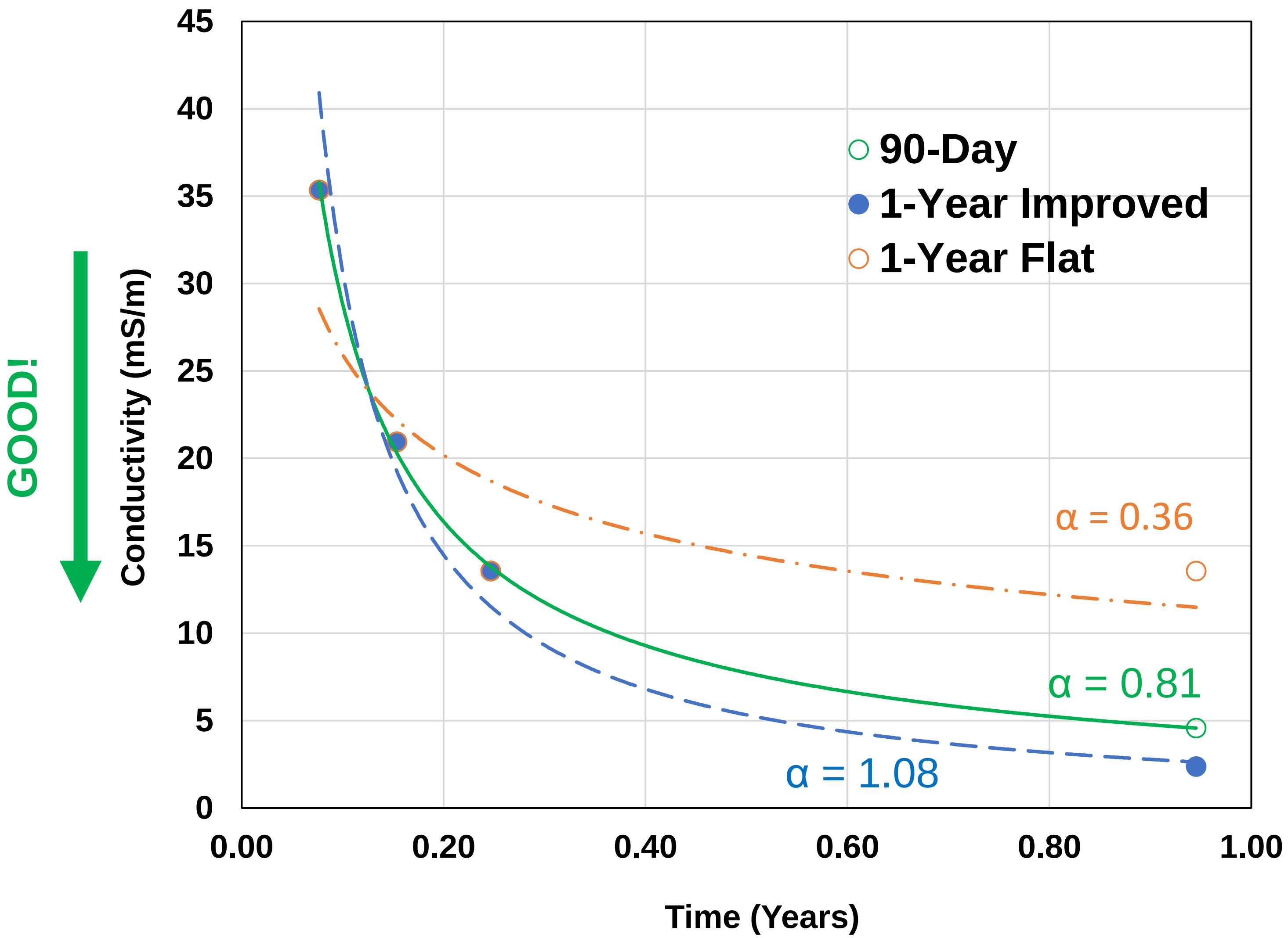
1. Should α be capped?

   Are values artificially high because of ‘early-age’ measurements?

   Maybe not…

   Higher α at 1-year (in this case)

RESISTIVITY VALUES (~1 YEAR)



QUESTIONS

2. When should α be determined?

   Potentially big difference between actual and expected values! (Schrödinger's Aging Coefficient)

   1-year results shockingly consistent (in this case)

AGING COEFFICIENTS

Aggregate	FA%	Setting	α	
			90-Day	*~1-Year*
A	20	Lab	0.64	0.73
B	20	Lab	0.31	0.58
C	20	Lab	0.43	0.58

AGING COEFFICIENTS

Aggregate	FA%	Setting	α	
			90-Day	*~1-Year*
A	20	Lab	0.64	0.73
B	20	Lab	0.31	0.58
C	20	Lab	0.43	0.58
A	45	Lab	0.81	1.08
A	45	Field	1.00	1.08
B	45	Lab	0.64	0.93
B	45	Field	0.74	0.93

PART I QUESTIONS

1. Should α be capped?

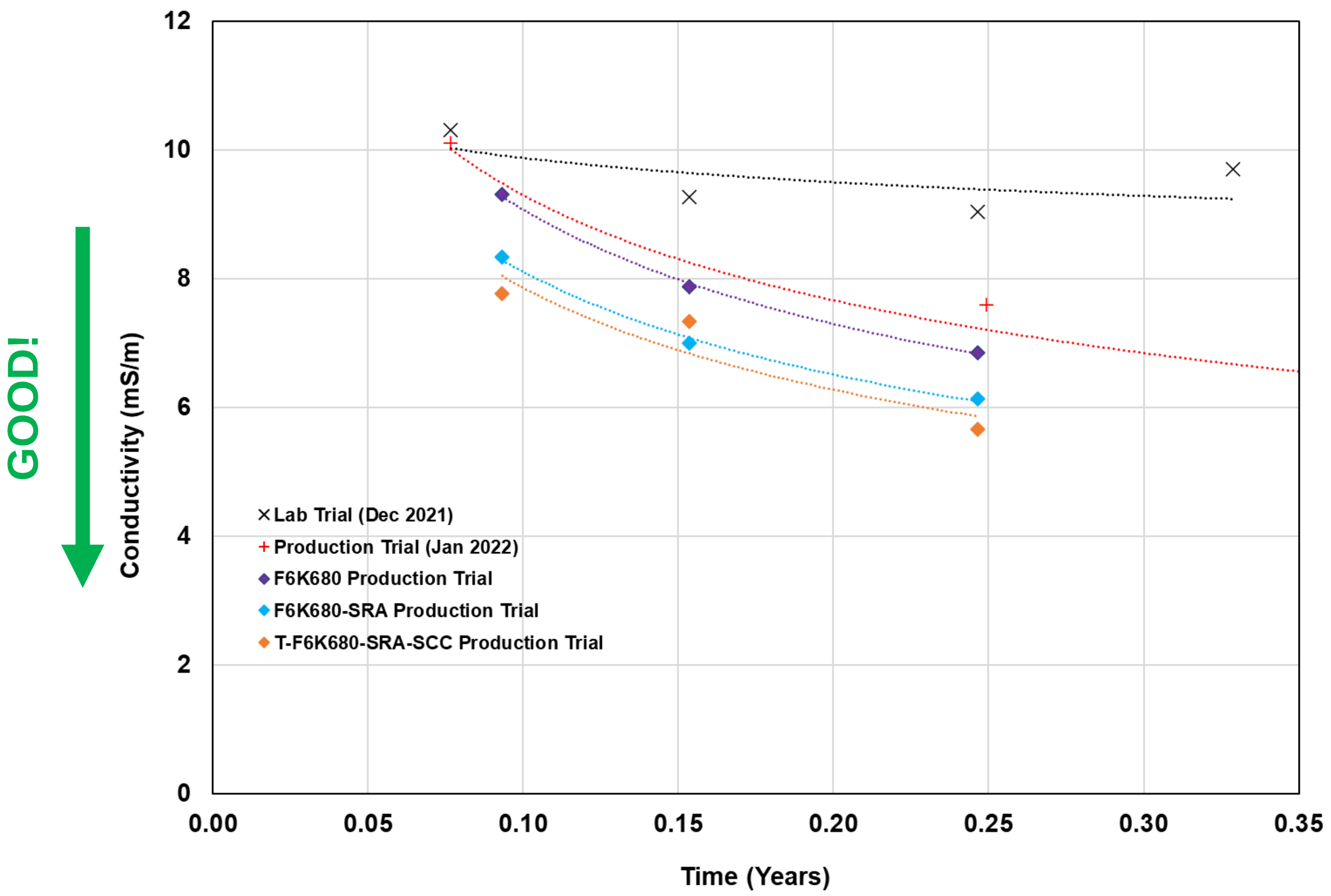
2. When should α be determined?

PART II – STOP MAKING SENSE

PROJECT TIMELINE

Lab Trials (Fall 2021) → Production Trials (April 2022) → Mock-Ups (Sep 2022) → Placements (Dec 2022 - Present)

