AMERICAN ENGINEERING TESTING, INC.

CONSULTANTS
· ENVIRONMENTAL
· GEOTECHNICAL
· MATERIALS
· FORENSICS

November 16, 2016

Minnesota Concrete Council
Research Committee
4125 137th Street West
Rosemount, MN 55068

Subj: Minnesota Concrete Council (MCC) Research Committee's Study on
Performance of Recycled Aggregate Concrete
AET Project No. 29-02189

Research Committee:

American Engineering Testing, Inc. (AET) has finished the research study commissioned by the committee this past summer. The research consisted of a 2^3 factorial statistical study on the performance of recycled aggregate concrete. The design of the study allowed for the analysis of three independent variables.

Independent Variables

The three (3) independent variables tested are:

1. Source of recycled coarse aggregate
2. Recycled aggregate replacement percentage
3. Design strength of concrete

Two (2) sources of recycled coarse aggregate tested in this study were crushed concrete aggregate (CCA) and recycled concrete aggregate (RCA). CCA consisted of concrete that had been returned to the original batch plant and allowed to hardened. The hardened concrete was then subsequently crushed and available for reuse. RCA consisted of concrete and other construction material sourced from out of service and demolished infrastructure. A complete listing of factorial points to be tested is given in Table 1 below. Each factorial point corresponds to a unique concrete mix.

Table 1
Independent Variables for Performance of Recycled Aggregate Concrete

Factorial Point	Aggregate Source	Replacement Percentage	Design Strength (psi)
1	RCA	30%	4,000
2	RCA	30%	6,000
3	RCA	60%	4,000
4	RCA	60%	6,000
5	CCA	30%	4,000
6	CCA	30%	6,000
7	CCA	60%	4,000
8	CCA	60%	6,000
9	RCA	45%	4,000
10	RCA	45%	6,000
Control	-	0%	4,000
Control	-	0%	6,000

Note: Factorial points 9 and 10 have been included to test the significance of curvature.

Table 2

Mix Proportions	1	2	3	4	5	6	7	8	9	10	11	12
Cement (lbs)	439	595	439	595	439	595	439	595	439	595	439	595
Fly Ash (lbs)	78	105	78	105	78	105	78	105	78	105	78	105
Sand (lbs)	1374	1235	1374	1235	1374	1235	1374	1235	1374	1235	1374	1235
River Gravel (lbs)	1329	1194	569	682	1329	1194	569	682	1044	938	1926	1732
RCA (lbs)	569	512	1329	1024	-	-	-	-	854	768	-	-
CCA (lbs)	-	-	-	-	569	512	1329	1024	-	-	-	-
Water (lbs)	220	287	220	287	220	287	220	287	220	287	220	287
f'c (psi)	4000	6000	4000	6000	4000	6000	4000	6000	4000	6000	4000	6000
Replacement (%)	30	30	60	60	30	30	60	60	45	45	0	0

Materials

Cement	Holcim St. Genevieve, Type I/II Portland Cement (ASTM C150)
Fly Ash	Headwaters Coal Creek (ASTM C618, Class F)
Fine Aggregate	Empire Concrete Sand (ASTM C33)
Coarse Aggregate	Empire 3/4" Rock (ASTM C33)
Water Reducer	KB-1000 (ASTM C494, Type A)

Dependent Variables

There are a total of eight (8) dependent variables that were tested for each factorial point and controls. These are listed below with relevant testing standard.

1. Slump - ASTM C143/C143M-15, "Standard Test Method for Slump of Hydraulic Cement Concrete."

2. Air Content – ASTM C231/C231M-14, "Standard Test Method for Air Content of Freshly Mix Concrete by the Pressure Method."

3. Finishability – Subjective evaluation by three experienced finishers who applied a magnesium and wood floot finish to a 24x24-inch test slab.

   Finishing Scale
   1. Very difficult
   2. Difficult
   3. Moderate
   4. Easy
   5. Very easy

4. Setting Time – ASTM C403/C403M-08, "Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance."

5. Shrinkage – ASTM C157/C157M-08 (2014), "Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete."

6. Chloride Penetration (Wenner Probe Method) – AASHTO T358-15, "Standard Method of Test for Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration."

Surface Resistivity Test

Chloride Ion Penetration	4x8-in cylinder kΩ-cm
High	< 12
Moderate	12-21
Low	21-37
Very low	37-254
Negligible	>254

7. Compressive Strength – ASTM C39/C39M-15, "Standard Test Method for Compression Strength of Cylindrical Concrete Specimens."

8. Flexural Strength – ASTM C78/C78M-15a, "Standard Test Method for Flexural Strength of Concrete (using Simple Beam with Third-Point Loading)."

Test Results

Test results can be found on the attached tables and graphs.

Discussion of Test Results

Sincerely,
American Engineering Testing, Inc.

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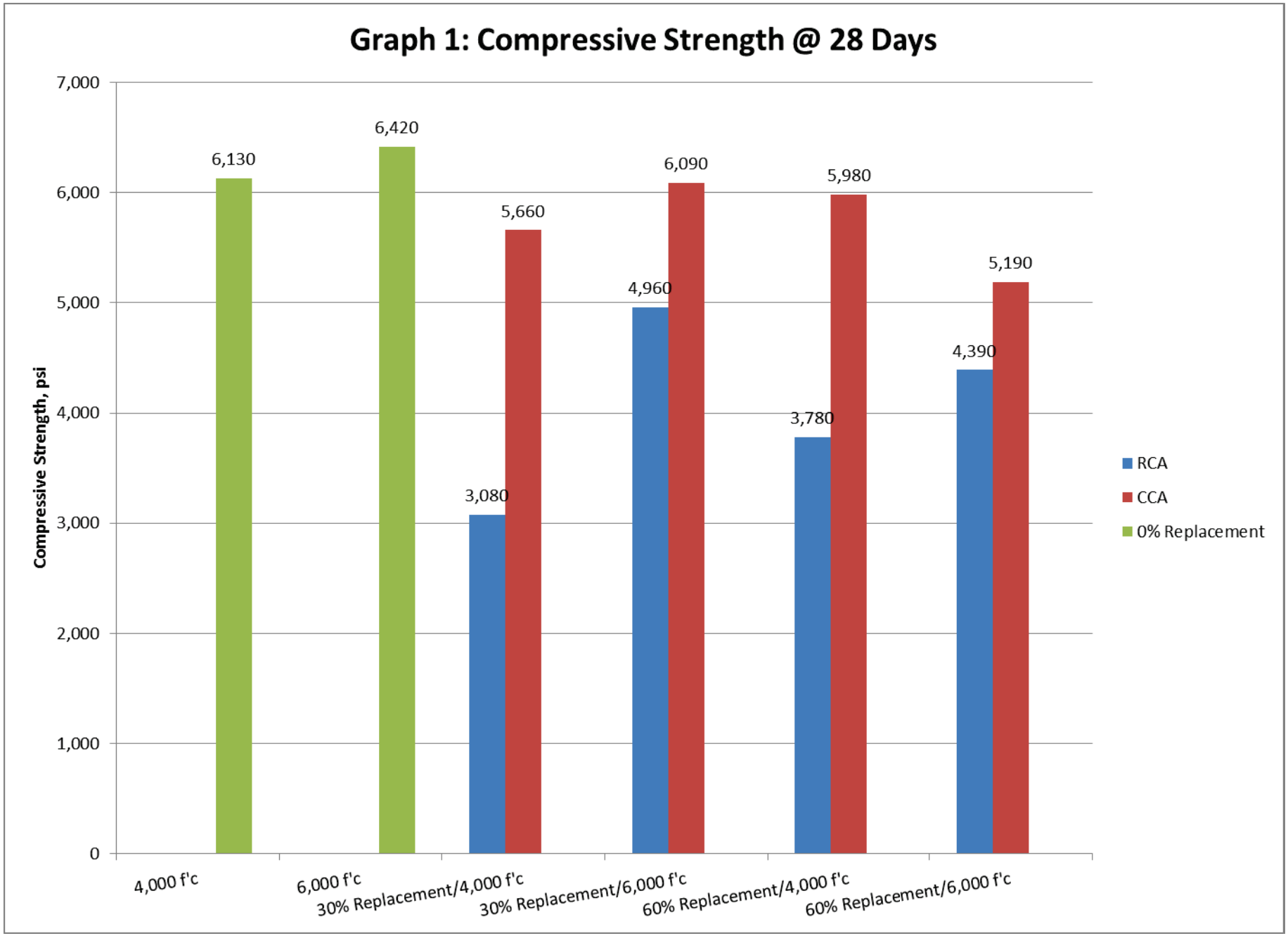
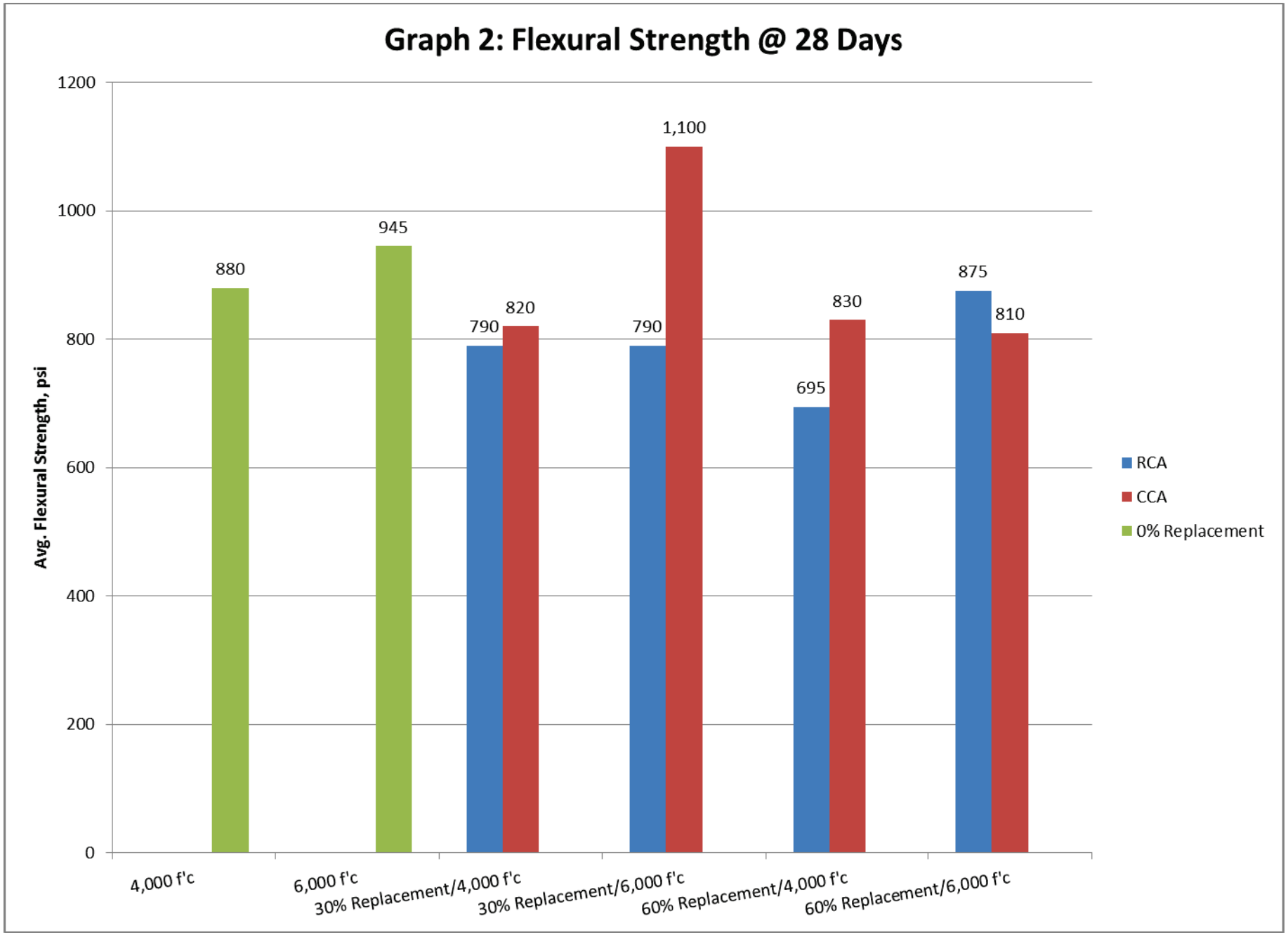
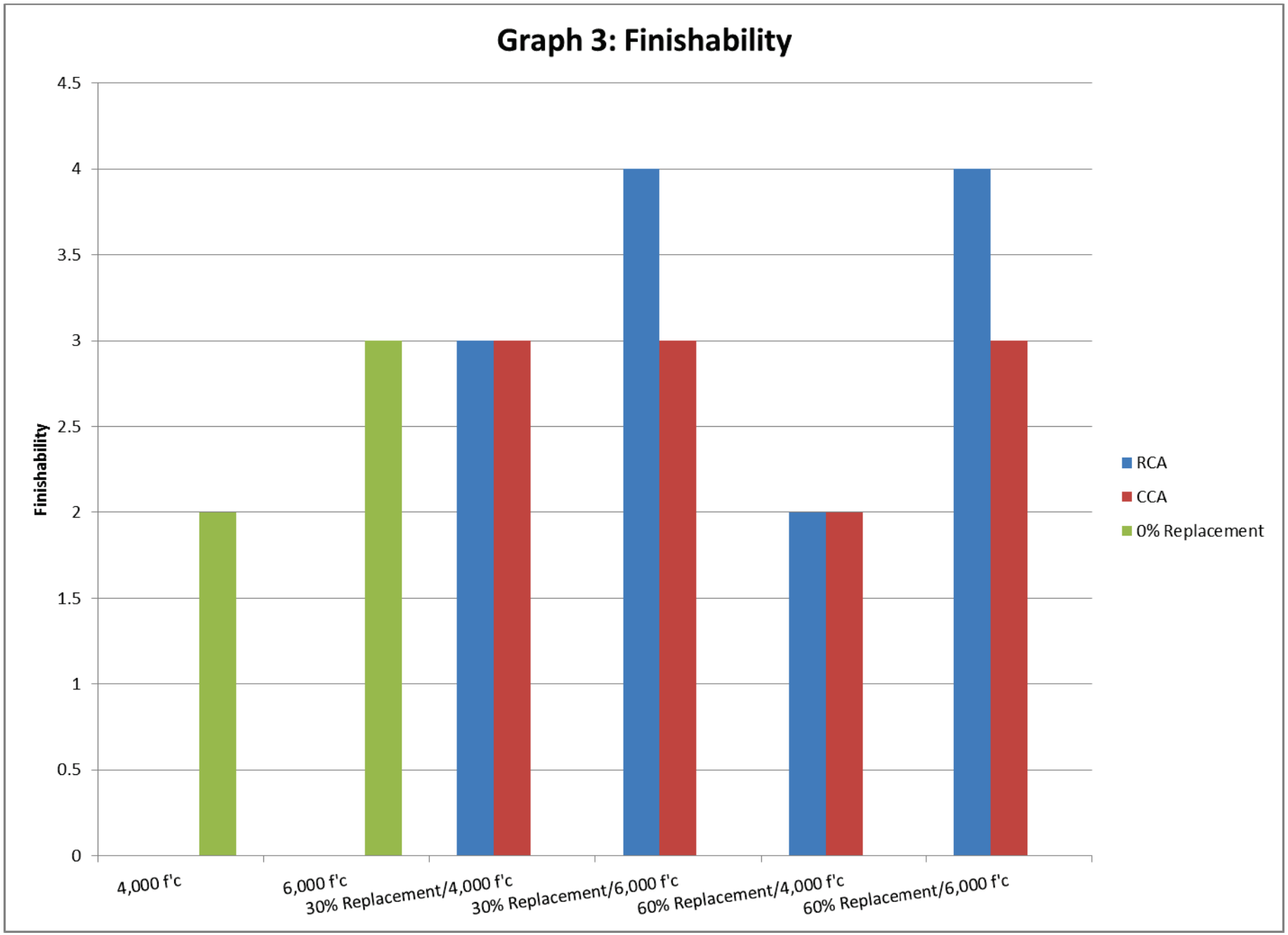
Principal Engineer

