Aggregate Optimization

Quality Assurance Workshop
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CONCRETE PRECAST AGGREGATE MARINE

Outline

- Background on Aggregate Optimization
- Utilization of Optimized Aggregate Mixes
- PennDOT Pro Team Study
- Field Data
- Specification

Background

Evaluating the overall particle size distribution of a concrete mix.

Aggregate optimization really gained traction in the 1980’s when Shilstone developed various metrics to evaluate the optimal aggregate curves.

Coarseness Factor Chart

Power 45 Curve

Combined % Retained

Updated Tarantula Curve

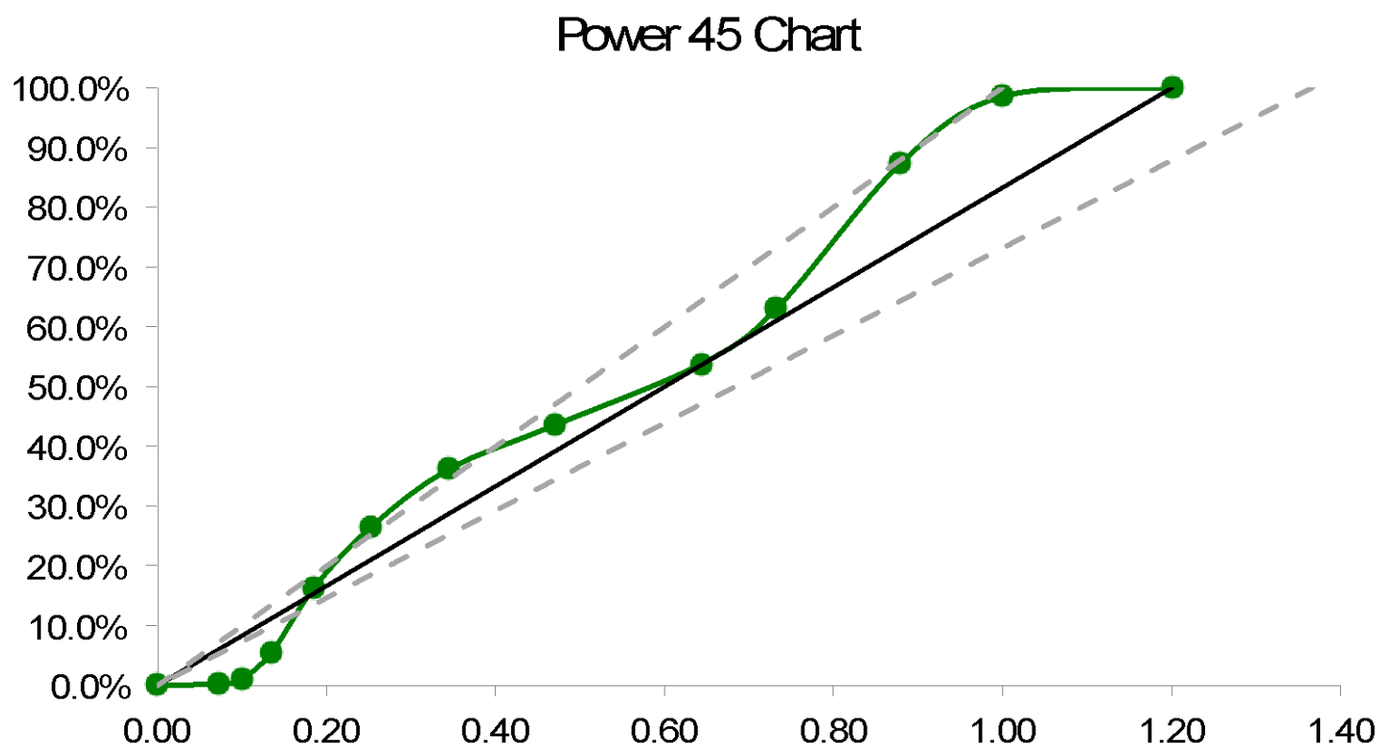
Control Charts

- Graphic Illustrations that track aggregate gradation
- Used to control blends
- Visually optimizing aggregate proportions within a mix design

Power 45 Chart

Cumulative % Passing (y-axis) vs. Sieve Sizes ^0.45 (x-axis)

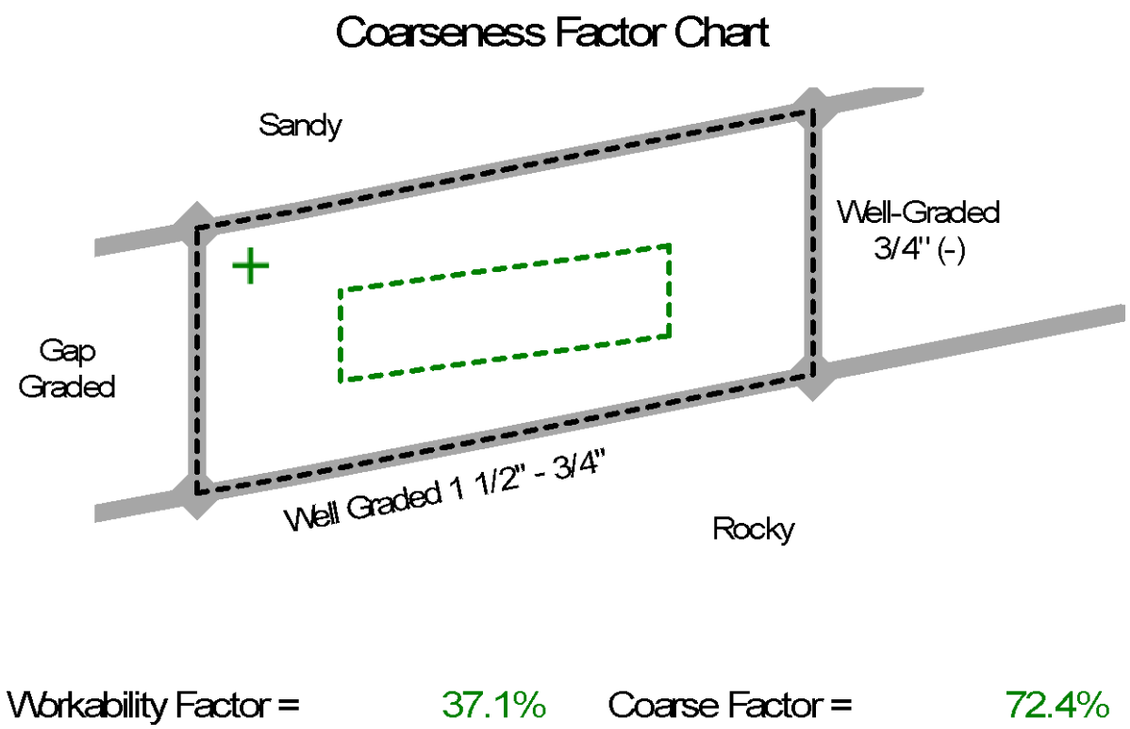
Maximum Density Line = (individual sieve size / nominal maximum sieve size) ^0.45