RESISTIVITY
0.40 w/cm | 50% SLAG

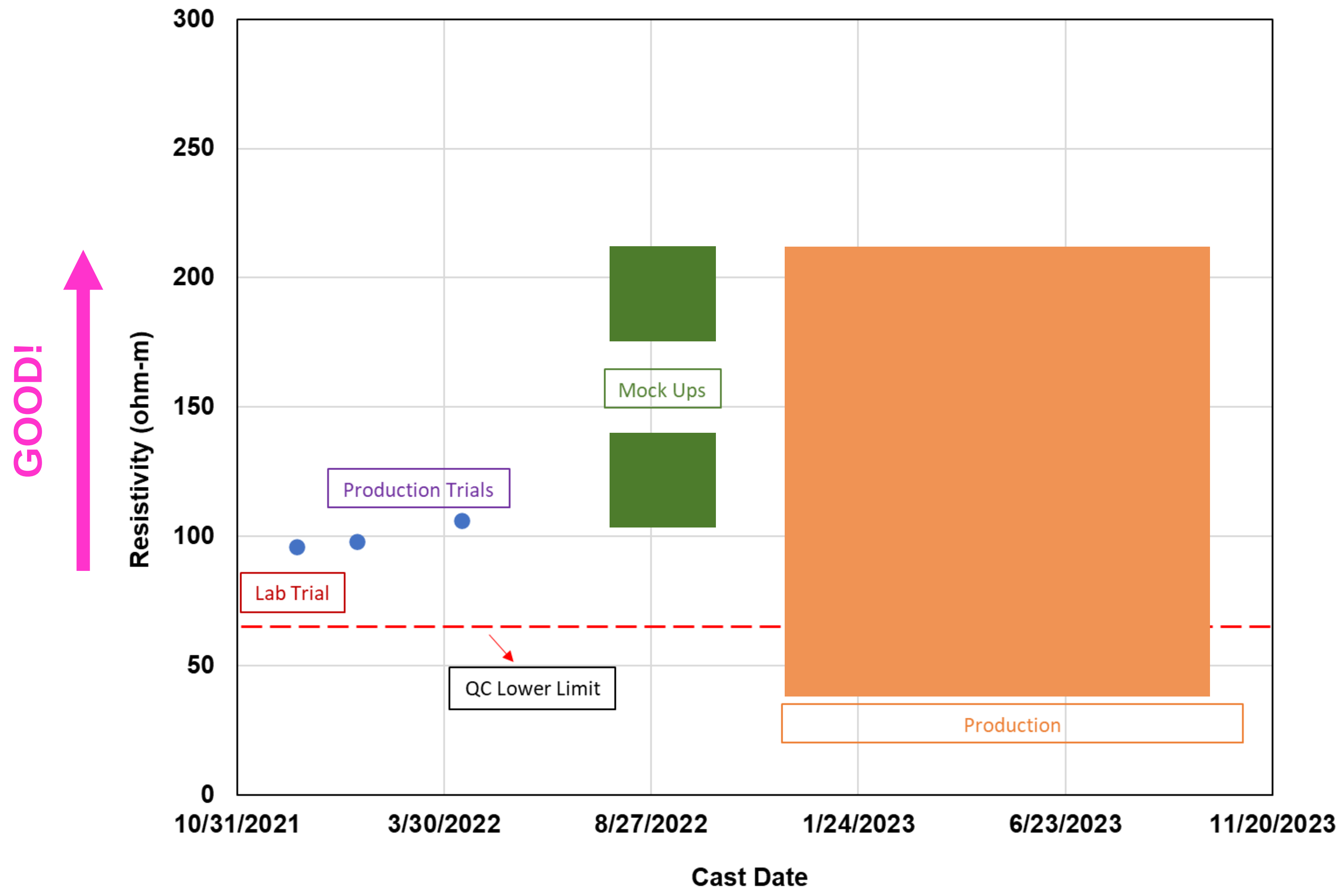


Cast Date	Location	α 90 Days
12/13/21	Lab Trial	0.11
01/26/22	Field Trial	0.25
04/12/22		0.31
04/12/22		0.31
04/12/22		0.32

TAKEAWAYS

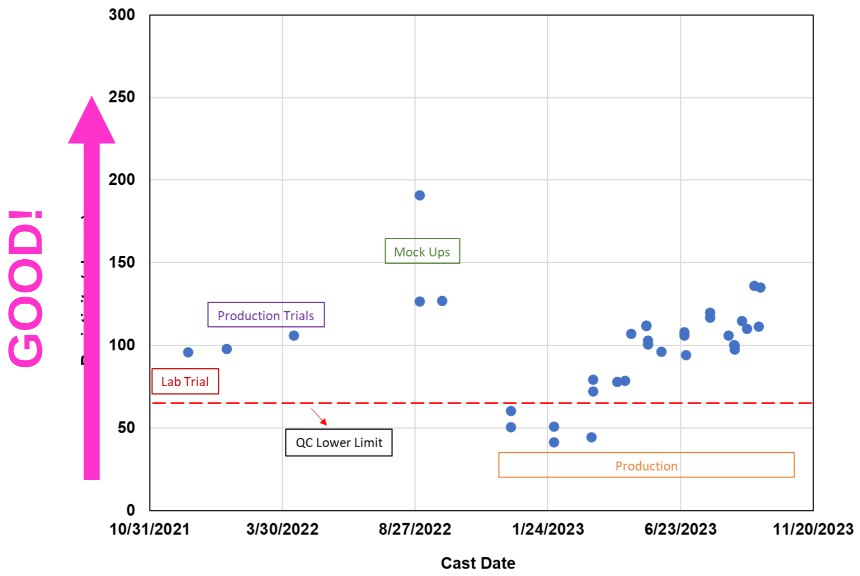
- Slag seemingly behaving like cement (α~0.30)
- 90-day α same as 9-month α
- Unremarkable but consistent results