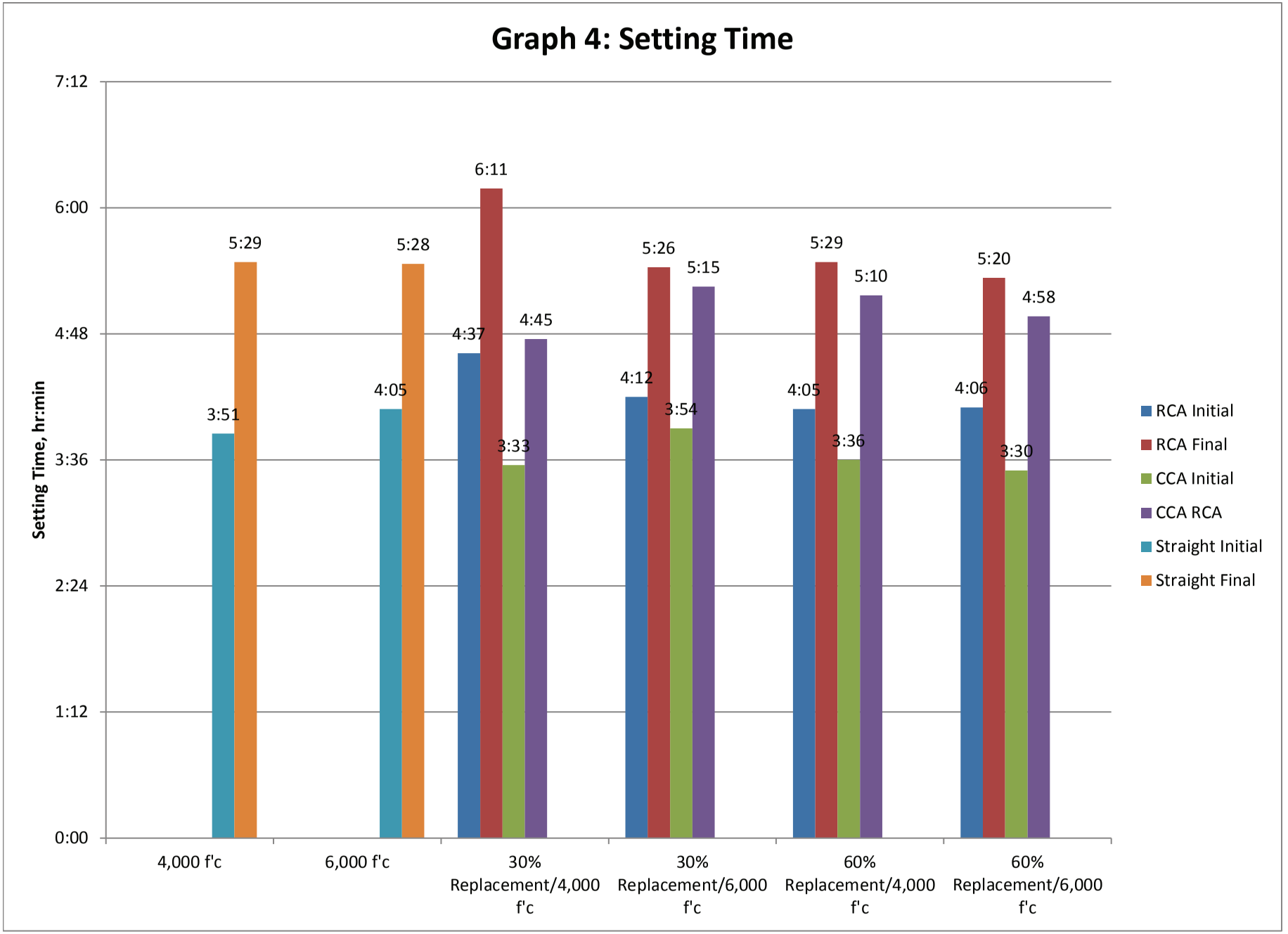
Table 3

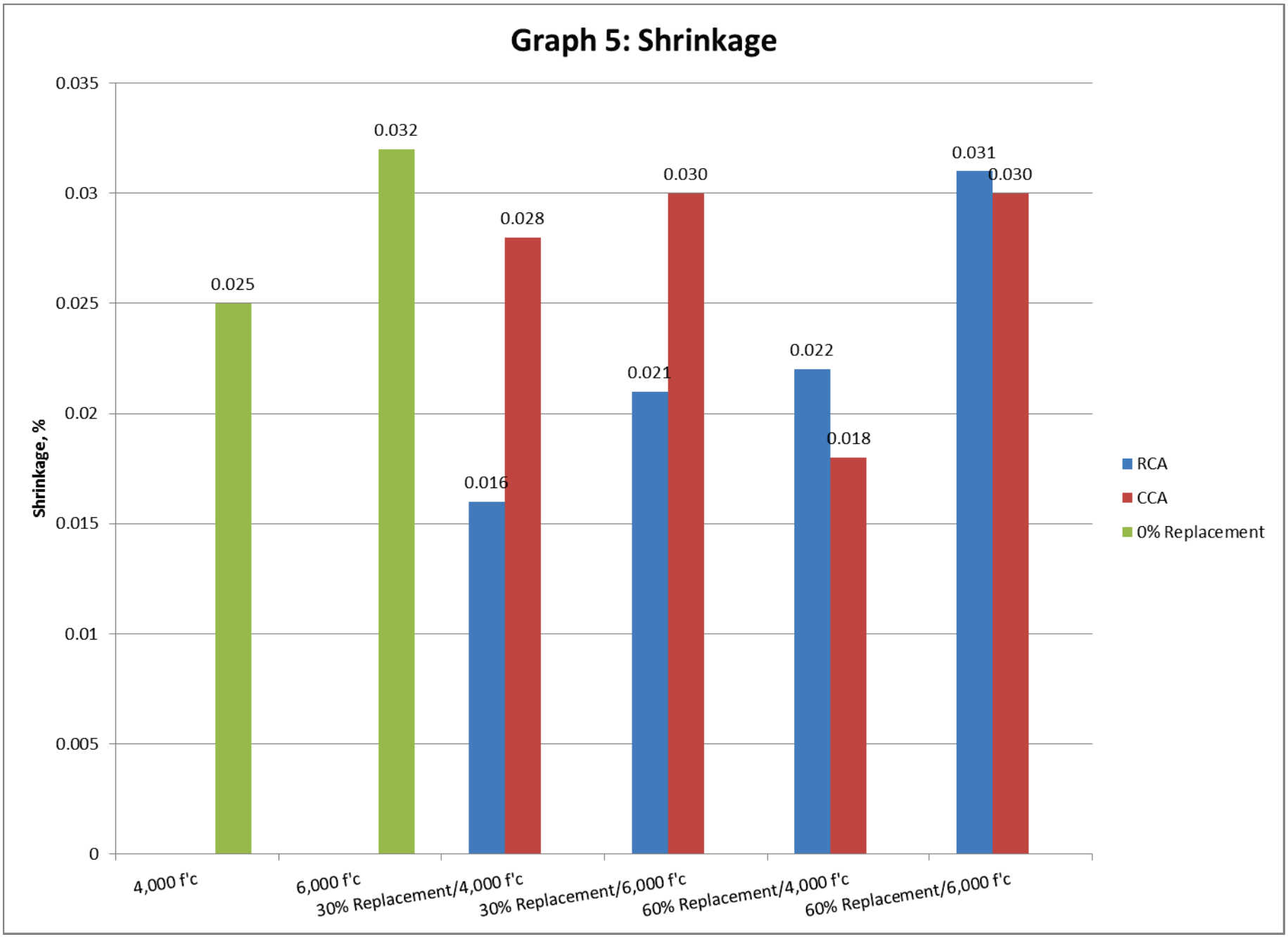
					Compression				Flexural						Surface Resistivity kΩ-cm
			Slump	Air	3-days	7-days	28-days	56-days	7-days	28-days	Finishability	Setting Initial	Time Final	Shrinkage, %	
RCA	30%	4,000	4	2.4	2530	3010	3080	4190	585	790	3	4:37	6:11	-0.016	11.8
RCA	30%	6,000	5	1.5	3120	3920	4960	5130	715	790	4	4:12	5:26	-0.021	12.1
RCA	60%	4,000	3	3.2	2340	3000	3780	4010	660	695	2	4:05	5:29	-0.022	11.6
RCA	60%	6,000	5	1.5	2730	3430	4390	5060	660	875	4	4:06	5:20	-0.031	10.9
CCA	30%	4,000	4.5	4.8	3570	4700	5660	6020	755	820	3	3:33	4:45	-0.028	14.6
CCA	30%	6,000	4	2.5	4060	4990	6090	6880	710	1100	3	3:54	5:15	-0.030	12.5
CCA	60%	4,000	3	2.0	3640	4120	5980	5500	700	830	2	3:36	5:10	-0.018	14.9
CCA	60%	6,000	4	2.0	4000	4190	5190	6240	745	810	3	3:30	4:58	-0.030	12.0
RCA	45%	4,000	3.75	2.4	2980	3860	4510	5120	700	850	2	4:00	5:23	-0.022	12.7
RCA	45%	6,000	3.75	2.6	3830	4210	5780	6025	680	860	3	3:41	5:07	-0.028	12.9
-	-	4,000	3	3.0	3930	4790	6130	6800	705	880	2	3:51	5:29	-0.025	16.5
-	-	6,000	4	2.5	4390	5290	6420	7090	875	945	3	4:05	5:28	-0.032	14.1


Graph 1: Compressive Strength @ 28 Days
Compressive Strength, psi
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
6,130
6,420
3,080
5,660
4,960
6,090
3,780
5,980
4,390
5,190
4,000 f'c
6,000 f'c
30% Replacement/4,000 f'c
30% Replacement/6,000 f'c
60% Replacement/4,000 f'c
60% Replacement/6,000 f'c
RCA
CCA
0% Replacement


Graph 2: Flexural Strength @ 28 Days
Avg. Flexural Strength, psi
1200
1000
800
600
400
200
0
880
945
790
820
790
1,100
695
830
875
810
4,000 f'c
6,000 f'c
30% Replacement/4,000 f'c
30% Replacement/6,000 f'c
60% Replacement/4,000 f'c
60% Replacement/6,000 f'c
RCA
CCA
0% Replacement


Graph 3: Finishability
Finishability
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
4,000 f'c
6,000 f'c
30% Replacement/4,000 f'c
30% Replacement/6,000 f'c
60% Replacement/4,000 f'c
60% Replacement/6,000 f'c
RCA
CCA
0% Replacement


Graph 4: Setting Time
Setting Time, hr:min
7:12
6:00
4:48
3:36
2:24
1:12
0:00
3:51
5:29
4:05
5:28
4:37
6:11
3:33
4:45
4:12
5:26
3:54
5:15
4:05
5:29
3:36
5:10
4:06
5:20
3:30
4:58
4,000 f'c
6,000 f'c
30% Replacement/4,000 f'c
30% Replacement/6,000 f'c
60% Replacement/4,000 f'c
60% Replacement/6,000 f'c
RCA Initial
RCA Final
CCA Initial
CCA RCA
Straight Initial
Straight Final


Graph 5: Shrinkage
Shrinkage, %
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0.025
0.032
0.016
0.028
0.021
0.030
0.022
0.018
0.031
0.030
4,000 f'c
6,000 f'c
30% Replacement/4,000 f'c
30% Replacement/6,000 f'c
60% Replacement/4,000 f'c
60% Replacement/6,000 f'c
RCA
CCA
0% Replacement

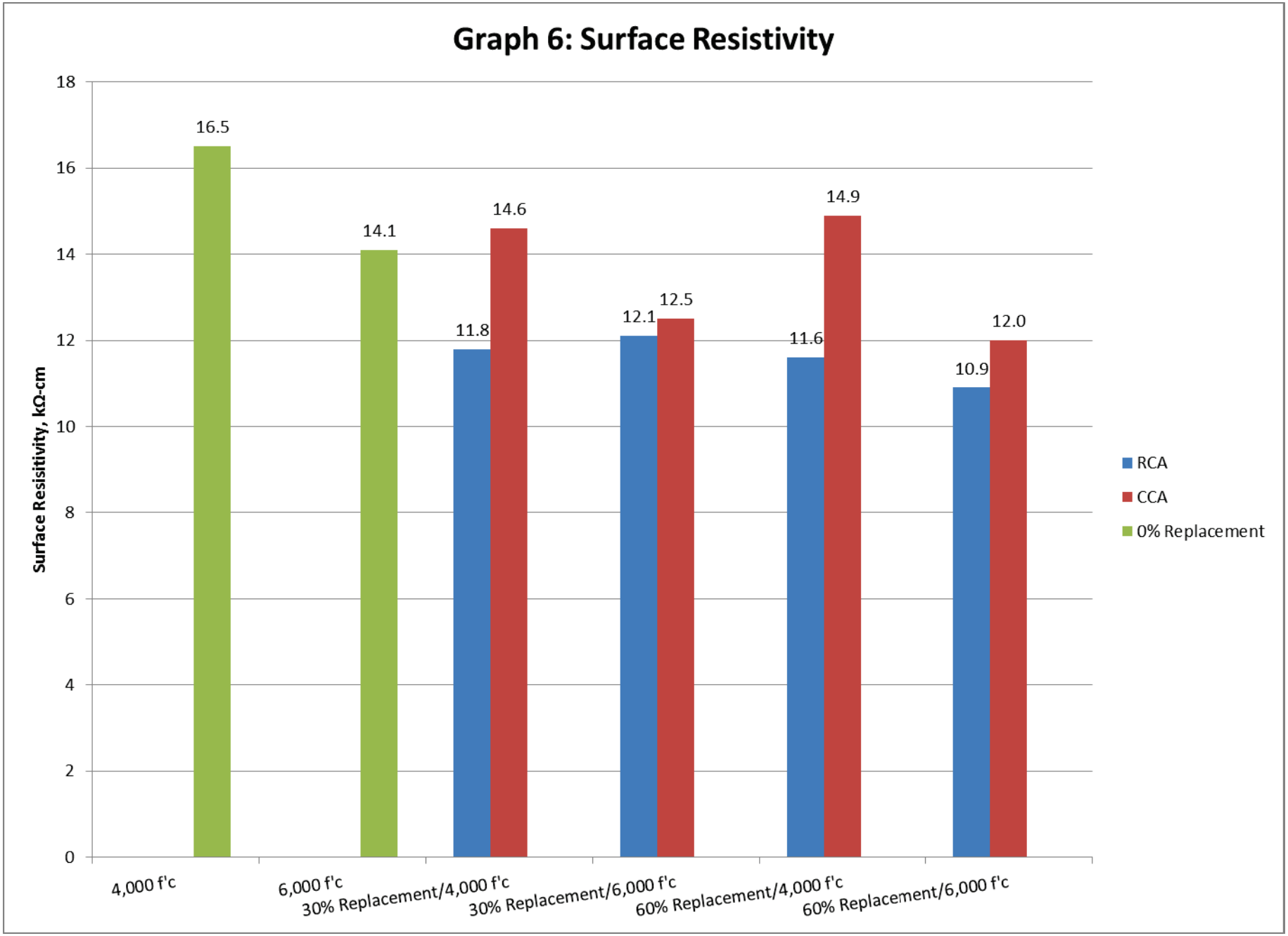

Graph 6: Surface Resistivity
Surface Resisitivity, kΩ-cm
18
16
14
12
10
8
6
4
2
0
16.5
14.1
11.8
14.6
12.1
12.5
11.6
14.9
10.9
12.0
4,000 f'c
6,000 f'c
30% Replacement/4,000 f'c
30% Replacement/6,000 f'c
60% Replacement/4,000 f'c
60% Replacement/6,000 f'c
RCA
CCA
0% Replacement

