High-Volume Recycled Materials for Sustainable Pavement Construction

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Research on Concrete Applications for Sustainable Transportation

RE-CAST

Research Objective

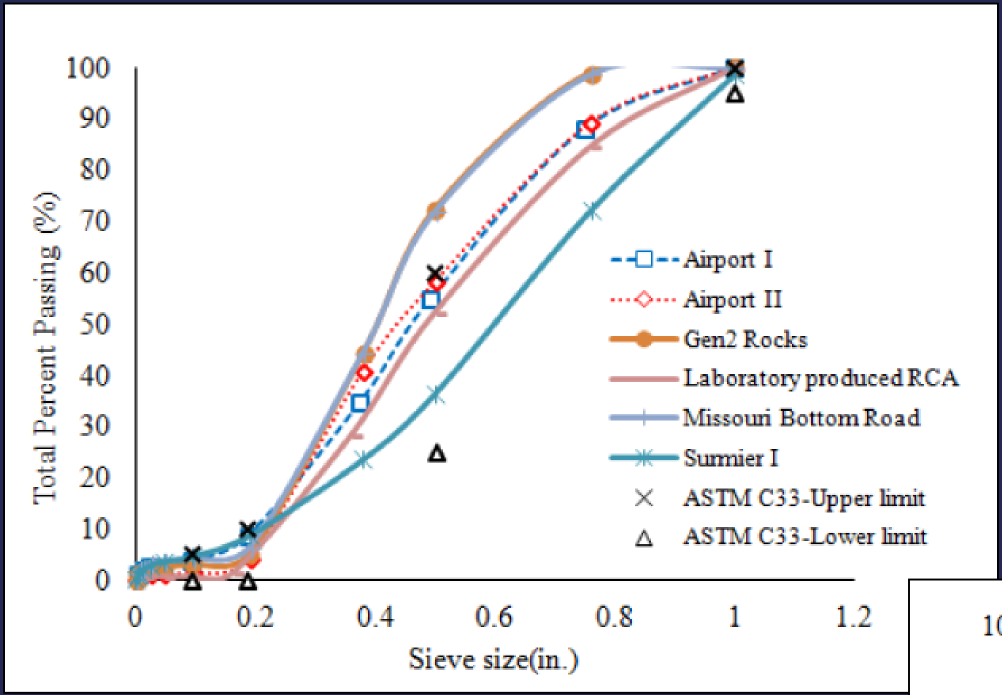
- To develop *eco-friendly* concrete mixtures with at least **50%** of mass replaced by recycled materials for pavement application
- Two types of concrete pavements:
  1) Eco-friendly concrete for single layer pavement
  2) Eco-friendly concrete for two-lift pavement

RCA Selection

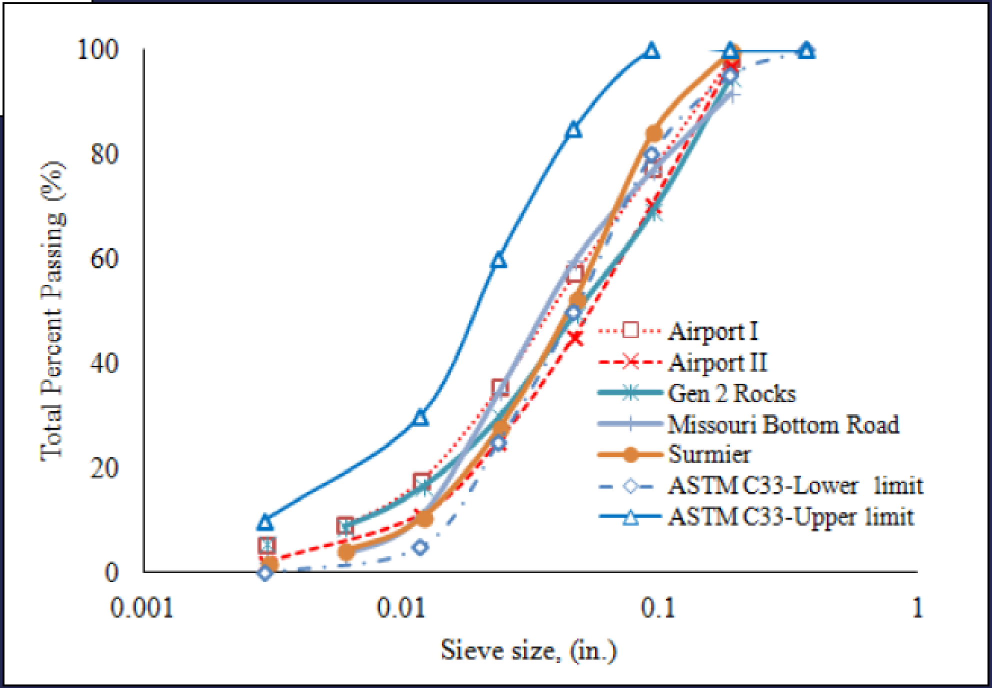
RCA Materials

Aggregate	Specific gravity	Dry rodded unit weight (pcf)	Absorption (%)	Los Angles abrasion (%)	Source
Fine RCA I	2.41	-	6.8	-	Lambert Airport, I
Fine RCA II	2.11	-	7.33	-	Lambert Airport, II
Fine RCA III	2.10	-	9.29	-	Gen2 Rocks
Fine RCA IV	2.05	-	10.47	-	Surmier Recycling
Fine RCA V	1.90	-	14.19	-	Missouri Bottom Road
Coarse RCA I	2.38	91.0	4.2	33	Lambert Airport, I
Coarse RCA II	2.35	90.2	4.46	33	Lambert Airport, II
Coarse RCA III	2.21	86.1	6.66	43	Surmier Recycling I
Coarse RCA IV	Rejected in visual inspection				Surmier Recycling II
Coarse RCA V	2.32	88.4	4.99	35	Gen2 Rocks
Coarse RCA VI	2.15	85.0	8.17	43	Missouri Bottom Road
Coarse RCA VII	2.35	89.7	4.56	41	Laboratory produced

RCA Gradations



Coarse RCA



Fine RCA

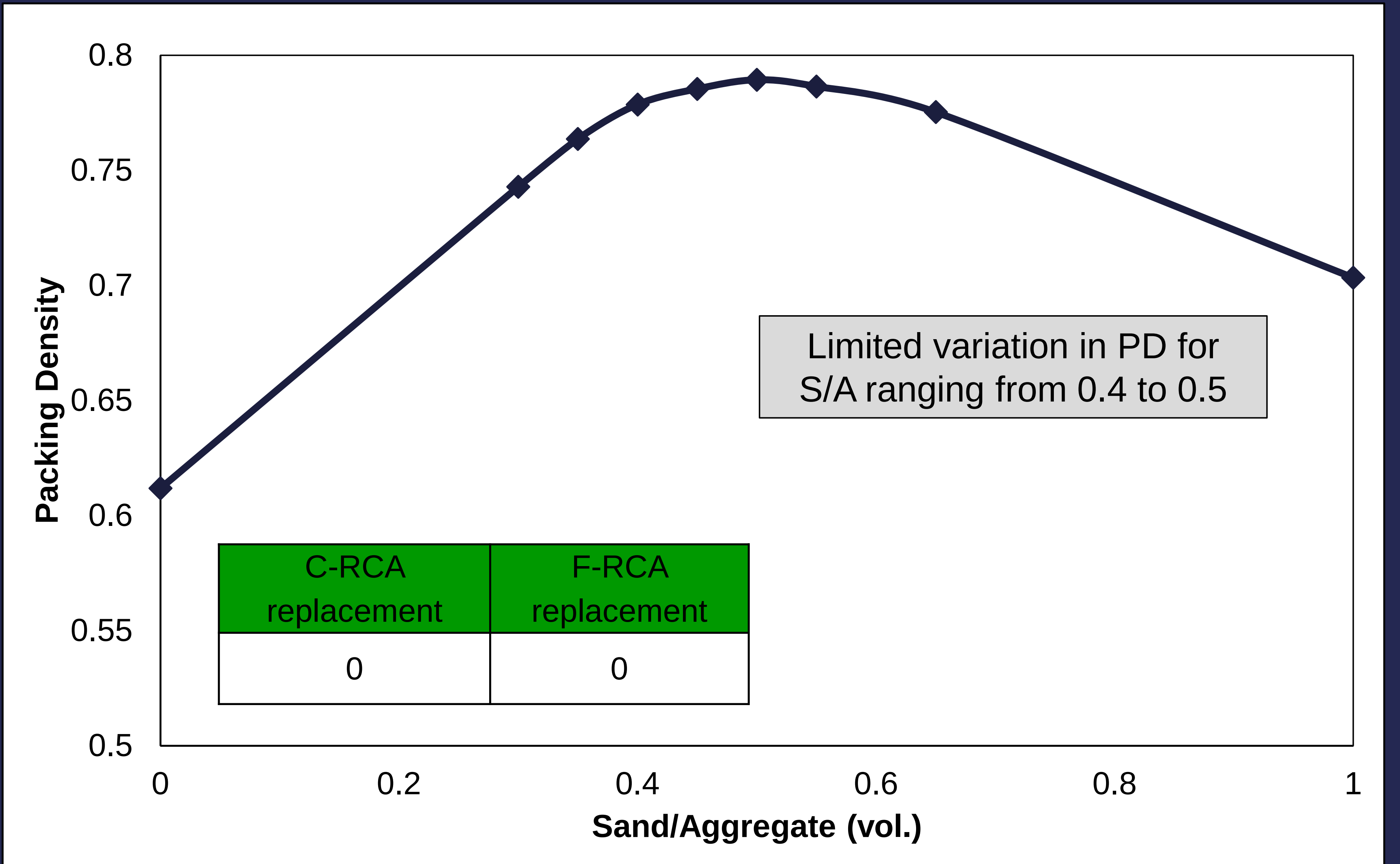
Packing Density

Fine-to-Aggregate ratio	0-100% (vol.)
Coarse aggregate	Dolomite, Coarse RCA
Fine aggregate	Sand, Fine RCA
Coarse RCA content	0-100%
Fine RCA content	0-50%

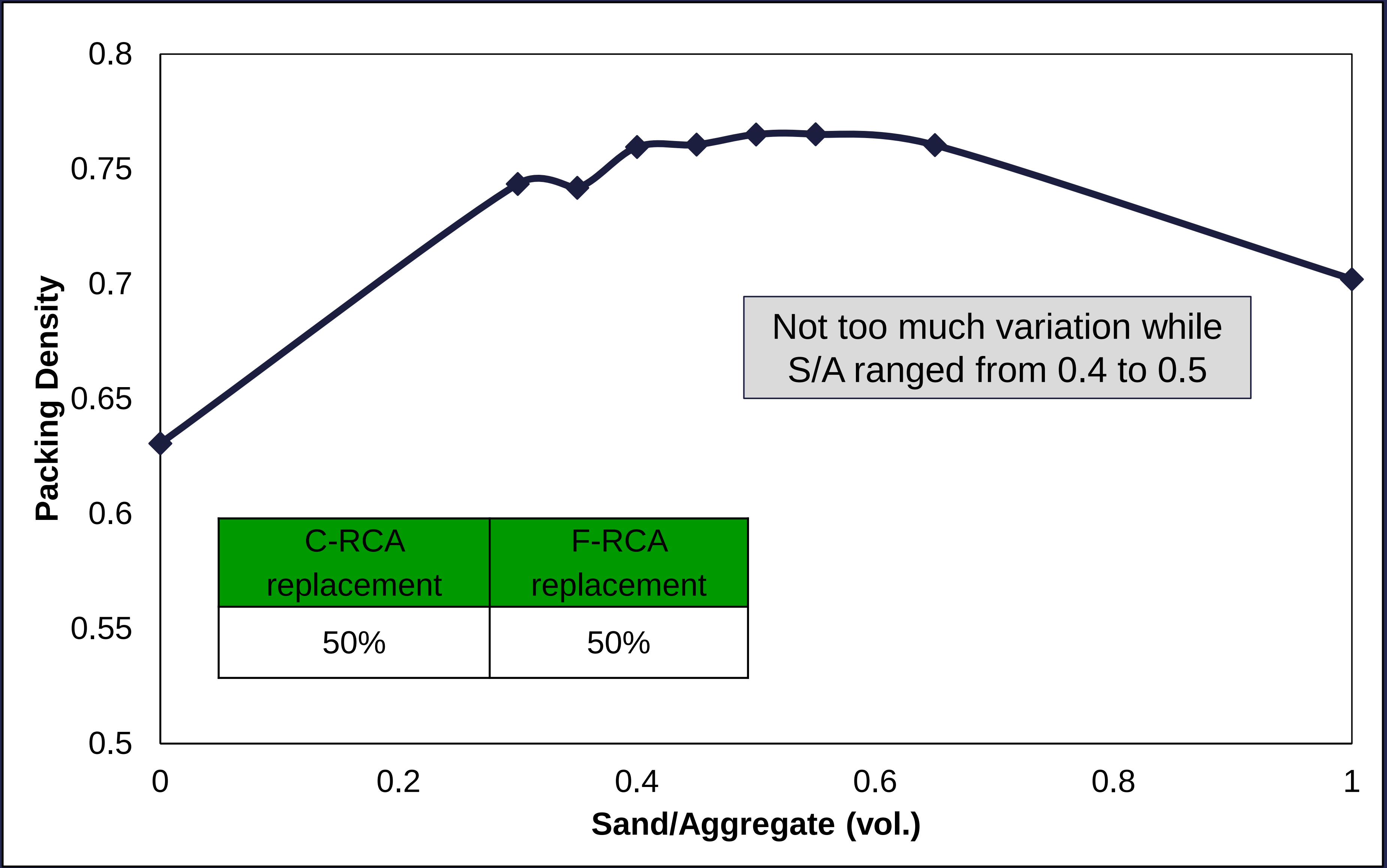
<table>
<tr><th>S/A</th><th>C-RCA</th><th>F-RCA</th><th colspan="3">Scenario</th><th>Replications</th></tr>
<tr><td rowspan="9">0, 0.20, 0.30, 0.35, 0.4, 0.45, 0.50, 0.55, 0.65, 1.00</td><td>0</td><td>0</td><td rowspan="4">Top layer</td><td rowspan="2"></td><td rowspan="4"></td><td rowspan="9">2</td></tr>
<tr><td>30%</td><td>0</td></tr>
<tr><td>30%</td><td>20%</td><td rowspan="5">Single layer</td></tr>
<tr><td>50%</td><td>0</td></tr>
<tr><td>50%</td><td>50%</td><td rowspan="5"></td><td rowspan="5">Bottom layer</td></tr>
<tr><td>60%</td><td>40%</td></tr>
<tr><td>70%</td><td>30%</td></tr>
<tr><td>70%</td><td>50%</td><td rowspan="2"></td></tr>
<tr><td>100%</td><td>50%</td></tr>
</table>