28-DAY RESISTIVITY

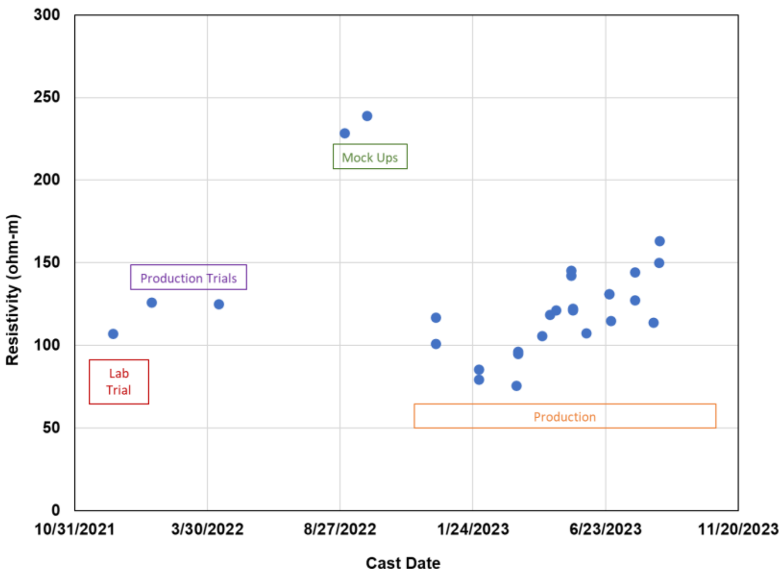


RESISTIVITY AT MULTIPLE AGES

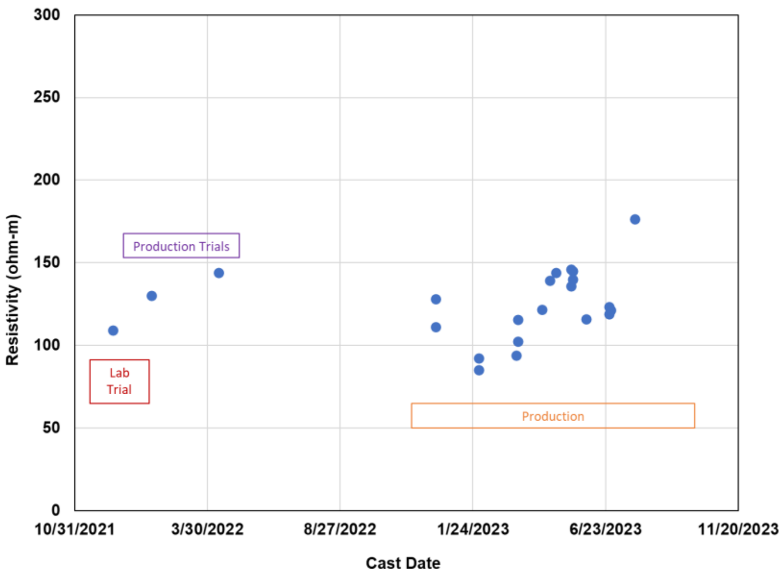
28 Days



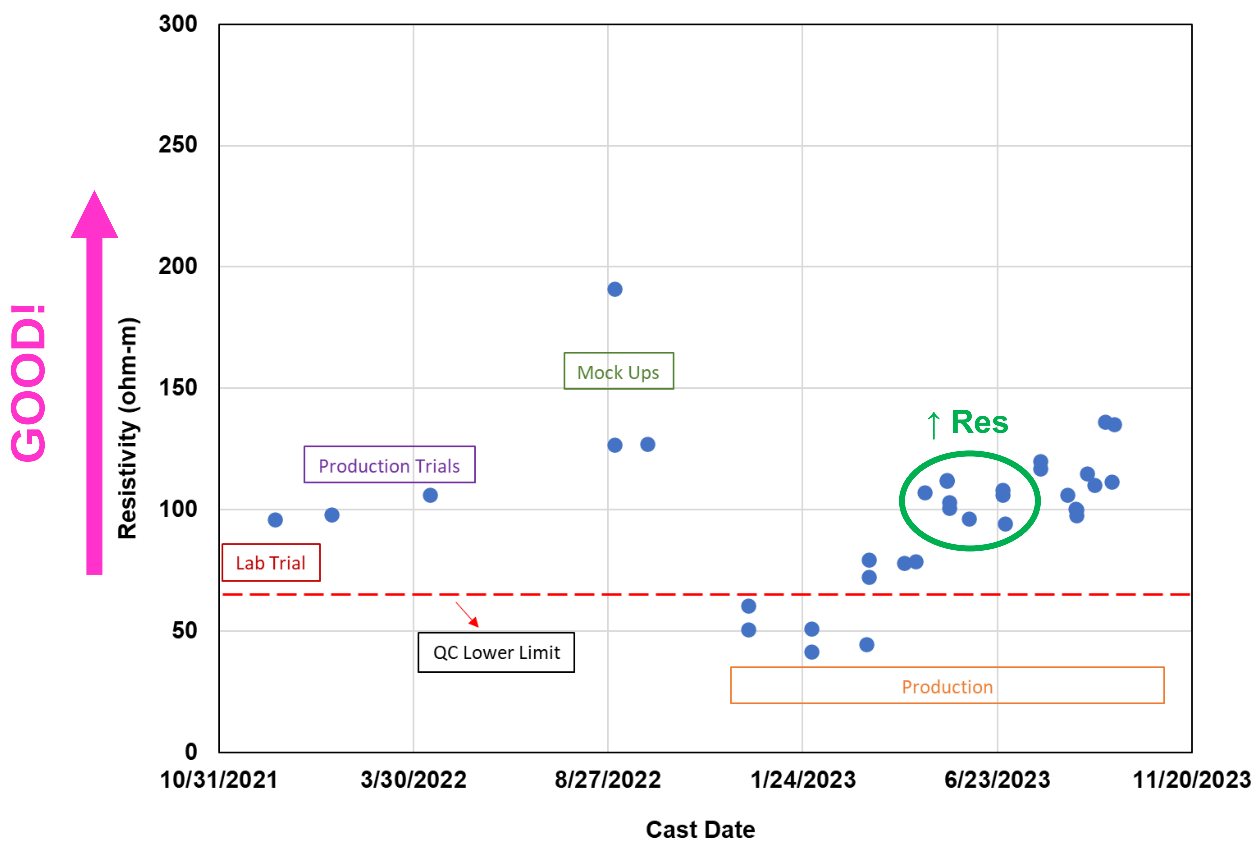
56 Days

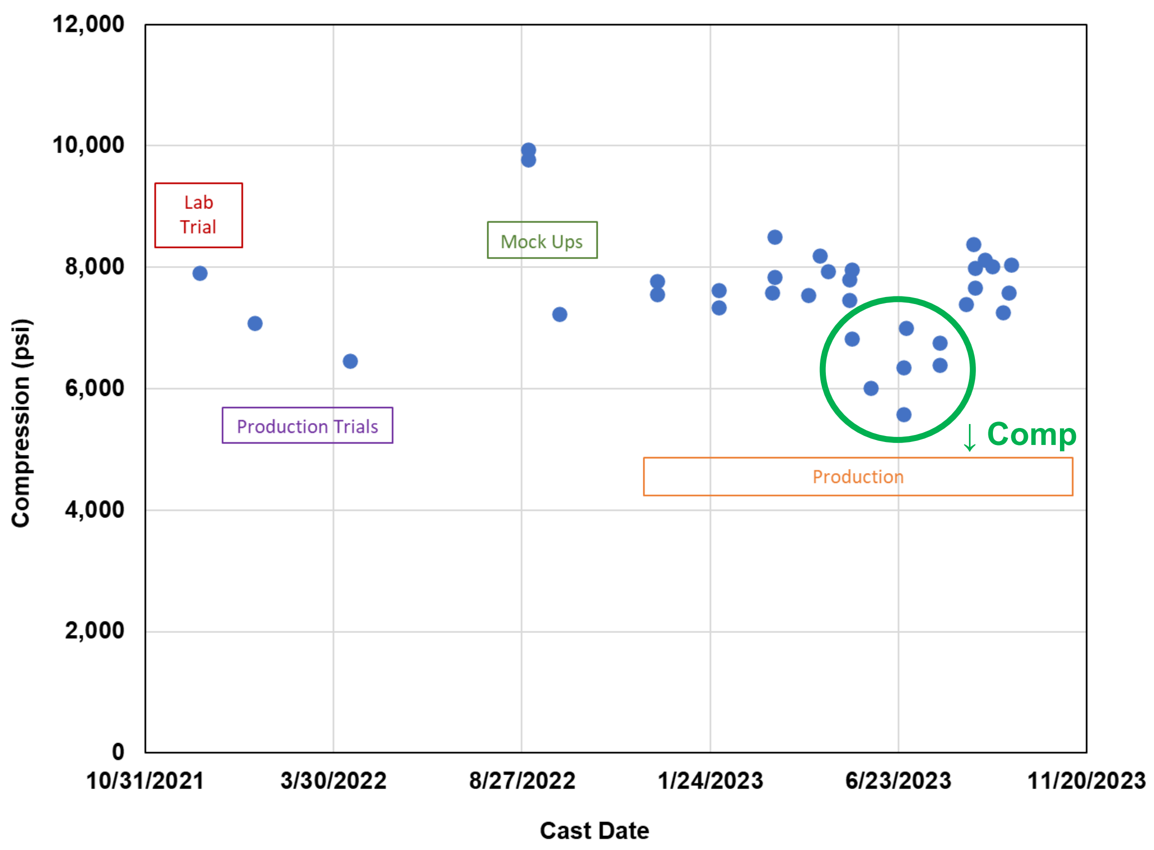


90 Days



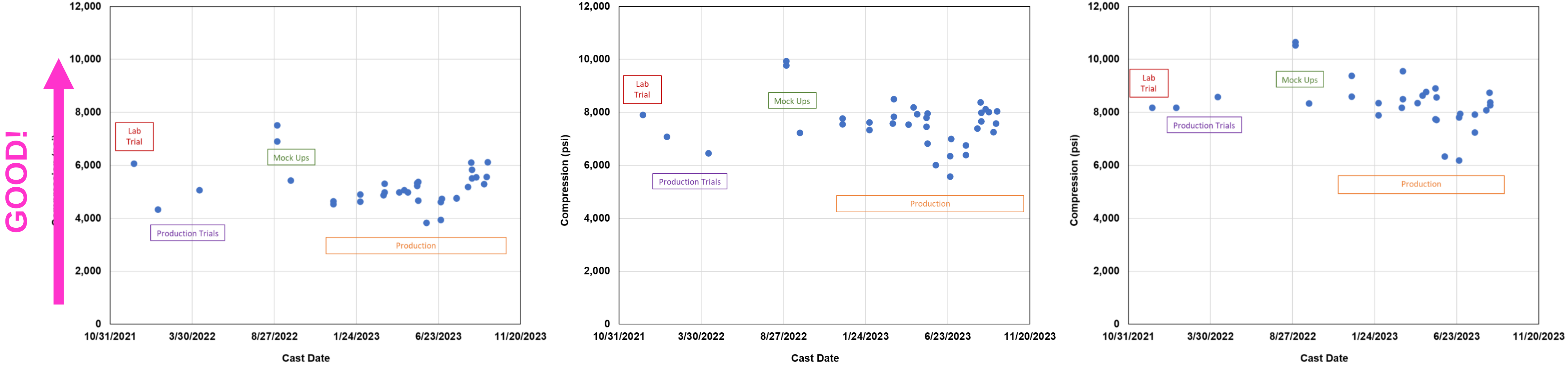
RESISTIVITY AND STRENGTH (28 DAYS)



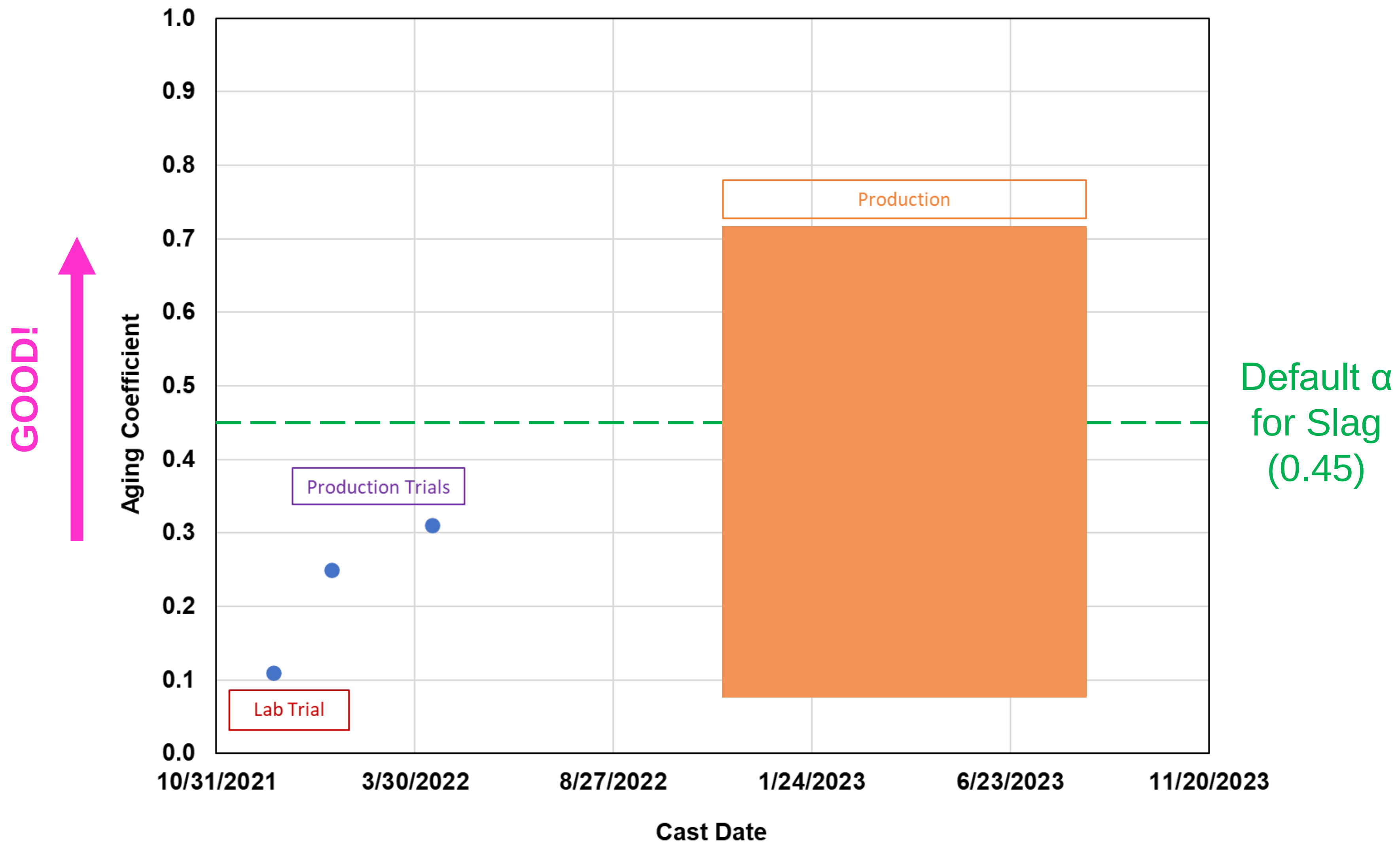


STRENGTH AT MULTIPLE AGES

7 Days | 28 Days | 56 Days



90-DAY AGING COEFFICIENT (35 DATA POINTS!)



