THE ALKALI-SILICA REACTION: A STUDY OF REACTIVE AGGREGATES AND PRODUCTION OF EXPANSIVE CONCRETE SPECIMENS

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INTRODUCTION

MOTIVATIONS

- The alkali-silica reaction was identified by Stanton in 1940
- Observed in dams and bridges worldwide
- Recently discovered in the Seabrook NPP *(Saouma & Hariri, 2014)*
- Nuclear power plants in US are licensed for an initial 40 years
- Unlimited 20-year license extensions possible *(NUREG-980, 2013)*
- Effects of ASR on shear strength poorly understood

OBJECTIVES

- Identify a local source of reactive aggregates
- Characterize aggregate ASR reactivity
- Design an aggressively-reactive concrete mix
- Concrete mix must be reasonably representative
- Construct reactive concrete specimens
- Assemble shear test apparatus
- Prescribe curing program

ORGANIZATION

1. Introduction
2. Background information
3. Shear testing program
4. Identification of reactive aggregates
5. Concrete testing program
6. Concrete mix design
7. Conclusions

BACKGROUND INFORMATION

- ASR occurs when alkali in cement reacts with amorphous or disordered silica in aggregate minerals

$$Silica + Alkali \rightarrow Gel$$
$$xSiO_2 + yNa(K)OH \rightarrow Na(K)_y Si_x O_z$$

- Product is hygroscopic silica gel, which expands when hydrated

$$Gel + Water \rightarrow Hydrated\ gel$$
$$Na(K)_y Si_x O_z + wH_2O \rightarrow Na(K)_y Si_x O_z \cdot wH_2O$$

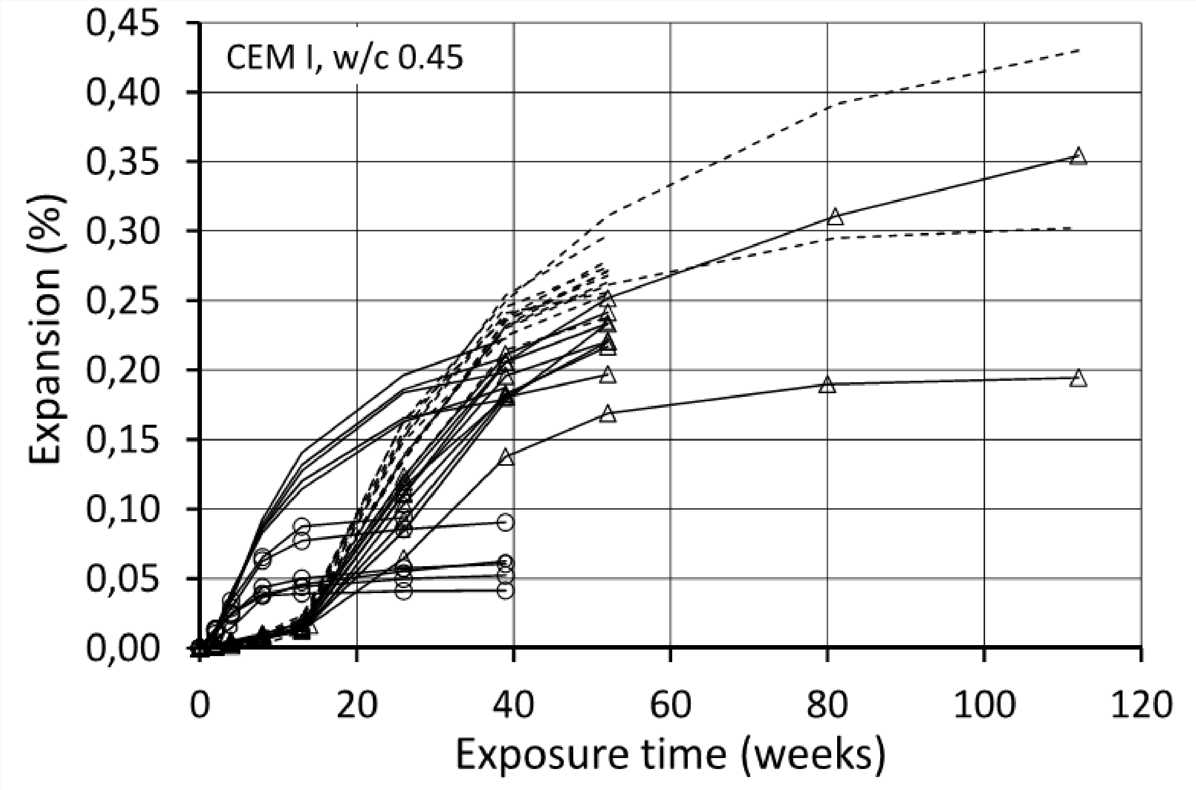
- Three necessary components for ASR *(Hobbs, 1988)*

1. Reactive minerals in aggregate
2. Sufficient alkali in cement
3. Sufficient humidity to hydrate resulting gel

- Reaction rate strongly influenced by temperature *(Larive 1998)*

- Lindgård (2013) exhaustively tested concrete prisms
- Found drastic variation depending on curing conditions

1. Alkali leaching
2. Internal moisture
3. Temperature
4. Initial alkali content
5. Diffusion rate (porosity)



Reproduced from Lindgård (2013)

- Influence of ASR on mechanical properties widely studied
  (Swamy & El Asali, 1988) (Monette, 1997) (Ahmed et. al, 2003) (Multon, 2004) etc.

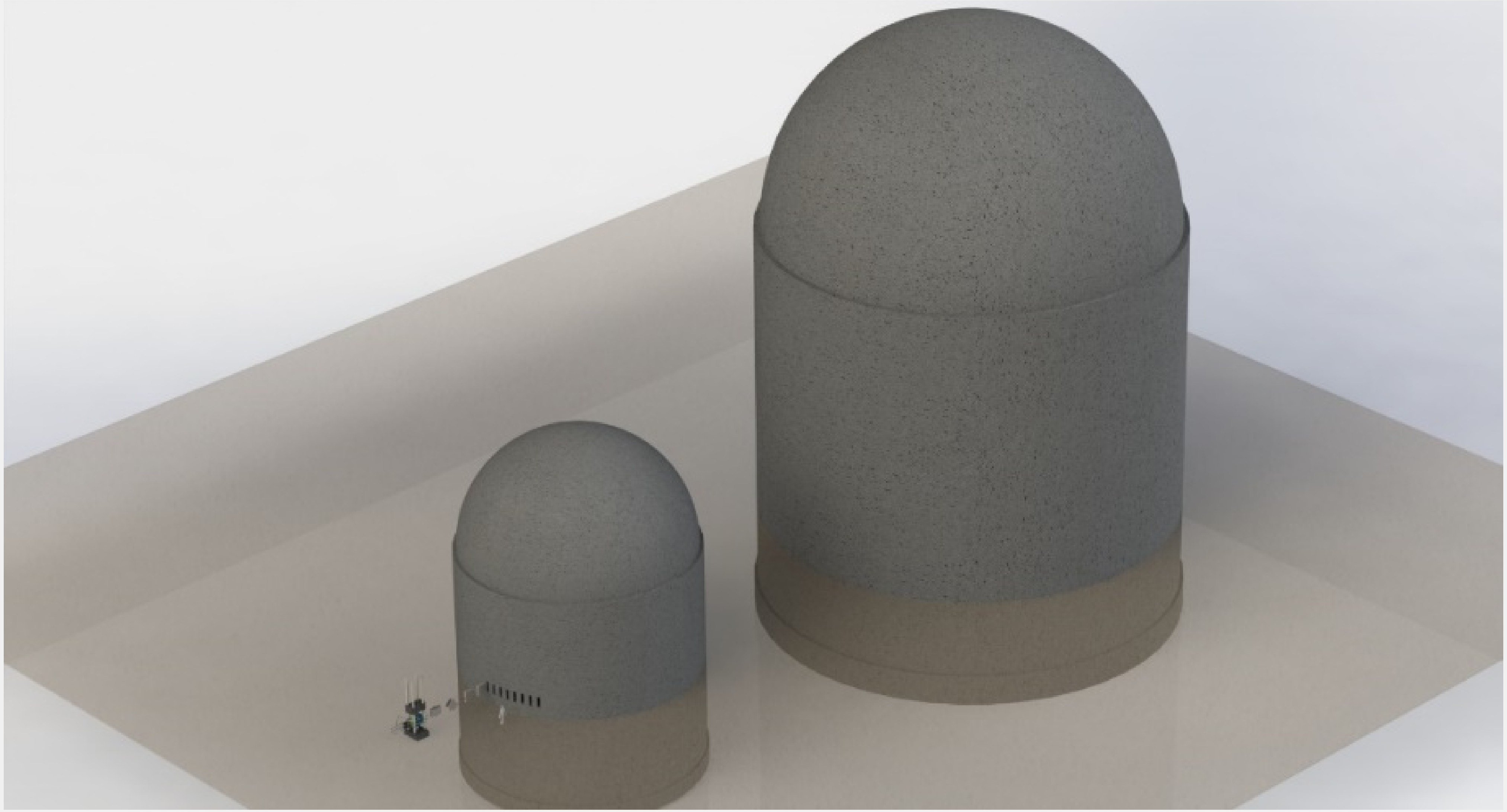
- As expansion proceeds, following effects observed