Gyratory Compactor

Example Test Result



Example Test Result



Binder Type Optimization

Concrete Equivalent Mortar

Mixture proportions	w/cm	Cementitious materials (lb/yd^3)	Water (lb/yd^3)	Sand (lb/yd^3)	Coarse aggregate(lb/yd^3)	Sand equivalent to coarse aggregate (lb/yd^3)
MoDOT-PCCP	0.4	545	218	1260	1890	-
CEM	0.4	545	218	1260	-	166

Property	Testing age
Compressive strength	1, 7, 28, 56, and 91 days
Carbonation depth	30-d and 50-d exposure to accelerated environment
Electrical resistivity	28, 56, and 91 days
Shrinkage	1week of moist curing, measurement up to 120 days
Cost	$/ ton of binder
CO_2 emission	kg CO_2/ kg binder

Testing Protocol

Mixture No.	OPC	GGBS	FA-C	FA-F	GP
1	100	-	-	-	-
2	50	-	50	-	-
3	50	-	50	-	-
4	50	50	-	-	-
5	30	70	-	-	-
6	50	15	35	-	-
7	35	30	35	-	-
8	30	20	50	-	-
9	45	40	15	-	-
10	50	50	-	-	-
11	40	10	50	-	-
12	40	10	50	-	-
13	35	50	15	-	-
14	50	25	25	-	-
15	30	20	50	-	-
16	30	45	25	-	-
17	30	70	-	-	-
18	50	-	-	50	-
19	50	-	-	50	-
20	50	15	-	35	-
21	35	30	-	35	-
22	30	20	-	50	-
23	40	35	-	25	-
24	40	10	-	50	-
25	40	10	-	50	-
26	30	55	-	15	-
27	50	25	-	25	-
28	30	20	-	50	-
29	30	45	-	25	-
30	90	-	-	-	10
31	80	-	-	-	20
32	70	-	-	-	30
33	60	-	-	-	40
34	50	-	-	-	50