Coarseness Factor

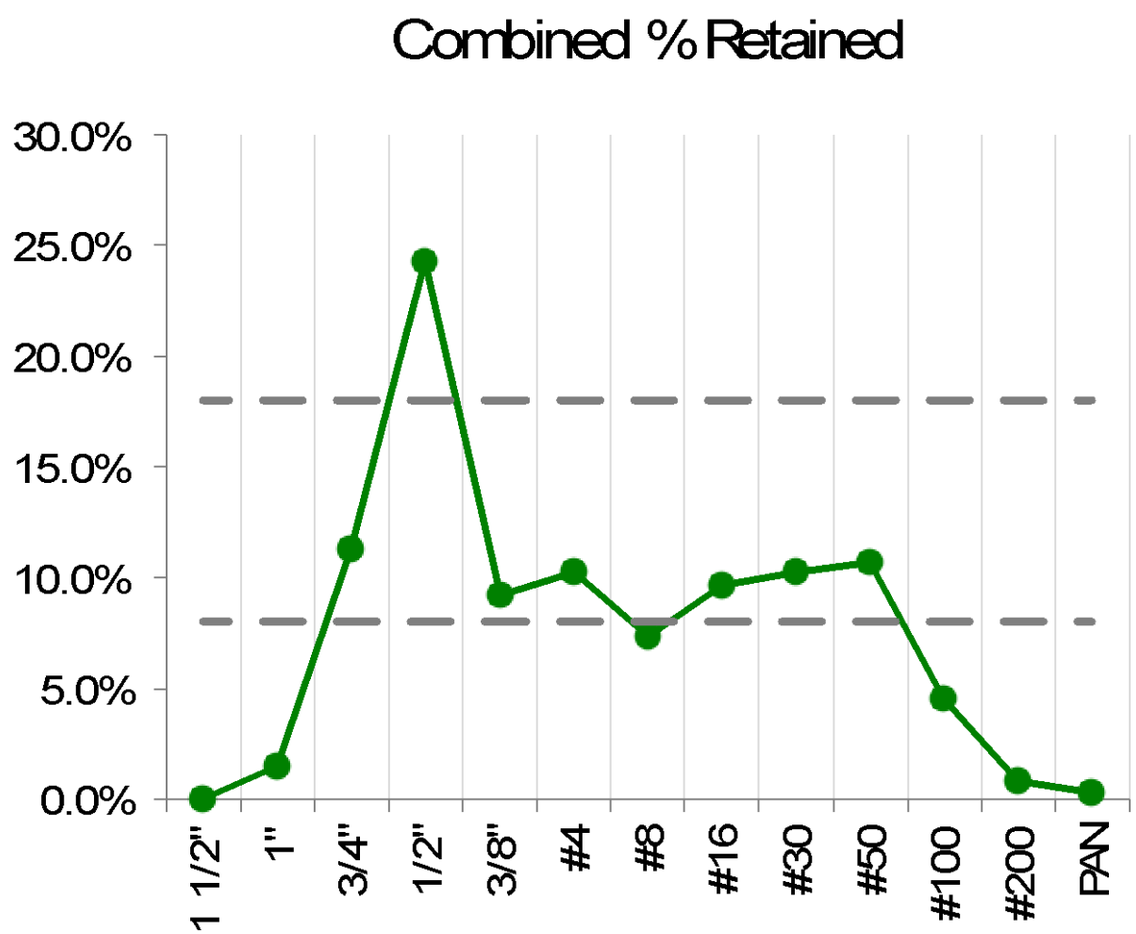
Coarseness Factor = (cumulative % retained 3/8” sieve / cumulative % retained on #8 sieve)

Workability Factor = cumulative combined % passing #8 sieve +/- 2.5% for every 94 lbs/cyd cement above or below 564 lbs/cyd



Combined Percent Retained

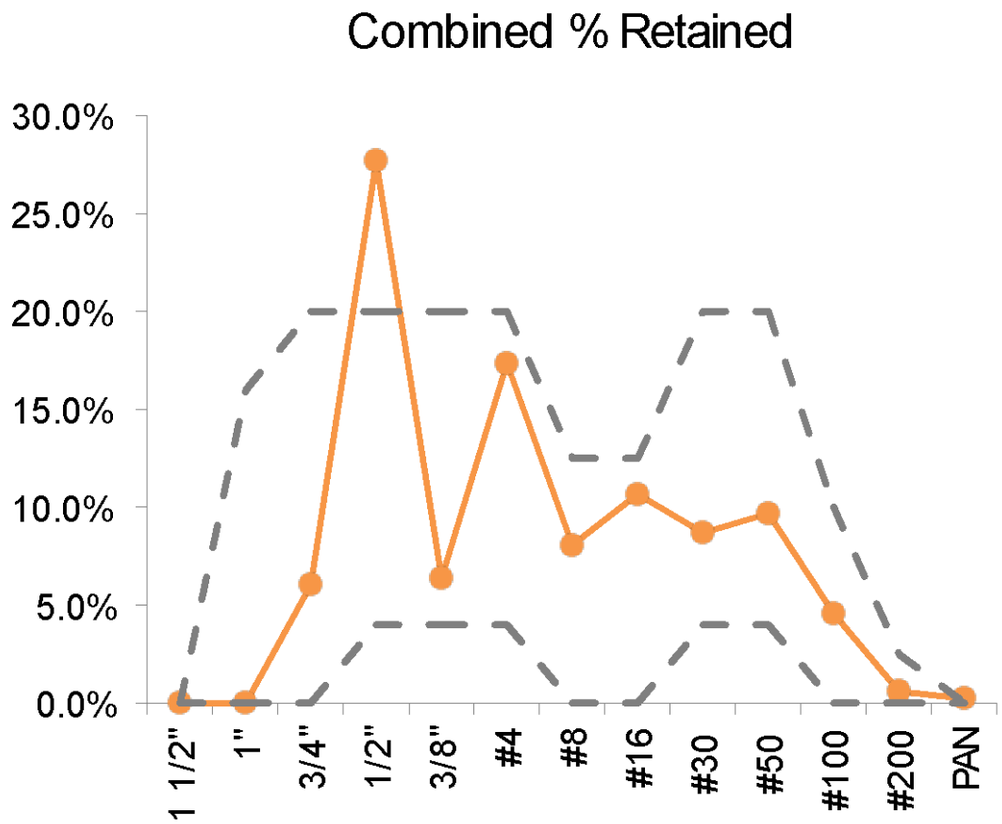
Sum of the % Retained on adjacent sieves, excluding the first and last sieve.



Combined Percent Retained – Tarantula Curve

Sum of the % Retained on adjacent sieves, excluding the first and last sieve.

Adjustments made in the combined % retained tolerances.



Utilization of Charts in DESIGN

- Designing a mix to utilize optimum aggregate blend
- Charts provide graphic illustration of blend.
- MANY other variables and considerations during mix design development.
- Changes in aggregate blends & proportions change other aspects of a design and should be considered.
    - Coarse aggregate volume (pumping or paving)
    - Paste volume
    - Aggregate surface area
    - Paste to sand ratio (mortar fraction)
    - Overall mix rheology

Utilization of Charts in PRODUCTION

- Provide quick indication as to how well the mix is blended based on design.
- Chart and track gradation blends.
- Minor adjustments to blends as gradations fluctuate before production.