1. Compressive strength initially climbs then declines
2. Tensile strength falls nonlinearly
3. Elastic modulus declines almost linearly

(Esposito et. al, 2016)

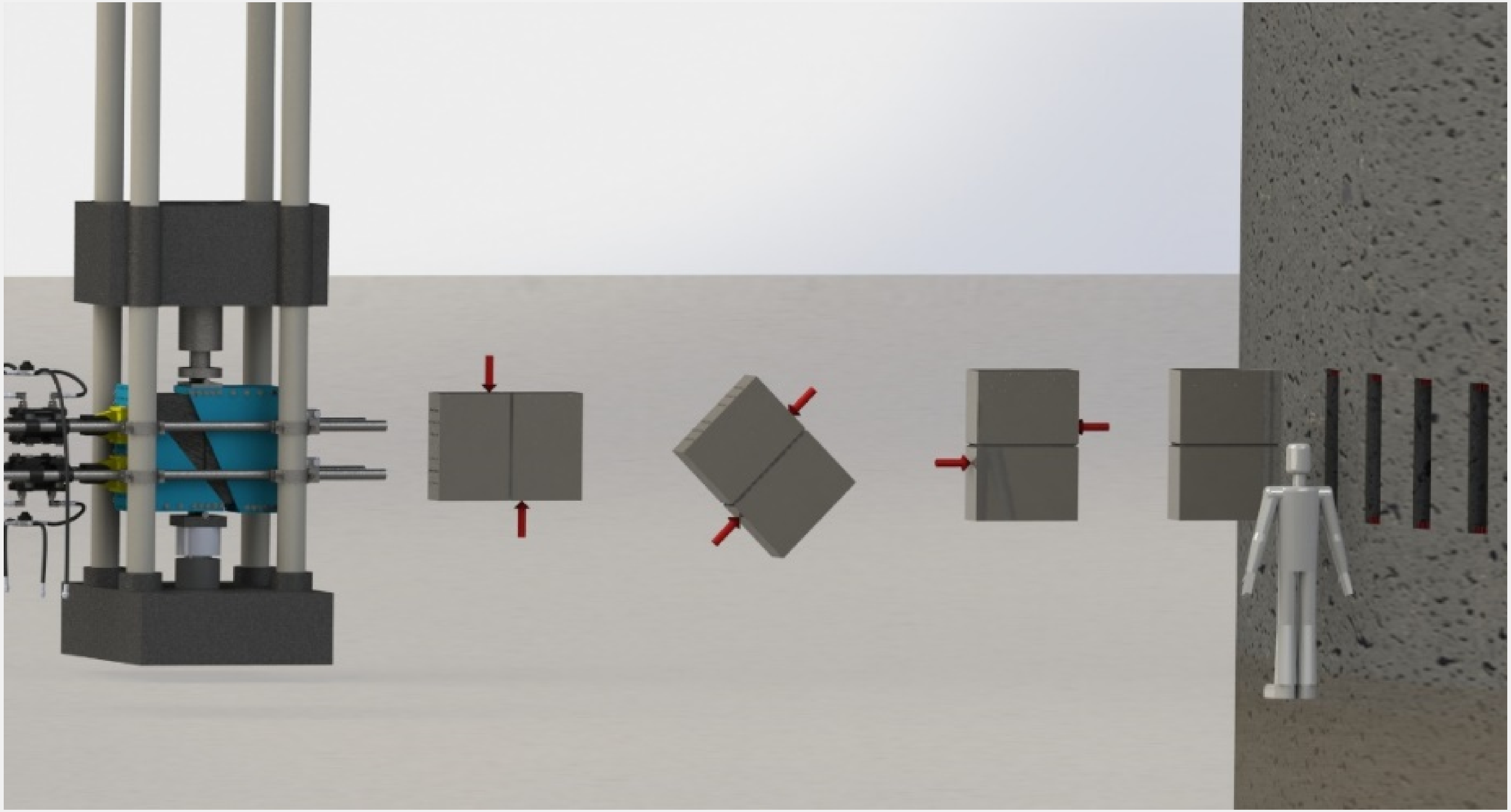
- Effects of ASR on shear strength not well understood
  - No effect? *(Bach et. al, 2003)*
  - Shear strength declines? *(den Uijl & Kaptijn, 2003) (Nakamura et. al, 2008)*
  - Shear strength increases? *(Ahemd, Burley, & Rigden, 1998)*

SHEAR TESTING PROGRAM



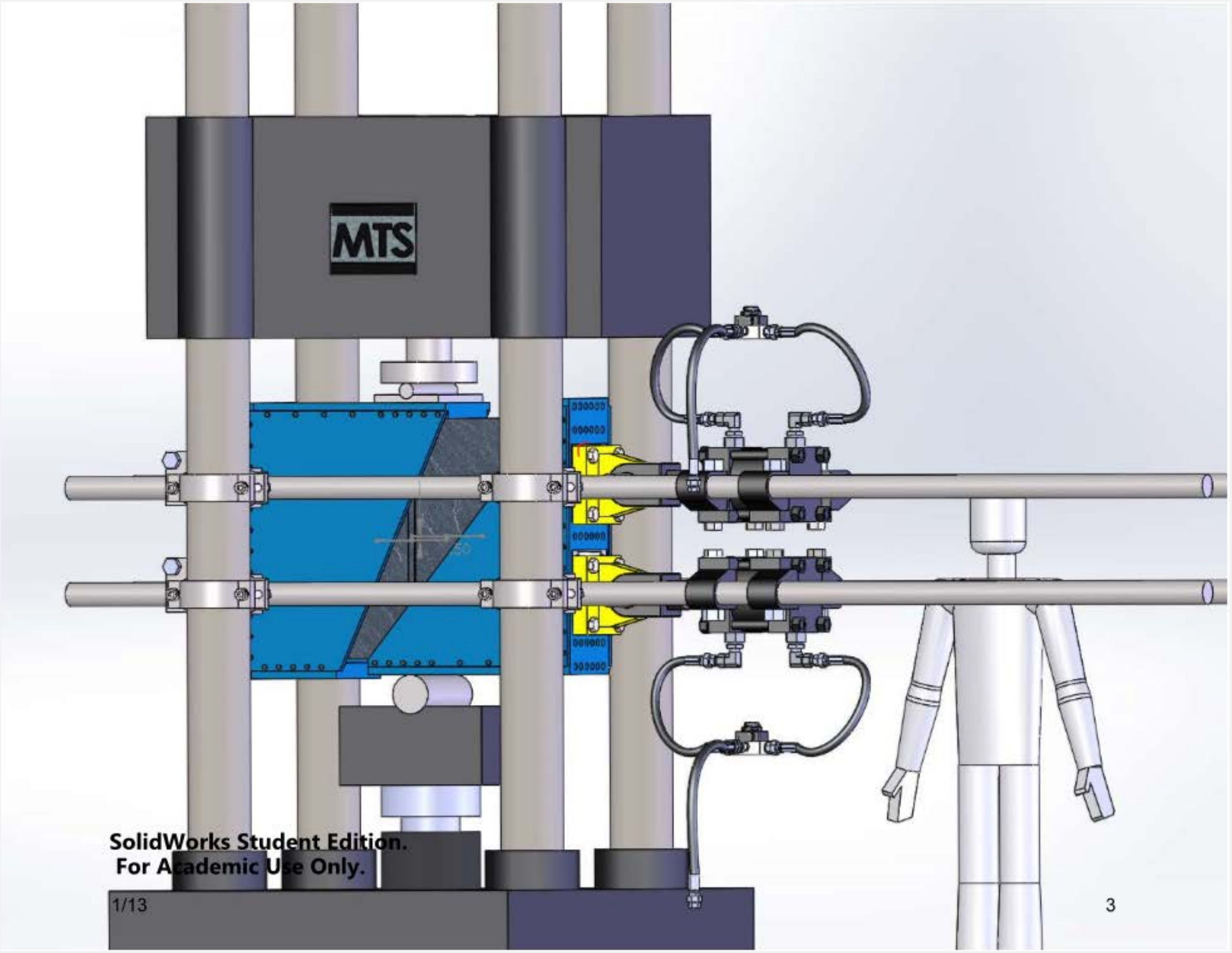
Prototype Structure	
Inner radius (ft)	63
Wall thickness (ft)	4.5
Wall height (ft)	122
Foundation thickness (ft)	10
Grade level (ft above foundation base)	56

Model Structure	
Scale Factor	0.56
Inner radius (ft)	35
Wall thickness (ft)	2.5
Wall height (ft)	68
Foundation thickness (ft)	5.6
Grade level (ft above foundation)	31



SHEAR TEST APPARATUS

- Apparatus designed for previous study
- Brought out of storage
- Inventoried
- Cleaned
- Painted
- Assembly began January 15th, 2016