PART II QUESTIONS

1. Should α be capped?

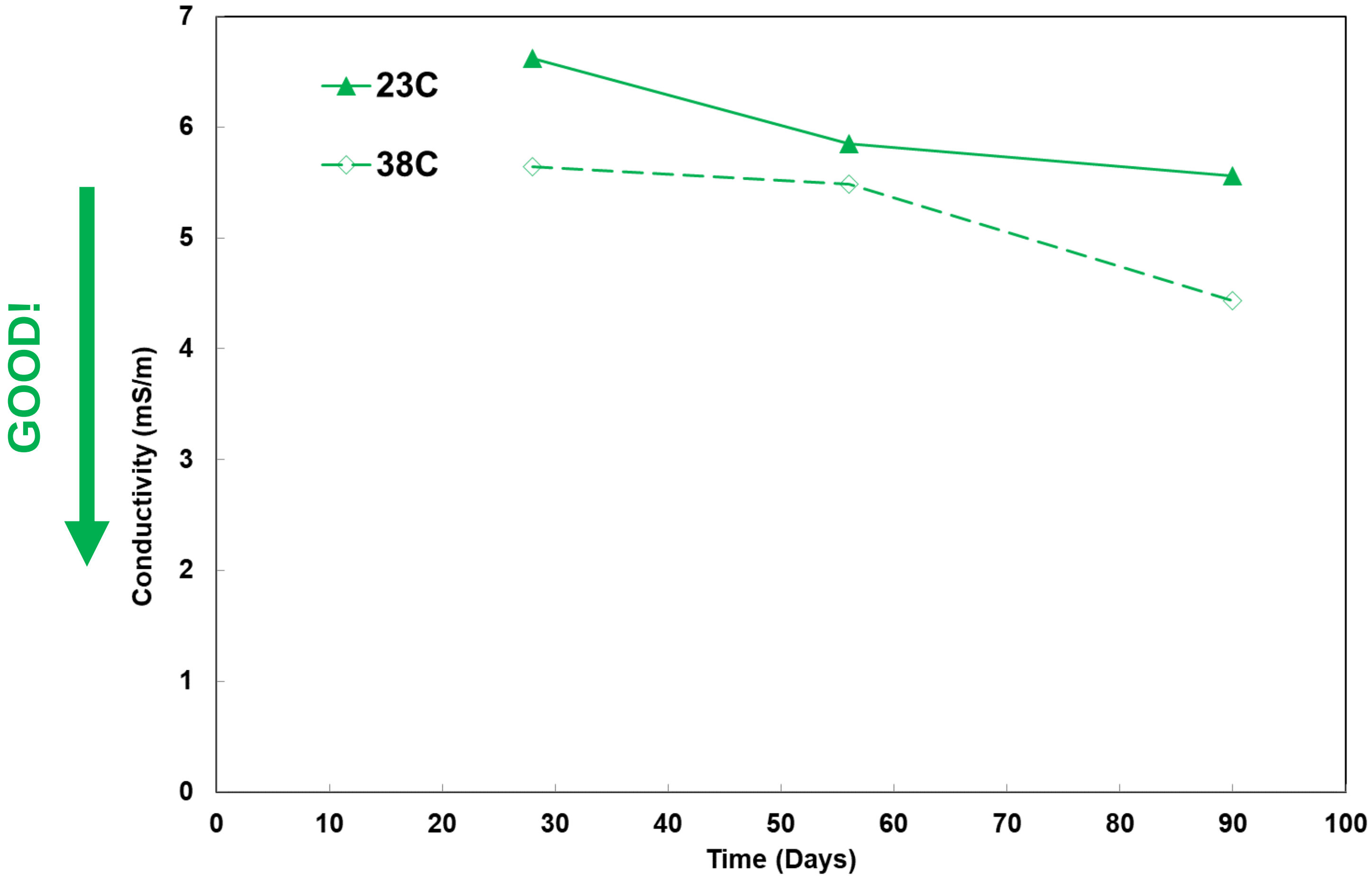
2. When should α be determined?

3. What caused resistivity values to fluctuate?

4. Is resistivity accurately and reliably capturing permeability for slag mixes?

PART III – NEW IDEAS

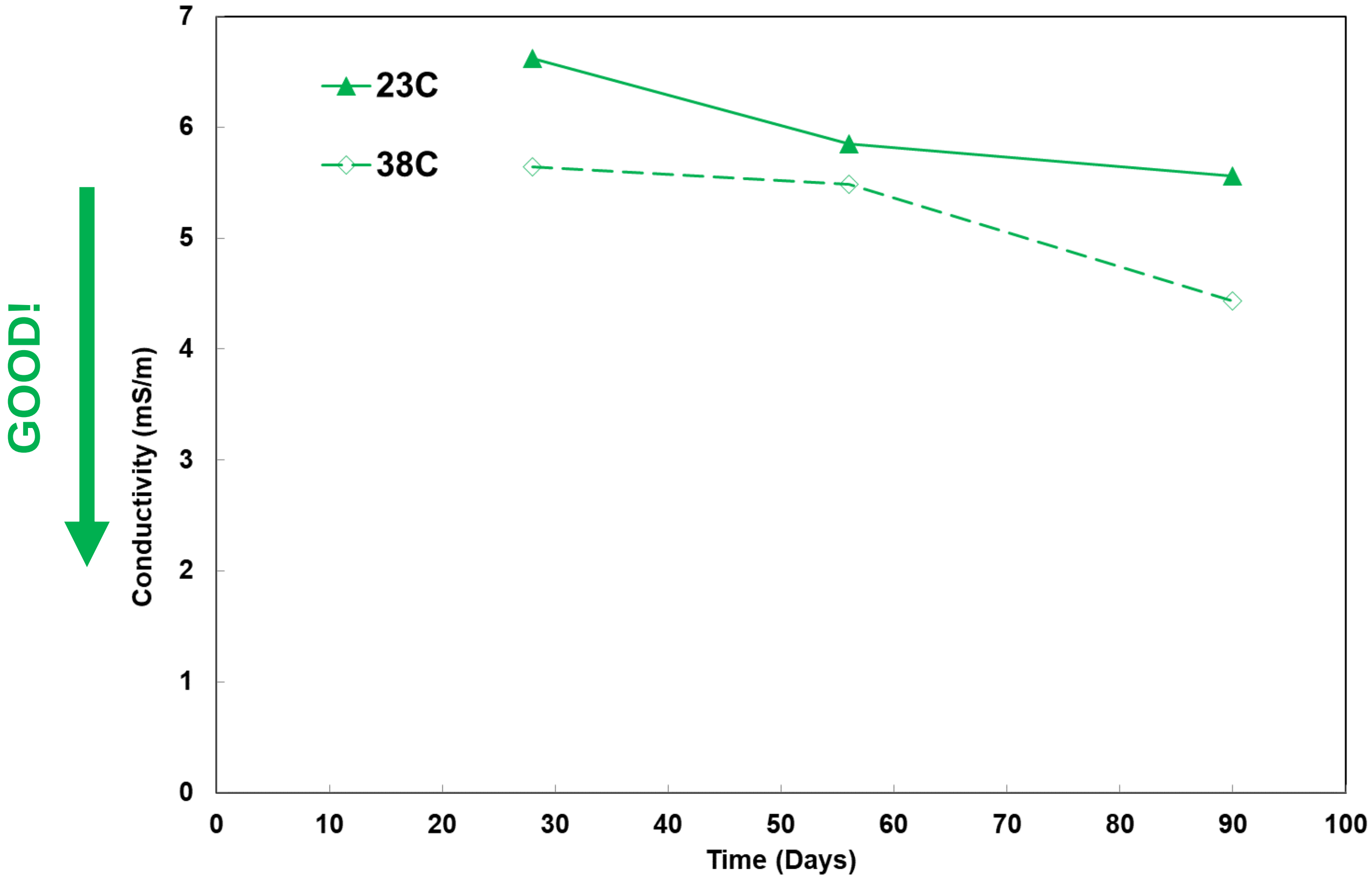
A) PARALLEL CURING TEMPERATURES



DETAILS

- Resistivity testing
- Accelerated:
  23 °C for 7 days and then 38 °C
- Cool Acc sample to 23 °C before measurement