Benefits of Aggregate Optimization

- Improved Workability
  - Water Reduction
  - Improved Consolidation
  - Reduction in Vibration Effort
- Reduced Paste Content
  - Reduction in Shrinkage & Propensity to Crack
  - Reduction in Permeability
  - Reduction in Heat of Hydration
- Increase in compressive strength
  - Paste efficiency by increased surface area

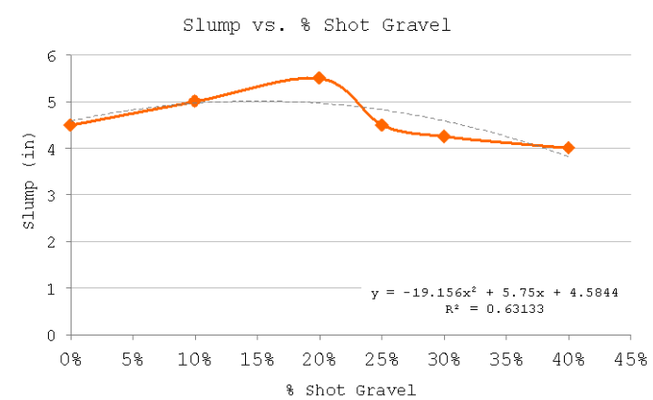
Water Demand with Aggregate Optimization

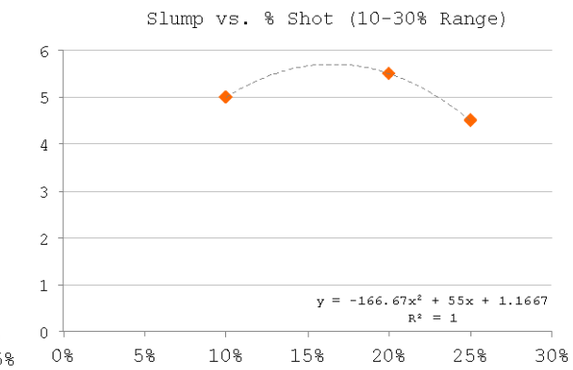
- Basic study by adding a % of #8s
- Total Cementitious Constant
- W/C Ratio Constant
- Coarse Agg Volume Constant
- Increased % of #8 Gravel, reducing #67 Gravel volume
- Slump increased until optimum concentration reached, then dropped.
- Compressive strengths improved slightly.
- Result - Increased slump by 1” without the addition of water, only the addition of 20% #8 Gravel.

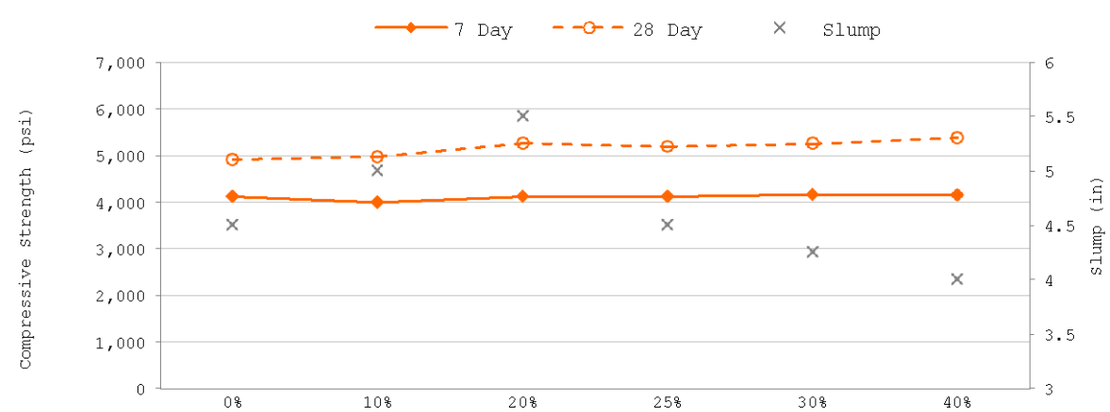
TEST DATA

Mix	% Shot	Slump	Unit WGT	W/C	T.CA Vol	Cement Factor	7 Day		28 Day	
0% Shot	0%	4.5	145.2	0.50	11.0 cf	550 lbs	4,120	psi	4,910	psi
10% Shot	10%	5	145.2	0.50	11.0 cf	550 lbs	3,990	psi	4,970	psi
20% Shot	20%	5.5	145.3	0.50	11.0 cf	550 lbs	4,120	psi	5,260	psi
25% Shot	25%	4.5	145.4	0.50	11.0 cf	550 lbs	4,110	psi	5,180	psi
30% Shot	30%	4.25	145.4	0.50	11.0 cf	550 lbs	4,160	psi	5,250	psi
40% Shot	40%	4	145.5	0.50	11.0 cf	550 lbs	4,140	psi	5,380	psi