MTS
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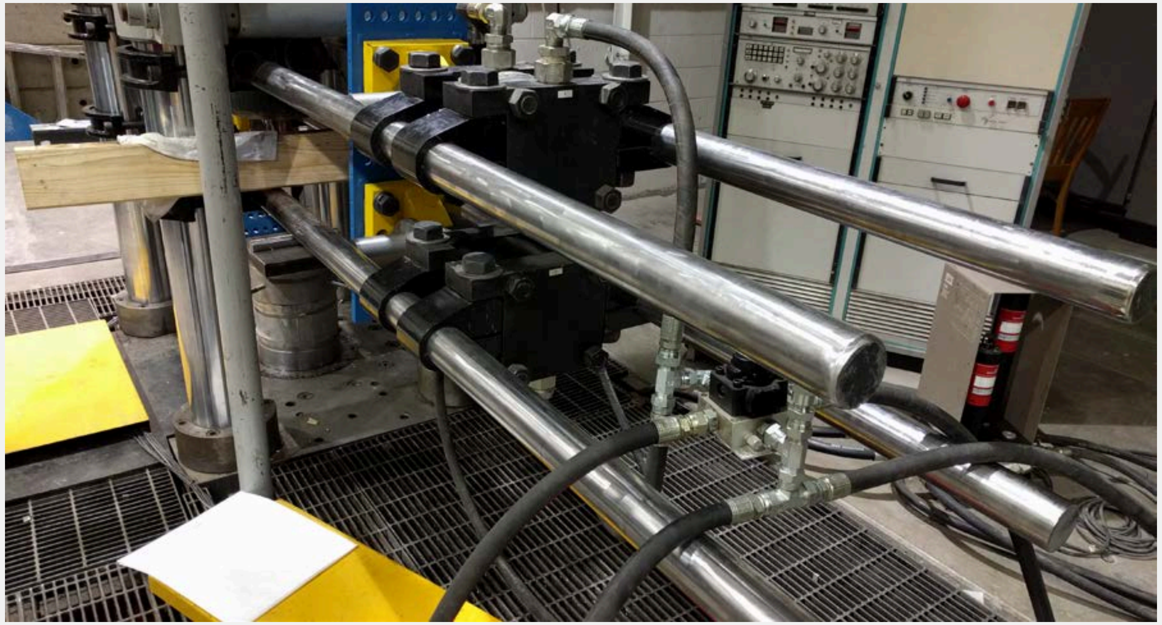
BUSHINGS, CLAMPS AND CLEVIS BRACKETS

INSTALLING REACTION BARS

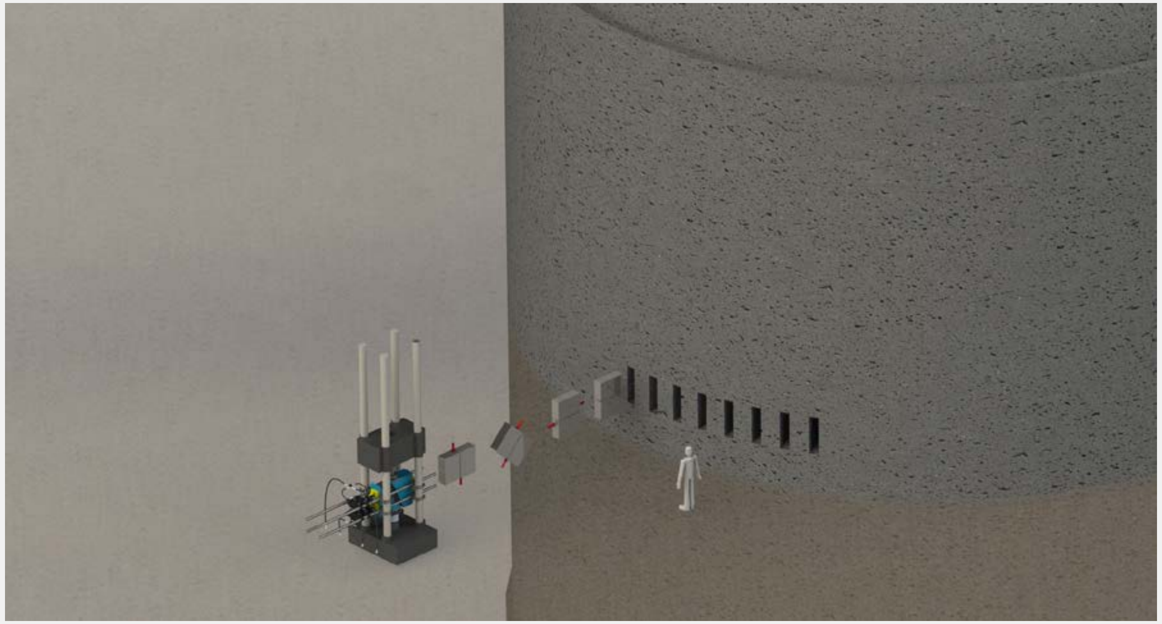
ALIGNING REACTION BARS WITH TAPE & SPIRIT LEVEL

ALIGNING REACTION BARS WITH TAPE & SPIRIT LEVEL

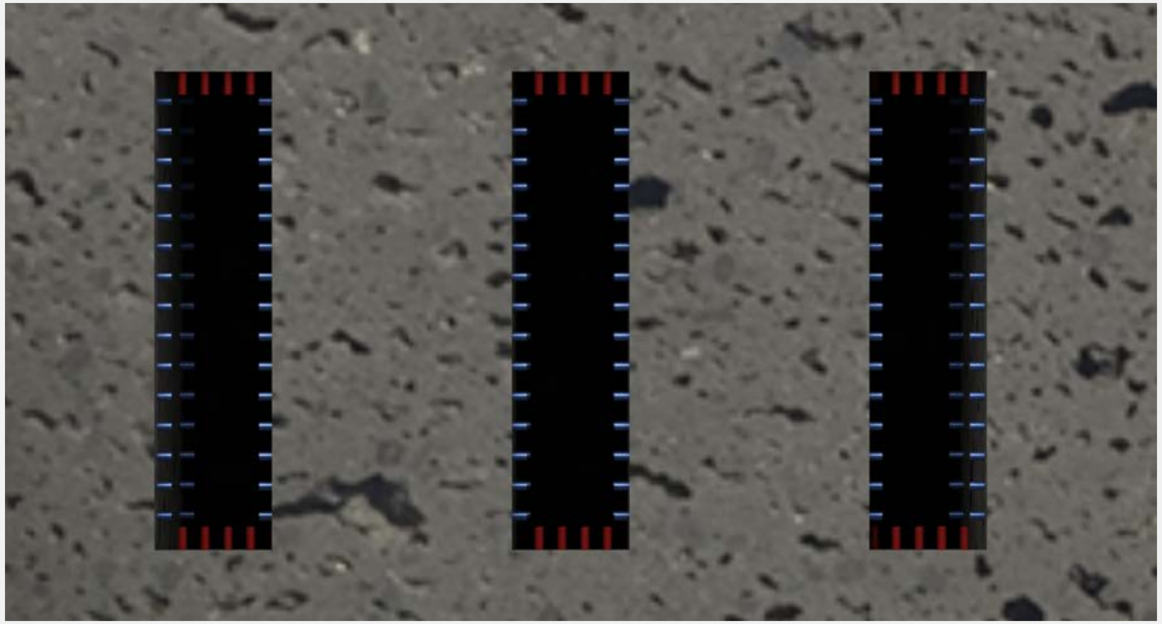


REINFORCEMENT

- Prototype structure reinforced in both axial and circumferential directions
- Details of prototype reinforcement not known
- No attempt made to model a particular NPP
- Model reinforcement must be:
  - Constructible
  - Representative