91-day Compressive Strength

Area of optimum strength

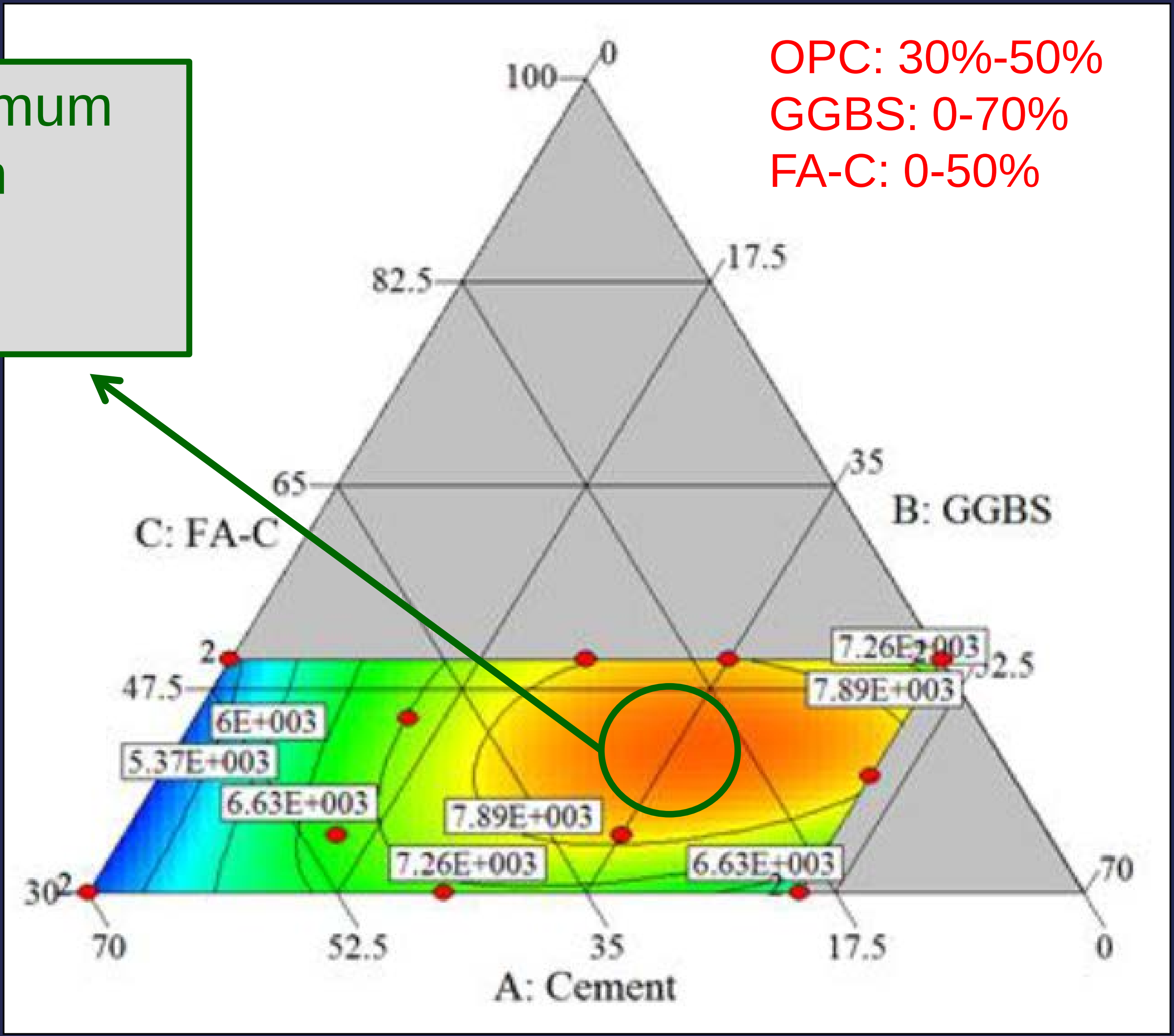
~ 35% FA-C

~25% GGBS

OPC: 30%-50%

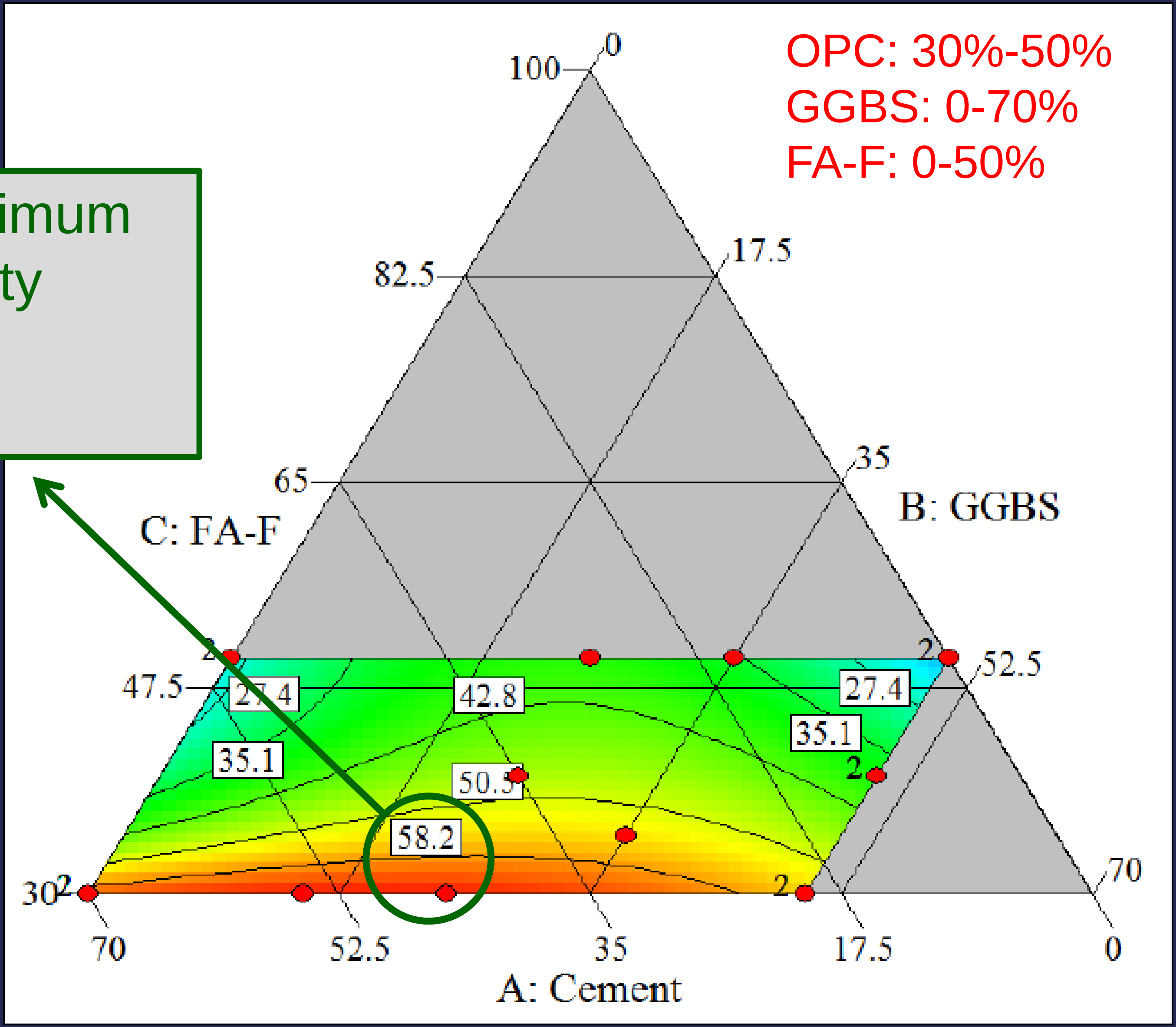
GGBS: 0-70%

FA-C: 0-50%



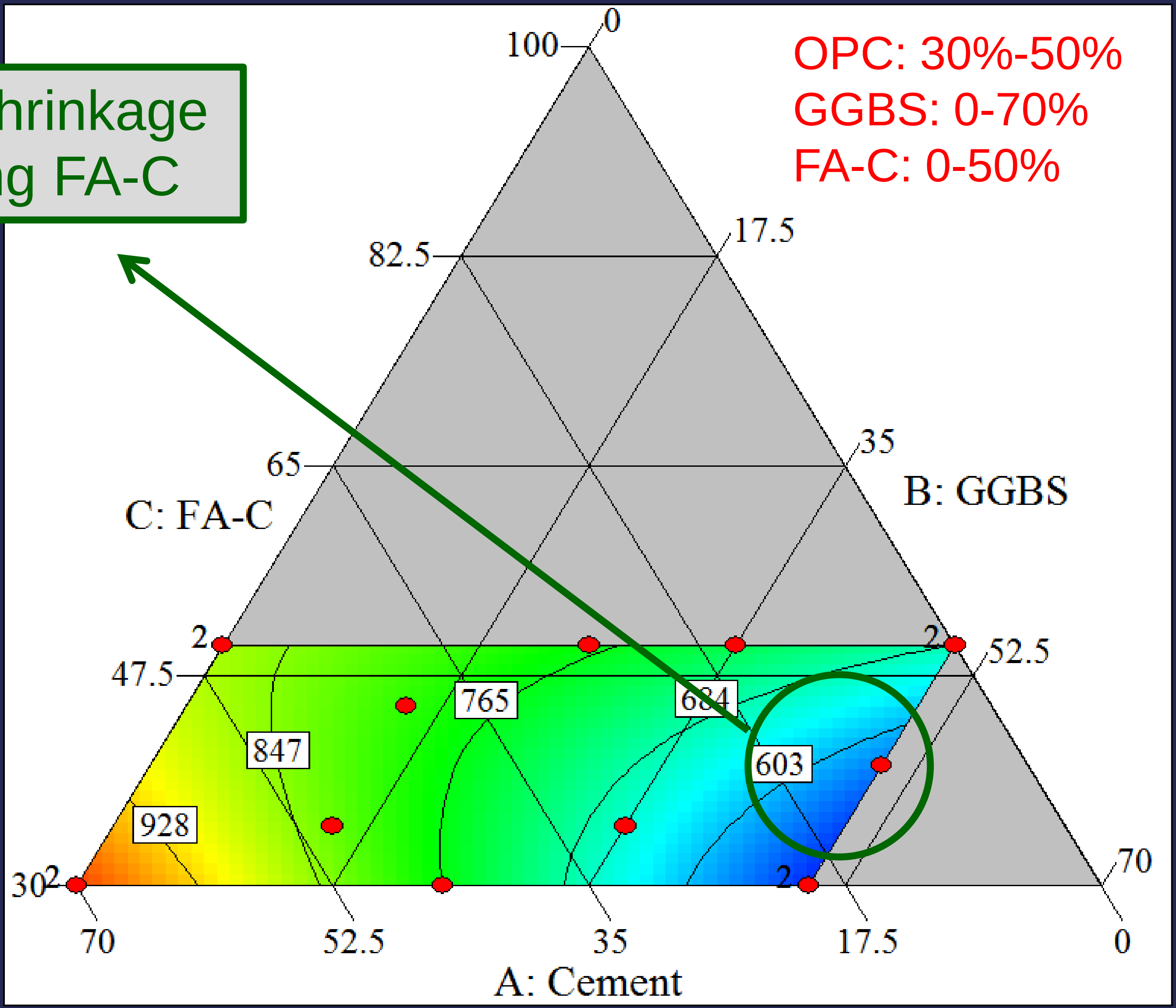
91-day Bulk Resistivity

Area of optimum resistivity
~25% FA-F
~45% GGBS

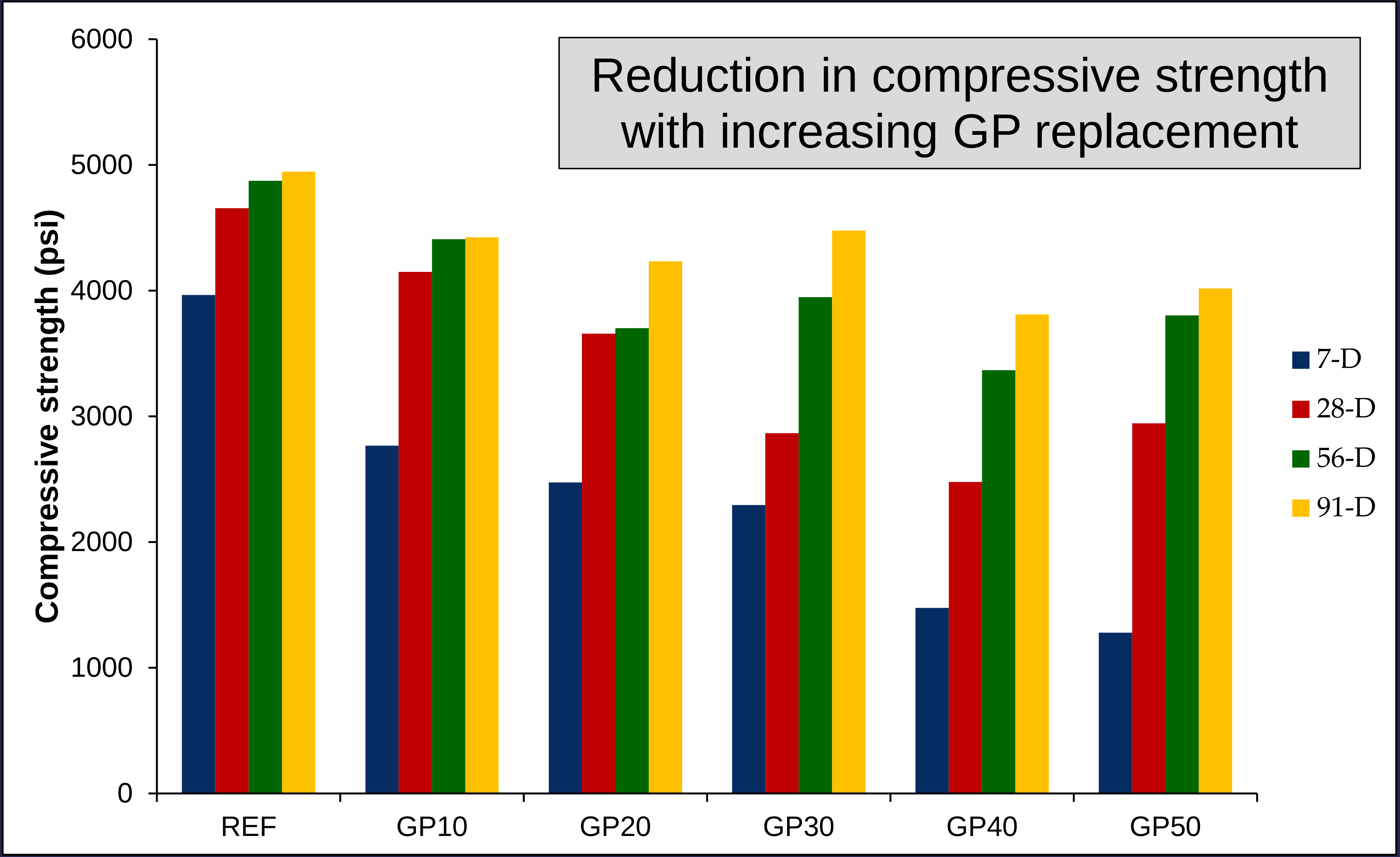


120-day Shrinkage

Reduction in shrinkage with increasing FA-C

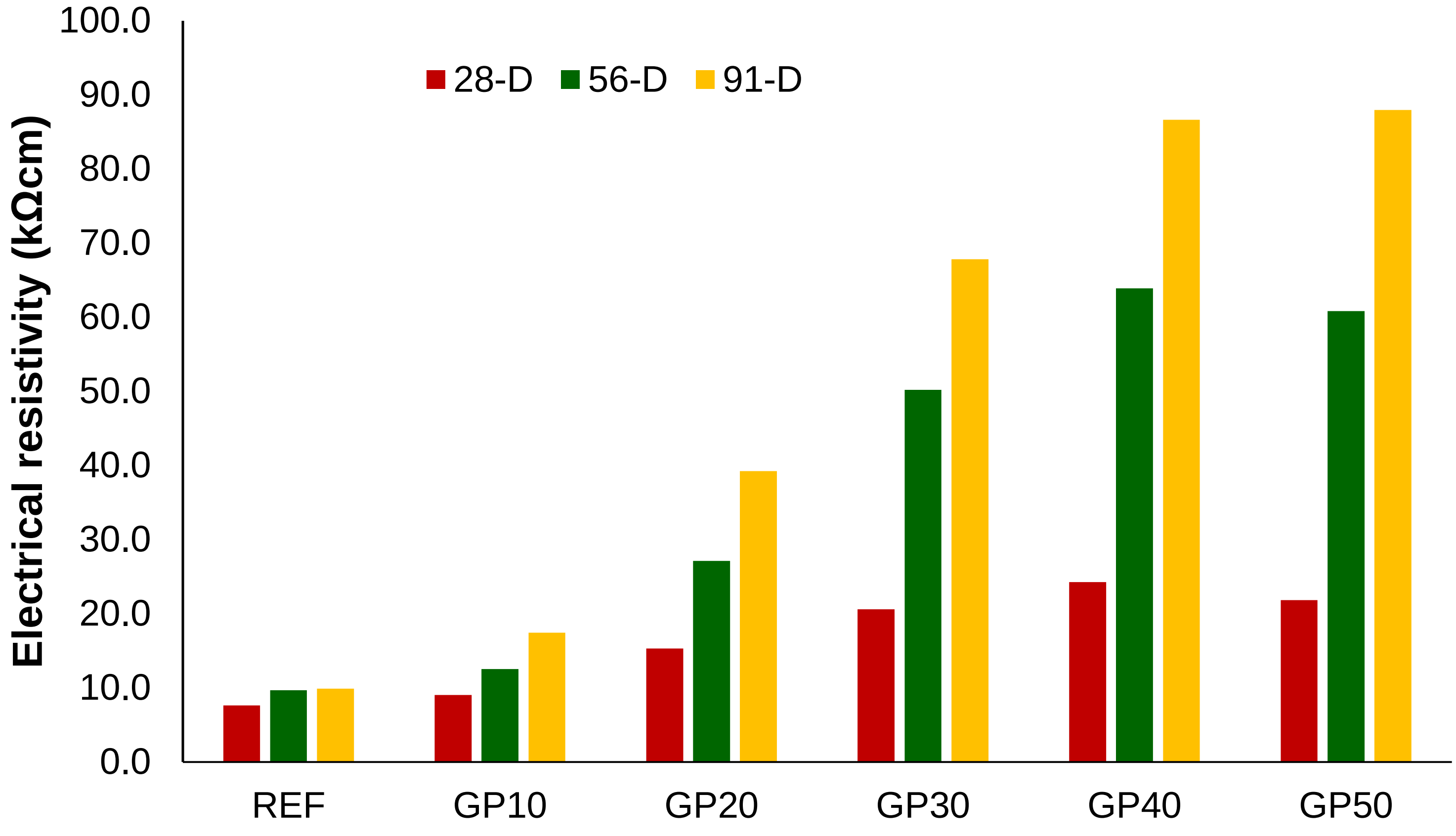


Glass Powder

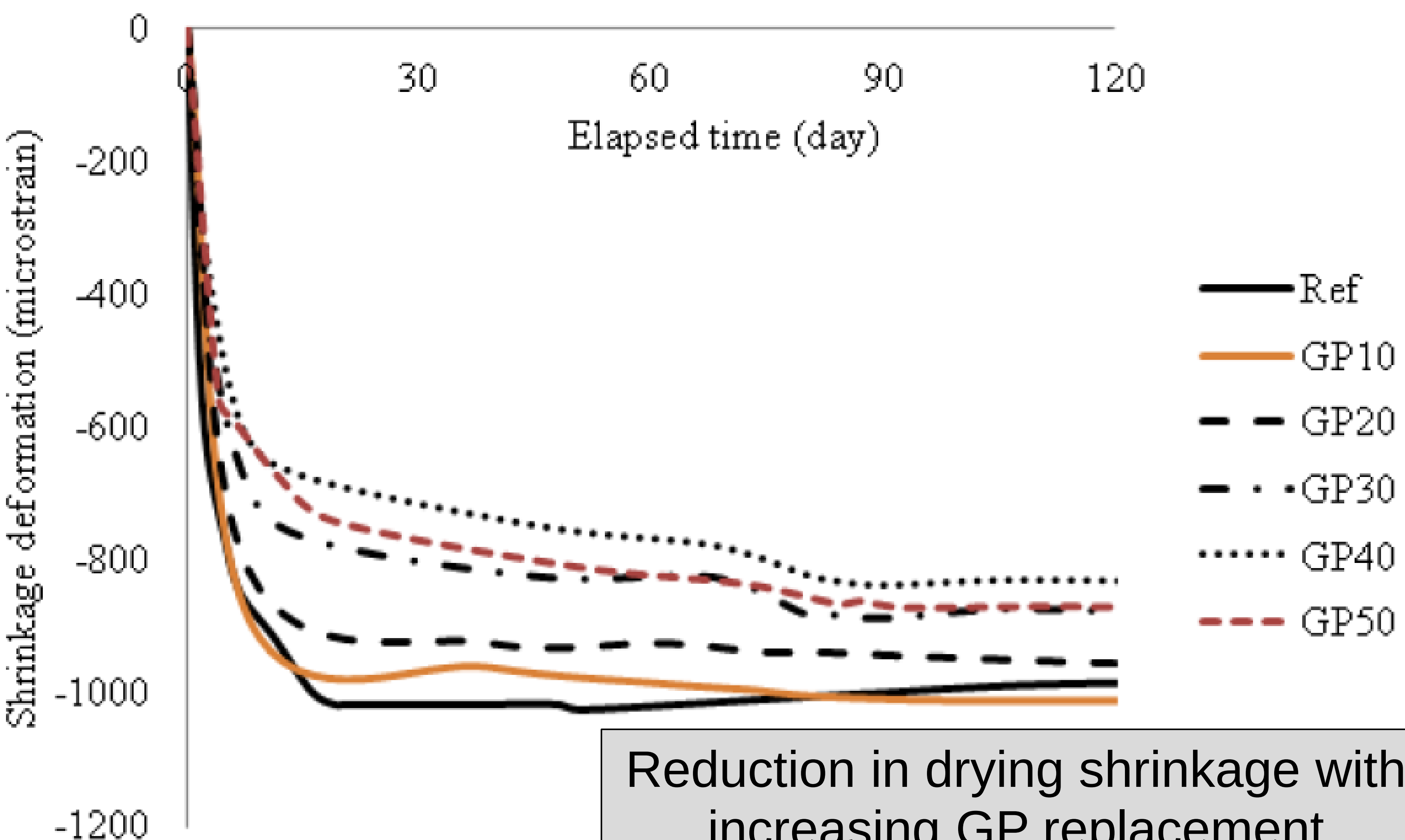


Glass Powder

Significant improvements in electrical resistivity with increasing GP replacement



Glass Powder



Reduction in drying shrinkage with increasing GP replacement

Cost & Emission Values

	OPC	FA-C	FA-F	GGBS
Cost ($/ton) *	100	45	68	91
Emission rate (kg/ton)	960	93	93	155

** Cost from 2014*

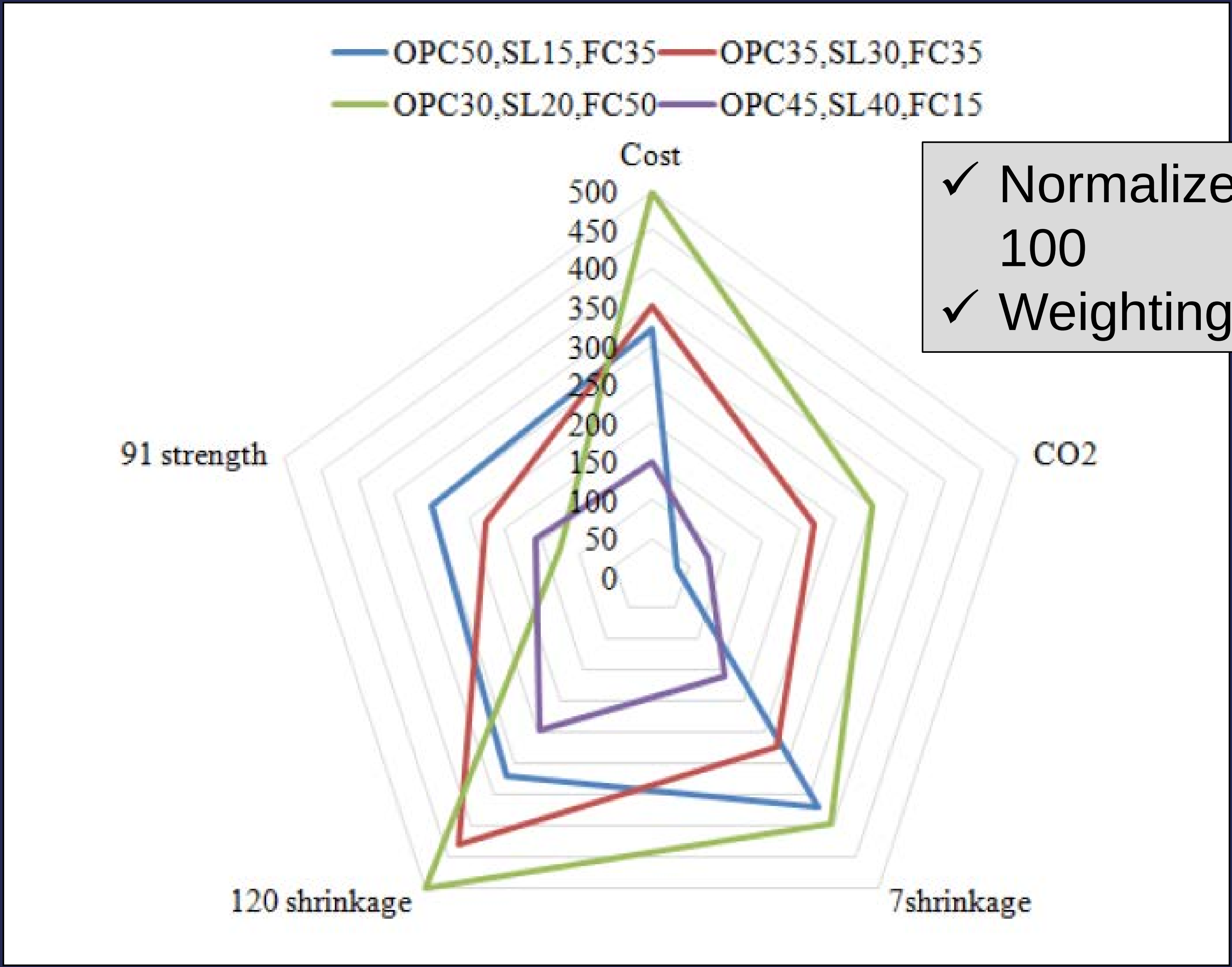
$$\text{Binder cost (\$/ton)} = 100 \times OPC + 45 \times FA\text{-}C + 68 \times FA\text{-}F + 91 \times GGBS$$

$$CO_2 \text{ emission (kg/ton of binder)} = 960 \times OPC + 93 \times \text{Fly Ash} + 155 \times GGBS$$