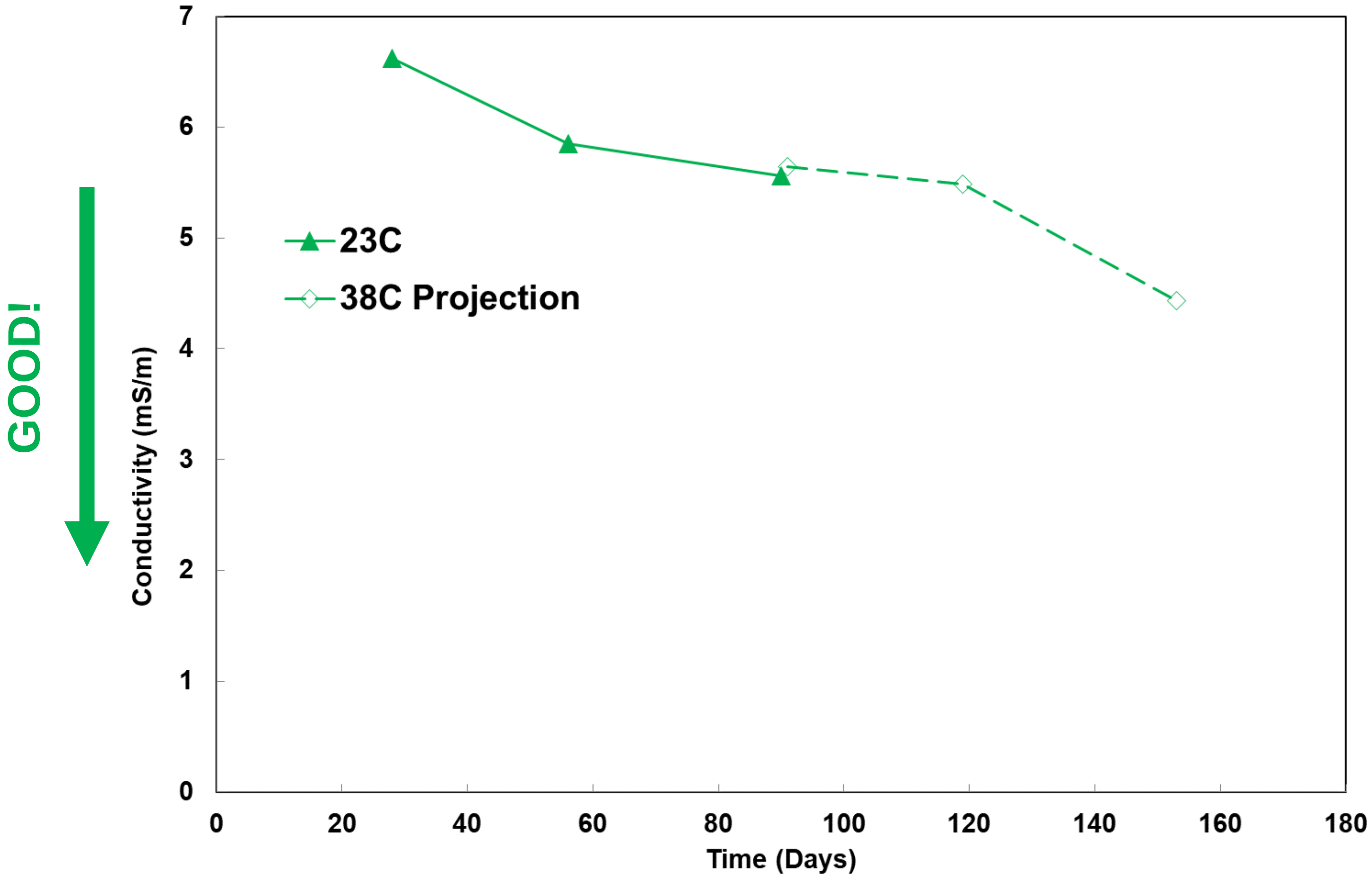
A) PARALLEL CURING TEMPERATURES



BIG IDEAS

1. Use Acc values to project future measurements (like maturity)

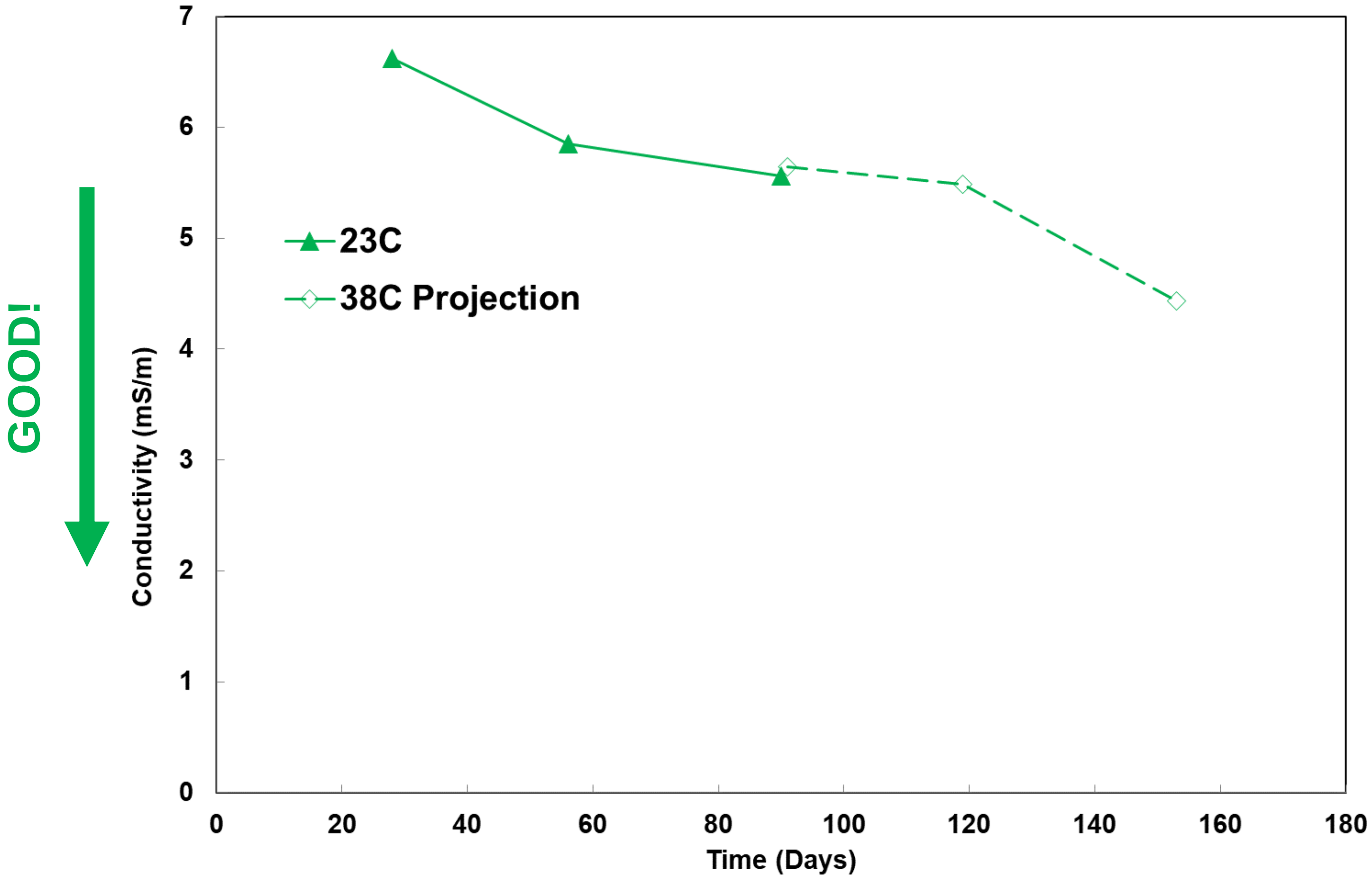
A) PARALLEL CURING TEMPERATURES



BIG IDEAS

1. Use Acc values to project future measurements (like maturity)

A) PARALLEL CURING TEMPERATURES



BIG IDEAS

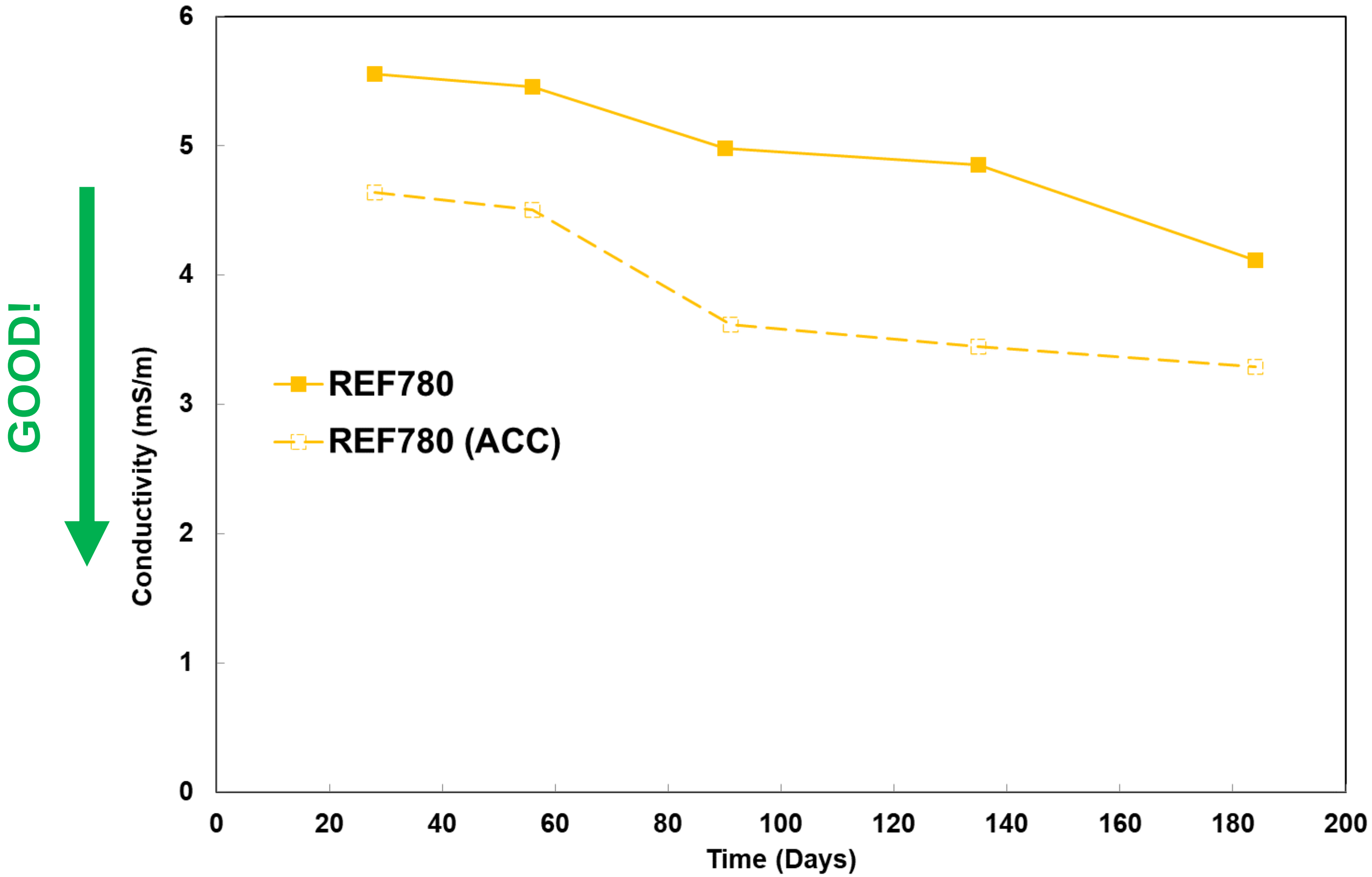
1. Use Acc values to project future measurements (like maturity)
2. Can calculate three α values (23C, 38C, and Projection)