Table 4 - Overall Average CCA vs RCA

	Compression				Flexural		Finishability	Setting Initial	Time Final	Shrinkage, %	Surface Resistivity kΩ-cm
	3-days	7-days	28-days	56-days	7-days	28-days					
RCA	2680	3340	4250	4600	655	790	3.25	4:15	5:37	.023	11.6
CCA	3820	4500	5730	6160	725	890	2.75	3:38	5:02	.027	13.5

Table 5 - Overall Average 30% vs 60%

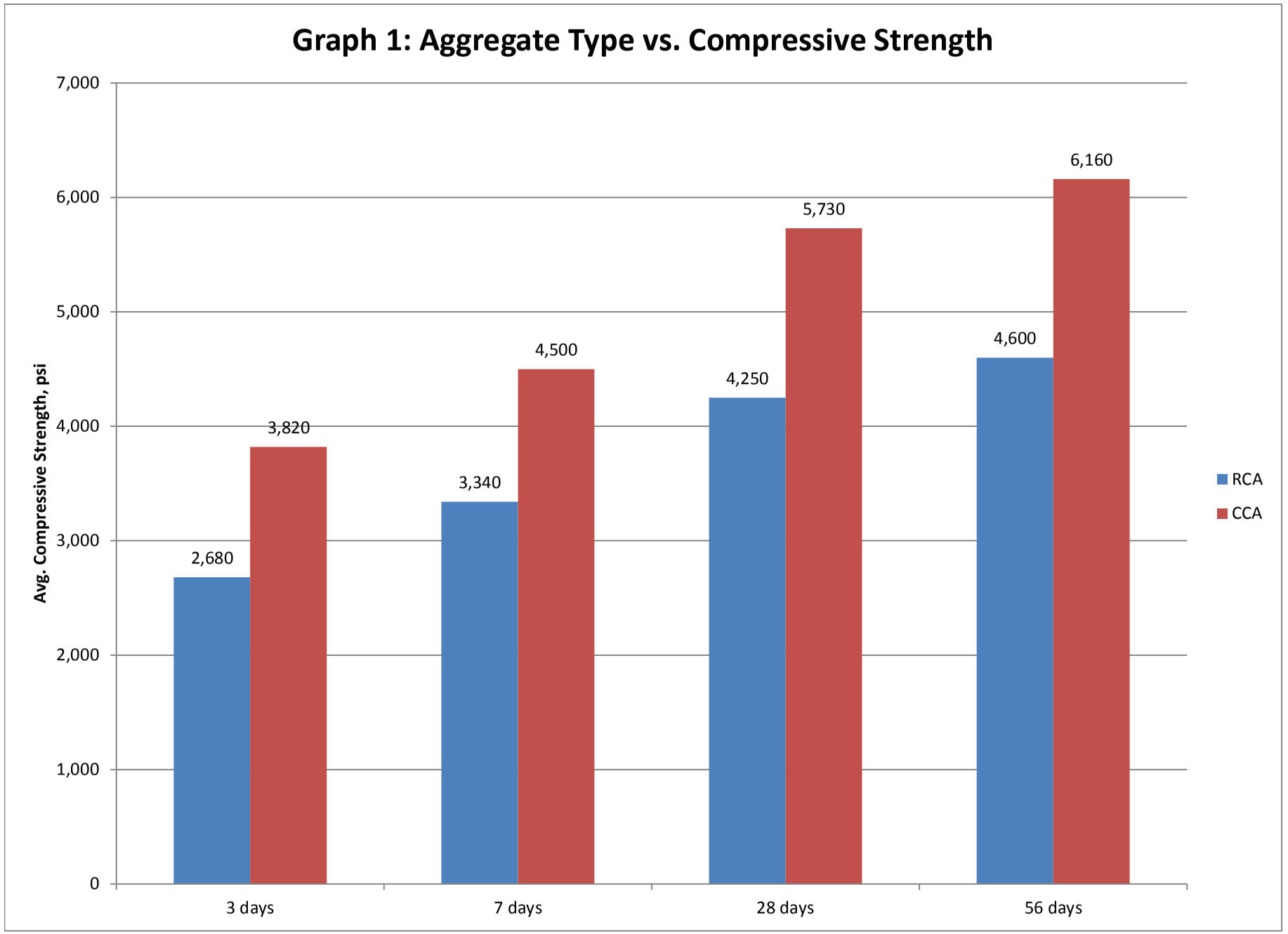
	Compression				Flexural		Finishability	Setting Initial	Time Final	Shrinkage, %	Surface Resistivity kΩ-cm
	3-days	7-days	28-days	56-days	7-days	28-days					
30%	3320	4160	5140	5560	690	875	2.75	4:04	5:24	.024	12.8
60%	3180	4030	4840	5200	700	800	2.75	3:49	5:14	.025	12.4

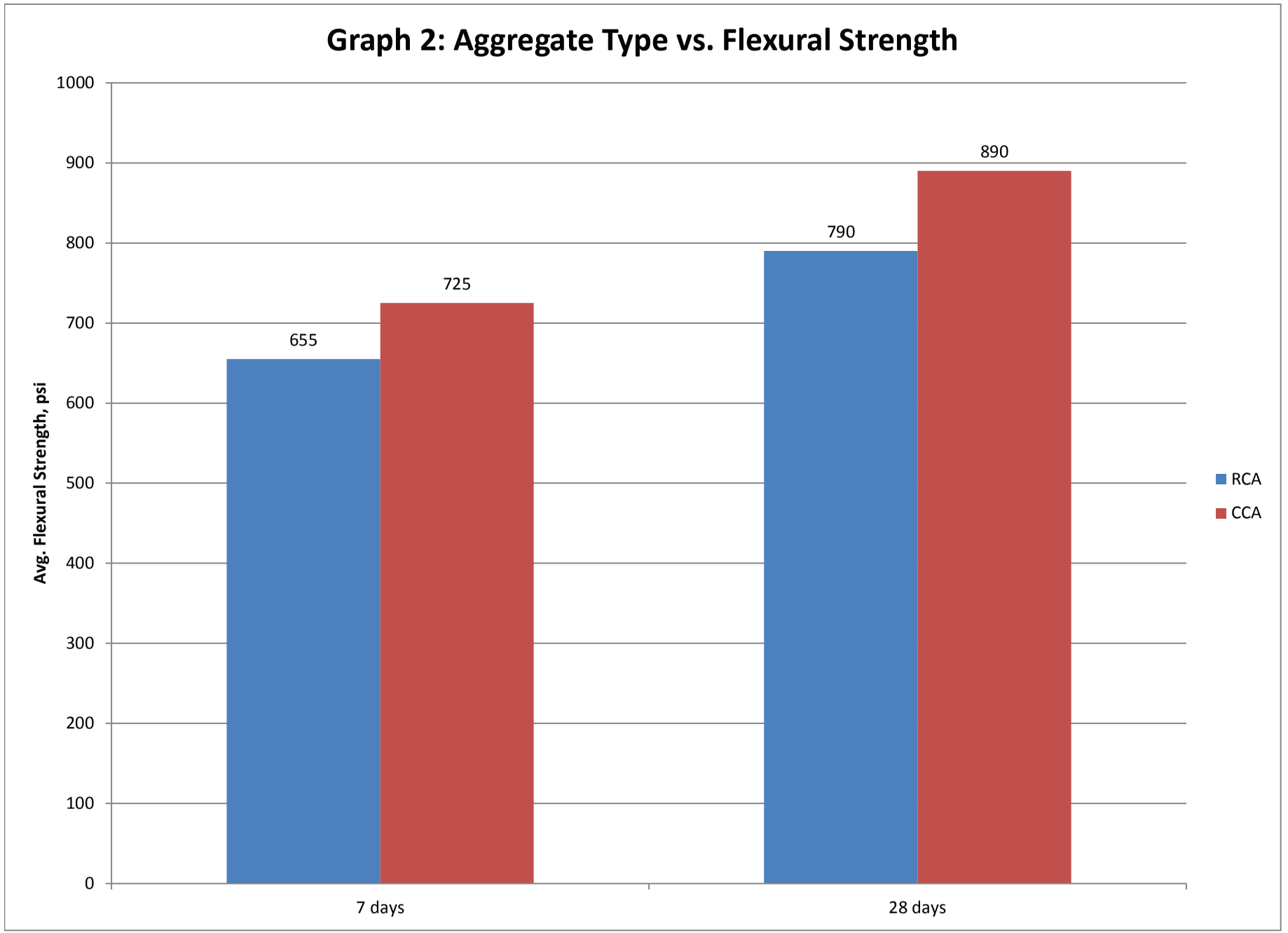
Table 6 - Overall Average 4,000 psi vs 6,000 psi

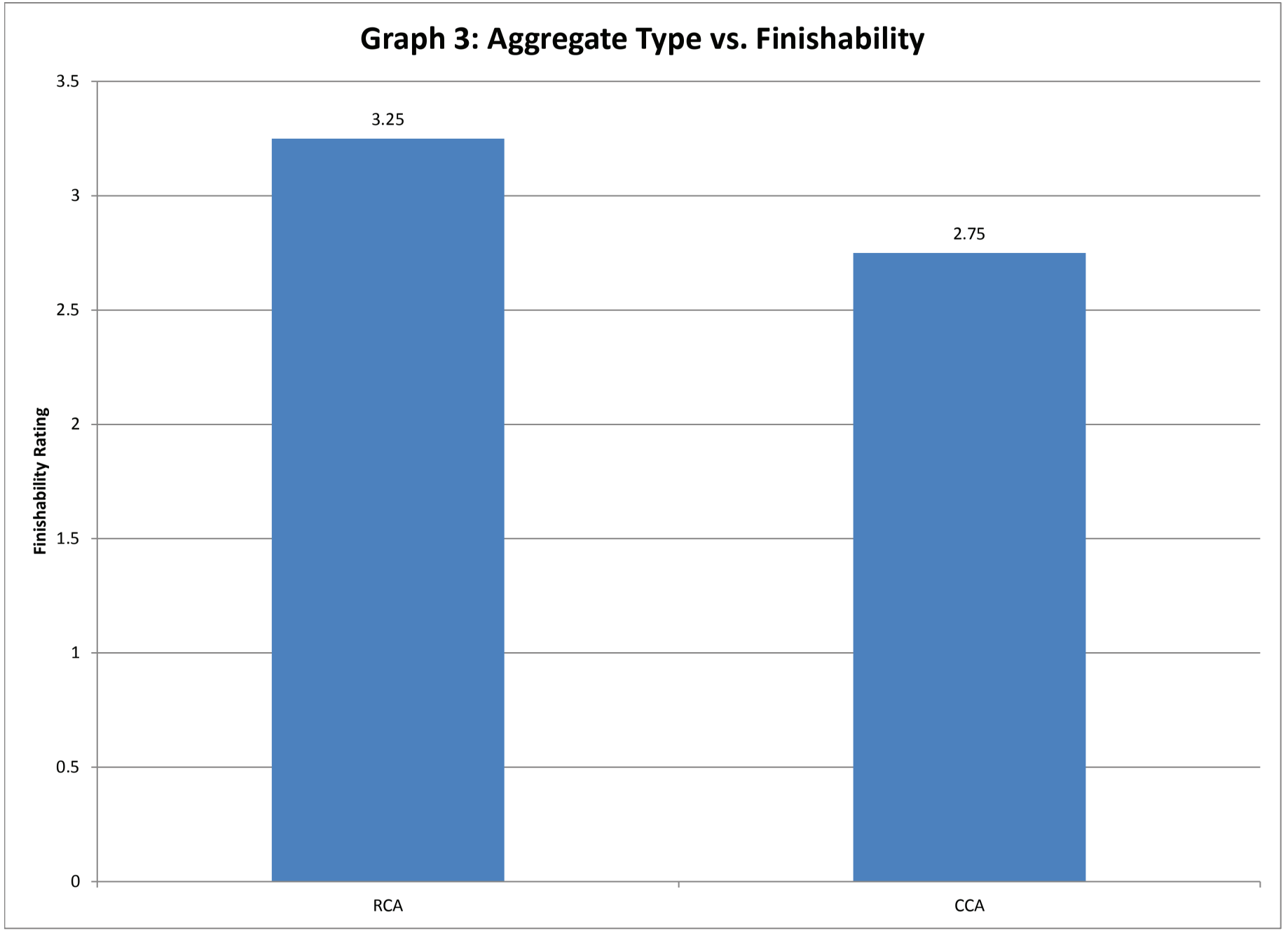
	Compression				Flexural		Finishability	Setting Initial	Time Final	Shrinkage, %	Surface Resistivity kΩ-cm
	3-days	7-days	28-days	56-days	7-days	28-days					
4,000	3020	3590	4820	4930	675	785	2.5	3:58	5:24	.021	13.2
6,000	3480	4130	5160	5830	725	895	3.75	3:55	5:15	.028	11.9