Weighting

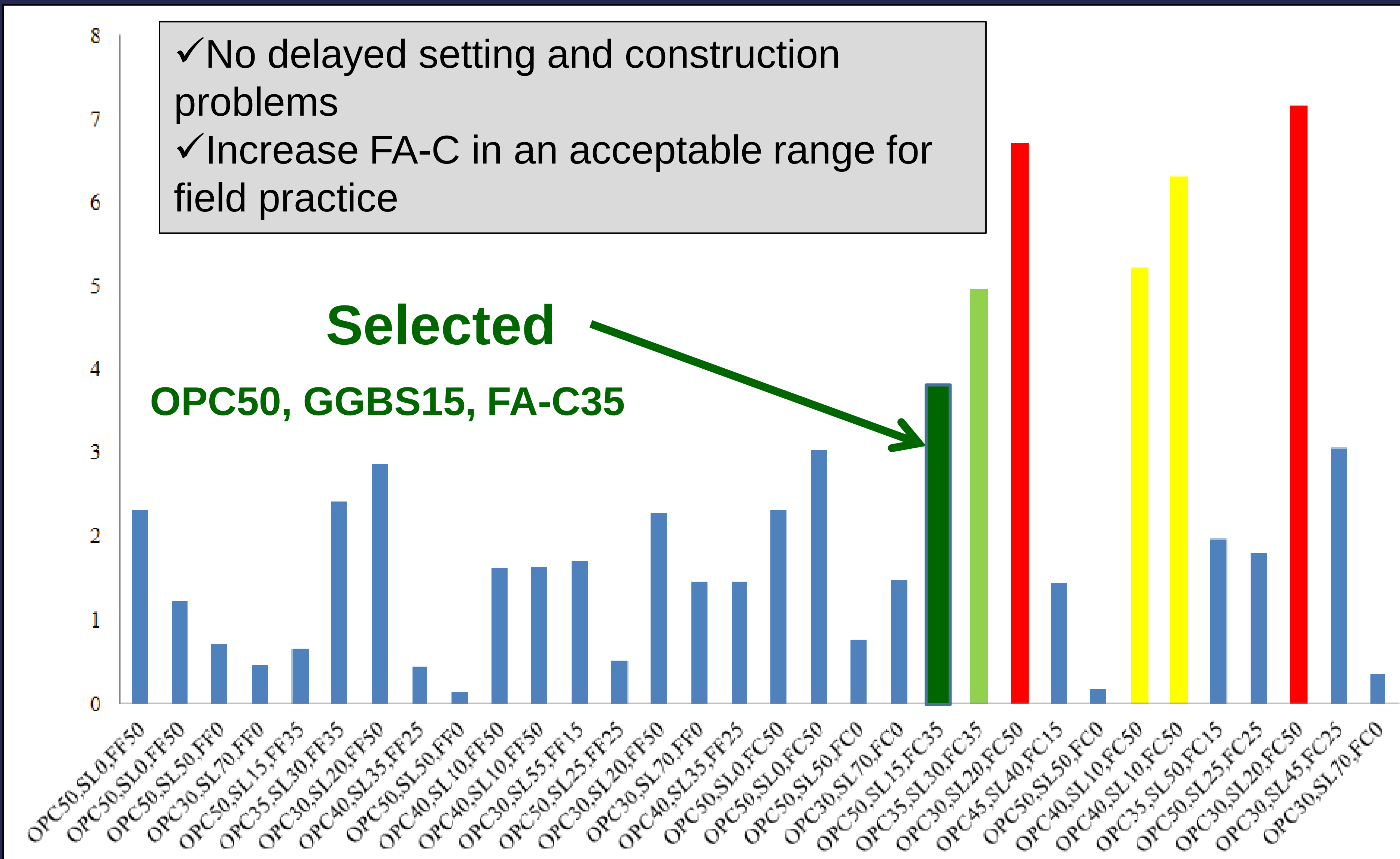
Factor	Compressive strength	Shrinkage	Cost	CO_2 emission
Importance weight	3	5	5	3

Star Graph



- ✓ Normalized from 0 to 100
- ✓ Weighting applied

Ranking Overall Performance



Mechanical Properties

Testing Protocol

Mixture No.		Concrete type			C-RCA (%)	F-RCA (%)	w/cm	Binder type
1	MoDOT Ref.			Top layer	0	0	0.40	25% FA-C
2	Opt. Binder			Top layer	0	0	0.40	35%FA-C+15%SL
3	30C-GP-37			Top layer	30	0	0.37	35%FA-C+15%GP
4	30C-37			Top layer	30	0	0.37	35%FA-C+15%SL
5	30C			Top layer	30	0	0.40	35%FA-C+15%SL
6	30C15F-37		Single layer	Top layer	30	15	0.37	35%FA-C+15%SL
7	30C15F		Single layer	Top layer	30	15	0.40	35%FA-C+15%SL
8	40C15F		Single layer		40	15	0.40	35%FA-C+15%SL
9	50C-37		Single layer		50	0	0.37	35%FA-C+15%SL
10	50C		Single layer		50	0	0.40	35%FA-C+15%SL
11	50C15F-37		Single layer		50	15	037	35%FA-C+15%SL
12	50C15F		Single layer		50	15	0.40	35%FA-C+15%SL
13	50C30F	Bottom layer	Single layer		50	30	0.40	35%FA-C+15%SL
14	50C40F	Bottom layer			50	40	0.40	35%FA-C+15%SL
15	60C30F	Bottom layer			60	30	0.40	35%FA-C+15%SL
16	70C-37	Bottom layer			70	0	0.37	35%FA-C+15%SL
17	70C	Bottom layer			70	0	0.40	35%FA-C+15%SL
18	70C15F	Bottom layer			70	15	0.40	35%FA-C+15%SL
19	70C30F	Bottom layer			70	30	0.40	35%FA-C+15%SL

Fresh Properties

Air Content

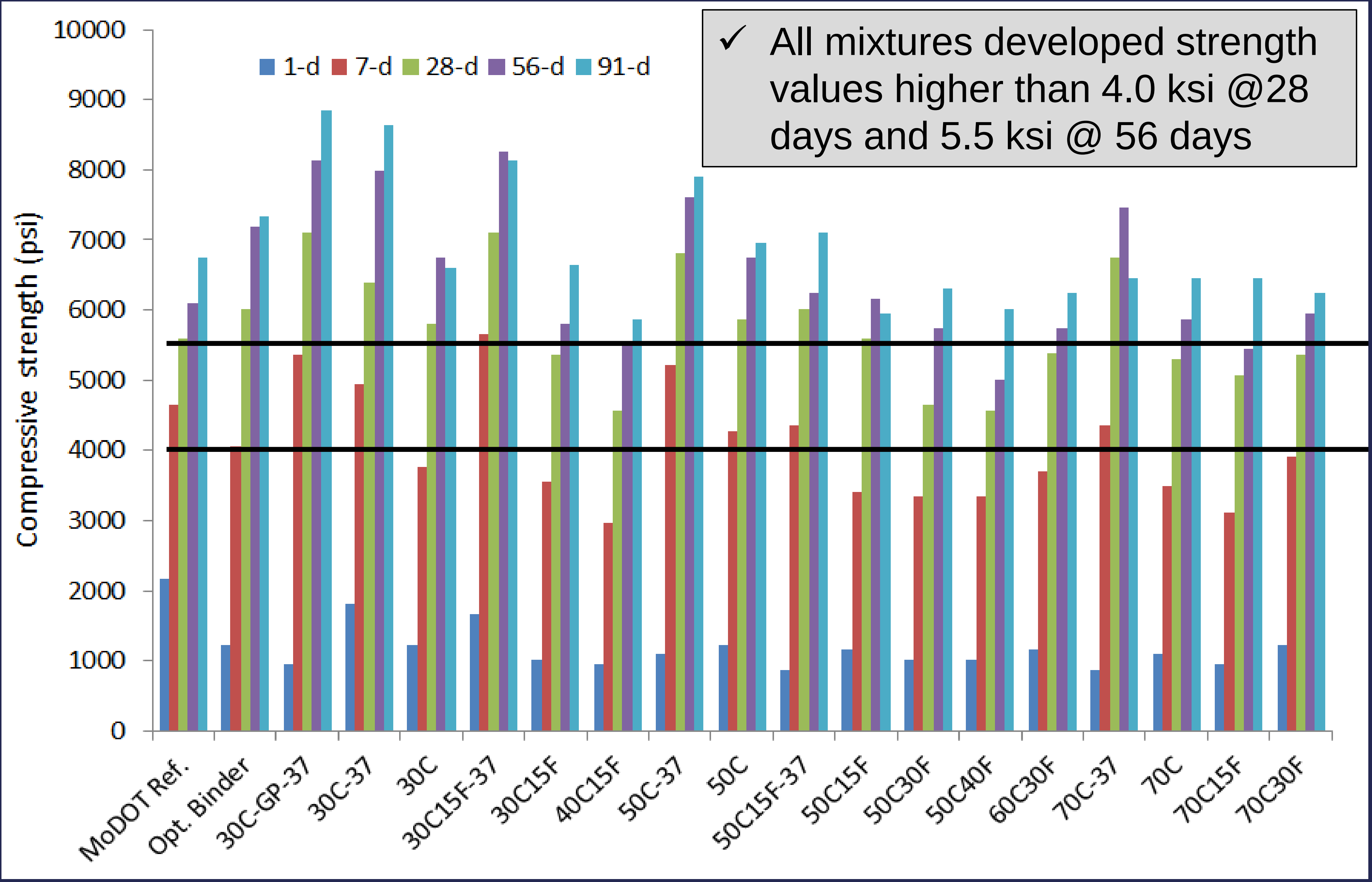
Range: 5.0 to 7.0%

Slump

Range: 1 to 3.5 in.

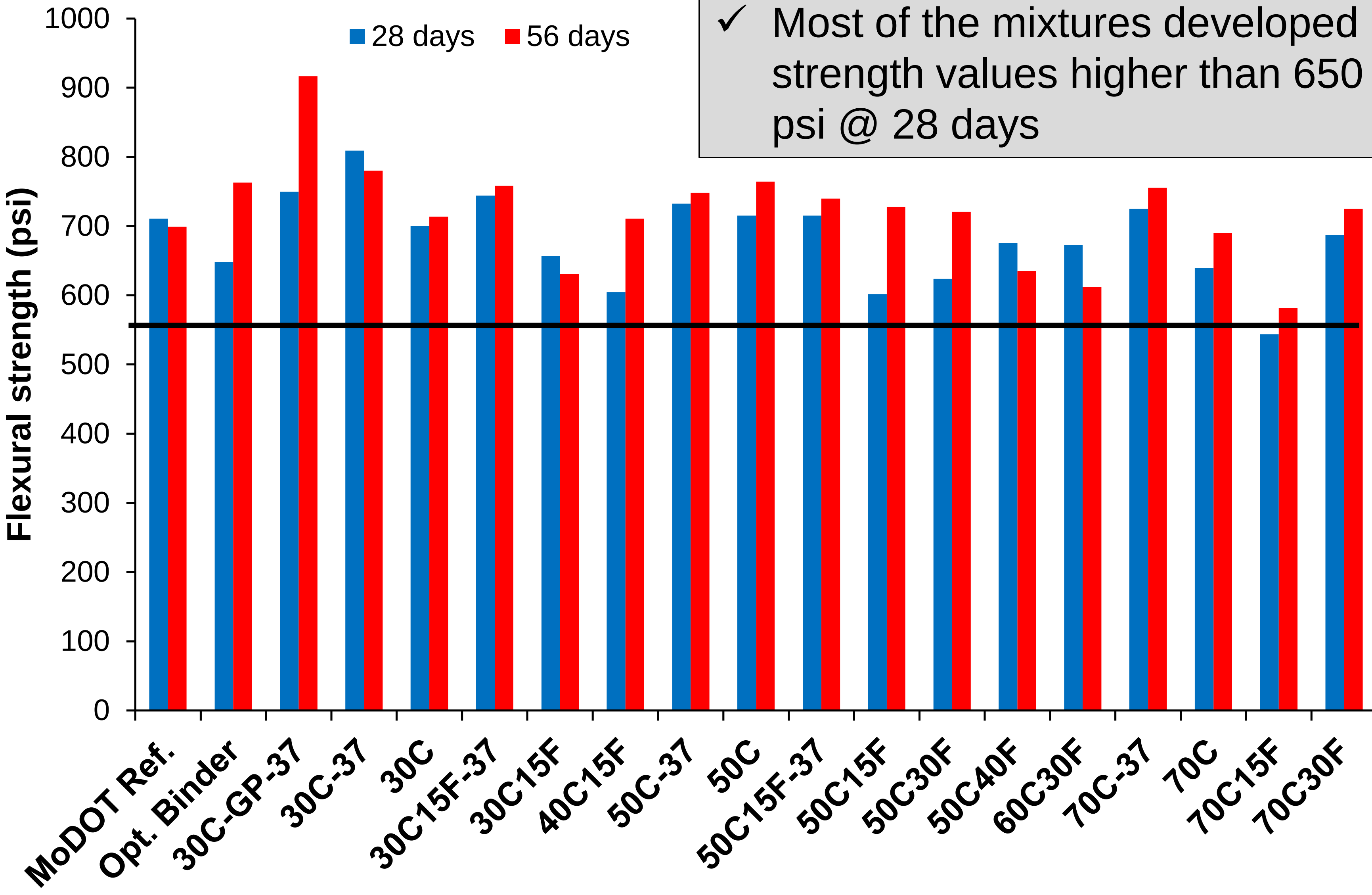
	Mixture	Slump (in.)	Air content (%)
1	MoDOT Ref.	3.5	6.2
2	Opt. Binder	3.5	5.0
3	30C-GP-37	3.0	5.5
4	30C-37	3.5	6.8
5	30C	2.5	5.0
6	30C15F-37	3.5	5.0
7	30C15F	1.5	5.0
8	40C15F	2.5	5.9
9	50C-37	3.5	7.0
10	50C	2.0	5.4
11	50C15F-37	3.5	6.8
12	50C15F	2.5	5.6
13	50C30F	3.5	5.0
14	50C40F	2.0	5.0
15	60C30F	2.0	5.0
16	70C-37	3.0	5.5
17	70C	3.5	6.9
18	70C15F	2.0	5.4
19	70C30F	1.0	5.2