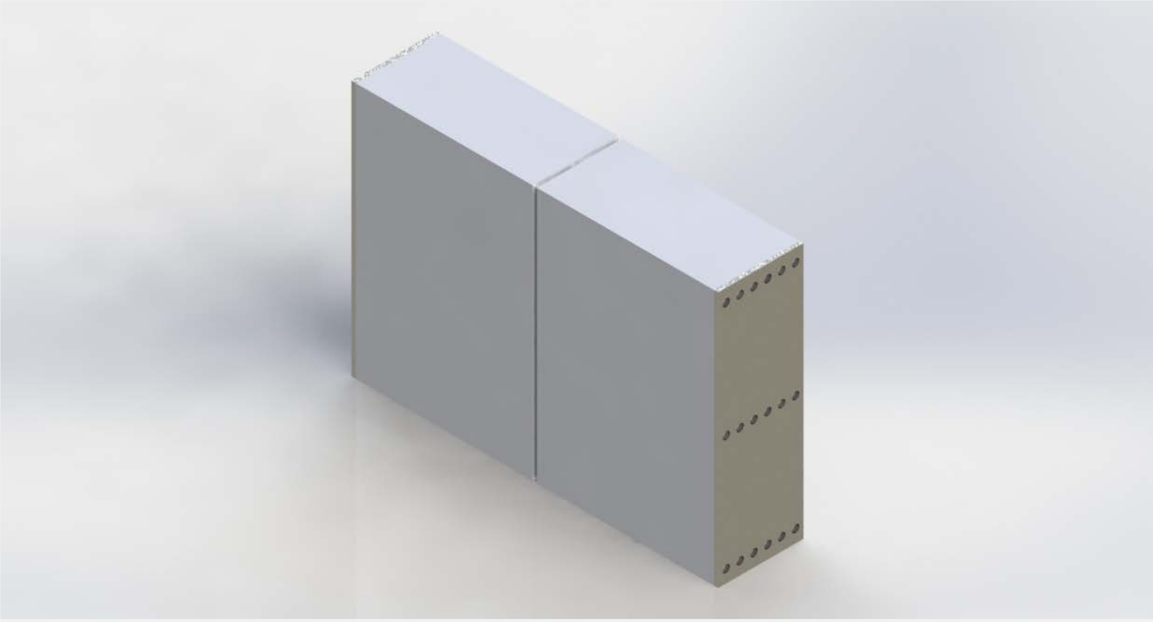


SHEAR SPECIMEN ORIENTATION IN MODEL

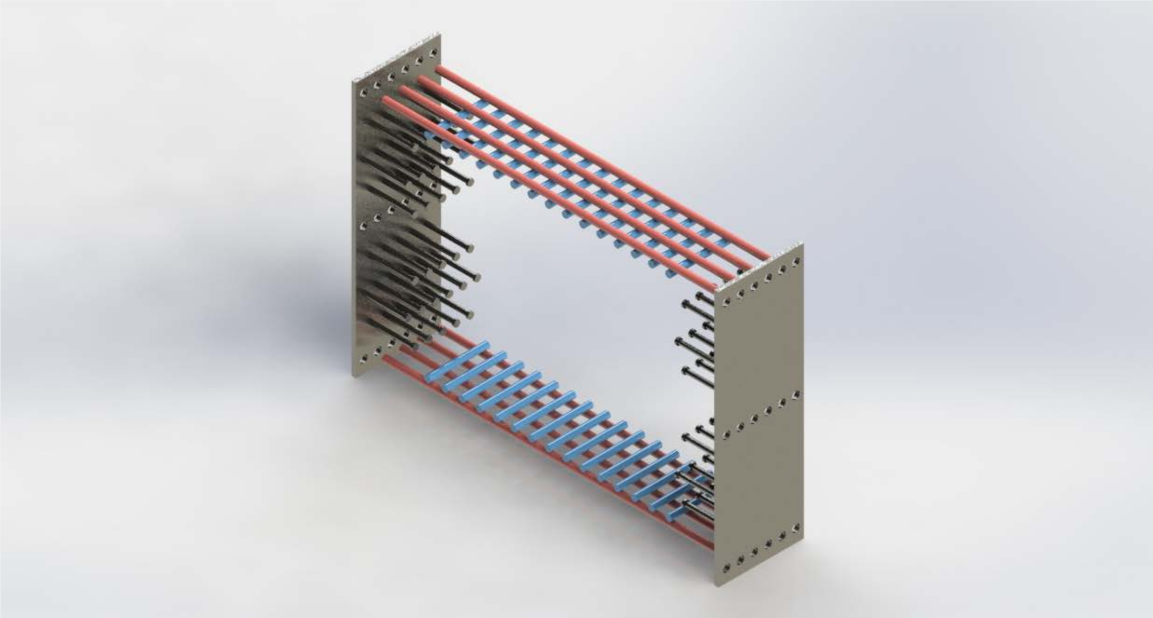


AXIAL AND CIRCUMFERENTIAL REINFORCEMENT IN PROTOTYPE

SHEAR SPECIMEN



REINFORCEMENT



Circumferential reinforcement ratio selection				
Sample Dimensions (in^2)		Lyy	30	Concrete Area, (in^2)
		Lxx	42	1260
Bar Number	Steel area per bar A_{bar} (in)	Reinforcement ratio, ρ	Required steel area, A_s (in^2)	Number of bars required per layer
5	0.31	0.2%	2.52	9
		0.5%	6.30	21
		1.0%	12.60	41
6	0.44	0.2%	2.52	6
		0.5%	6.30	15
		1.0%	12.60	29
7	0.6	0.2%	2.52	5
		0.5%	6.30	11
		1.0%	12.60	21
8	0.79	0.2%	2.52	4
		0.5%	6.30	8
		1.0%	12.60	16

Axial reinforcement ratio selection				
Sample Dimensions (in^2)		Lzz	10	Concrete Area (in^2)
		Lyy	30	300
Bar Number	Steel area per bar, A_{bar} (in)	Reinforcement ratio, ρ	Required steel area, A_s (in^2)	Number of bars required per layer
4	0.2	0.2%	0.6	3
		0.5%	1.5	8
		1.0%	3	15
5	0.31	0.2%	0.6	2
		0.5%	1.5	5
		1.0%	3	10
6	0.44	0.2%	0.6	2
		0.5%	1.5	4
		1.0%	3	7
7	0.6	0.2%	0.6	1
		0.5%	1.5	3
		1.0%	3	5

(All dimensions in inches)	Bar Number	Bar Diameter	Bar Length	Number of bars per layer	Bar spacing (center to center)	ρ_{actual}	Total bars required
Circumferential Reinforcement	7	0.875	8	11	2.813	0.52%	242
Axial Reinforcement	6	0.75	42	4	2.083	0.59%	88

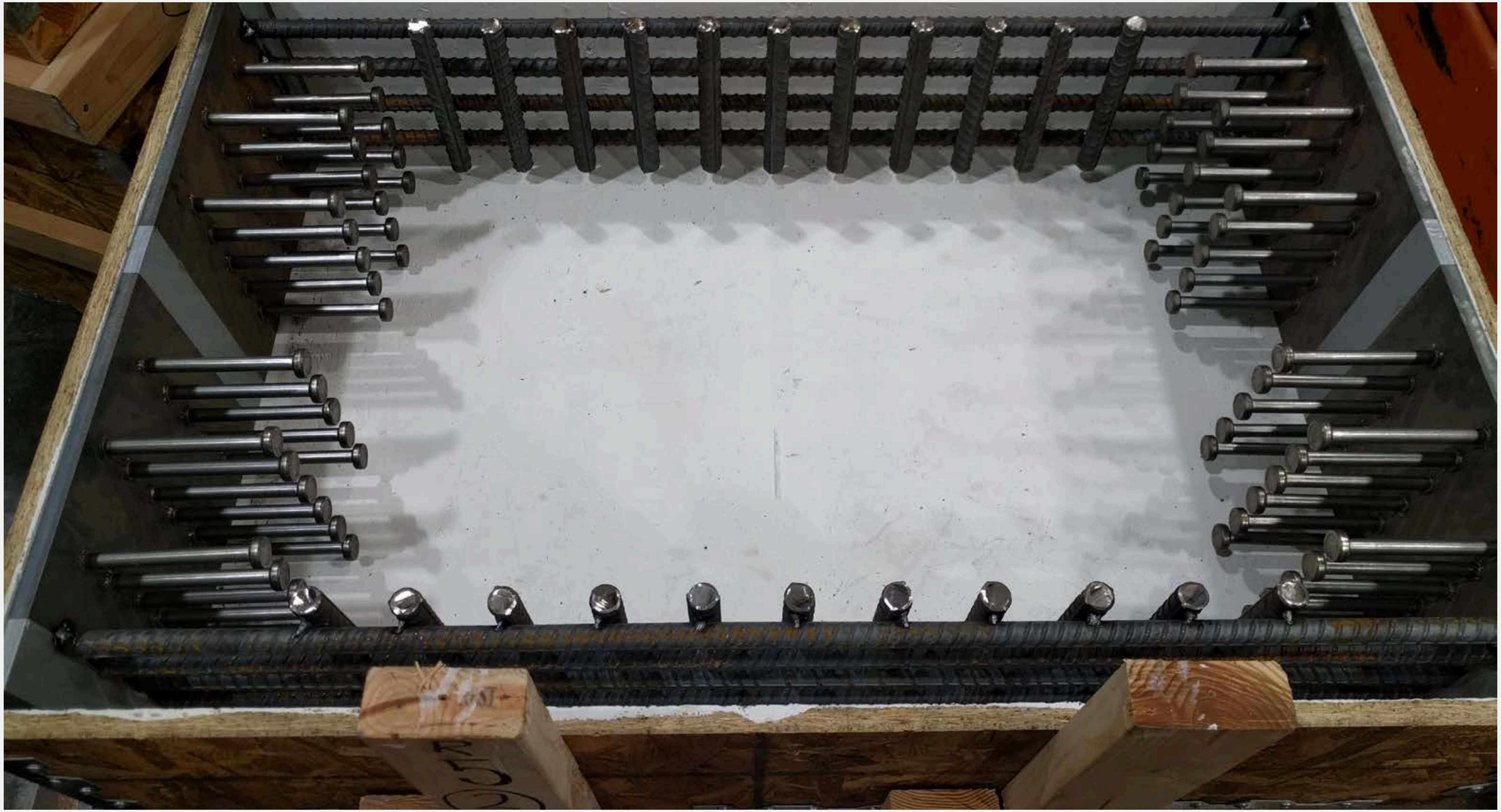
- Development Length is a problem
- Standard hooks exceed specimen dimensions
  - #7 Hook length = 10.5”
  - #7 Bend diameter = 7”
- Other anchorage options also too large
- Decision: weld bars to one another and to end plates
  - Permits axial bars to provide aid development for circumferential
  - Disadvantage: weakens rebar by an unknown amount