GRAPHS



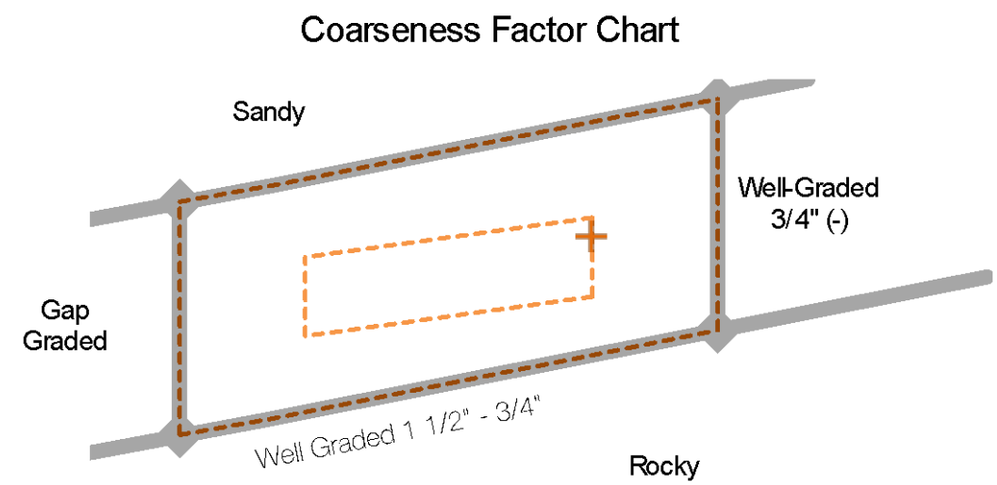




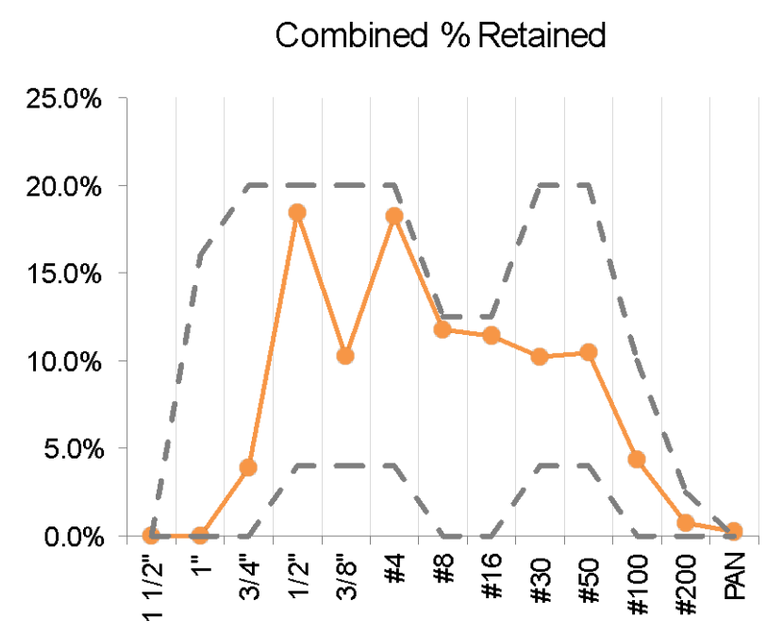
	0%	10%	20%	25%	30%	40%
7 Day	4,120	3,990	4,120	4,110	4,160	4,140
28 Day	4,910	4,970	5,260	5,180	5,250	5,380
Slump	4.5	5	5.5	4.5	4.25	4

Aggregate Gradations – 20% Shot Gravel

- Taking the mix that gave us the best water reduction
- We can see it falls in the well graded side of the coarseness factor chart
- Falls inside of the Tarantula Curve



Workability Factor = 37.0% Coarse Factor = 52.1%



Compressive Strength with Aggregate Optimization

- Using the same study…
- Target consistant slump by reducing water content.
- Reducing W/C Ratio
- Thus increasing compressive strength accordingly.

Commercial Applications

- Warehouse floors
- Driveways
- Standard for majority of flatwork
- Compressive strength ranges 3,000psi and up

PennDOT Pro-Team

- To determine the cause of cracking through the investigation of concrete bridge deck…

- DESIGN
- CONSTRUCTION
- MATERIALS

Bridge Deck Cracking

- Pro-Team comprised of Pennsylvania Aggregate and Concrete Association (PACA) Technical Committee Members
- Pro-Team to continue the developments set forth with AAAP and determine additional design considerations to improve the performance of the materials
- Main focus was Aggregate Optimization

Aggregate Blending

Develop a mix utilizing the optimum particle size distribution for various aggregate sizes.

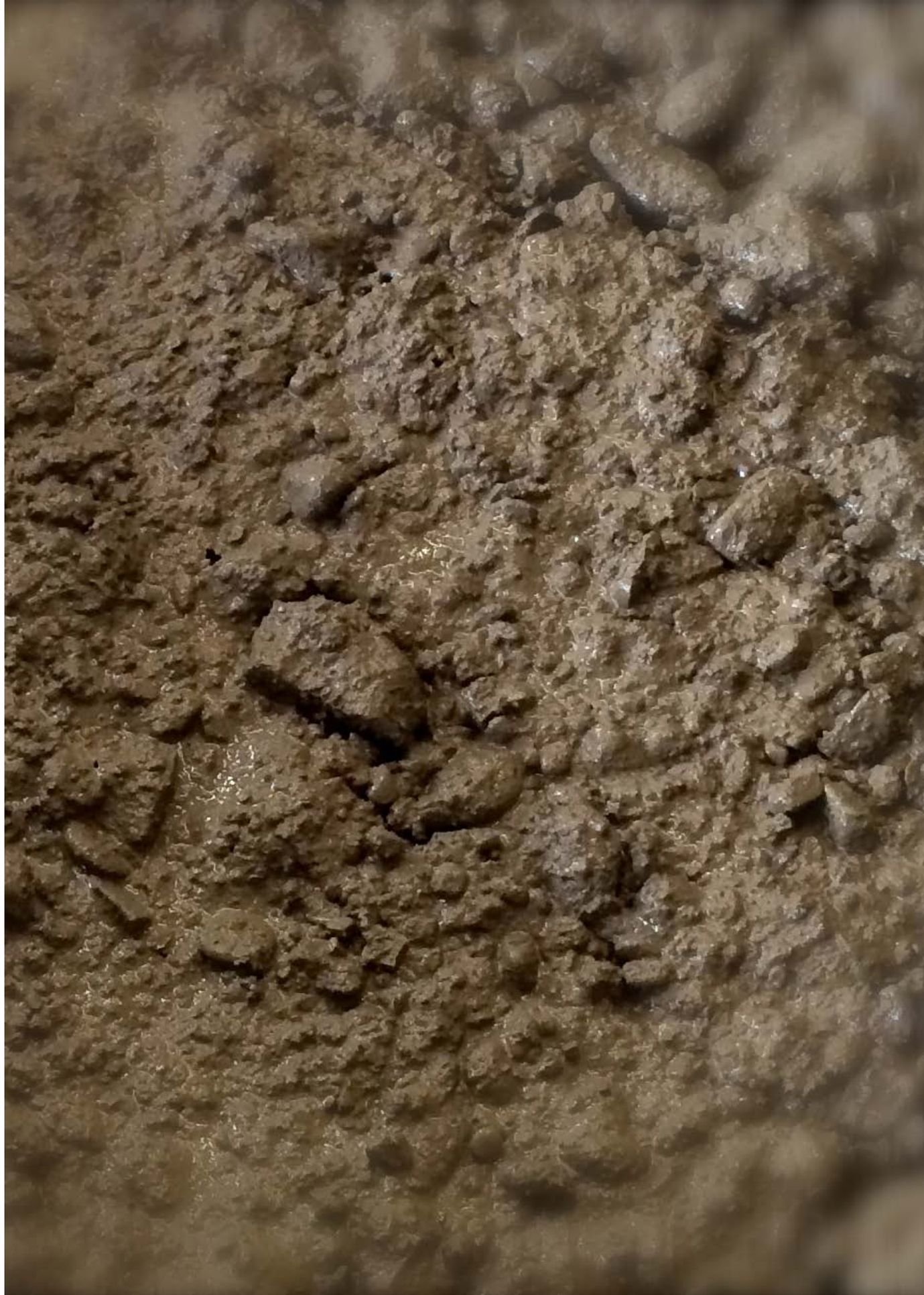
Adjust weights and blends to fit targeted control charts.

Test several mixes and blends.

Also run high cement mixes to compare shrinkage improvements.

ASTM C 1581

Restrained Ring Test



ASTM C 1581 - Restrained Ring Test

- Test method is used for determining the crack potential of concrete mixtures with aggregate under ½” in size.
- Difficult to find testing equipment.
- Only evaluate concrete with ½” and smaller aggregate.
- We decided to build the ring molds at our machine shop per ASTM material Standards.
- Needed to make testing modifications to accommodate larger aggregate sizes.

ASTM C 1581
Restrained Ring Test

Modification to ASTM C 1581

The outside ring diameter per the specifications is 16 +/- 0.12 inches which matches 80-16 PVC Pipe

The ASTM specifies that the largest aggregate to be used with the test method is 1/2”

We decided to increase the outer ring diameter to 20” to accommodate standard #57 aggregate (provided 3” annular space).

Also added “control” joints to increase the rings propensity to crack.

We initially found it was taking too long to crack and we weren’t able to get enough data in a reasonable amount of time.