Compressive Strength (psi)



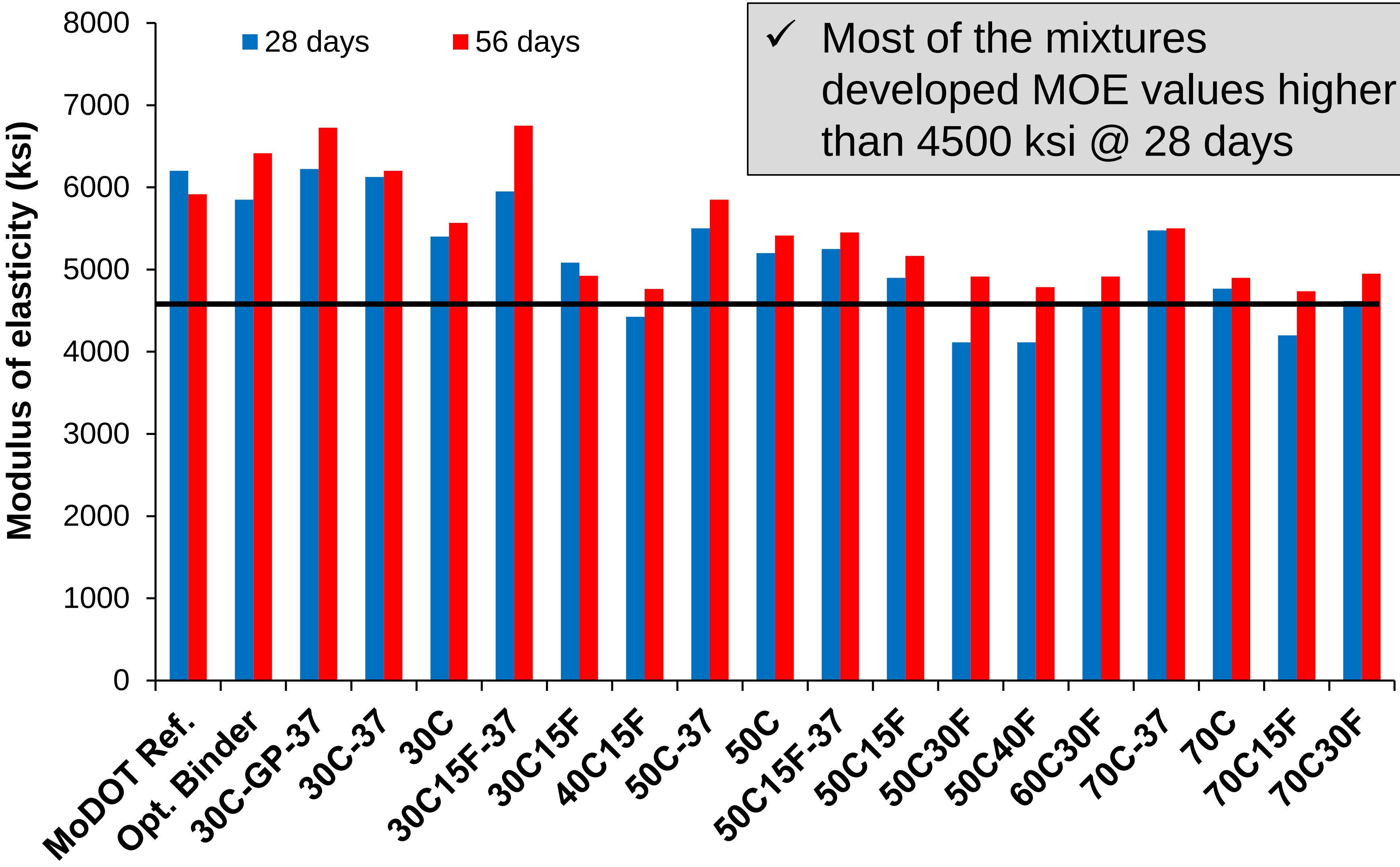
- ✓ All mixtures developed strength values higher than 4.0 ksi @28 days and 5.5 ksi @ 56 days

Flexural Strength (psi)



✓ Most of the mixtures developed strength values higher than 650 psi @ 28 days

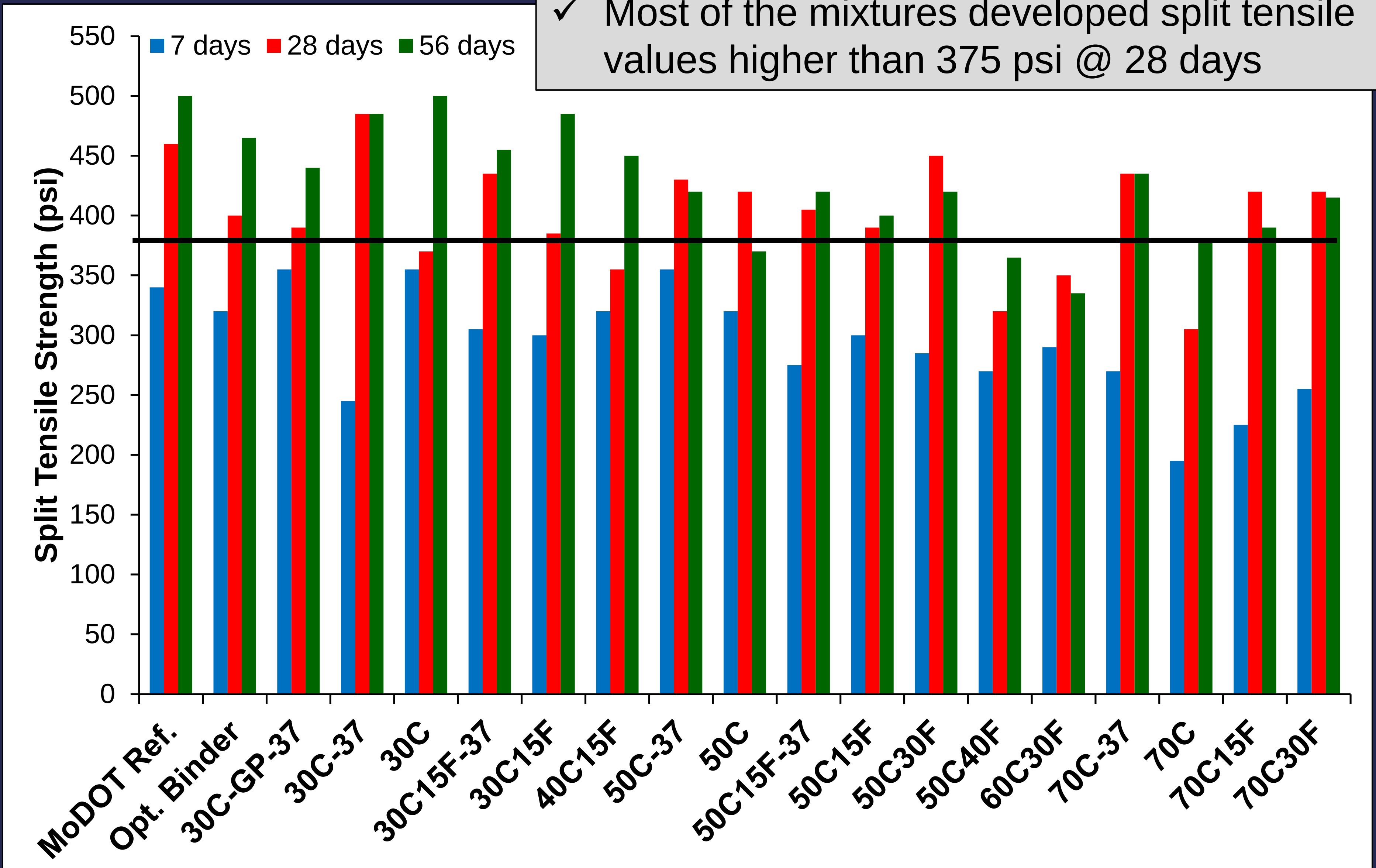
Modulus of Elasticity (ksi)



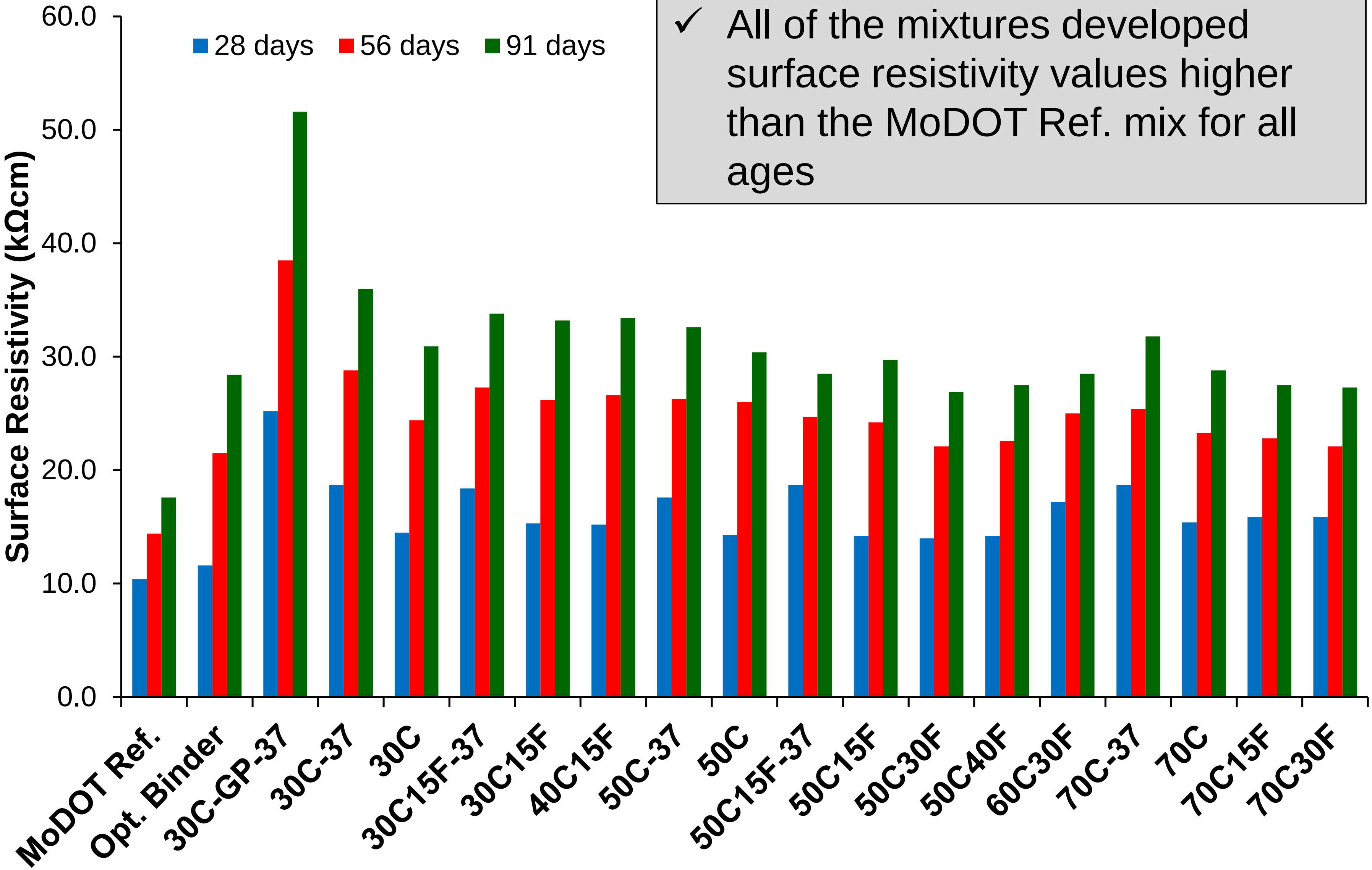
✓ Most of the mixtures developed MOE values higher than 4500 ksi @ 28 days

Split Tensile Strength (psi)

✓ Most of the mixtures developed split tensile values higher than 375 psi @ 28 days