CONSTRUCTING ALIGNMENT JIG

REBAR SAW-CUT AND GROUND TO FINAL SIZE

USING JIG TO ALIGN REBAR

COMPLETED REBAR CAGES



FORMWORK

- Small number of reusable forms using more-expensive *Plyform?*
- Larger number of single-use forms using less-expensive OSB?
- Tight casting schedule mandated single-use forms
- Trial run with dummy form suggested considerable water absorption
- Mitigated by painting forms with primer

FORMWORK DESIGN

PAINTED INTERIOR TO MINIMIZE WATER LOSS TO FORM

CASTING PLAN

- Number and types of specimens
- Large volume of concrete requires 4 castings
- Casting to take place at Fall Line laboratory
- April 25th and 27th
- Specimens permitted to cure 24 hours before transport to CU

Reactive Specimens	Number	Volume (yd^3)
Shear specimens with rebar	9	2.43
Shear specimens without rebar	3	0.81
Wedge splitting test	3	0.02
Cylinder, 4”x8”	36	0.08
Cylinder, 6”x12”	12	0.09
Blocks without rebar	6	0.35
Blocks with rebar	3	0.18
Prism 4”x4”x12”	6	0.06
Wastage factor	15.0%	
Total	4.54	

Non-Reactive Specimens	Number	Volume (yd^3)
Shear specimens with rebar	2	0.54
Shear specimens without rebar	2	0.54
Wedge splitting test	3	0.02
Cylinder, 4”x8”	12	0.03
Cylinder, 6”x12”	4	0.03
Blocks without rebar	3	0.18
Blocks with rebar	3	0.18
Prism 4”x4”x10”	3	0.03
Wastage factor	15.0%	
Total	1.73	

Grand Total (yd^3)	6.27

THREE-CUBIC YARD MIXER AT FALL LINE

MOBILE BATCH PLANT

MATERIAL SUPPLY

- Received sufficient aggregates February 1st, 2016
- Aggregates tested and stored at Fall Line
- Aggregates donated by Whitewater Building Materials
- Transportation donated by Brady Trucking
- Cement donated by Holcim of Hagerstown, MD
- Lithium nitrate donated by Grace Concrete Products

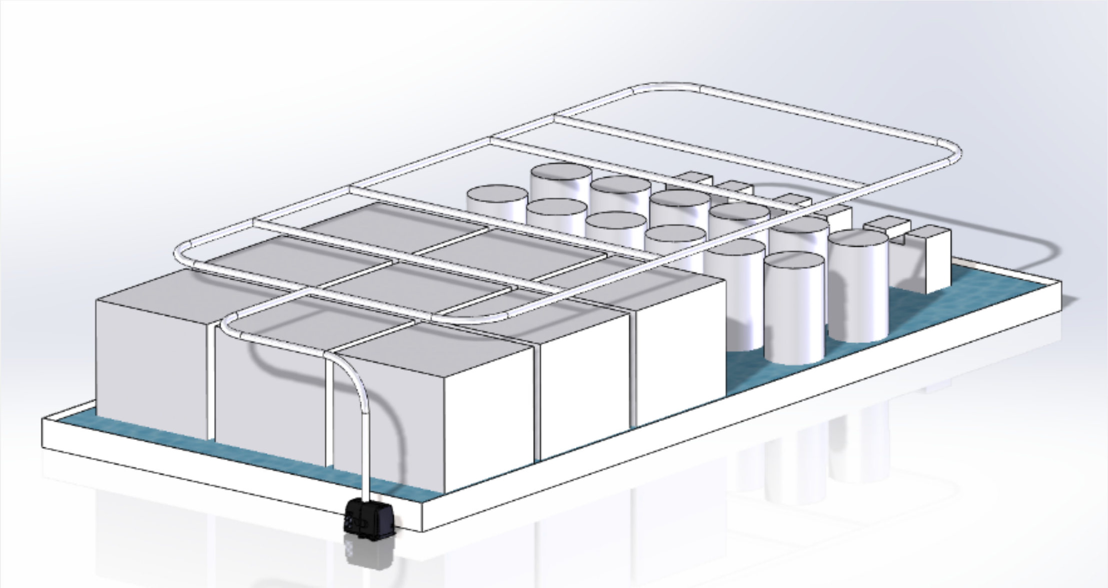
Material	lbs	kg
Portland Cement, Type 1, Holcim	4,200	2,500
Fine Aggregate: Manufactured Sand	10,100	6,100
Coarse Aggregate: 3/4" Crushed Rock	8,600	5,300
Admixtures		Unit
NaOH(s) Doping Additive (kg)		12.2
Lithium Nitrate Additive (L)		34.5

OFFLOADING AGGREGATE

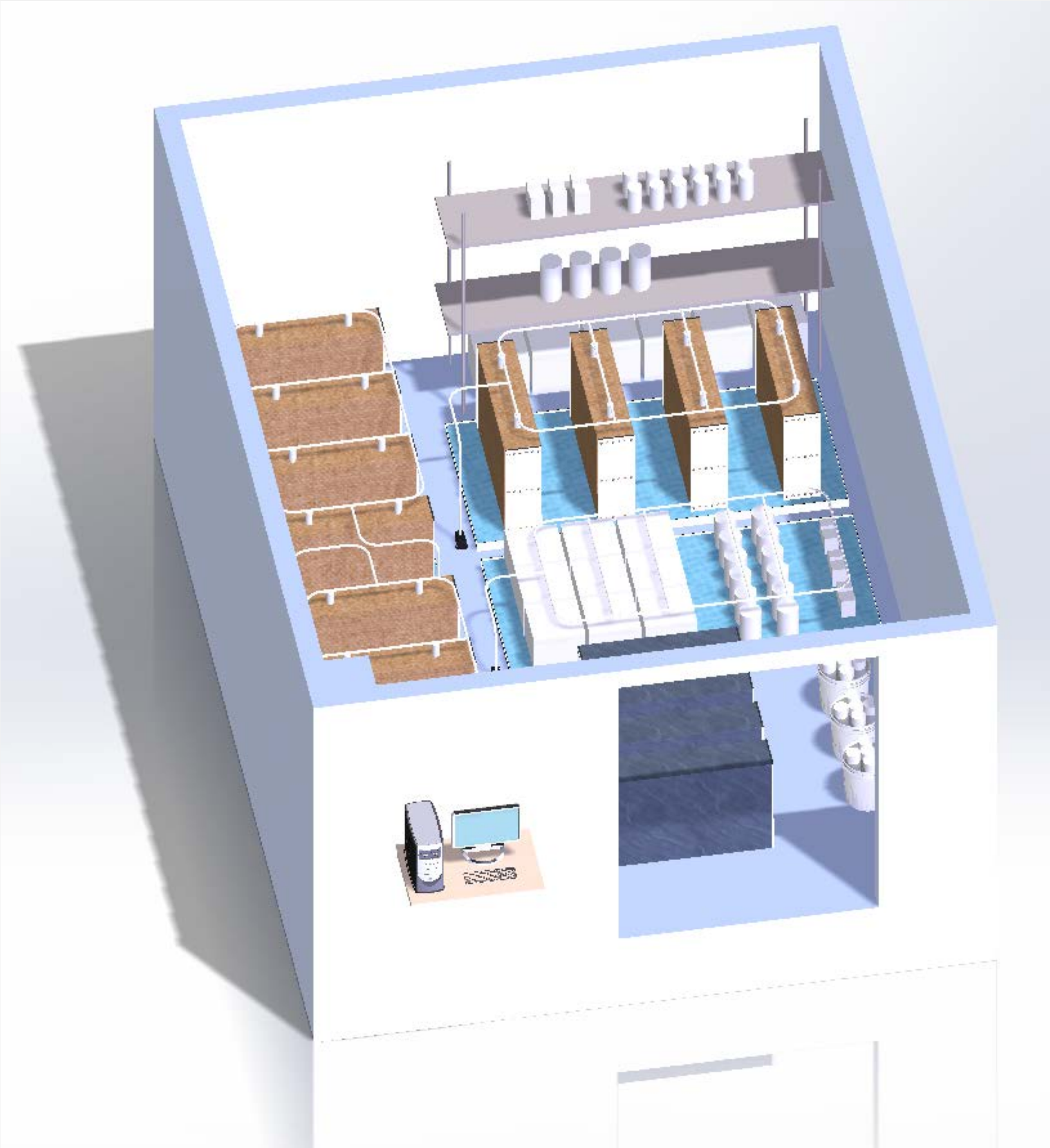
AGGREGATES TESTED, CONDITIONED, MIXED & COVERED UNTIL USE

ASR DEVELOPMENT CONDITIONS

1. Objective is to maximize expansion in limited time available for sample curing (approximately 6 months)
2. High temperatures promote rapid expansion
3. High alkalinity wash prevents alkali leaching
4. High relative humidity prevents loss of alkali wash and shrinkage due to dessication