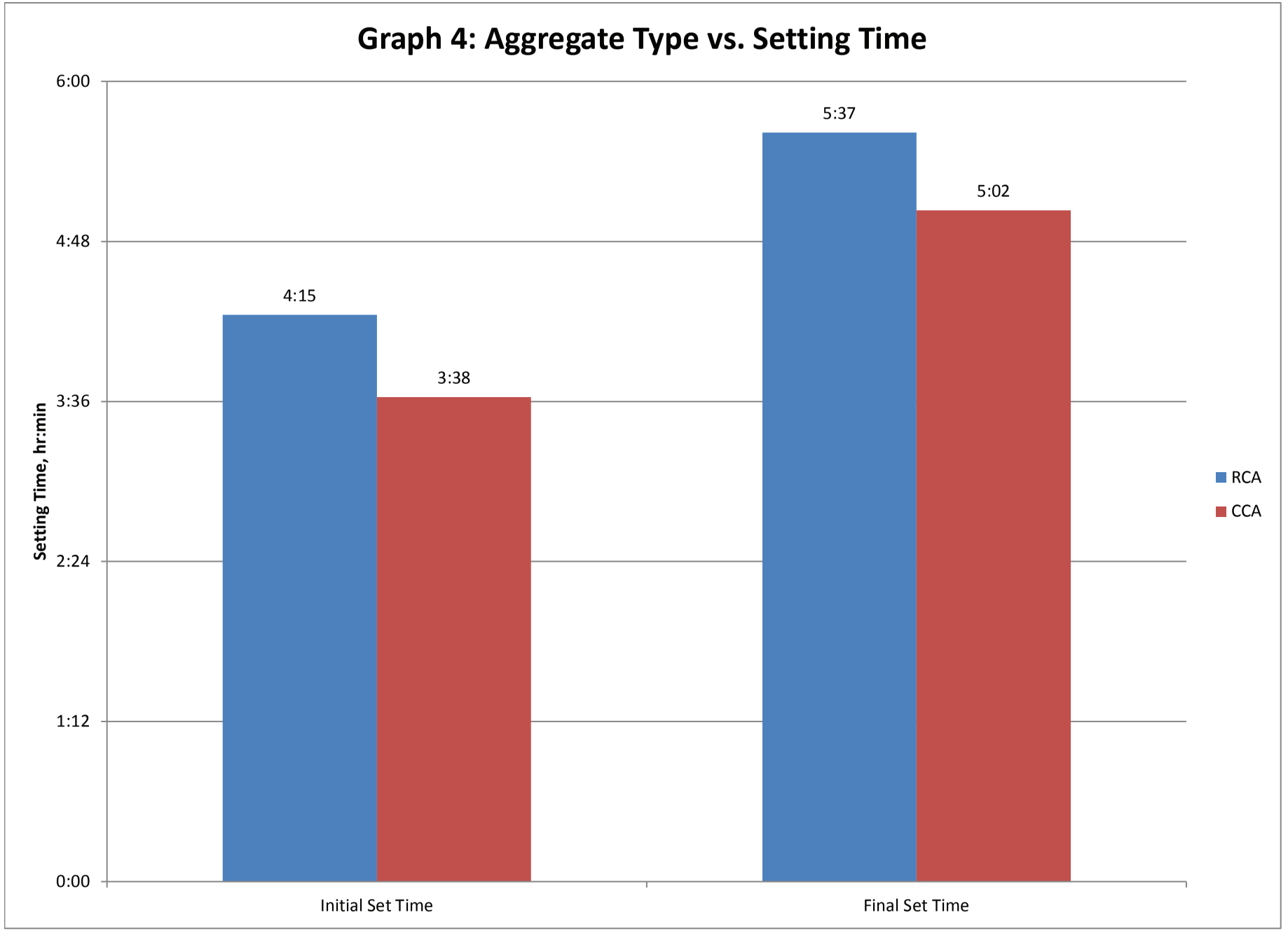
Table 7 – Curvature Check on RCA Mixtures

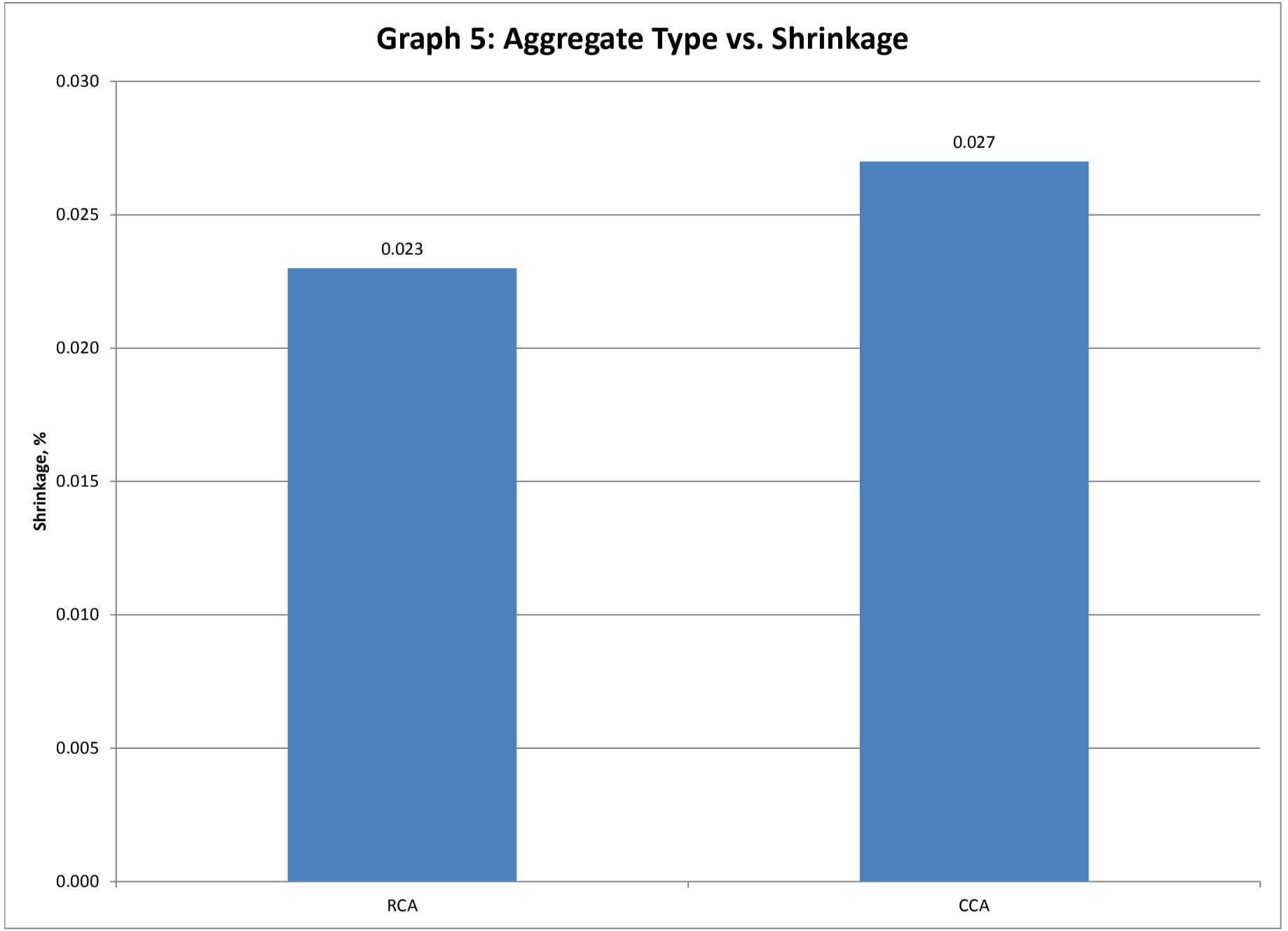
	Compression				Flexural		Finishability	Setting Initial	Time Final	Shrinkage, %	Surface Resistivity kΩ-cm
	3-days	7-days	28-days	56-days	7-days	28-days					
30%	3320	4160	5140	5560	690	875	2.75	4:04	5:24	.024	12.8
45%	3400	4030	5150	5570	690	855	2.5	3:51	5:15	.025	12.8
60%	3180	4030	4840	5200	700	800	2.75	3:49	5:14	.025	12.4

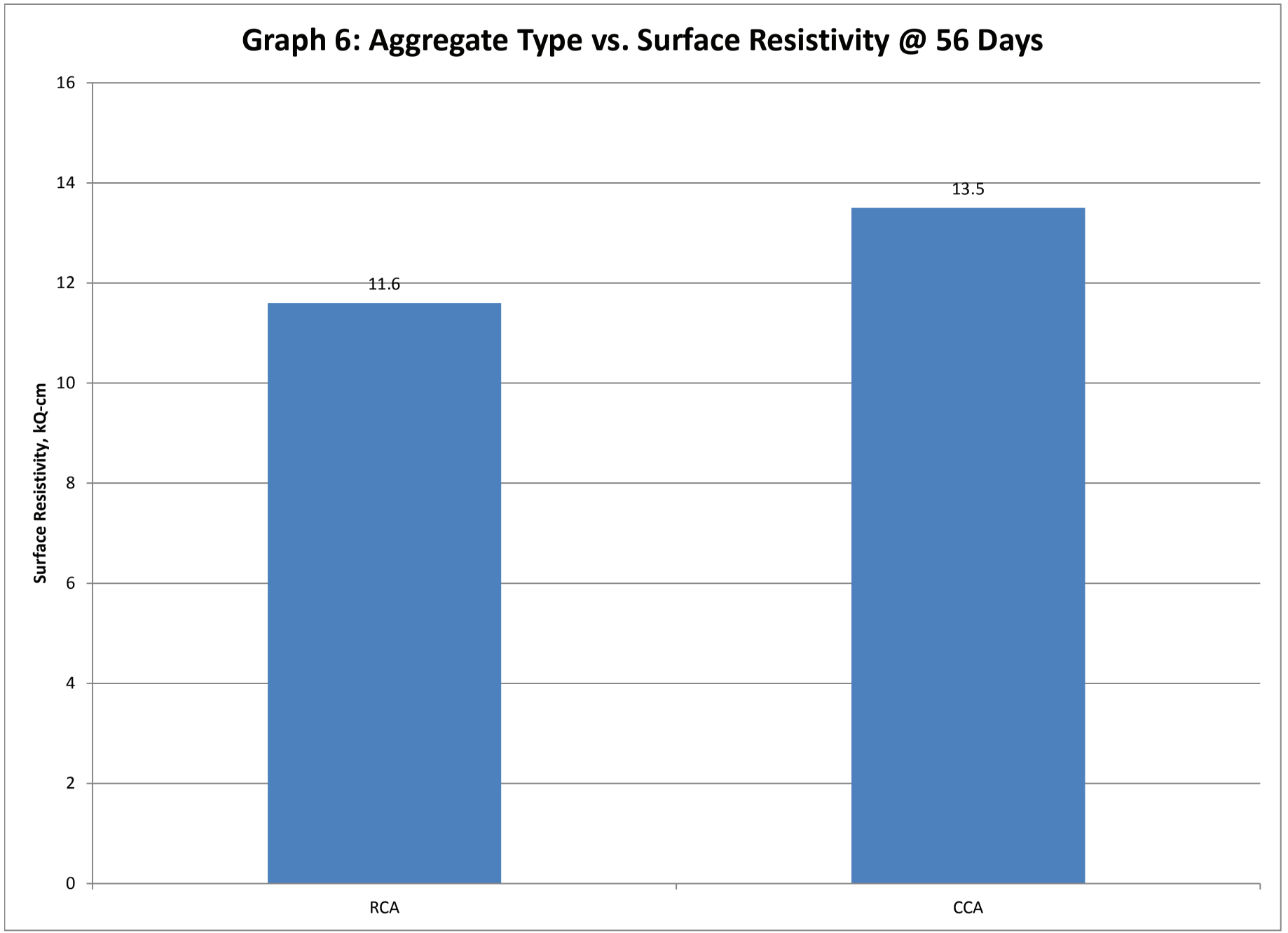

Graph 1: Aggregate Type vs. Compressive Strength
Avg. Compressive Strength, psi
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
2,680
3,820
3,340
4,500
4,250
5,730
4,600
6,160
3 days
7 days
28 days
56 days
RCA
CCA

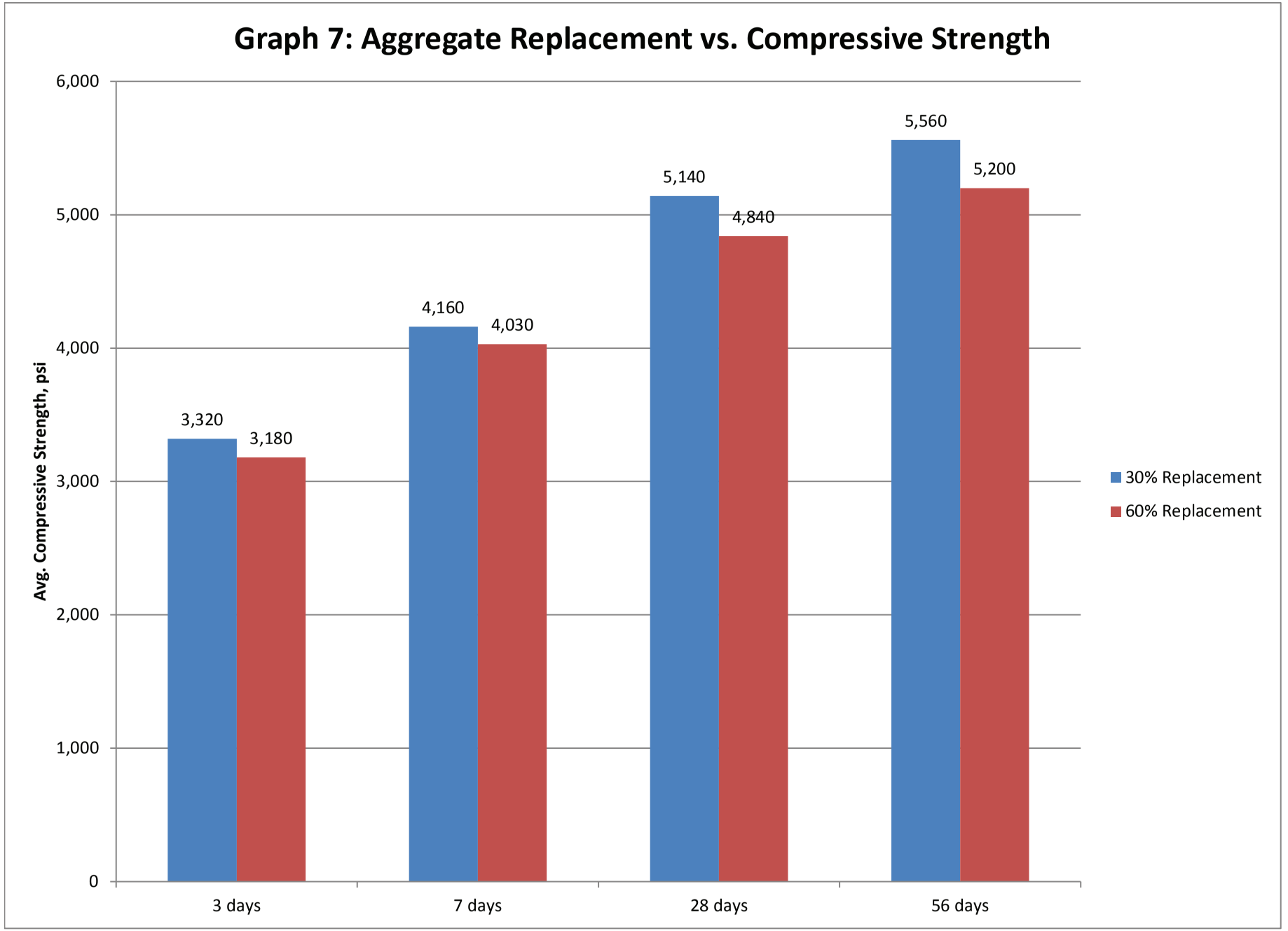

Graph 2: Aggregate Type vs. Flexural Strength
Avg. Flexural Strength, psi
1000
900
800
700
600
500
400
300
200
100
0
655
725
790
890
7 days
28 days
RCA
CCA