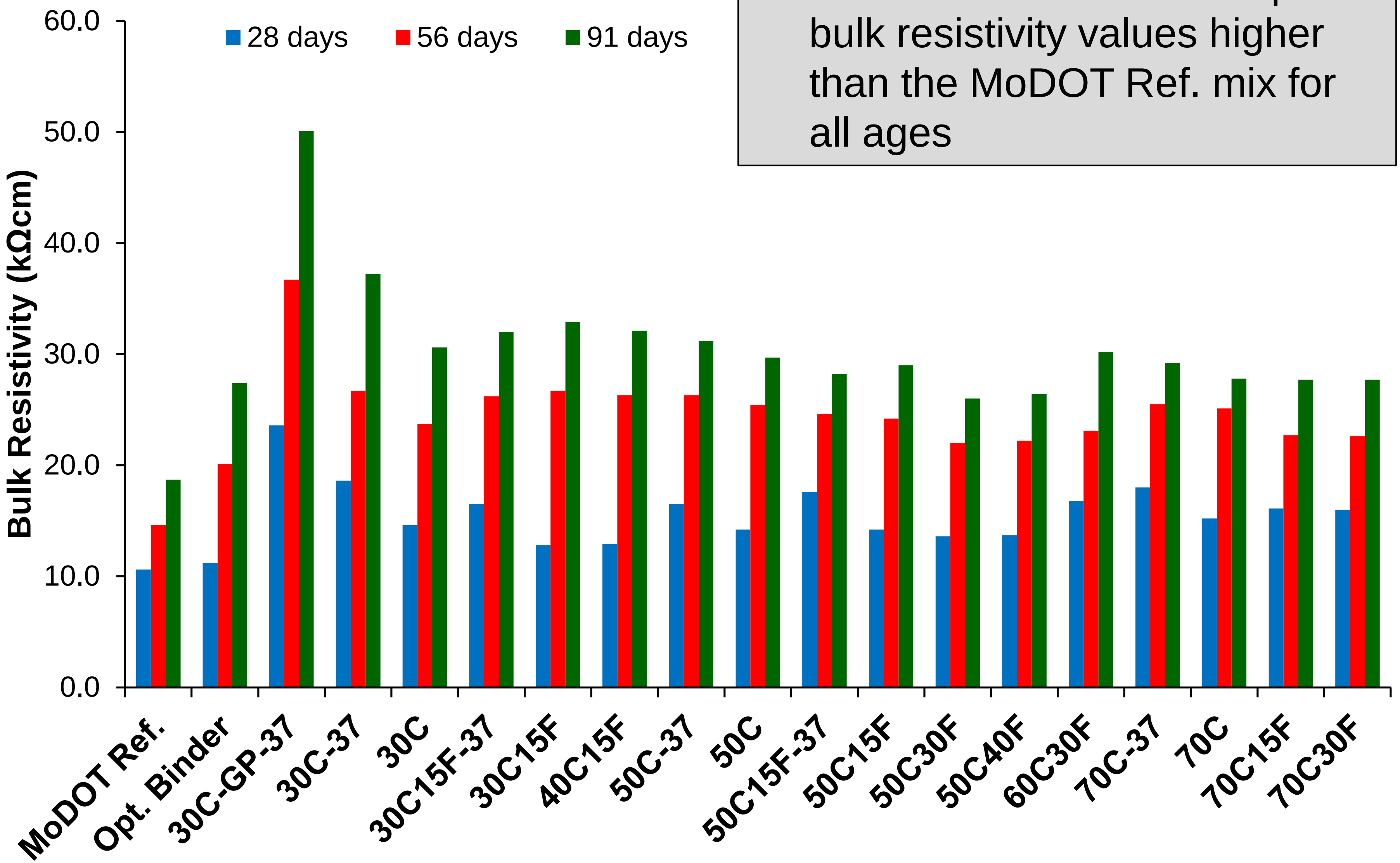


Surface Resistivity (kΩcm)



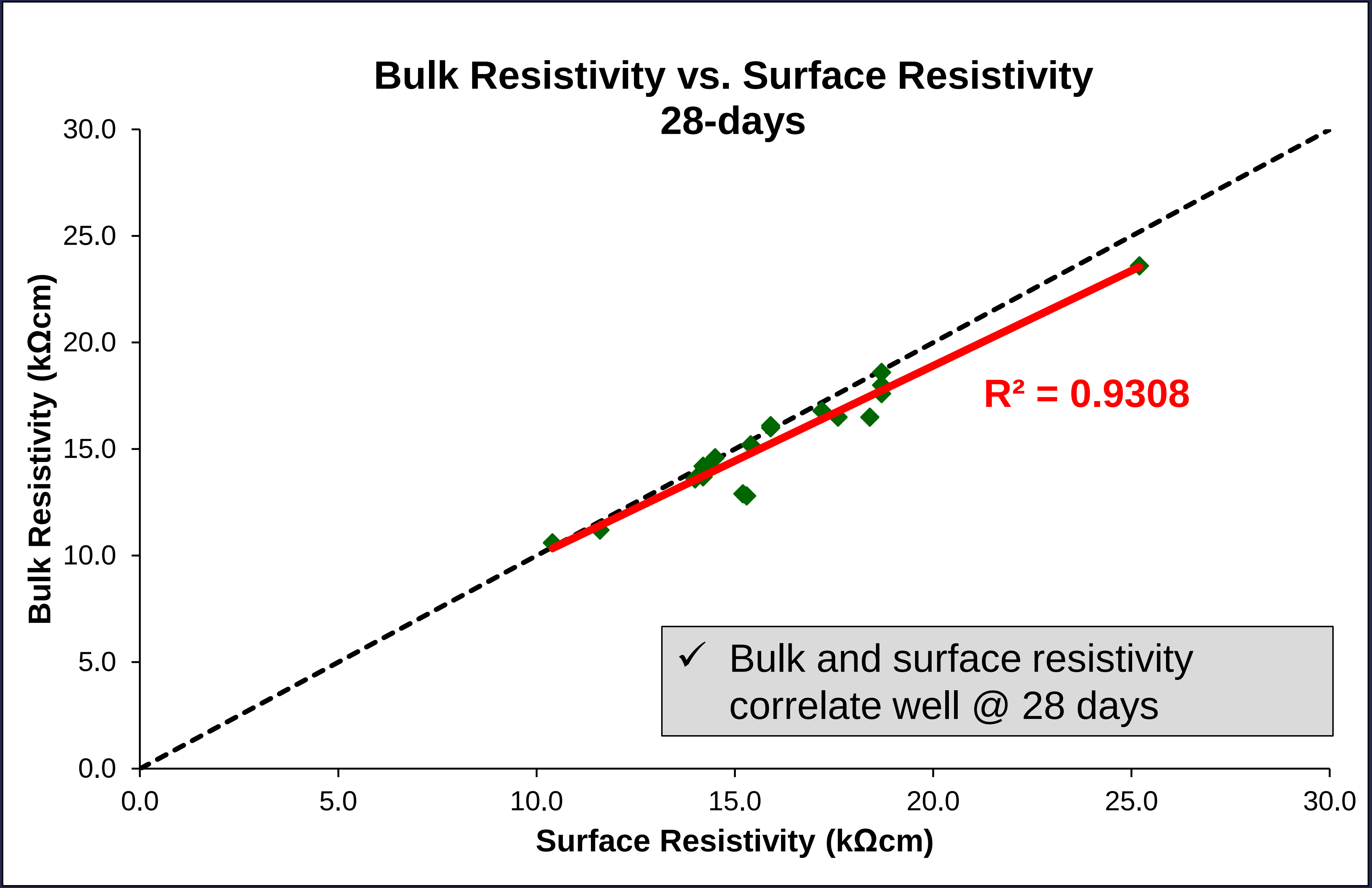
✓ All of the mixtures developed surface resistivity values higher than the MoDOT Ref. mix for all ages

Bulk Resistivity (kΩcm)

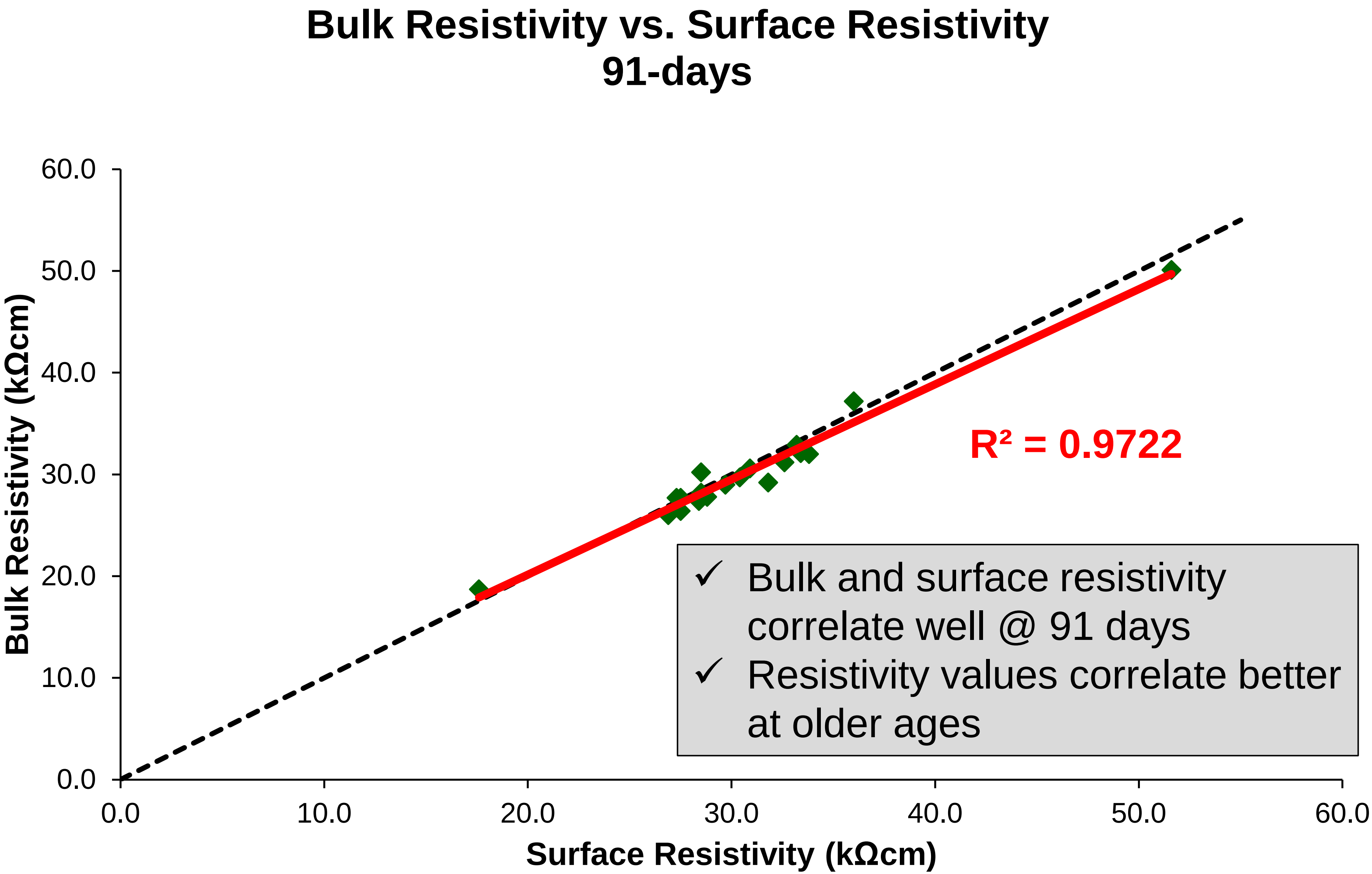


- ✓ All of the mixtures developed bulk resistivity values higher than the MoDOT Ref. mix for all ages