ASTM C 1581 - Restrained Ring Test

CURING MODIFICATION:

- Moist cured in molds for 24 hours (burlap & plastic)

- Remove outer ring after 24 hours

- Seal top surface with foil tape or wax

- Cure in environmentally controlled room

    73.5 +/- 3.5 degrees F

    50 +/- 4% relative humidity

ASTM C 1581 - Restrained Ring Test

Strain gauges are attached to inside of steel ring.

Monitor strain in the steel caused by shrinkage of concrete.

Strain reading normalized at start of test.

Heat of hydration causes steel to expand showing positive strain.

Then compresses as concrete shrinks

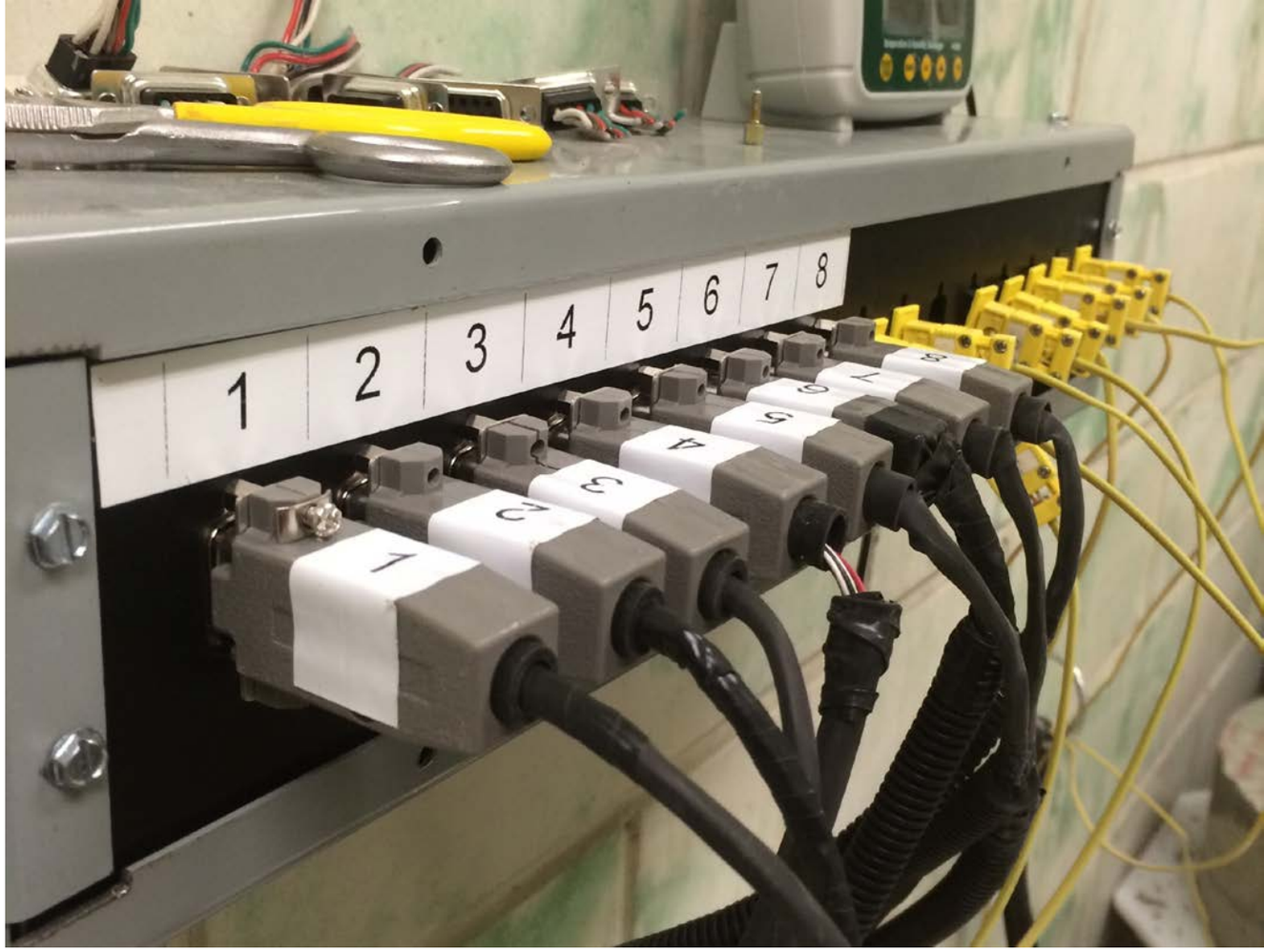
Until cracking occurs.

Ring Testing - Humidity Controlled Room

Data Acquisition

Strain gauges and thermocouples attached to interior of steel ring

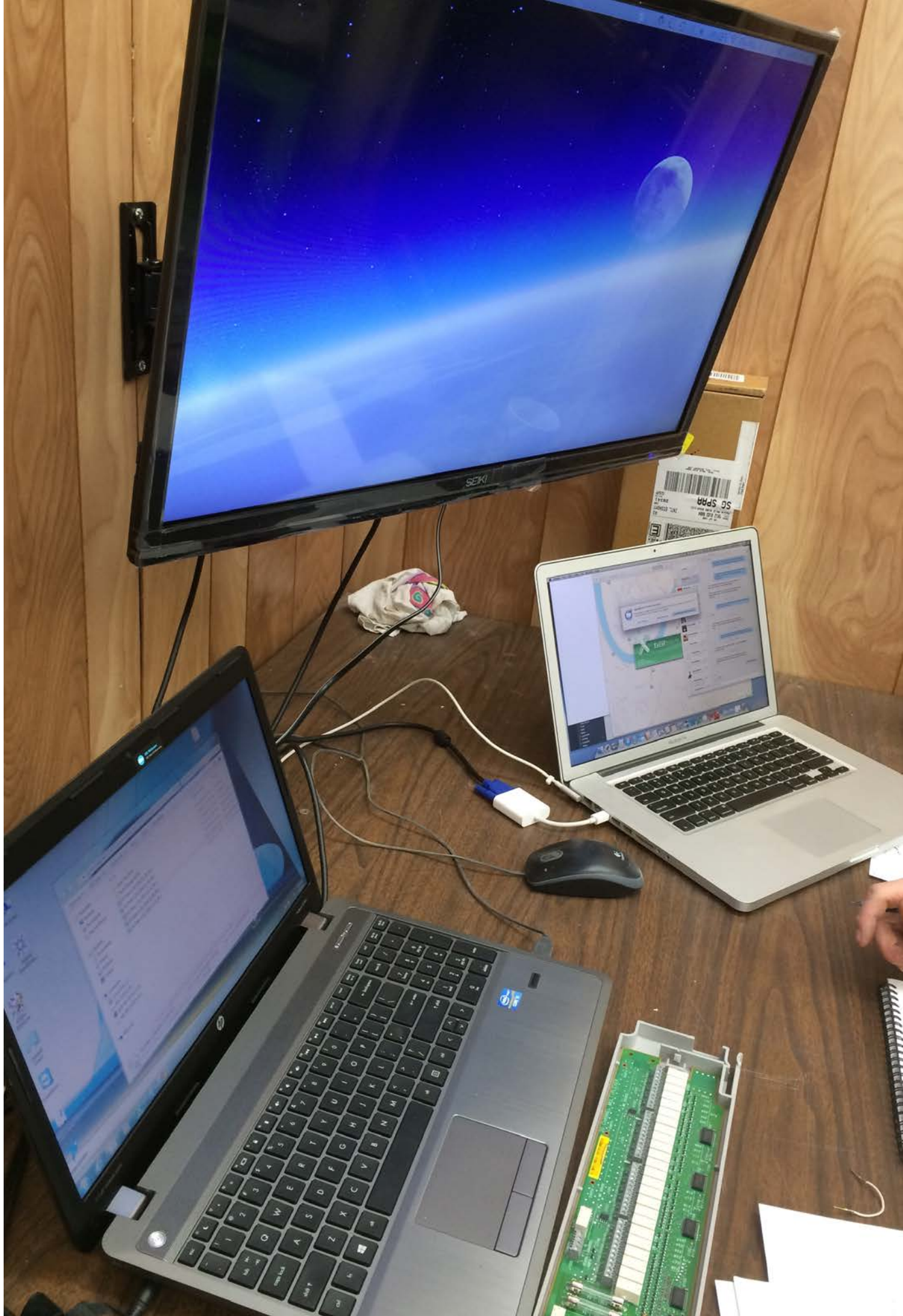
Data transmitted through 9-pin jack to data logger to be stored