α_{23C}: 0.15

α_{38C}: 0.20

α_{Pro}: 0.20

A) PARALLEL CURING TEMPERATURES

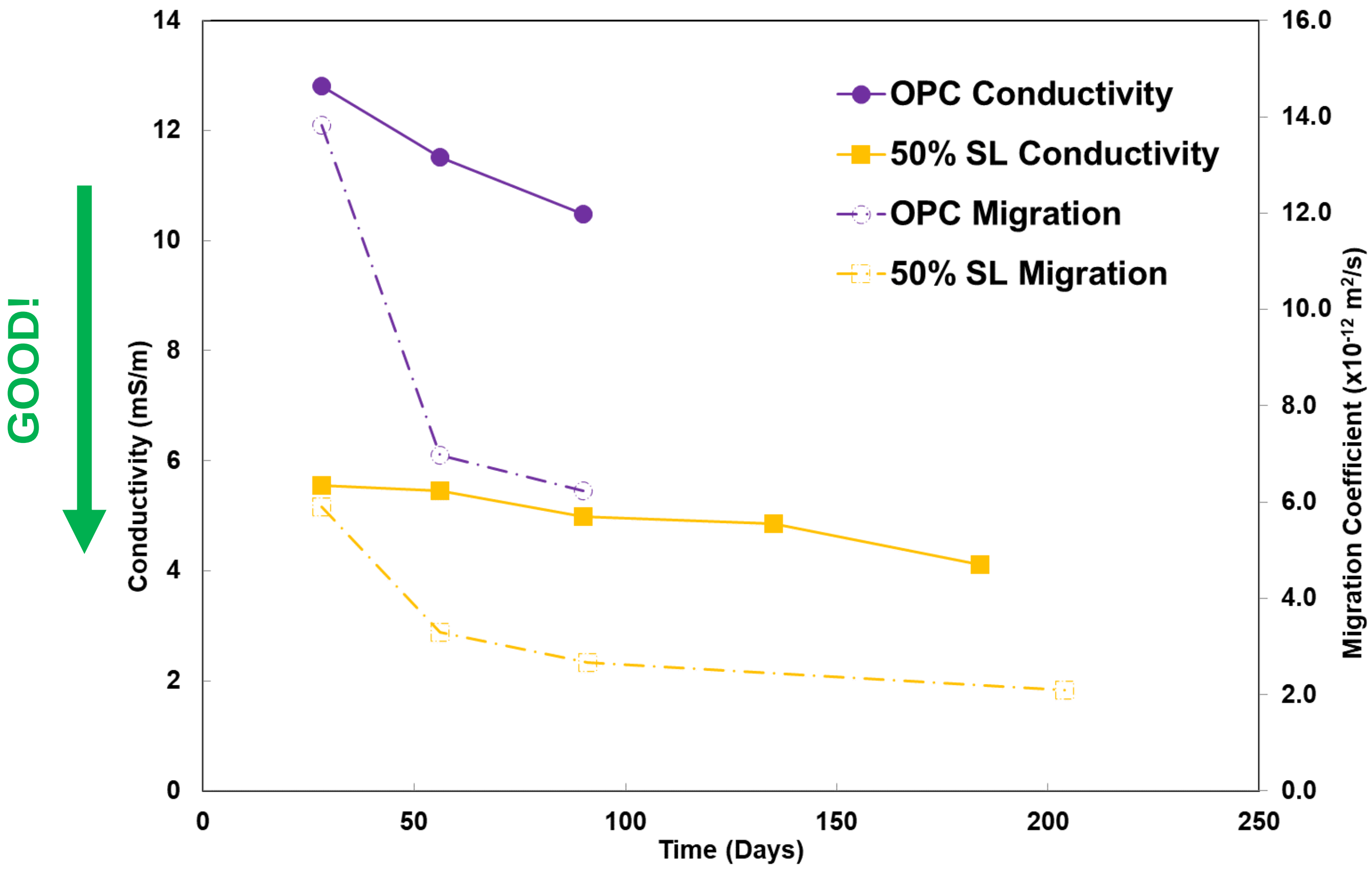


BIG IDEAS

1. Use Acc values to project future measurements
2. Can calculate three α values (23C, 38C, and Projection)
3. Find plateau

<u>Verdict:</u>
Promising but low α values persist and general variability

B) PARALLEL TYPES OF TESTING



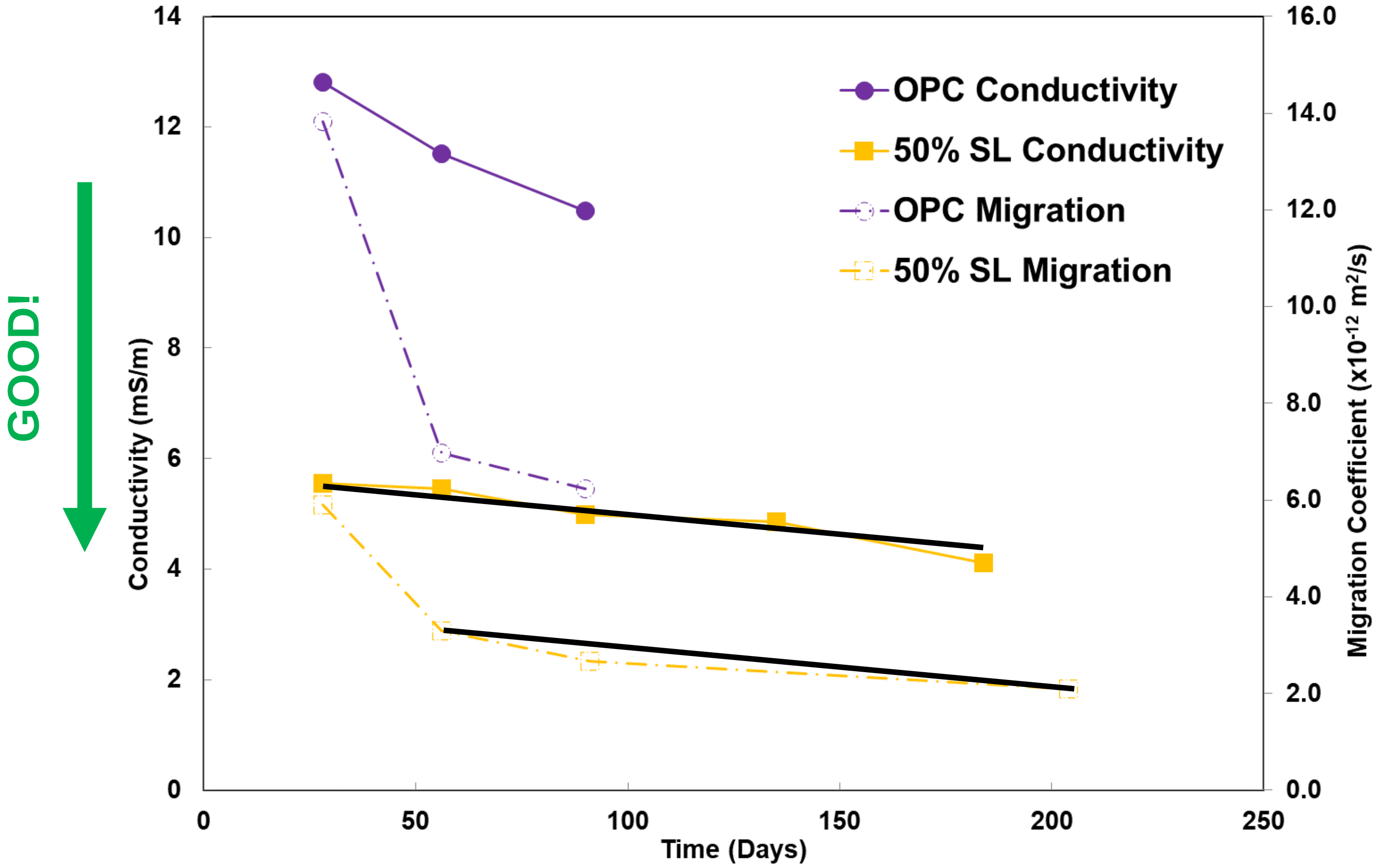
DETAILS

- Multiple permeability tests (Migration, Resistivity, and RCPT)
- 28, 56, and 91-day values

BIG IDEAS

1. Compare α values across tests

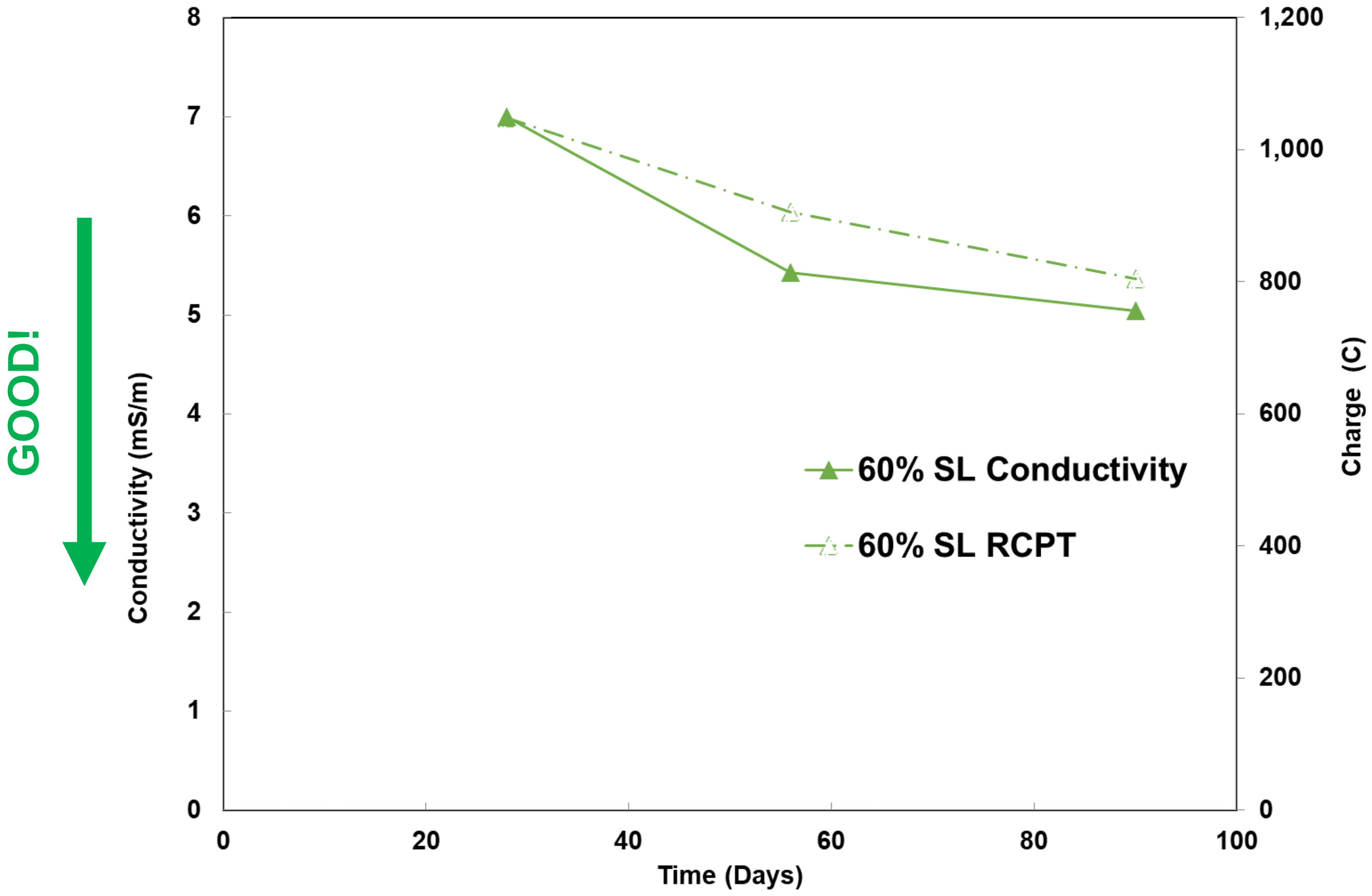
B) PARALLEL TYPES OF TESTING



TAKEAWAYS

1. Big disconnect between Migration and Resistivity/RCPT!
2. Parallel trend after 56 days!
3. OPC behaving pozzolanically! (reality check)