Resistivity – Bulk vs. Surface

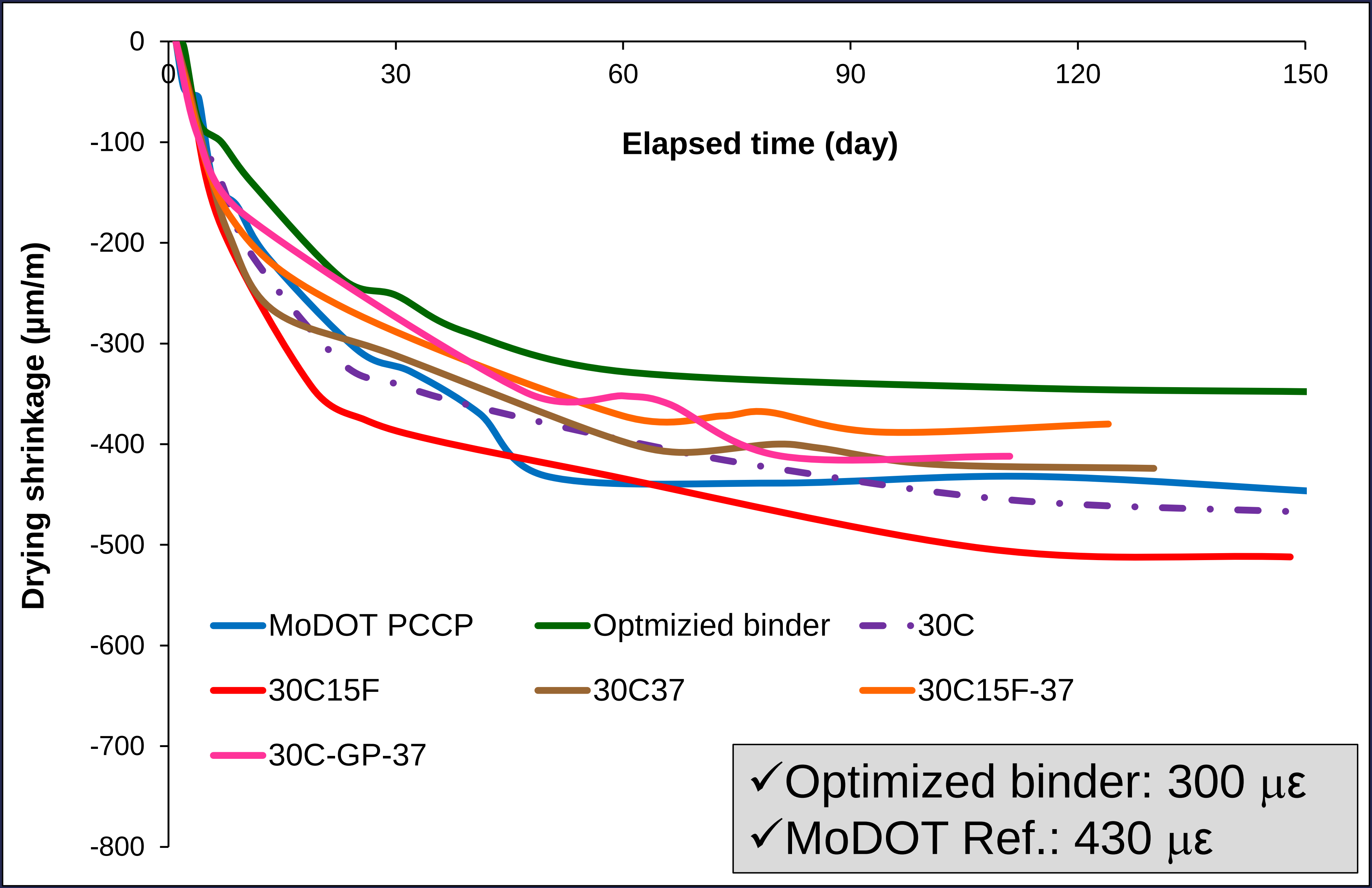


Resistivity – Bulk vs. Surface

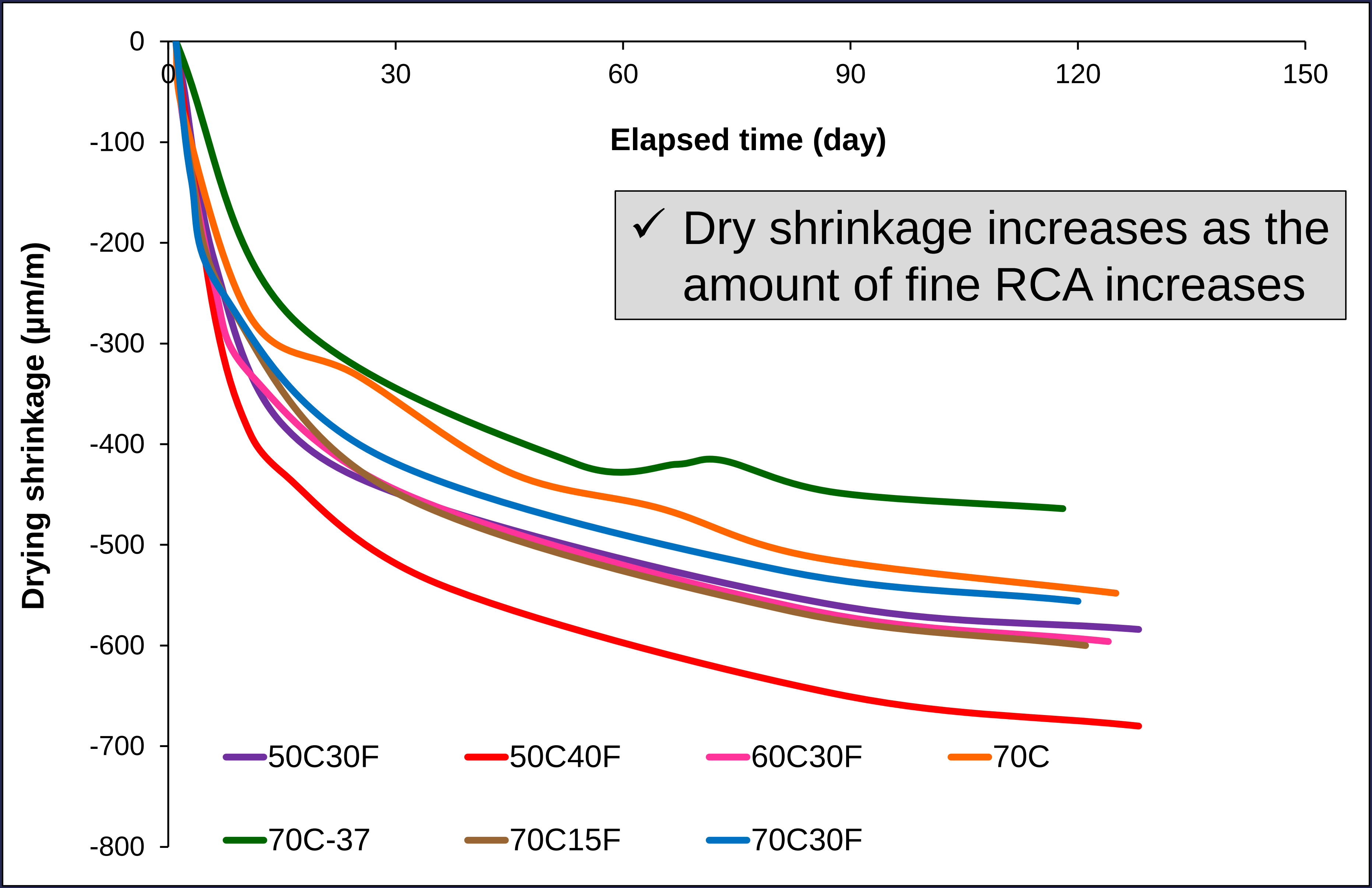


- ✓ Bulk and surface resistivity correlate well @ 91 days
- ✓ Resistivity values correlate better at older ages

Dry Shrinkage Top Layer (Two-Lift)

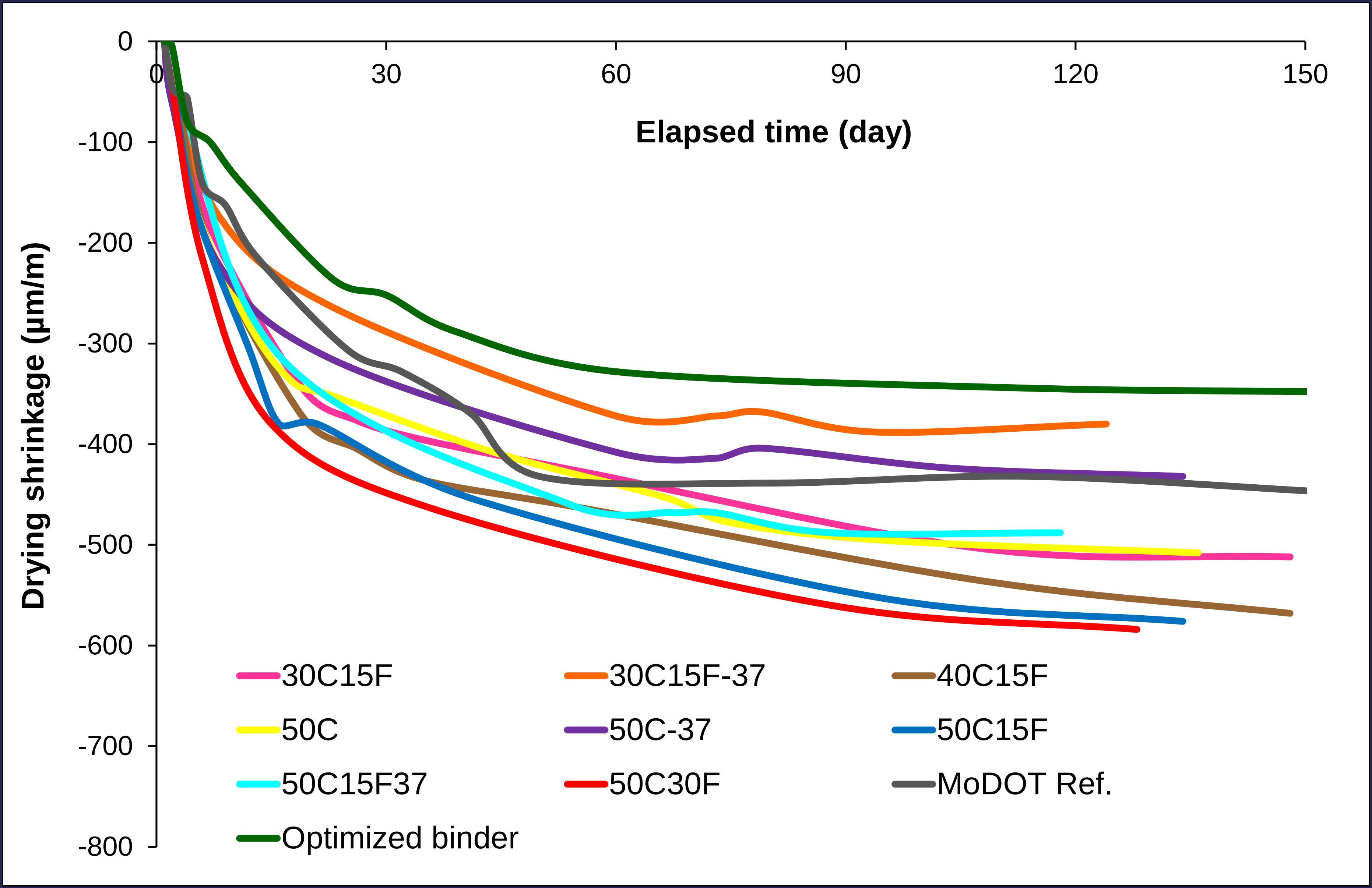


Dry Shrinkage Bottom Layer (Two-Lift)



Dry Shrinkage

Single Layer



Durability

Testing Protocol

<table>
<tr><th colspan="2">Mixture No.</th><th colspan="3">Scenario</th><th>Coarse RCA (%)</th><th>Fine RCA (%)</th><th>w/cm</th><th>Binder type</th><th>Binder content (lb/yd^3)</th></tr>
<tr><td>1</td><td>MODOT –PCCP</td><td rowspan="5" colspan="2"></td><td rowspan="7">Top layer</td><td>0</td><td>0</td><td>0.40</td><td>25% FA-C</td><td rowspan="10">545</td></tr>
<tr><td>2</td><td>Opt. Binder</td><td>0</td><td>0</td><td>0.40</td><td>35%FA-C, 15% GGBS</td></tr>
<tr><td>3</td><td>30C-GP-37</td><td>30</td><td>0</td><td>0.37</td><td>35%FA-C, 15% GP</td></tr>
<tr><td>4</td><td>30C-37</td><td>30</td><td>0</td><td>0.37</td><td rowspan="7">35%FA-C, 15% GGBS</td></tr>
<tr><td>5</td><td>30C</td><td>30</td><td>0</td><td>0.40</td></tr>
<tr><td>6</td><td>30C15F-37</td><td rowspan="3"></td><td rowspan="4">Single layer</td><td>30</td><td>15</td><td>0.37</td></tr>
<tr><td>7</td><td>30C15F</td><td>30</td><td>15</td><td>0.40</td></tr>
<tr><td>8</td><td>50C-37</td><td rowspan="3"></td><td>50</td><td>0</td><td>0.37</td></tr>
<tr><td>9</td><td>50C15F-37</td><td rowspan="2">Bottom layer</td><td>50</td><td>15</td><td>0.37</td></tr>
<tr><td>10</td><td>70C-37</td><td></td><td>70</td><td>0</td><td>0.37</td></tr>
</table>

Fresh Properties

Air Content

Range: 5.0 to 7.0%

Slump

Range: 1.5 to 3.5 in.

	Mixture	Slump (in.)	Air content (%)
1	MoDOT Ref.	3.5	6.2
2	Opt. Binder	3.5	5.0
3	30C-GP-37	3.0	5.5
4	30C-37	3.5	6.8
5	30C	2.5	5.0
6	30C15F-37	3.5	5.0
7	30C15F	1.5	5.0
8	50C-37	3.5	7.0
9	50C15F-37	3.5	6.8
10	70C-37	3.0	5.5

Coefficient of Thermal Expansion (E-6 in/in/ºF)

- ✓ Comparable performance for all mixtures
- ✓ MoDOT Ref. had the highest CTE value

	Mixture	CTE value
1	MoDOT Ref.	5.224
2	Opt. Binder	5.037
3	30C-GP-37	5.173
4	30C-37	5.187
5	30C	5.075
6	30C15F-37	5.064
7	30C15F	4.945
8	50C-37	5.136
9	70C-37	4.856

Salt Scaling

✓ RCA mixtures comparable to Opt. Binder mix.