TEMPERATURE = 38°C
HUMIDITY > 90%
ALKALI WASH WITH 1.6M $NaOH_{(aq)}$



IDENTIFICATION OF REACTIVE AGGREGATES

AGGREGATE SUPPLIERS

- Aggregates from two suppliers tested
- Both draw material from quarries along Gunnison River
- Tested manufactured sand, 3/8” gravel, and 3/4” gravel
- Whitewater Building Materials
- Grand Junction Ready-Mix
- Samples obtained January 21st 2015
- Primary test ASTM 1567

WHITEWATER BUILDING MATERIALS

GRAND JUNCTION READY MIX

From left: 3/4" rock, 3/8" rock, and sand from Grand Junction Ready-Mix

From left: 3/4" rock, 3/8" rock, and sand from Whitewater Building Materials

OVERVIEW OF ASTM 1567

- Widely accepted test for ASR reactivity of aggregates
- Accelerated mortar bar test
- Provides results in 16 days
- Classifies aggregates as ‘Reactive’ or ‘Nonreactive’

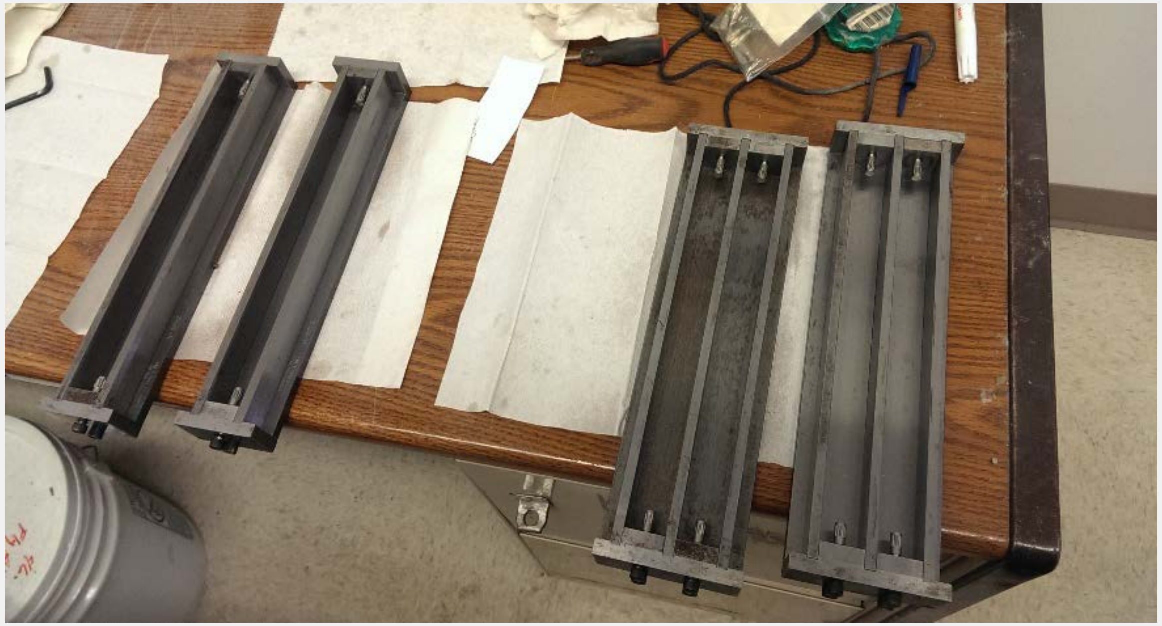
COARSE AGGREGATES ARE CRUSHED

MORTAR MIXED FROM PRESCRIBED GRADATION

SIEVED FRACTIONS ARE WASHED

DRIED IN OVEN BEFORE WEIGHING

MORTAR BARS ARE 1”X1”X10”



COMPONENT WEIGHTS AND MIXING TIMES AS PRESCRIBED

MORTAR TAMPED INTO MOLDS

INITIAL CURE 24 HOURS, COVERED IN FOG ROOM

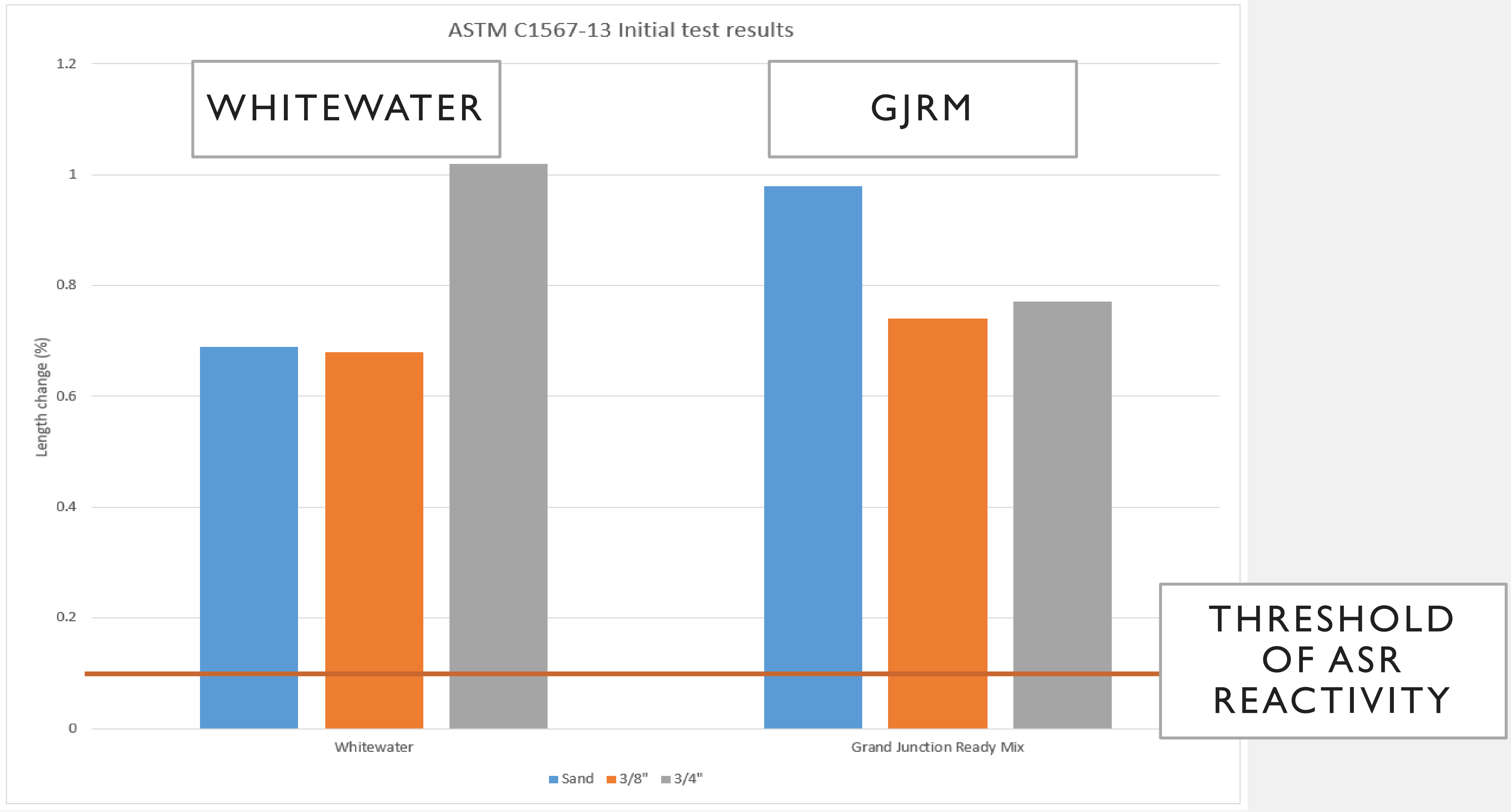
INITIAL READINGS TAKEN WITH LENGTH COMPAROMETER