B) PARALLEL TYPES OF TESTING



TAKEAWAYS

1. Big disconnect between Migration and Resistivity!
2. Parallel trend after 56 days!
3. OPC behaving pozzolanically!
4. Agreement between electrical methods (RCPT and Resistivity)

B) PARALLEL TYPES OF TESTING

Mix	Aging Coefficient @ 90 Days		
	Resistivity	*RCPT*	*Migration*
OPC	0.17	-	0.70
50% SL	0.09	-	0.68
60% SL	0.29	0.22	0.44

Verdict:
Thrilling results!
Even more questions!

TAKEAWAYS

1. Big disconnect between Migration and Resistivity!
2. Parallel trend after 56 days!
3. OPC behaving pozzolanically!
4. Agreement between electrical methods (RCPT and Resistivity)
5. Wide variation in α values!

PART III QUESTIONS

1. Should α be capped?
2. When should α be determined?
3. What caused resistivity values to fluctuate?
4. Is resistivity accurately and reliably capturing permeability for slag mixes?
5. How to assess variable performance by different permeability tests?
6. How should aging coefficients be determined?
7. What should Field QC criteria be?

SUMMARY

QUESTIONS

1. Should α be capped?
   → Life-365: 0.60 Max

2. When should α be determined?
   → fib Bulletin 76: 2 years

3. What caused resistivity values to fluctuate?
   → No clear culprit, but most likely caused by a change in cementitious materials
   → ASTM Specs for SCMs focus on strength, do not provide durability information

4. Is resistivity accurately and reliably capturing permeability for slag mixes?
   → Potential compatibility issue between testing and materials
   → Missing fudge factor?

QUESTIONS

5. How to assess variable performance by different permeability tests?
   → Research needed

6. Should aging coefficients be determined differently?
   → Research needed

7. What should Field QC criteria be?
   → Migration testing but less frequently?

REFERENCES

Corrosion Damage Model:
Bertolini, L. (2013). Corrosion of steel in concrete prevention, diagnosis, repair / Luca Bertolini ... [et al.]. (2nd ed.). Wiley-VCH.

fib Bulletin 34: Model Code for Service Life Design (2006):
https://www.fib-international.org/publications//model-code-for-service-life-design-pdf-detail.html

fib Bulletin 76: Benchmarking of deemed-to-satisfy provisions in standards
https://www.fib-international.org/publications/fib-bulletins/benchmarking-of-deemed-to-satisfy-provisions-in-standards-detail.html

Life-365:
http://www.life-365.org/

QUESTIONS? ANSWERS?
THANK YOU!

Bruno Fong-Martinez, PhD
Concrete Engineer, Kiewit
bruno.fongmartinez@kiewit.com

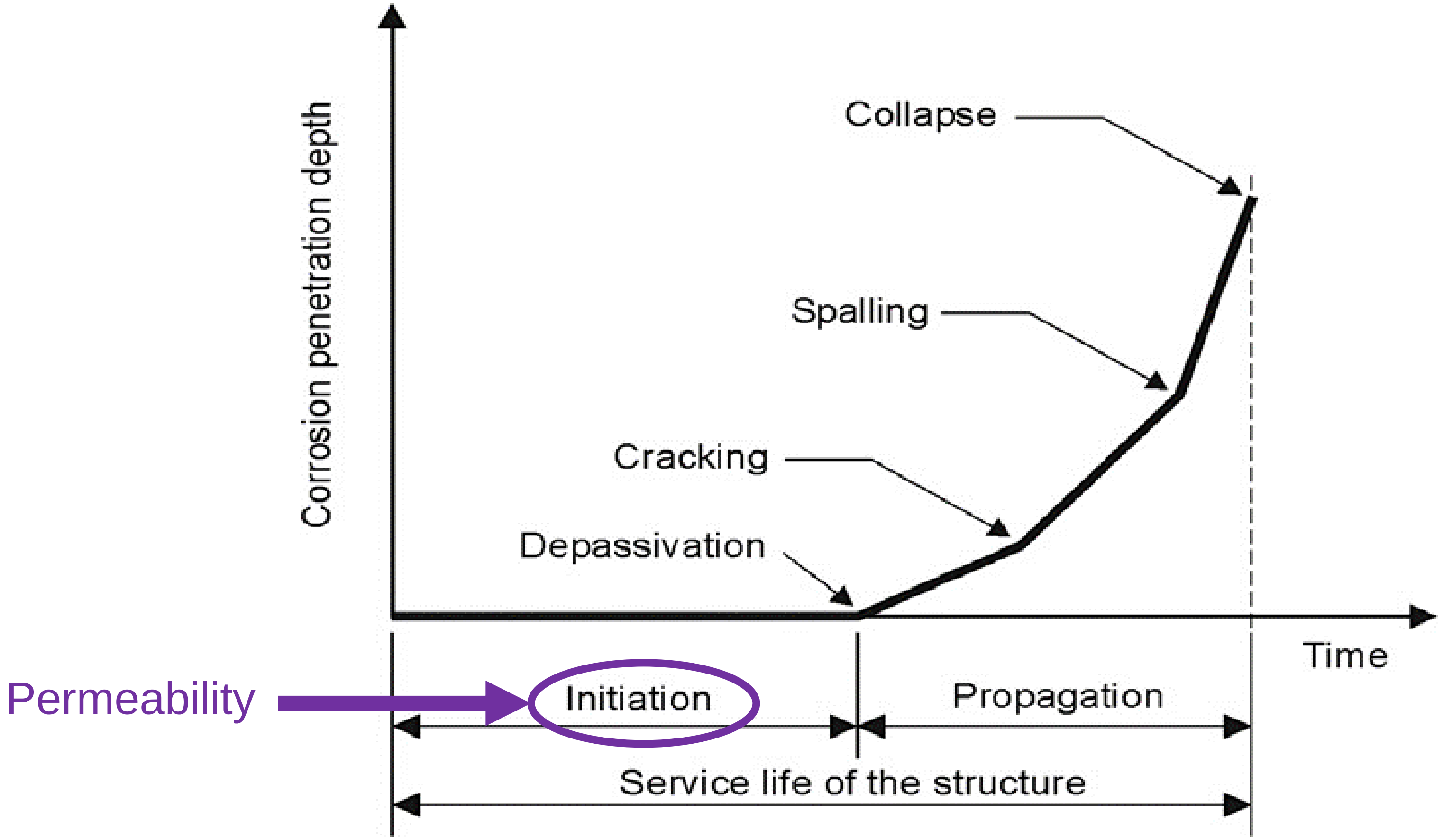
DURABILITY MECHANISMS

- Abrasion and Erosion
- Freezing and Thawing
- Exposure to Deicers and Anti-icers
- Alkali-Aggregate Reactivity
- Carbonation Corrosion
- Chloride Corrosion
- Sulfate Attack
- Salt Crystallization or Physical Sulfate Attack
- Delayed Ettringite Formation
- Acid Attack
- Seawater Exposure
- Shrinkage

Figure 11-12. V-shaped joints are a common sign of the effects of freeze-thaw damage in concrete pavements. Some joints exhibit an inverted V-shaped deterioration (Courtesy of D. Harrington).