Data Acquisition

Data transmitted through 9-pin jack to data logger to be stored

Downloaded into spreadsheet at set intervals



Mix Designs

Induced drying in humidity controlled room after 24 hours.

ASTM C 1581 - Restrained Ring Test

Results Gathered:

Age at Cracking – Day at which cracking occurs, TOC (day)

Initial Strain – Initial strain reading when drying begins, $\mu\varepsilon$

Maximum Strain – Strain when concrete cracks, $\mu\varepsilon_{max}$

Net Strain, ε_{net} – Difference between strain at time t and initial strain

Strain Rate Factor, α = Rate of strain (in/in)/day

Stress rate, q – Stress rate at cracking (psi/day)

ASTM C 1581 - Restrained Ring Test

Strain development over time

ASTM C 1581 - Restrained Ring Test

Strain Rate Factor

α = Rate of strain = $\mu\varepsilon_{net}$ (in/in)/day

Calculated by $\varepsilon_{net} = \alpha\sqrt{t} + k$

Linear regression analysis of net strain vs. square root of elapsed time.

$$S = \sum_i (y_i^{th}(a,b) - y_i^{obs} / \partial_i)^2$$
$$S = \sum_i (a + bx_i - y_i / \partial_i)^2$$

Least squares curve fit is defined as the process of obtaining the best description of data in terms of some theory, involving parameters or variables that are initially unknown.

ASTM C 1581 - Restrained Ring Test

Results:

Time of Crack (TOC, hours or days)

Stress rate, q – Stress rate at cracking.

$$q = (G\,|\alpha_{avg}|) / 2\sqrt{t_r}$$

q = stress rate (psi/day)
G (constant) = 10.47×10^6 psi
$|\alpha_{avg}|$ = absolute value of avg strain rate factor (in/in)/ day
t_r = elapsed time at cracking (day)