BARS STORED IN WATER FOR 24 HOURS AT 80°C, THEN ZERO MEASUREMENT TAKEN

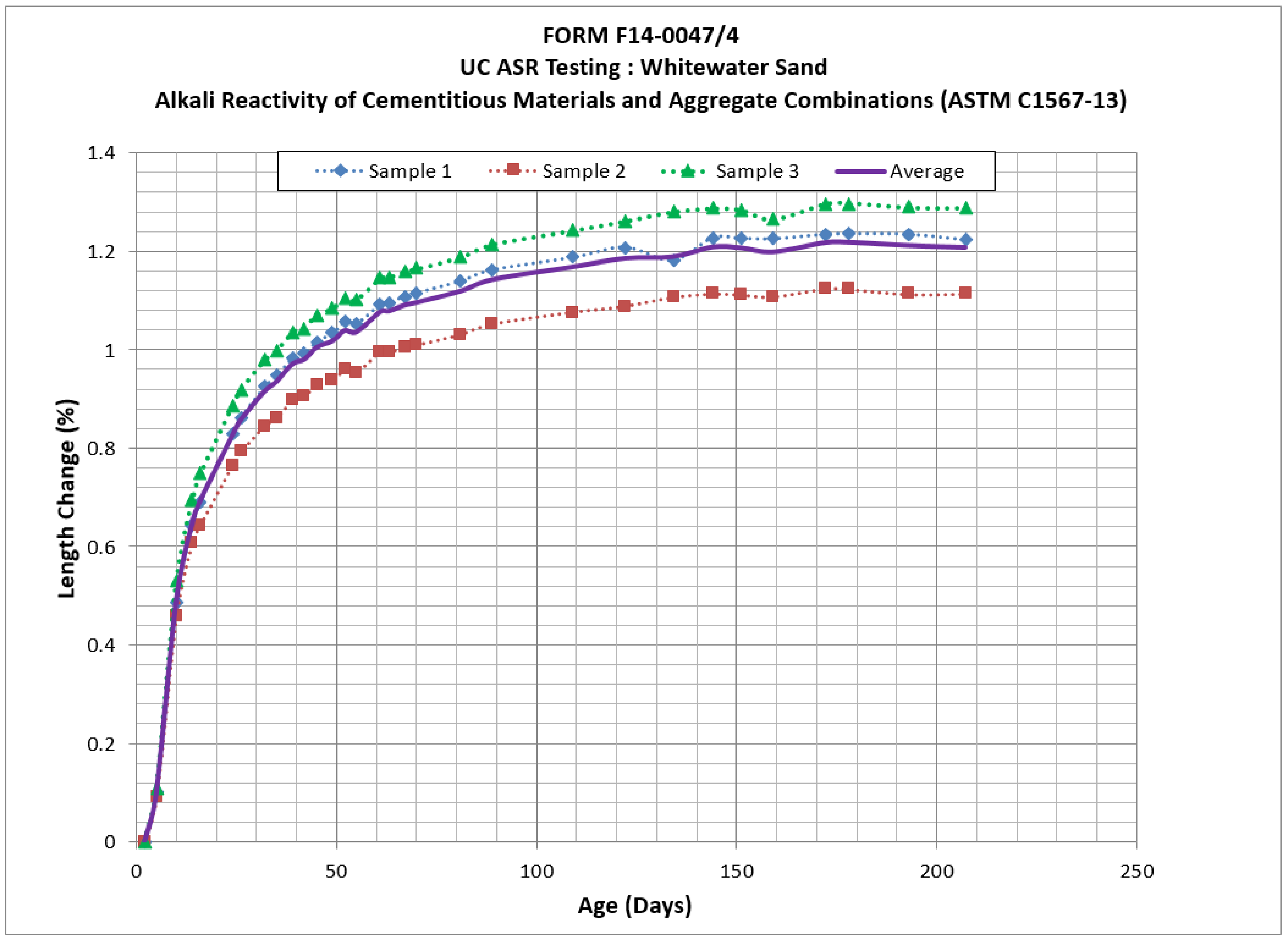
PLACED IN 1M NaOH AND RETURNED TO OVEN

TEST RESULTS

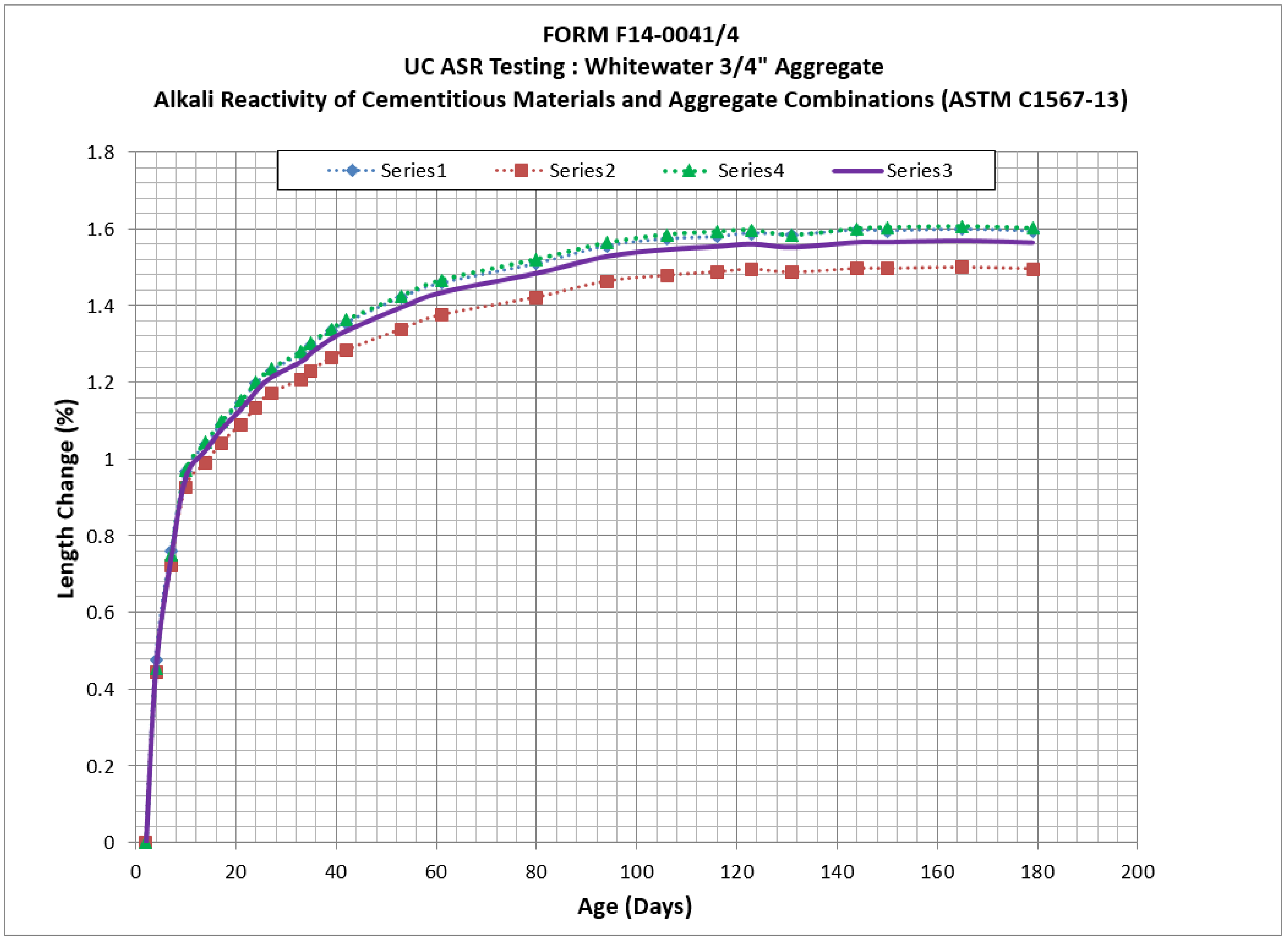
- Subsequent measurements taken every 4 days
- Final reading taken 16 days after casting
- All aggregates exceed 0.1% threshold for ASR reactivity


ASTM C1567-13 Initial test results
1.2
1
0.8
0.6
0.4
0.2
0
Length change (%)
WHITEWATER
GJRM
THRESHOLD OF ASR REACTIVITY
Whitewater
Grand Junction Ready Mix
Sand
3/8"
3/4"

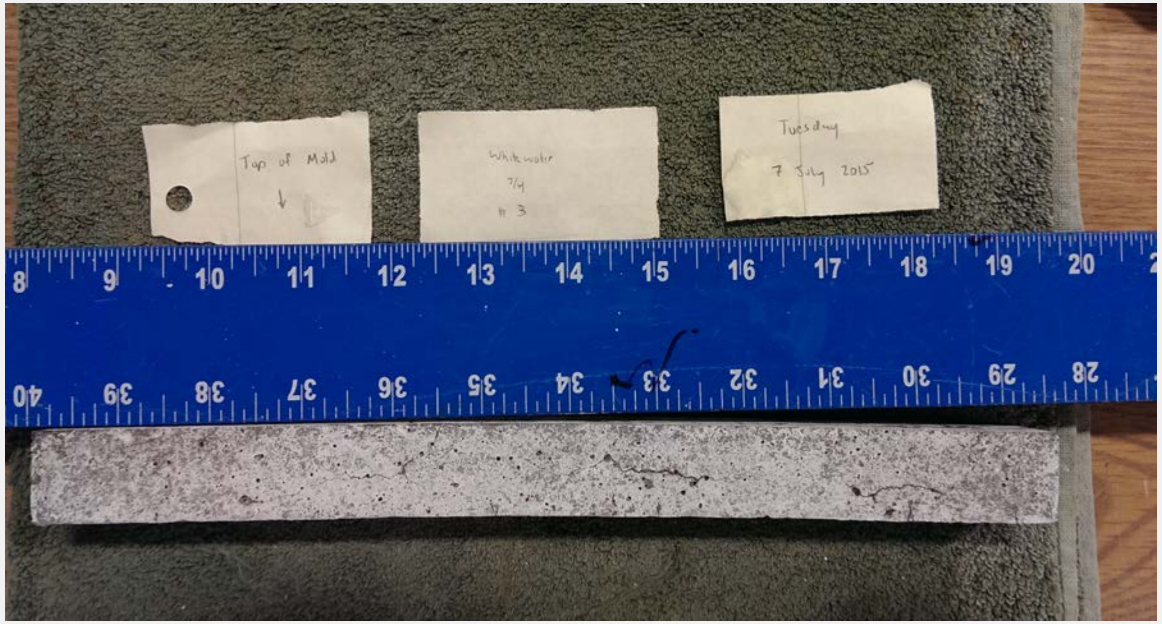
Percent expansion, 16 days after casting		
	Whitewater Building Materials	Grand Junction Ready Mix
Sand	0.69	0.98
3/8"	0.68	0.74
3/4"	1.02	0.77
Average	0.80	0.83