Figure from PCA Design and Control of Concrete Mixtures 15th Edition

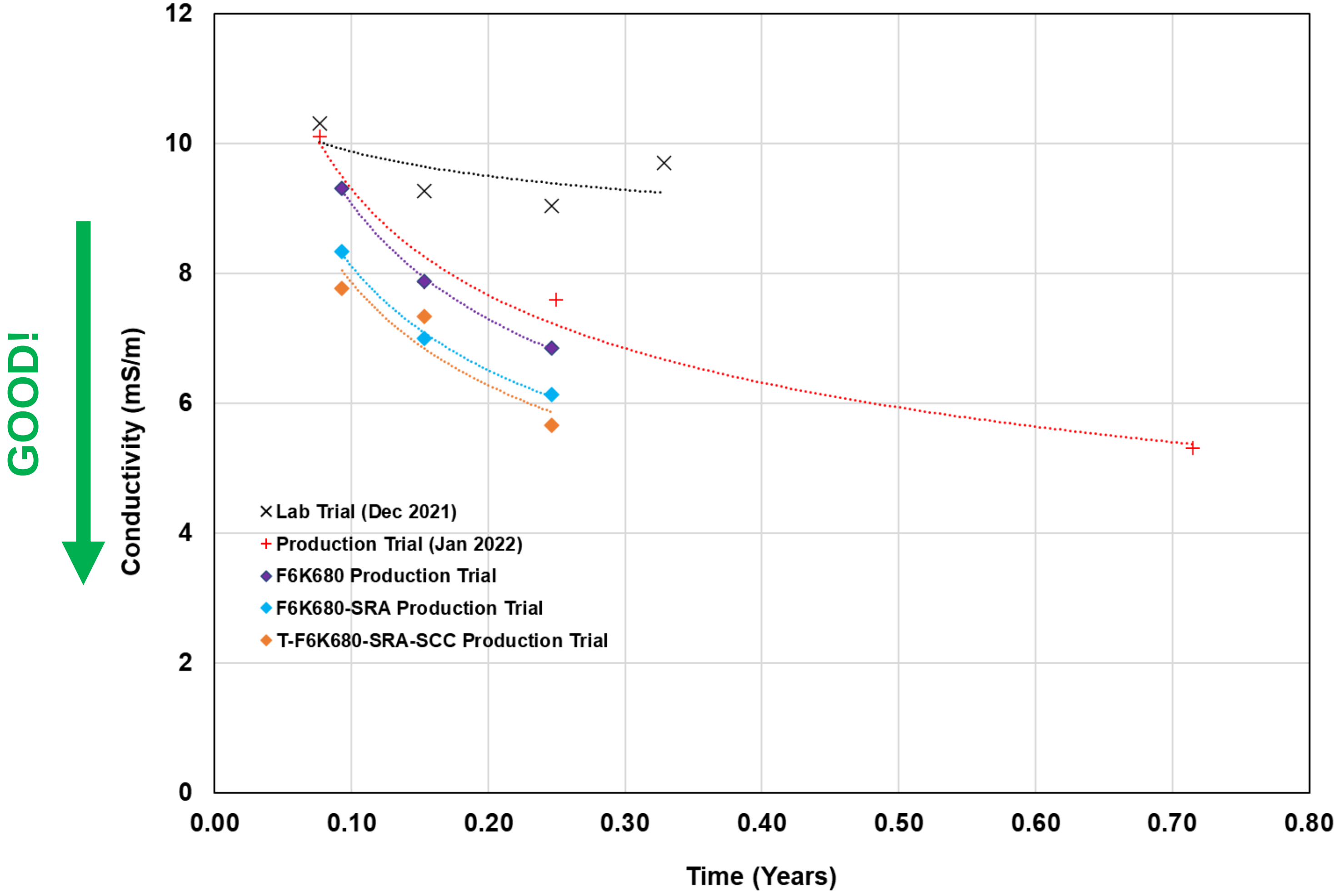
CORROSION DAMAGE MODEL



(Bertolini et al., 2013)

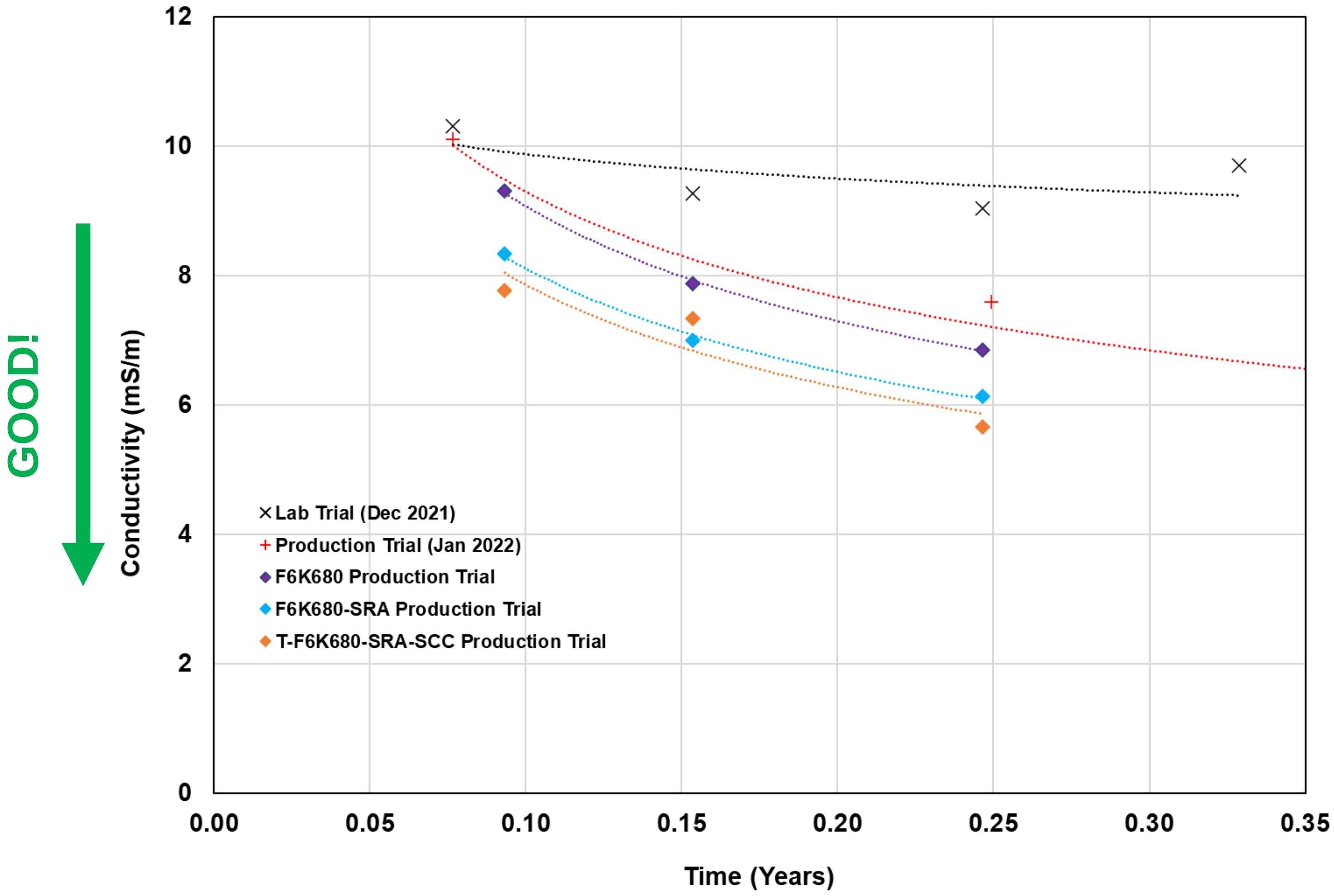
RESISTIVITY

0.40 w/cm | 50% SL



Cast Date	Location	α	
		90 Days	~9 Months
12/13/21	Lab Trial	0.11	
01/26/22	Field Trial	0.25	0.28
04/12/22		0.31	
04/12/22		0.31	
04/12/22		0.32	

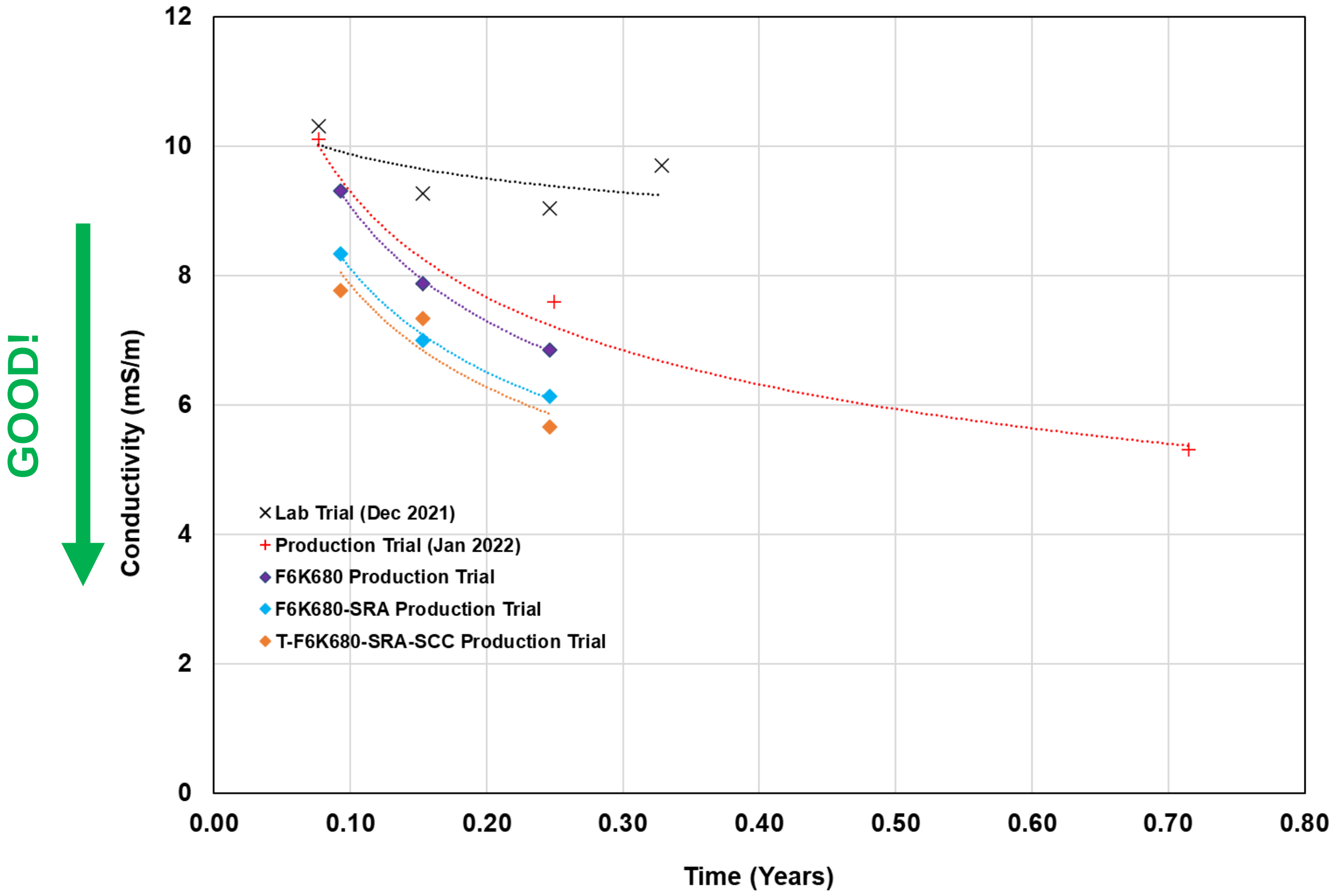
RESISTIVITY
0.40 w/cm | 50% SLAG



Cast Date	Location	α 90 Days
12/13/21	Lab Trial	0.11
01/26/22	Field Trial	0.25
04/12/22		0.31
04/12/22		0.31
04/12/22		0.32

RESISTIVITY

0.40 w/cm | 50% SL



TAKEAWAYS

- Slag seemingly behaving like cement (α~0.30)
- 90-day α same as 9-month α
- Unremarkable but consistent results