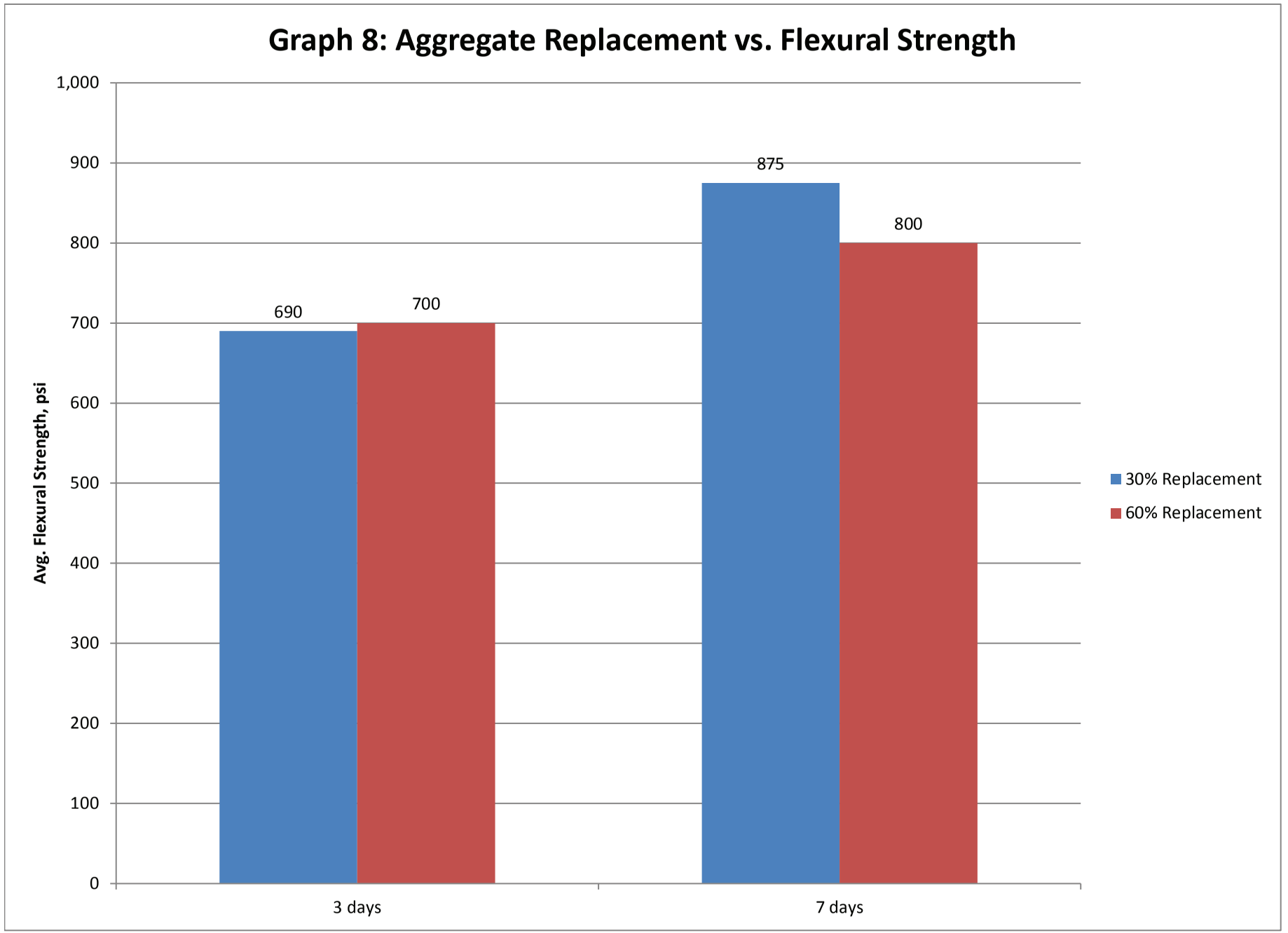

Graph 3: Aggregate Type vs. Finishability
Finishability Rating
3.5
3
2.5
2
1.5
1
0.5
0
3.25
2.75
RCA
CCA

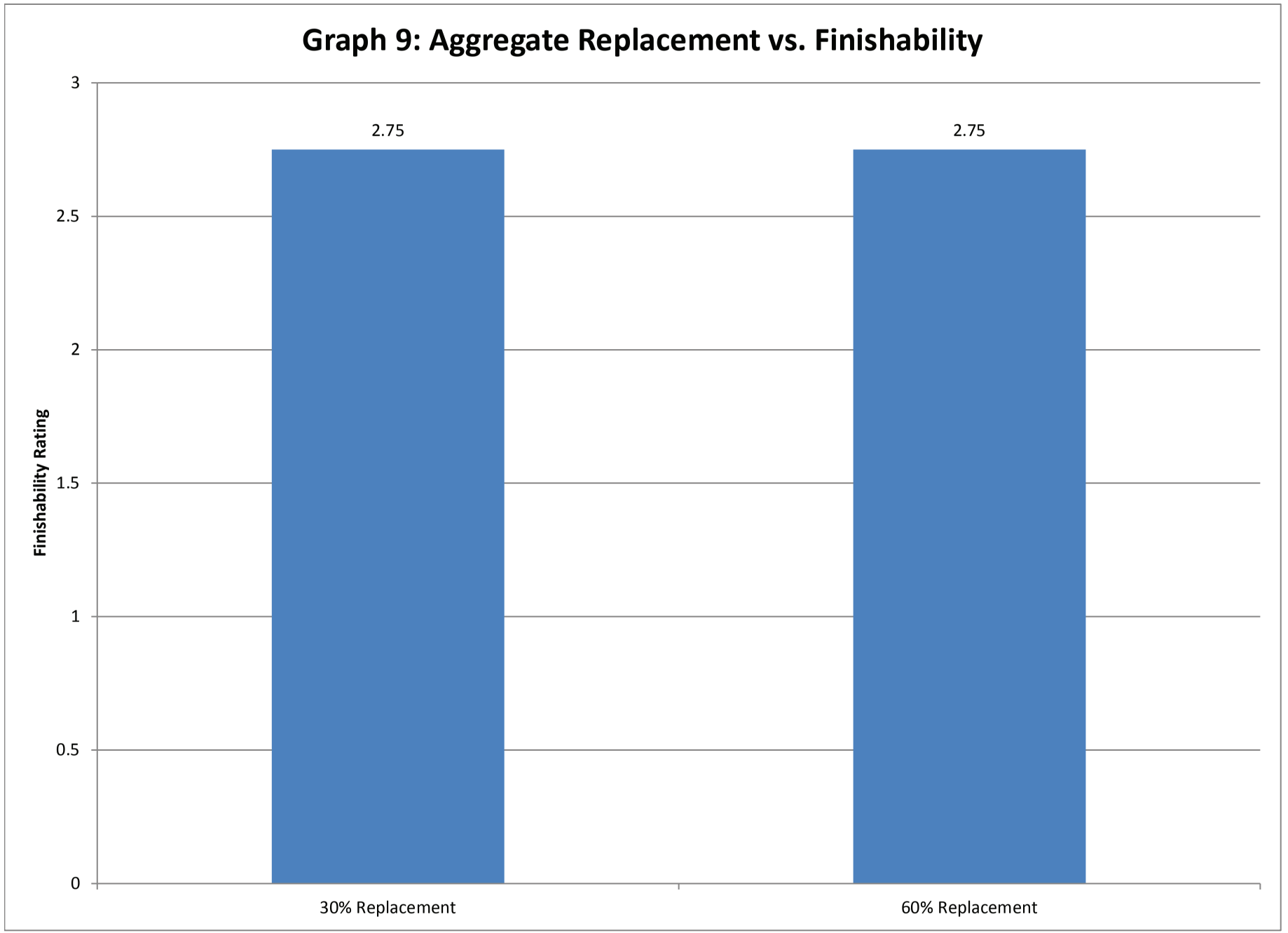

Graph 4: Aggregate Type vs. Setting Time
6:00
4:48
3:36
2:24
1:12
0:00
Setting Time, hr:min
4:15
3:38
5:37
5:02
Initial Set Time
Final Set Time
RCA
CCA

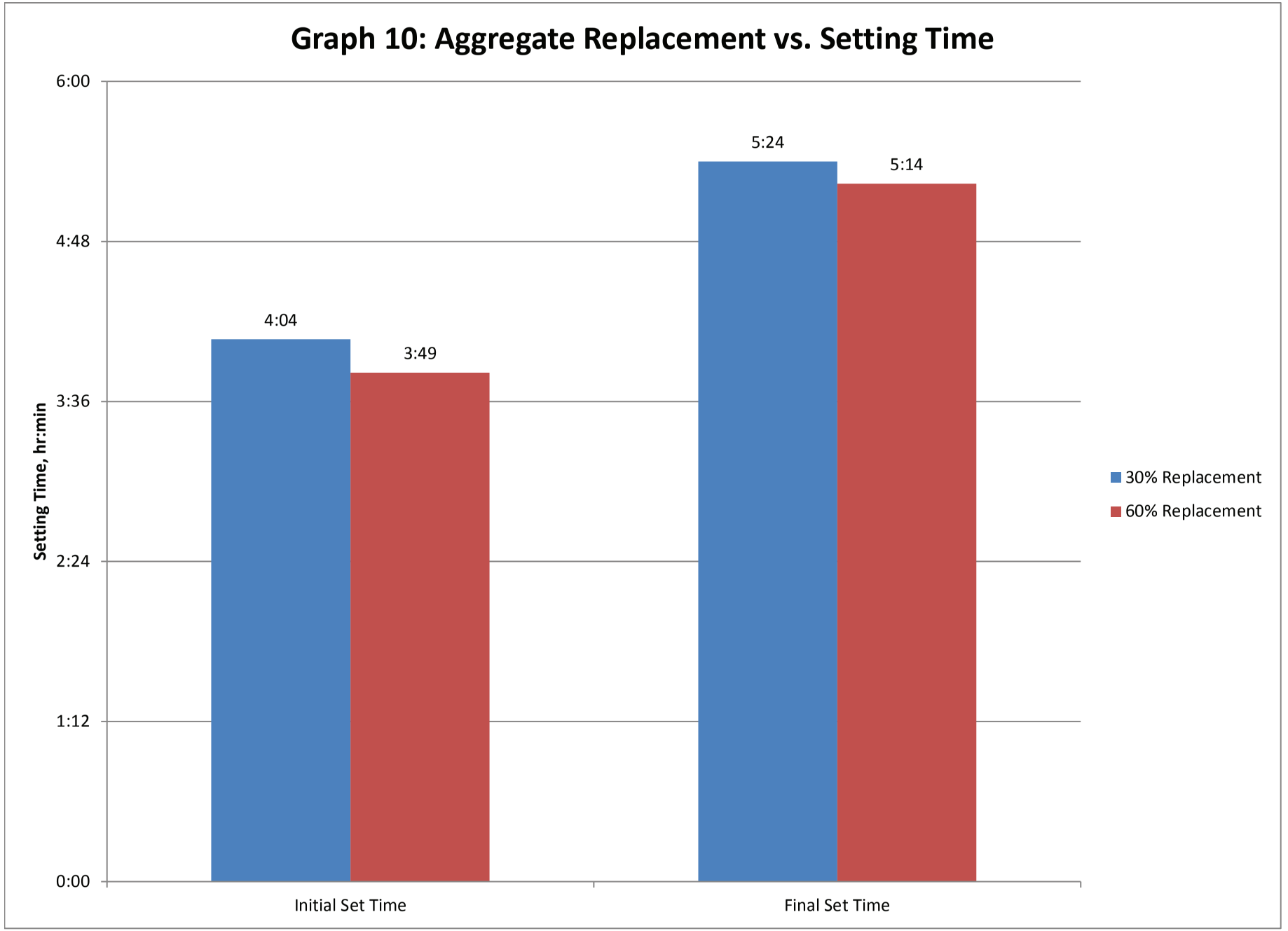

Graph 5: Aggregate Type vs. Shrinkage
Shrinkage, %
0.030
0.025
0.020
0.015
0.010
0.005
0.000
0.023
0.027
RCA
CCA