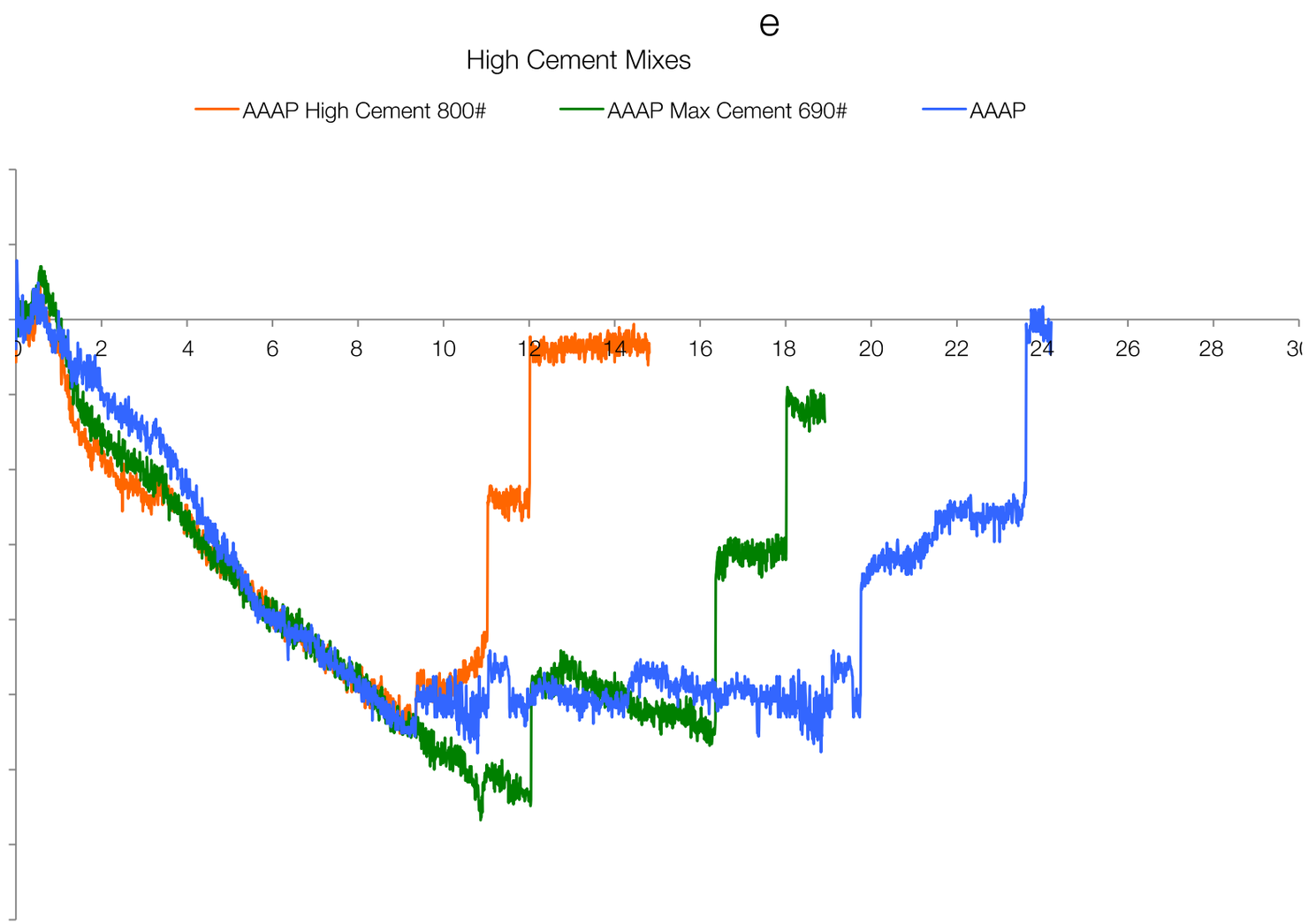
Results

Mix Designs & Data

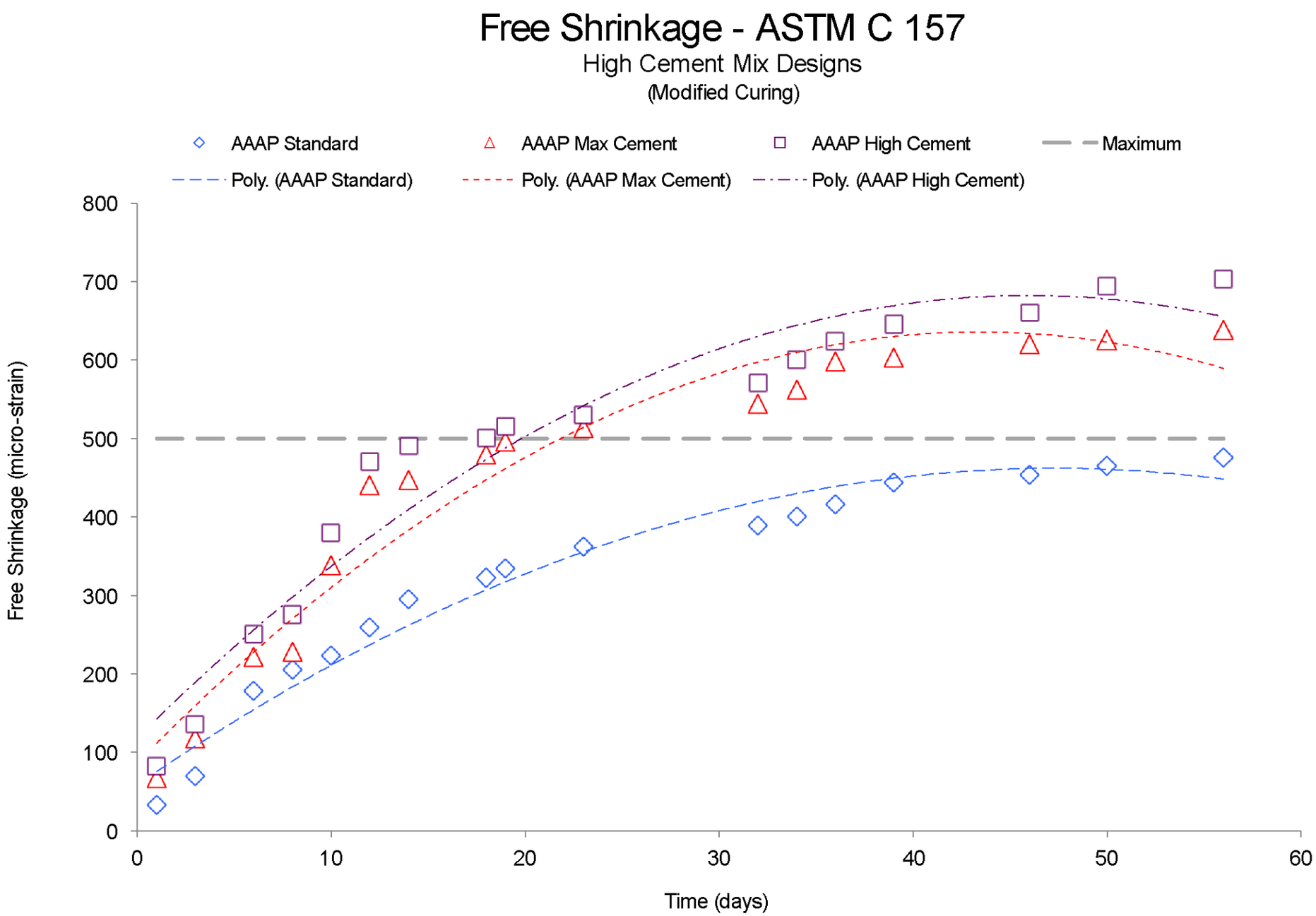
Mix Designs

Mix Name	Cement (lbs)	GGBFS (lbs)	#57 CA (lbs)	#8 CA (lbs)	CA Volume (cf)	W/C Ratio -	28 Day (psi)
AAAP Std	390	210	1769	0	10.50	0.45	6,750
AAA Blend	390	210	1598	167	10.50	0.45	7,110
AAAP Opt	390	210	1691	200	11.25	0.45	7,310
AAAP Max	690	0	1769	0	10.50	0.45	6,440
AAAP High	800	0	1769	0	10.50	0.45	7,010