	Mixture	Test cycle									
		5	10	15	20	25	30	35	40	45	50
1	MoDOT Ref.	0	0	0	1	1	1	1	1	1	1
2	Opt. Binder	0	1	1	1	2	2	3	3	3	3
3	30C-GP-37	1	1	2	2	2	3	3	3	4	4
4	30C-37	0	1	1	1	1	2	2	3	3	3
5	30C	0	0	1	1	1	2	2	3	3	3
6	30C15F-37	0	1	1	2	3	3	3	3	3	3
7	30C15F	1	1	1	1	2	2	3	3	3	3
8	50C-37	0	1	2	2	2	3	3	3	3	3
9	50C15F-37	1	2	2	2	3	3	3	3	3	3
10	70C-37	1	1	1	1	2	2	2	2	2	2

Durability Factor

	Mixture	Durability factor (%)
1	MoDOT Ref.	95.6
2	Opt. Binder	92.5
3	30C-GP-37	88.8
4	30C-37	97.1
5	30C	90.5
6	30C15F-37	96.0
7	30C15F	94.5
8	50C-37	92.2
9	50C15F-37	96.0
10	70C-37	96.0

- ✓ Good frost durability with DF higher than 88%

Abrasion Resistance

	Mixture	Mass loss (g)
1	MoDOT Ref.	1.2
2	Opt. Binder	1.2
3	30C-GP-37	0.4
4	30C-37	0.8
5	30C	1.3
6	30C15F-37	0.7
7	30C15F	1.1
8	50C-37	0.5
9	50C15F-37	0.7
10	70C-37	0.7

- ✓ Reducing w/cm improves abrasion resistance
- ✓ Slight increase due to C-RCA and F-RCA incorporation

Sorptivity

	Mixture	Initial sorptivity	Secondary sorptivity
1	MoDOT Ref.	2.23 E-6	8.9 E-7
2	Opt. Binder	1.49 E-6	5.5 E-7
3	30C-GP-37	0.95E -6	3.5 E-7
4	30C-37	1.23 E-6	5.1 E-7
5	30C	1.89 E-6	6.0 E-7
6	30C15F-37	0.86 E-6	3.7 E-7
7	30C15F	1.59 E-6	6.2 E-7
8	50C-37	1.23 E-6	5.0 E-7
9	50C15F-37	1.13 E-6	4.9 E-7
10	70C-37	1.29 E-6	5.3 E-7

- ✓ Max. sorptivity rate was observed for the reference concrete
- ✓ Reducing w/cm improves absorption rate
- ✓ Slight increase due to C-RCA and F-RCA incorporation

Conclusions

- Single Layer Pavement

Property	MoDOT PCCP	Opt. Binder	30C	50C-37
28-d Compressive strength (psi)	5,585	6,020	5,800	6,815
91-d Compressive strength (psi)	6,745	7,325	6,600	7,905
56-d Modulus of elasticity (ksi)	5,915	6,415	5,565	5,850
56-d Flexural strength (psi)	700	765	715	750
90-d Shrinkage (με)	430	340	450	420
Durability factor (%)	96	93	91	92
De-icing salt scaling rating	1	3	3	3
Mass loss due to scaling	100	735	870	700

Conclusions

- Two-Lift Pavement

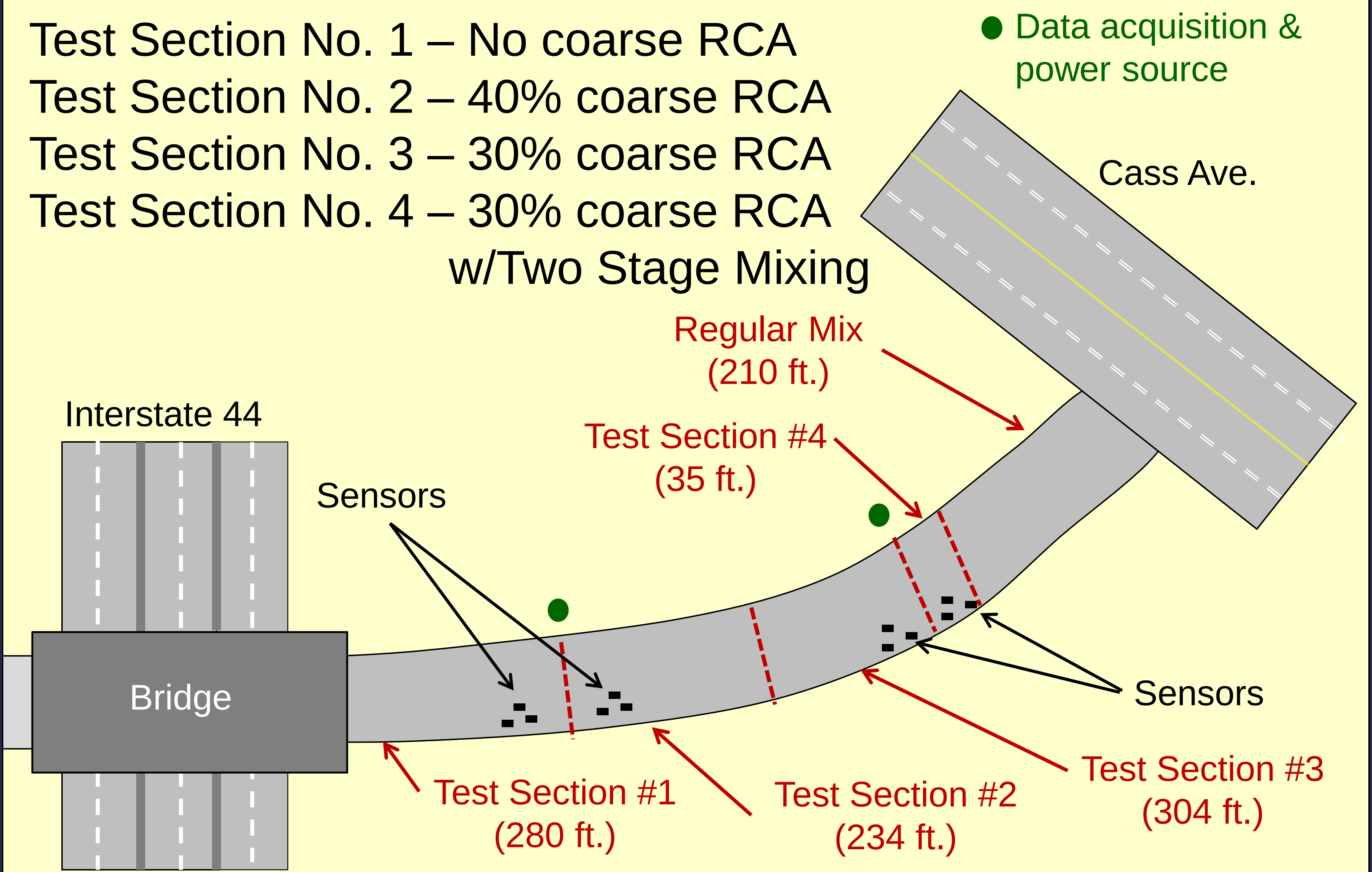
Application	Top layer			Bottom layer	
Property	MoDOT PCCP	Opt. Binder	30C	50C15F-37	70C-37
28-d Compressive strength (psi)	5,585	6,020	5,800	6,020	6,745
91-d Compressive strength (psi)	6,745	7,325	6,600	7,105	7,690
56-d Modulus of elasticity (ksi)	5,915	6,415	5,565	5,450	5,500
56-d Flexural strength (psi)	700	765	715	740	755
90-d Shrinkage (με)	430	340	450	490	450
Durability factor (%)	96	93	91	96	96
De-icing salt scaling rating	1	3	3	3	2
Mass loss due to scaling	100	735	870	800	450

Project Location

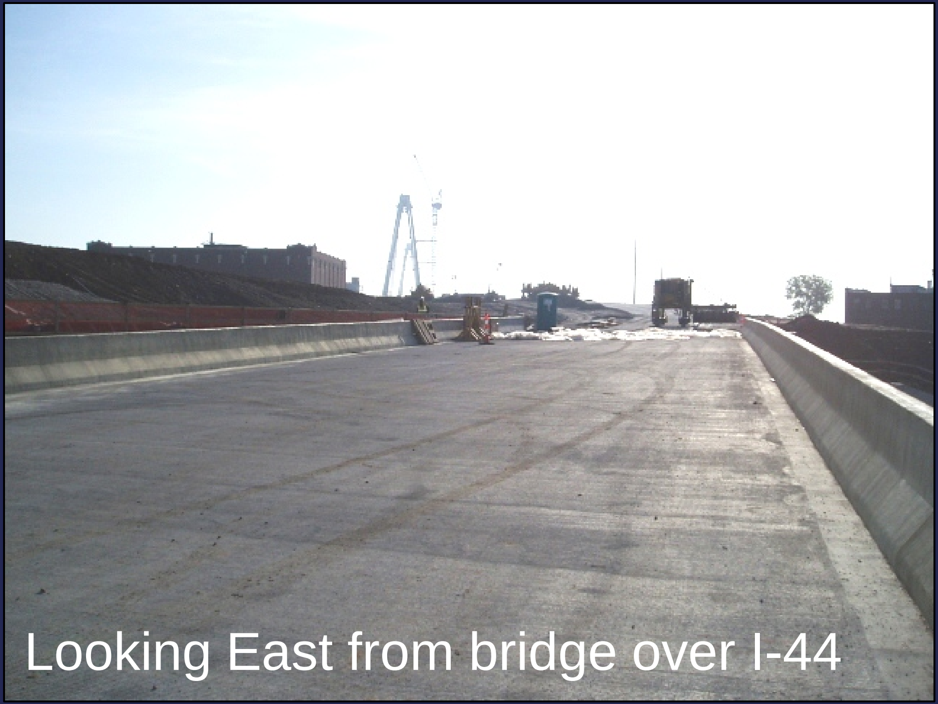
- MoDOT's first RCA project
- Placed on the Mississippi River Bridge project in St. Louis
  - Ramp to new bridge
  - Coarse RCA only
  - Four test sections
  - Constructed April 29, 2013

Test Sections

Test Section No. 1 – No coarse RCA
Test Section No. 2 – 40% coarse RCA
Test Section No. 3 – 30% coarse RCA
Test Section No. 4 – 30% coarse RCA w/Two Stage Mixing



Job Site


Looking East from bridge over I-44


Looking West from bridge over I-44


Looking towards Cass Ave.

Coarse Aggregate

Material	1” Max. L.S.	Coarse RCA
Bulk Sp. Gr.	2.652	2.396
Absorption	0.8	3.5
LA Abrasion	24	33
Soundness	3	32
Micro-Deval	15.0	14.4

	Sieve	% Passing	% Passing
Gradation	1 in.	100	100
	3/4 in.	88.5	80.3
	1/2 in.	40.5	31.1
	3/8 in.	20.1	16.8
	#4	3.1	3.3
	#8	1.8	1.8
	#200	1.4	0.7

Mix Designs

Design Criteria	No. 1	No. 2	No. 3	No. 4**
	Test Sections			
Cement Amount (lbs.)	546	546	546	546
w/c Ratio	0.40	0.40	0.40	0.40
% Fly Ash	25.0	25.0	25.0	25.0
% Fine Agg.	42.5	42.5	42.5	42.5
% Coarse RCA Agg.	---	40.0	30.0	30.0
Design Air Content (%)	6.0	6.0	6.0	6.0

*** Two stage mixing*

Test Section No. 1

- Reviewed September 2017 (48 months)

Control Mix
No RCA

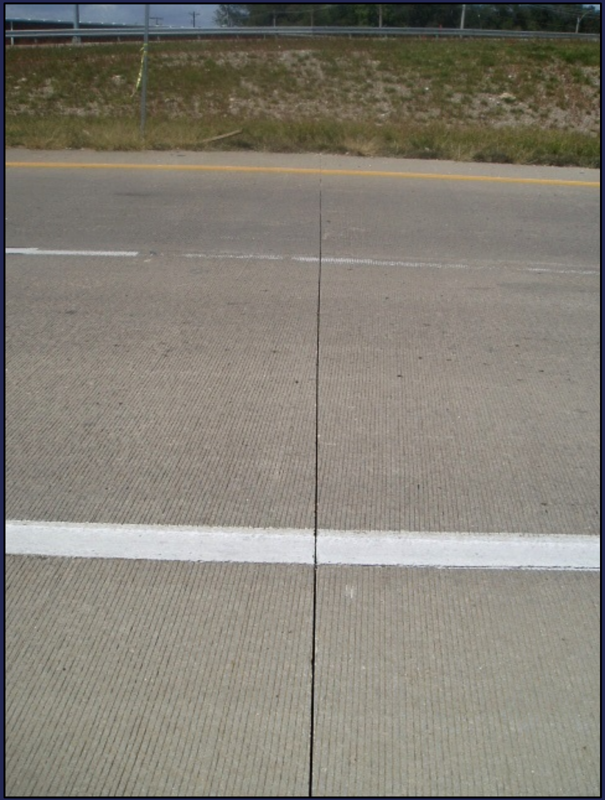
Test Section No. 1

- Reviewed September 2017 (48 months)

Test Section No. 2

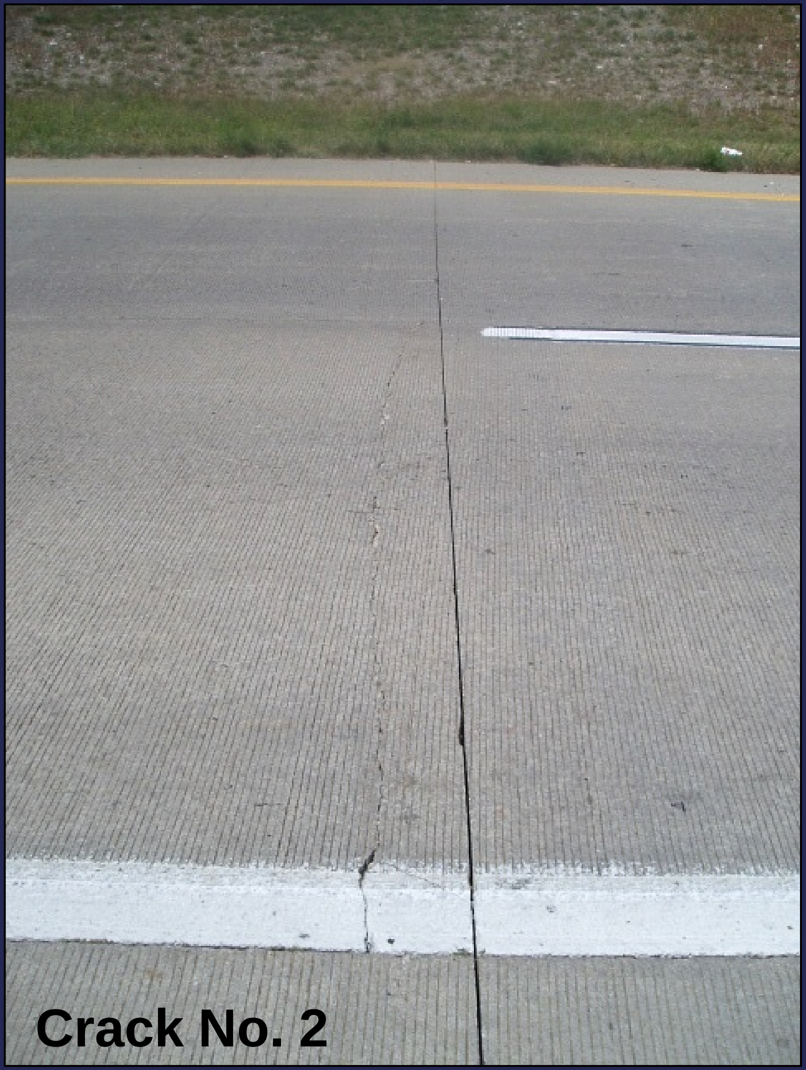
- Reviewed September 2017 (48 months)

40% RCA



Test Section No. 2

- Reviewed September 2017 (48 months)



Test Section No. 3

- Reviewed September 2017 (48 months)

30% RCA

Test **Section** No. 4

- Reviewed September 2017 (48 months)

30% RCA with two stage mixing

Questions

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https://library.modot.mo.gov/RDT/reports/TR201502/