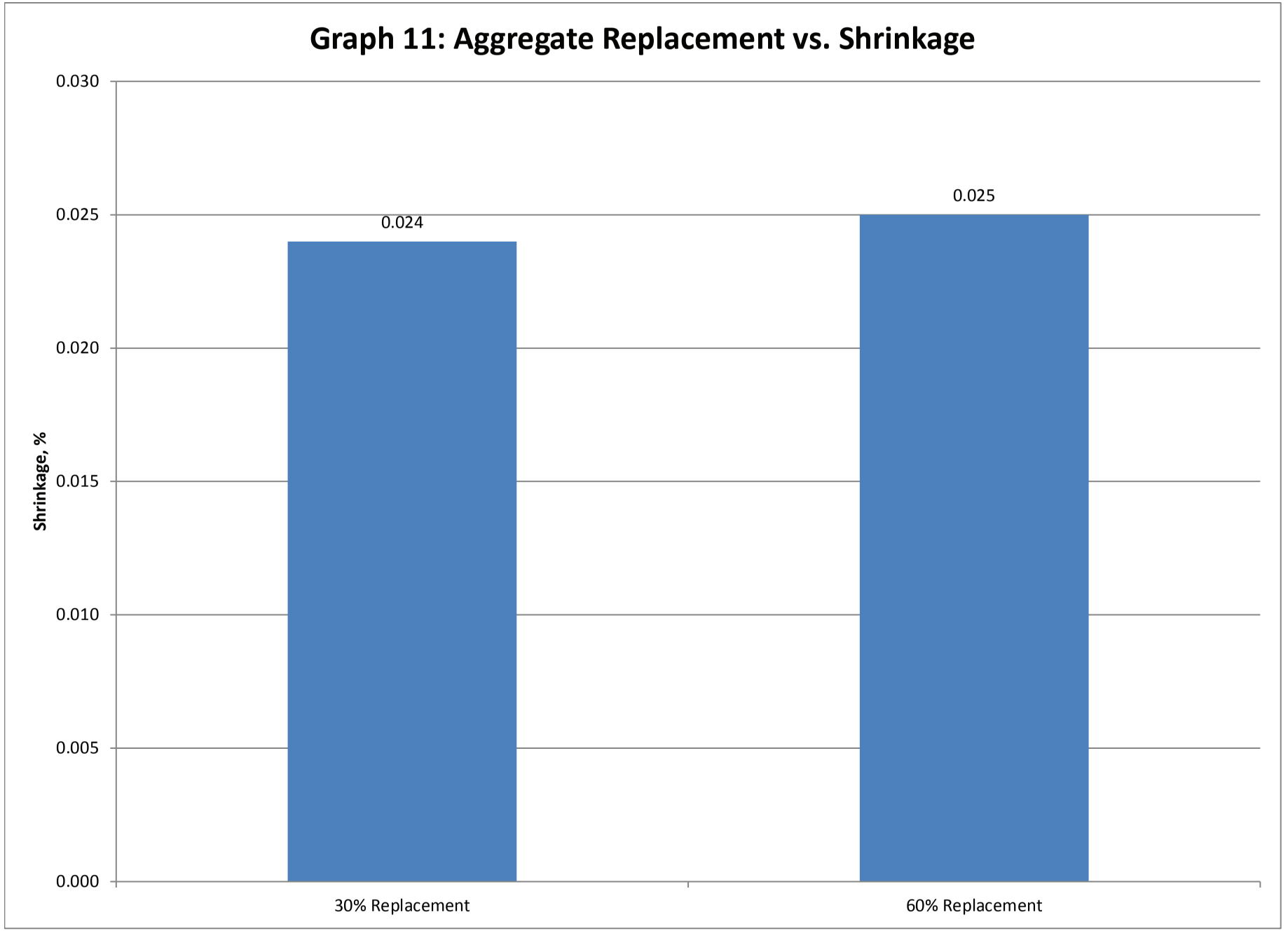

Graph 6: Aggregate Type vs. Surface Resistivity @ 56 Days
Surface Resistivity, kQ-cm
16
14
12
10
8
6
4
2
0
11.6
13.5
RCA
CCA

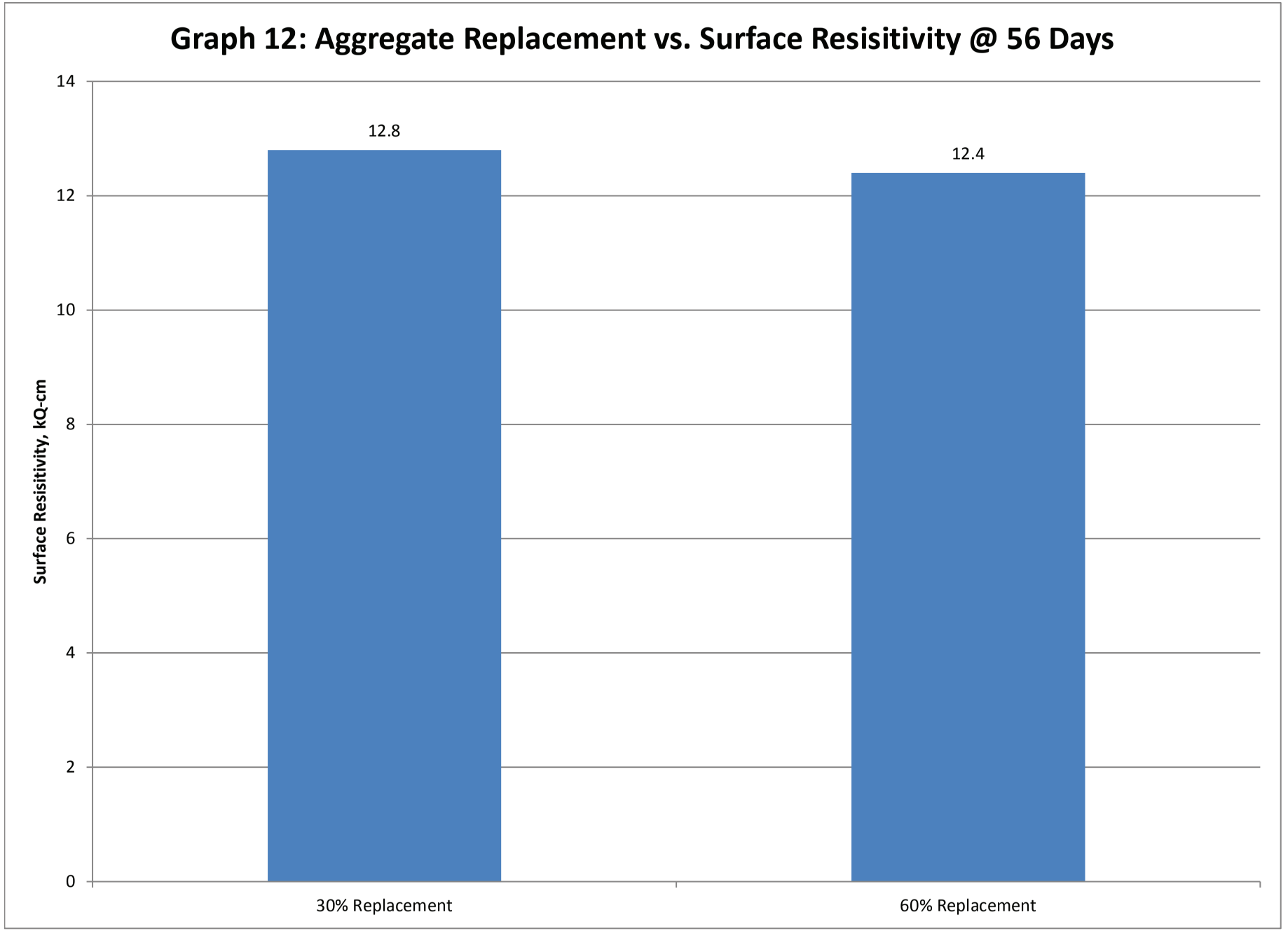

Graph 7: Aggregate Replacement vs. Compressive Strength
Avg. Compressive Strength, psi
6,000
5,000
4,000
3,000
2,000
1,000
0
3,320
3,180
4,160
4,030
5,140
4,840
5,560
5,200
3 days
7 days
28 days
56 days
30% Replacement
60% Replacement

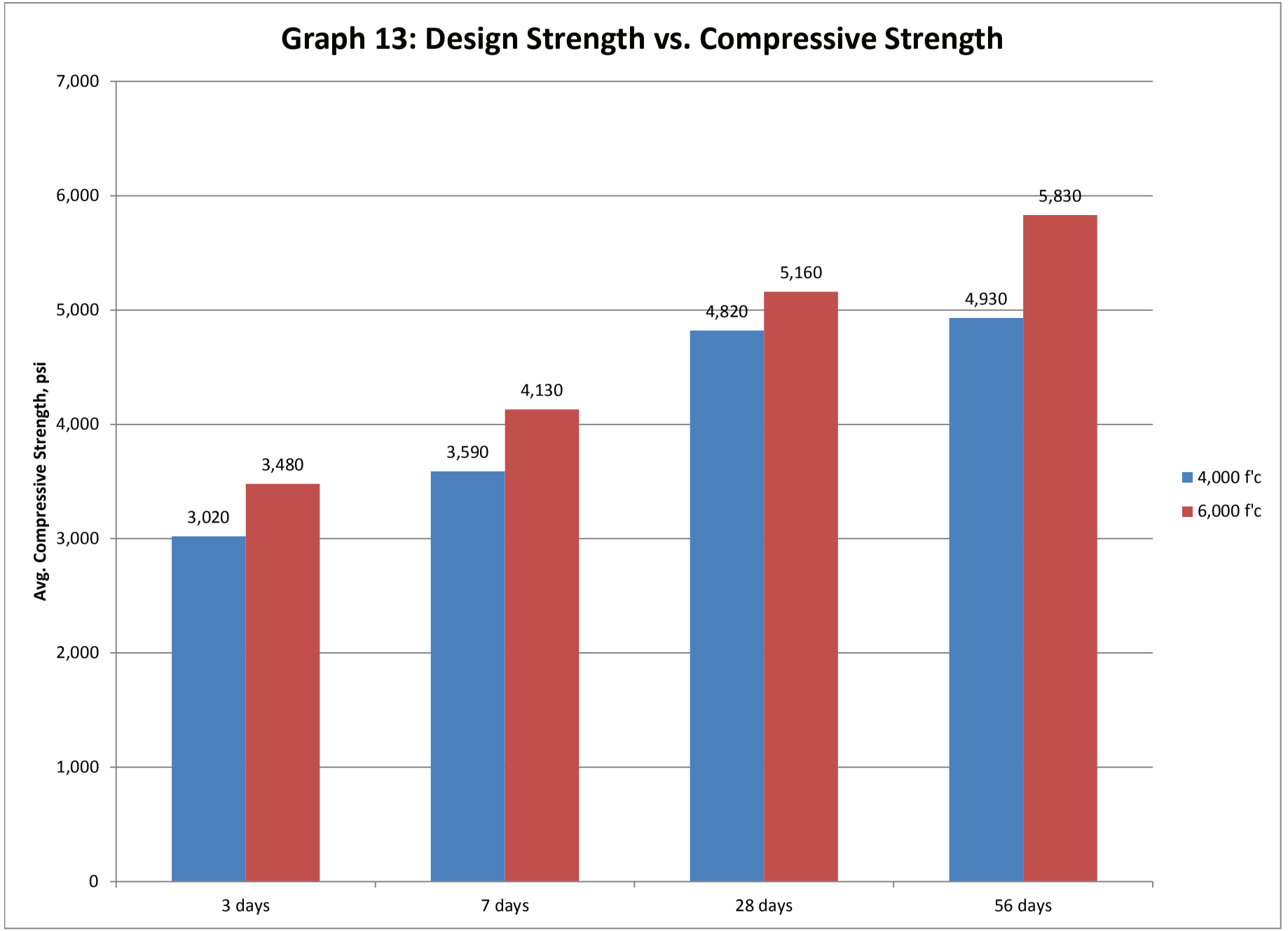

Graph 8: Aggregate Replacement vs. Flexural Strength
Avg. Flexural Strength, psi
1,000
900
800
700
600
500
400
300
200
100
0
690
700
875
800
3 days
7 days
30% Replacement
60% Replacement

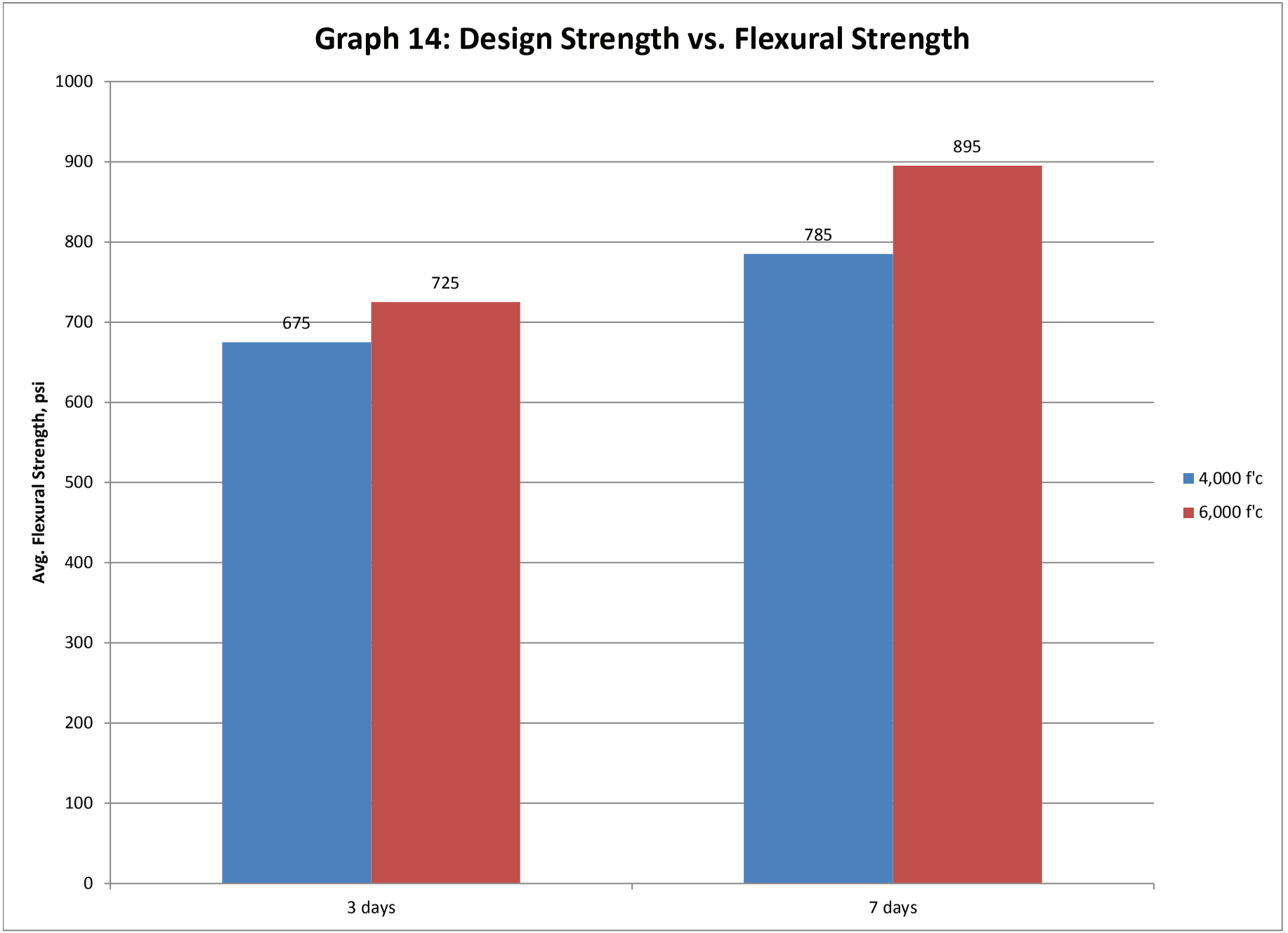

Graph 9: Aggregate Replacement vs. Finishability
Finishability Rating
3
2.5
2
1.5
1
0.5
0
2.75
2.75
30% Replacement
60% Replacement