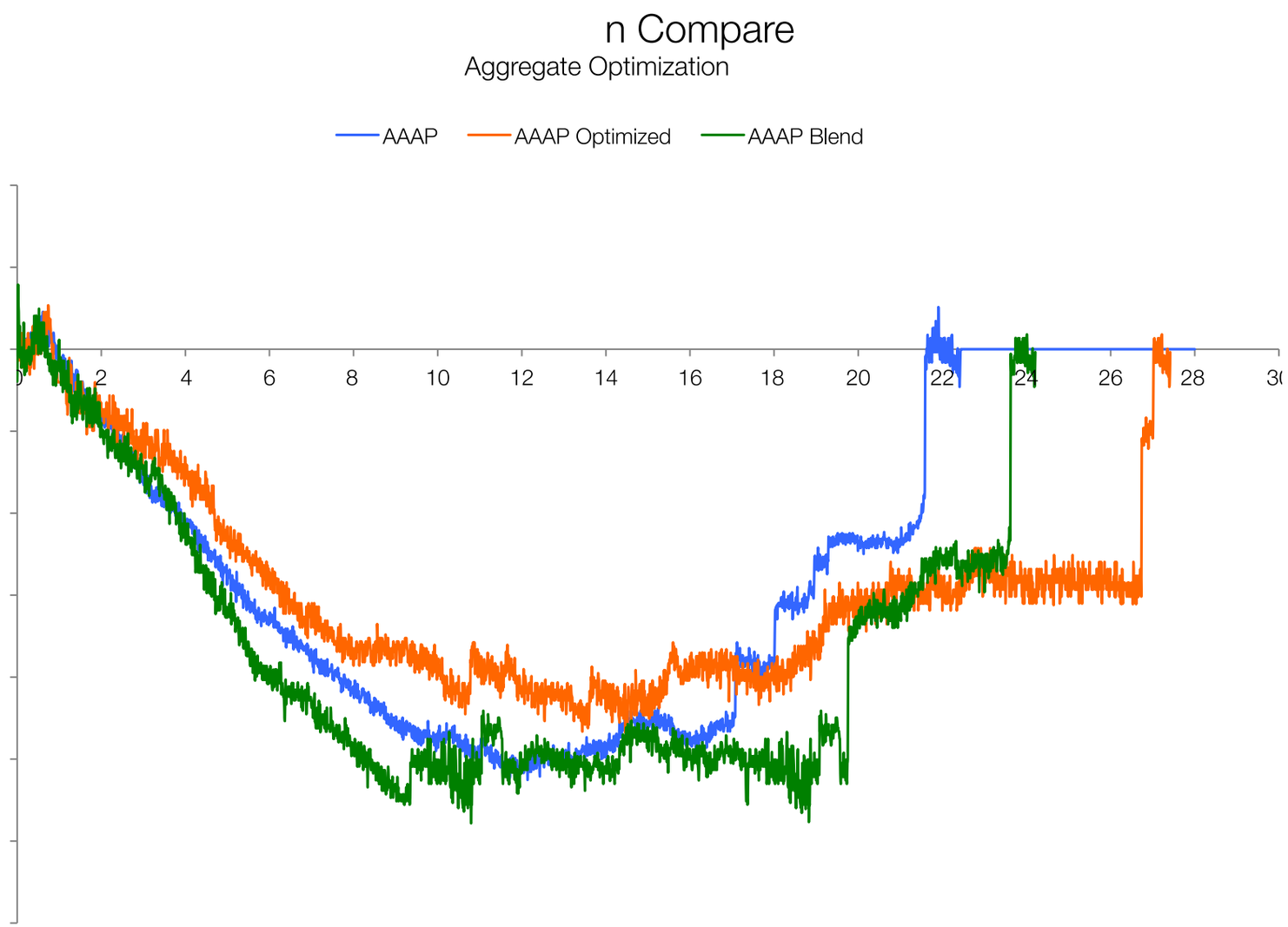
Restrained Shrinkage



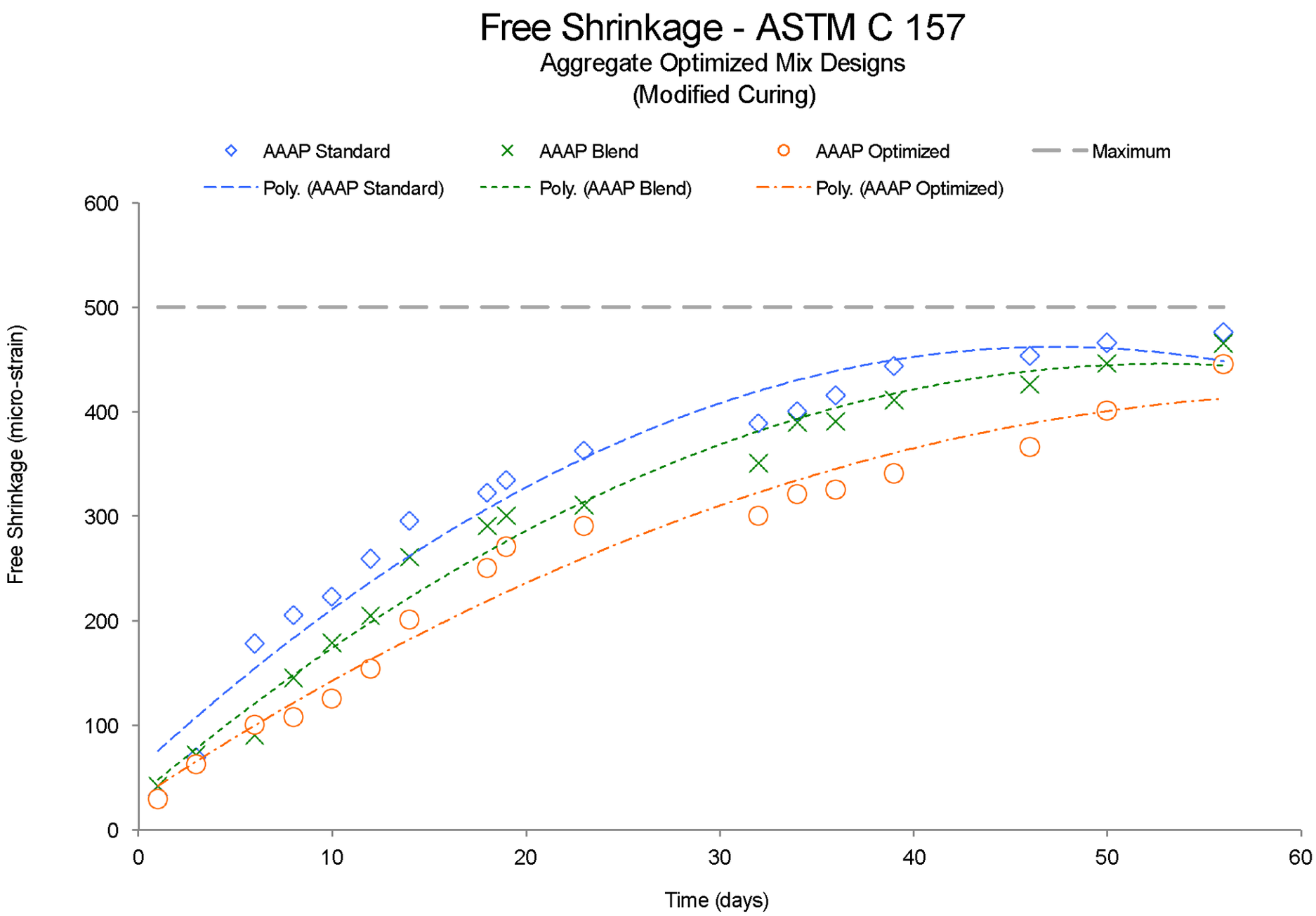
Free Shrinkage



Restrained Shrinkage



Free Shrinkage



PennDOT Deck Survey

Bridge Deck Crack Performance

PennDOT Bridge Deck Survey

Measure:

Weighted crack spacing based on total deck area and total crack length.. (YDS / SY)

Average spacing between cracks (YDS)

PennDOT Bridge Deck Survey – Preliminary Results

Simple Span Decks – Averaging 64 feet

Location	Mix Design Specification	Initial Cracking Metric	One Year Cracking Metric	Avg. Crack Spacing	One Year Avg. Crack Spacing
Statewide	AAA	0.200	0.087	5	11
Statewide	AAAP	0.040	0.040	25	25
Statewide	SSP-1	0.0028	NA	356	NA
Statewide	SSP-2	0.000	NA	NA	NA

PennDOT Bridge Deck Survey – Preliminary Results

Continuous Span Decks – Averaging 164 feet

Location	Mix Design Specification	Initial Cracking Metric	One Year Cracking Metric	Avg. Crack Spacing	One Year Avg. Crack Spacing
Statewide	AAA	0.054	0.200	19	5
Statewide	AAAP	0.023	0.066	25	25
Statewide	SSP-1	0.0028	NA	356	NA
Statewide	SSP-2	0.000	NA	NA	NA

AAA to AAAP

Improvements over AAA Concrete

- Reduced total Cementitious
- Required the use of a pozzolan
- Reduced Permeability
- 14 day Wet Cure

Improvements over AAAP Concrete

- Utilized Aggregate Optimization

Improving AAAP with Aggregate Optimization

Improvements over AAAP Concrete

- Utilizing control charts to optimize aggregate blend
- 500 micro strain Free Shrinkage limit
- Should see better workability in the field
- Should see better consolidation in the field.

Specifying Aggregate Optimization

The aggregate optimization charts should be used as targets.

Aggregates based on locally available materials.

Balanced with job applications, pumping/paving.

Cost components.

Moving Forward…

Continue to investigate concrete properties and their effects on shrinkage.

Evaluate curing practices in relation to shrinkage and long term durability.

PennDOT continue to monitor in place decks.

Continue to monitor the deck placements with new specification statewide.

Bridge Deck Cracking
Pro-Team Update

QUESTIONS

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