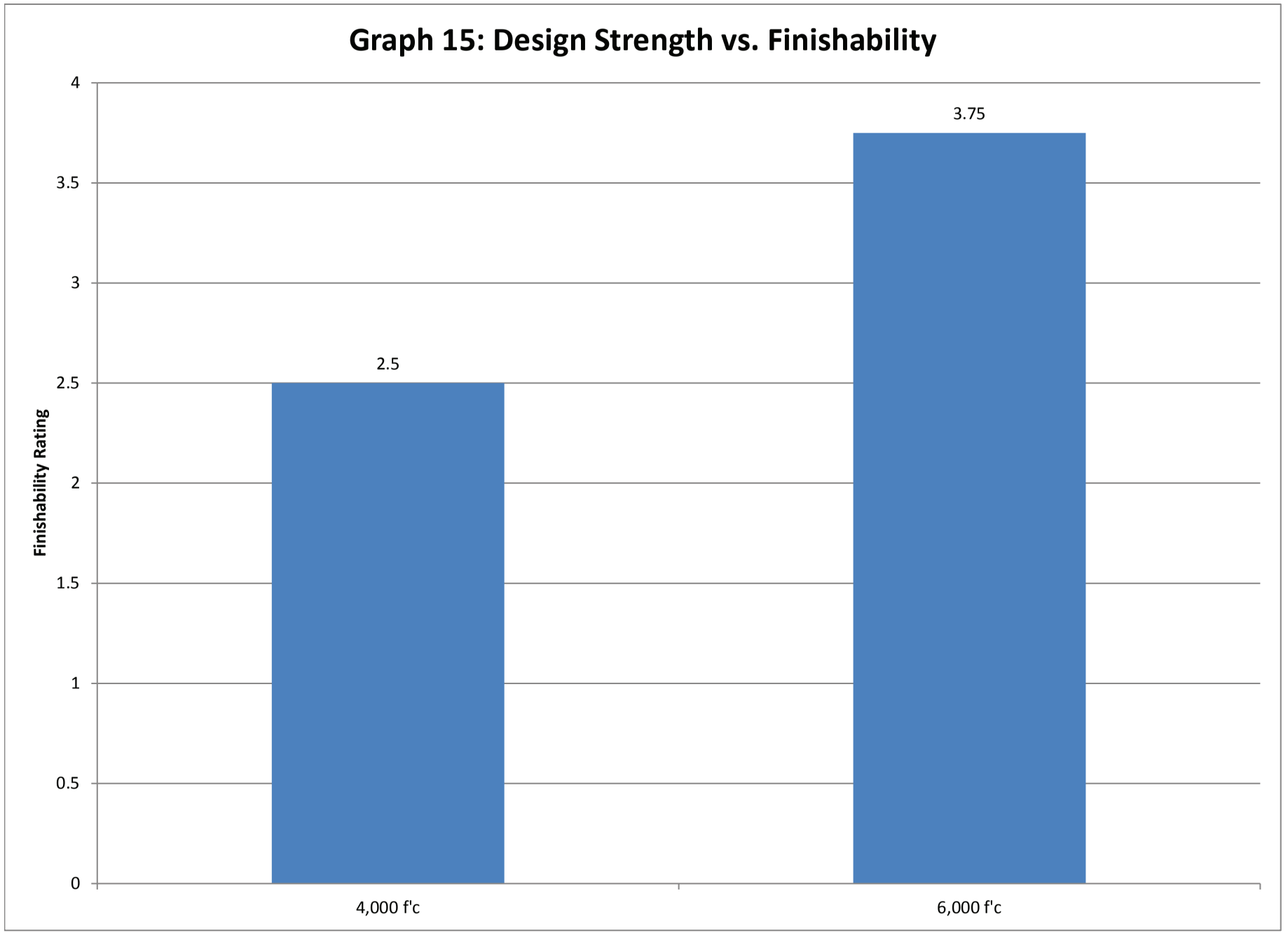

Graph 10: Aggregate Replacement vs. Setting Time
6:00
4:48
3:36
2:24
1:12
0:00
Setting Time, hr:min
4:04
3:49
5:24
5:14
Initial Set Time
Final Set Time
30% Replacement
60% Replacement

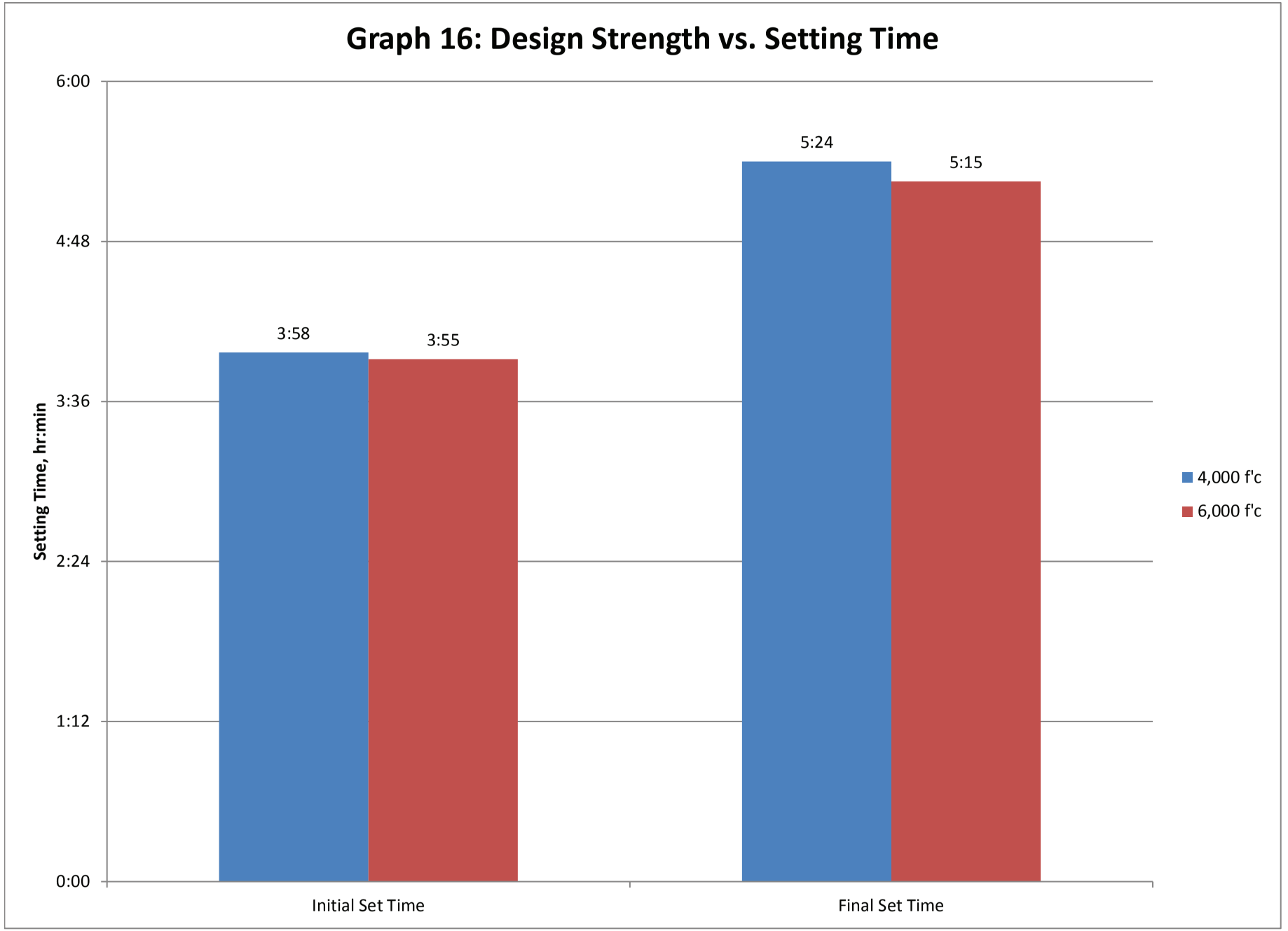

Graph 11: Aggregate Replacement vs. Shrinkage
0.030
0.025
0.020
0.015
0.010
0.005
0.000
Shrinkage, %
0.024
0.025
30% Replacement
60% Replacement

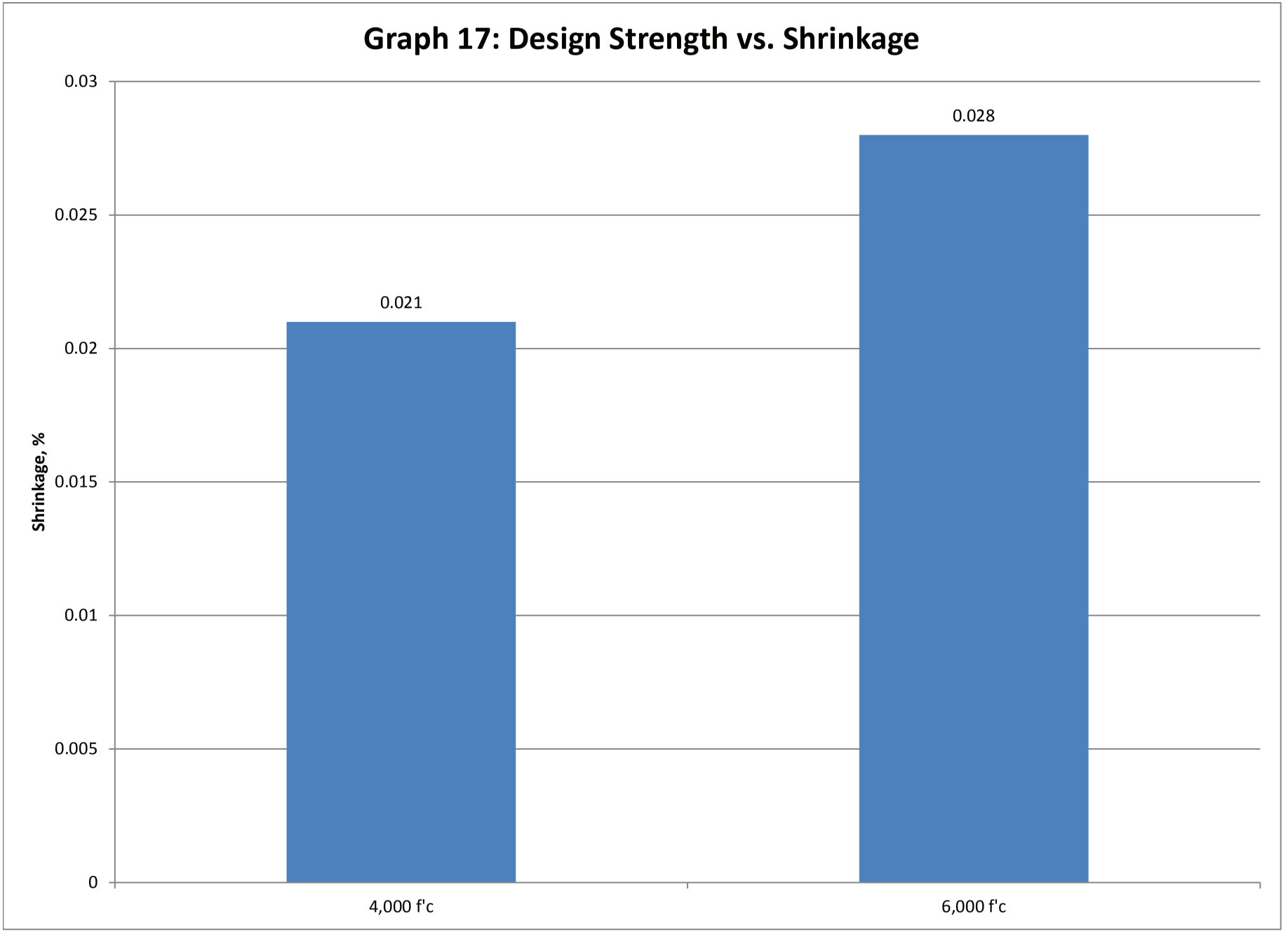

Graph 12: Aggregate Replacement vs. Surface Resisitivity @ 56 Days
Surface Resisitivity, kQ-cm
14
12
10
8
6
4
2
0
12.8
12.4
30% Replacement
60% Replacement

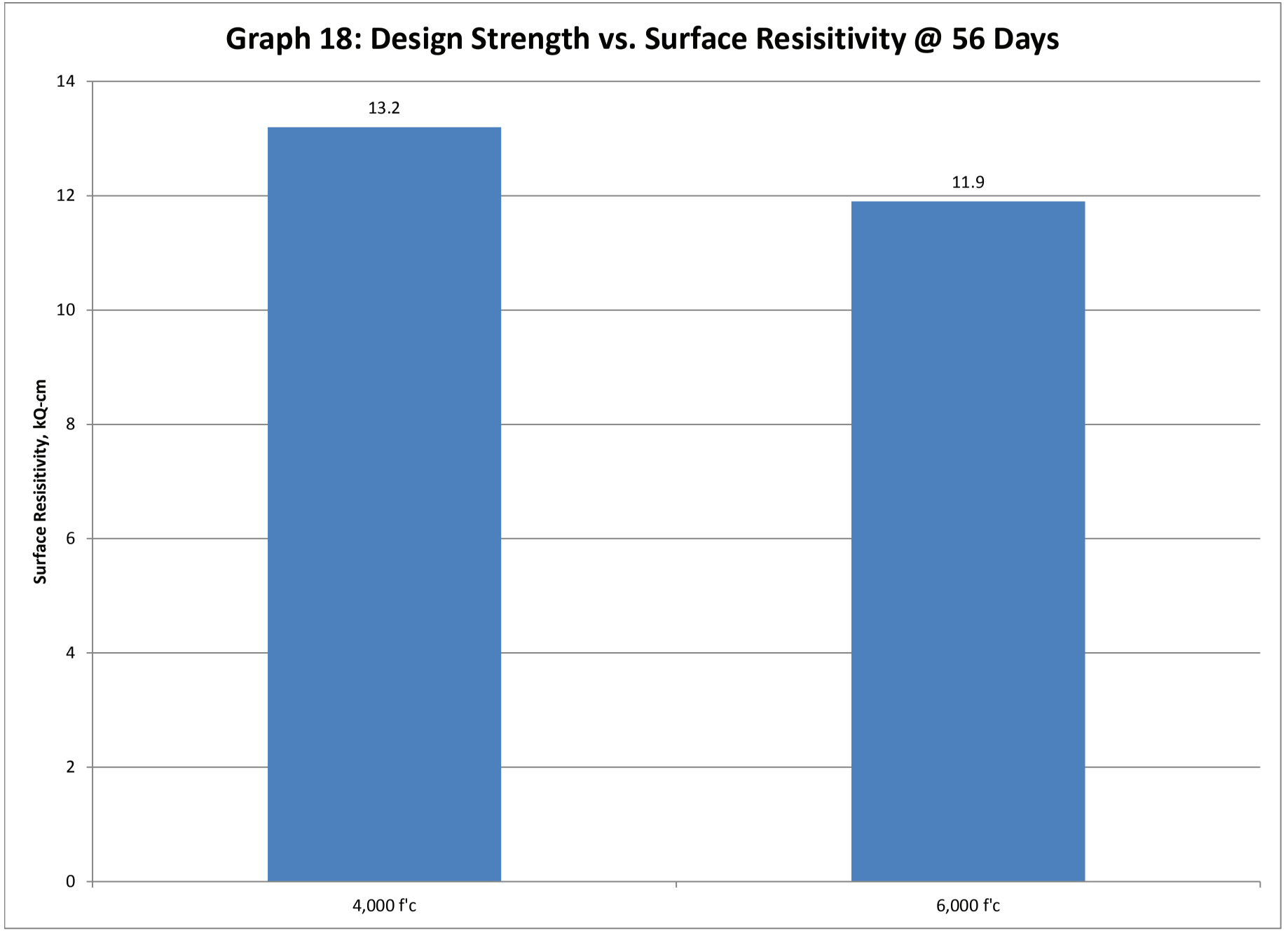

Graph 13: Design Strength vs. Compressive Strength
Avg. Compressive Strength, psi
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
3,020
3,480
3,590
4,130
4,820
5,160
4,930
5,830
3 days
7 days
28 days
56 days
4,000 f'c
6,000 f'c


Graph 14: Design Strength vs. Flexural Strength
Avg. Flexural Strength, psi
1000
900
800
700
600
500
400
300
200
100
0
675
725
785
895
3 days
7 days
4,000 f'c
6,000 f'c


Graph 15: Design Strength vs. Finishability
Finishability Rating
4
3.5
3
2.5
2
1.5
1
0.5
0
2.5
3.75
4,000 f'c
6,000 f'c


Graph 16: Design Strength vs. Setting Time
6:00
4:48
3:36
2:24
1:12
0:00
Setting Time, hr:min
3:58
3:55
5:24
5:15
Initial Set Time
Final Set Time
4,000 f'c
6,000 f'c


Graph 17: Design Strength vs. Shrinkage
0.03
0.025
0.02
0.015
0.01
0.005
0
Shrinkage, %
0.021
0.028
4,000 f'c
6,000 f'c


Graph 18: Design Strength vs. Surface Resisitivity @ 56 Days
Surface Resisitivity, kQ-cm
14
12
10
8
6
4
2
0
13.2
11.9
4,000 f'c
6,000 f'c

American Engineering Testing, Inc.
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St. Paul, MN 55114
(651) 659-9001
Toll Free: (800) 972-6364

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Albertville, MN 55301
(763) 428-5573
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Material Test Report

Report No: MAT:16-10740-S1
Issue No: 1

Client: MINNESOTA CONCRETE COUNCIL **CC:**

Project: MCC RESEARCH

ST. PAUL, MN
Job No: 29-02189

Date of Issue: 8/9/2016
Reviewed By: JESSE SICH
EIT, MNDOT Tech ID#17564

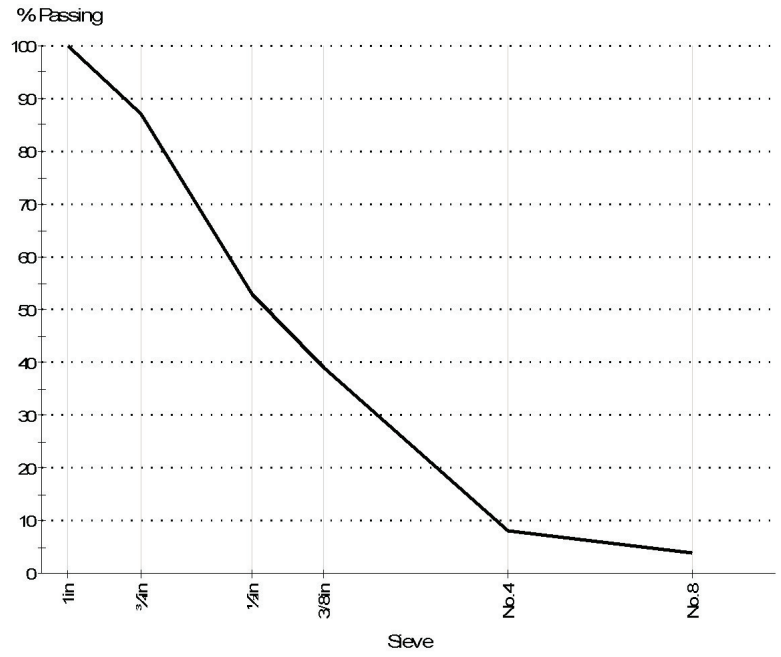
Sample Details

Sample ID	16-10740-S1
Date Sampled	8/4/2016
Source	
Material	Recycled
Specification	Project Specifications
Sampling Method	
Location	CCA
Date Submitted	8/4/2016

Other Test Results

Description	Method	Result	Limits
Specific Gravity (OD)	ASTM C 127	2.29	
Specific Gravity (SSD)		2.43	
Apparent Specific Gravity		2.65	
Absorption (%)		5.8	
Density Determined Without First Drying?		No	
Additional Notes			

Particle Size Distribution



Method: ASTM C 136
Drying by: Oven
Date Tested: 8/4/2016
Tested By:

Sieve Size	% Passing	Limits
1in (25.0mm)	100	
¾in (19.0mm)	87	
½in (12.5mm)	53	
3/8in (9.5mm)	39	
No.4 (4.75mm)	8.0	
No.8 (2.36mm)	4.0	

Comments

N/A

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Material Test Report

Report No: MAT:16-10740-S2
Issue No: 1

Client: MINNESOTA CONCRETE COUNCIL **CC:**

Project: MCC RESEARCH

ST. PAUL, MN
Job No: 29-02189

Date of Issue: 8/9/2016
Reviewed By: JESSE SICH
EIT, MNDOT Tech ID#17564

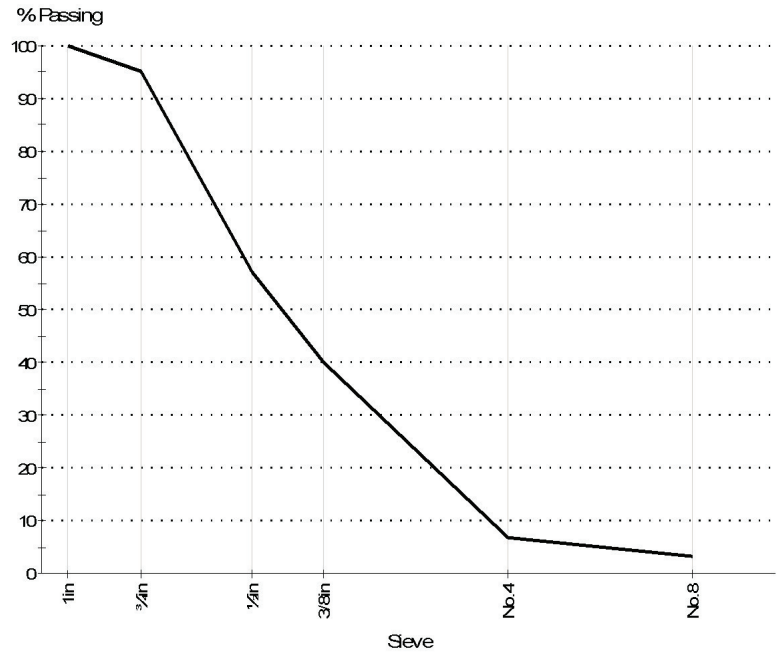
Sample Details

Sample ID	16-10740-S2
Date Sampled	8/4/2016
Source	
Material	Recycled
Specification	Project Specifications
Sampling Method	
Location	RCA
Date Submitted	8/4/2016

Other Test Results

Description	Method	Result	Limits
Specific Gravity (OD)	ASTM C 127	2.33	
Specific Gravity (SSD)		2.45	
Apparent Specific Gravity		2.65	
Absorption (%)		5.1	
Density Determined Without First Drying?		No	
Additional Notes			

Particle Size Distribution



Method: ASTM C 136
Drying by: Oven
Date Tested: 8/4/2016
Tested By:

Sieve Size	% Passing	Limits
1in (25.0mm)	100	
¾in (19.0mm)	95	
½in (12.5mm)	57	
3/8in (9.5mm)	40	
No.4 (4.75mm)	6.9	
No.8 (2.36mm)	3.2	

Comments

N/A

PHOTOGRAPHS
AET PROJECT NO. 29-02189

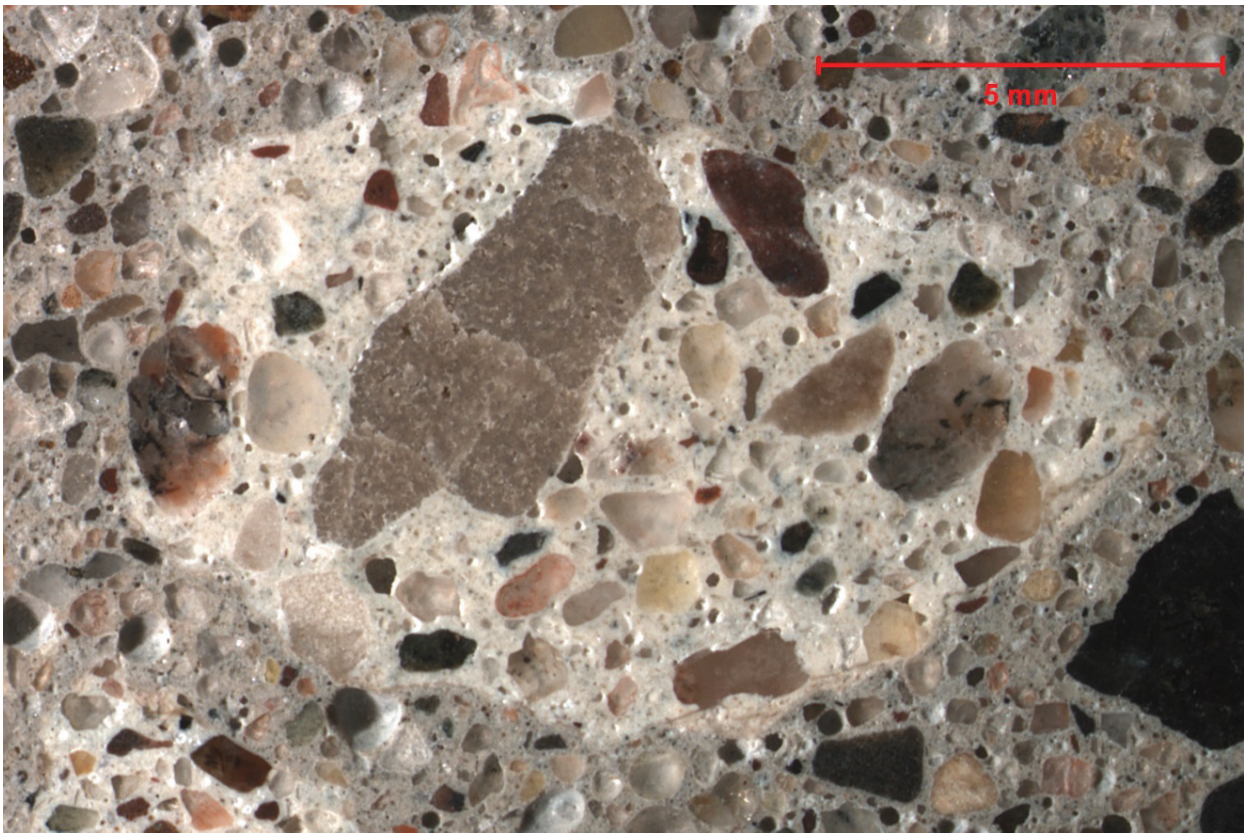


Photo 1:	Showing CCA particle.
Photo 2:	Showing magnified interface.

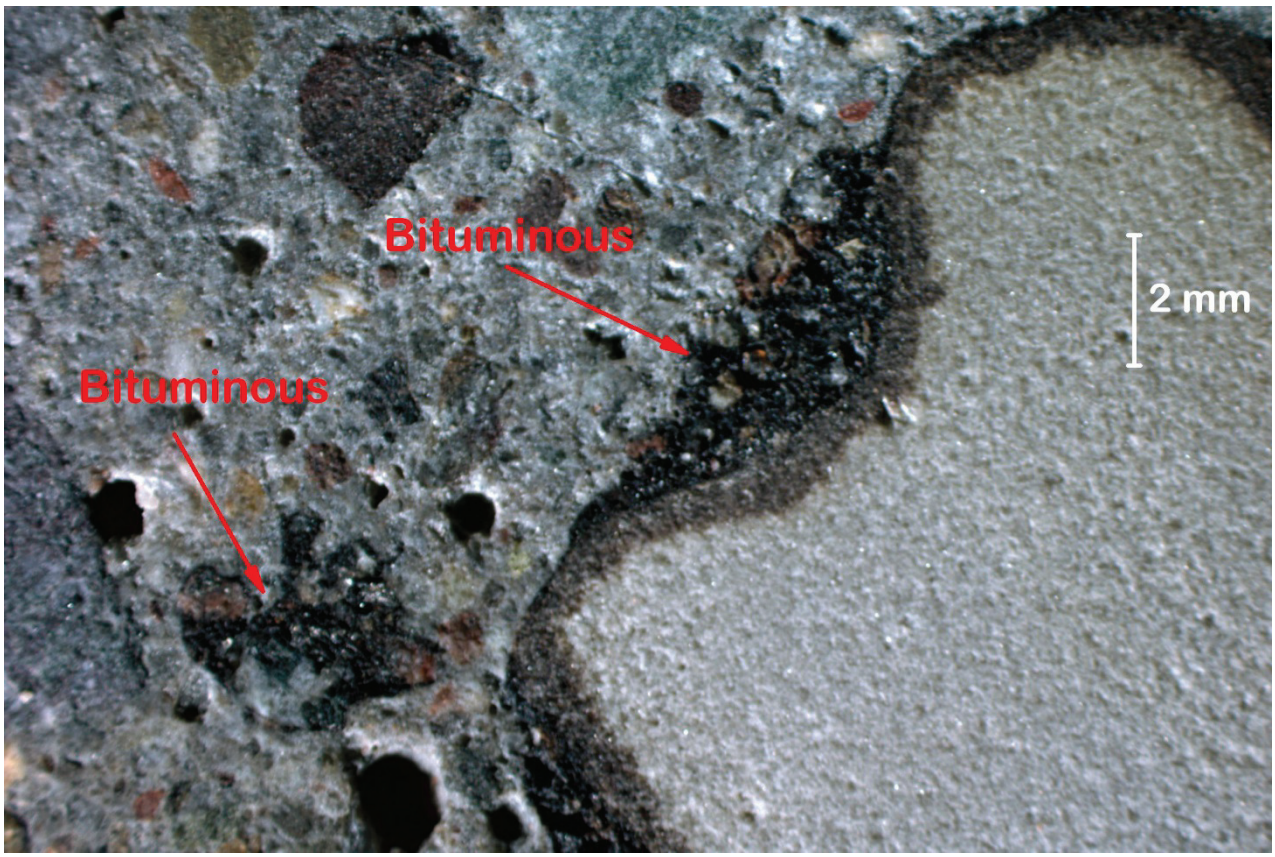


Photo 3: Showing asphalt in concrete containing RCA.