FORM F14-0047/4
UC ASR Testing : Whitewater Sand
Alkali Reactivity of Cementitious Materials and Aggregate Combinations (ASTM C1567-13)
Sample 1
Sample 2
Sample 3
Average
Length Change (%)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
50
100
150
200
250
Age (Days)

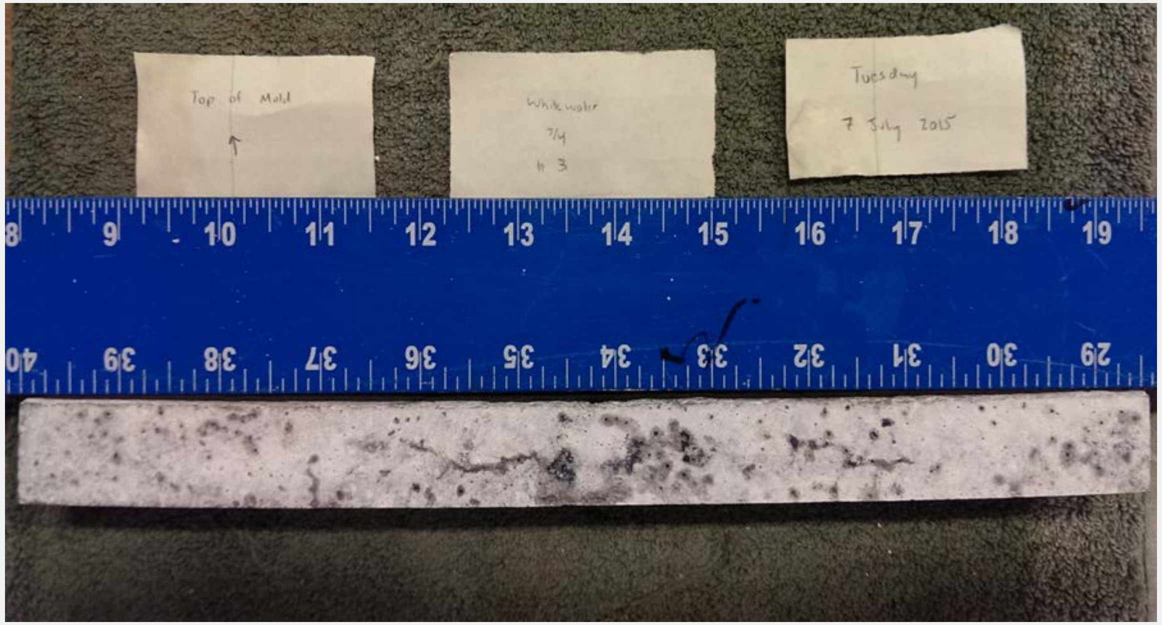
ASTM 1567 TEST RESULTS



MORTAR BARS EXTENSIVELY CRACKED & DEFORMED (IMAGE TAKEN 131 DAYS AFTER CASTING, ε=1.4%



CURVATURE ALWAYS CONCAVE UP TOWARD TOP OF MOLD



CONCLUSION

- Whitewater sand and 3/4” gravel selected for further study
- Highly reactive
- Supplier eager to participate in study

CONCRETE TESTING PROGRAM

AGGREGATE TESTS

- Tests performed on all aggregate samples upon receipt
- Reliance on standardized ASTM test procedures

Test	Standard
Coarse aggregate relative density	ASTM C127
Fine aggregate relative density	ASTM C128
Coarse aggregate bulk density	ASTM C29
Fineness modulus / gradation	ASTM C136
Moisture content	ASTM C566

AFTER SOAKING 24HRS, AGGREGATE DRIED TO SSD WEIGHED AT SSD AND IMMERSED

Whitewater 3/4 Specific Gravity	
Oven Dry Bulk Specific Gravity	2.604
SSD Bulk Specific Gravity	2.641
Apparent Bulk Specific Gravity	2.705
Absorption (%)	1.433

SAND BROUGHT TO SSD, INDICATED BY CONE MOLD

SAND PLACED IN VOLUMETRIC FLASK AND DE-AIRED; WEIGHED WITH AND WITHOUT SAND

Whitewater Sand Specific Gravity	
Oven Dry Bulk Specific Gravity	2.583
SSD Bulk Specific Gravity	2.623
Apparent Bulk Specific Gravity	2.690
Absorption (%)	1.551

COARSE AGGREGATE LOADED INTO MEASURE IN THREE LIFTS, EACH RODDED 25 TIMES

Whitewater 3/4" Bulk Density	
Bulk Specific Gravity	2.641
Bulk Density (pcf)	100.9
Void (%)	39%

AGGREGATE IS WASHED AND DECANTED, THEN OVEN-DRIED

AFTER SIEVING, EACH FRACTION IS WEIGHED

Whitewater Sand Sieve Analysis		
Sieve Size	Percent Retained	Percent Passing
3/8"	0.0	100.0
#4	2.8	97.2
#8	15.3	84.7
#16	31.0	69.0
#30	40.6	59.4
#50	67.8	32.2
#100	91.1	8.9
#200	98.3	1.7
Fineness Modulus		2.5

Whitewater 3/4 Sieve Analysis		
Sieve Size	Percent Retained	Percent Passing
1"	0.0	100.0
3/4"	6.0	94.0
1/2"	56.4	43.6
3/8"	77.8	22.2
#4	97.9	2.1

CONCRETE TESTS

- Tests performed on all concrete test mixes
- Reliance on standardized ASTM test procedures where possible

Test	Standard
Slump	ASTM C173
Unit Weight	ASTM C138
Air Content	ASTM C231
Temperature	ASTM C1064
Compressive Strength	ASTM C39
ASR Expansion	N/A

SLUMP MOLD FILLED IN 3 LAYERS, EACH TAMPED 25 TIMES

MOLD LIFTED IN ONE MOTION; SLUMP MEASURED FROM TOP OF CONE

AIR METER BOWL FILLED IN TWO LAYERS, EACH RODDED 25 TIMES

BOWL TAPPED 10-15 TIMES WITH MALLET AND STRUCK OFF

AFTER WEIGHING BOWL, AIR METER INSTALLED

WATER ADDED TO WEEP HOLE; METER TILTED AND ROLLED TO EXPEL ENTRAPPED AIR INTO GAUGE

4"X8" CYLINDER MOLDS;
FILLED IN 2 LIFTS;
EACH LIFT RODDED 25 TIMES

CYLINDERS ALLOWED TO REST 30 MINUTES TO CHECK FOR BLEEDING

UNBONDED CAPS USED FOR ALL BUT MIX 1, WHICH USED SULFUR

ASR EXPANSION TEST

- ASTM C1293 provides results after 1-2 years
- Test modified as follows
- For each candidate concrete mix, two curing conditions used
  - Accelerated conditions: 80°C, immersed in 1M NaOH
  - Unaccelerated conditions: 21°C, uncovered in fog room at >90% RH
  - 4 total prisms cast: 2 accelerated & 2 unaccelerated

4"X4"X10" STEEL MOLDS
FILLED IN 2 LAYERS
EACH RODDED 25 TIMES

CURED 24 HOURS, COVERED

AFTER DEMOLDING, INITIAL READING TAKEN

FOR UNACCELERATED PRISMS, THIS IS THE ZERO READING

ACCELERATED PRISMS IMMERSED IN WATER AND PLACED IN 80° OVEN

AFTER 24 HOURS IN HOT WATER, ZERO READING OF ACCELERATED PRISMS TAKEN

ACCELERATED PRISMS PLACED IN HOT 1M NaOH AND RETURNED TO OVEN

CONCRETE MIX DESIGN

OBJECTIVES

- Aggressively reactive
- Sufficient workability for producing shear specimens
- No attempt made to match prototype concrete
- Reasonably representative of a construction material
- No admixtures
  - Except NaOH to boost alkalinity
  - Except $LiNO_3$ to produce control specimens

Compressive Strength	4,500 psi	31.0 MPa
Slump	4.5-6.5 in	11-14 cm
Expansion	0.5%	
Air Content	Less than 3%	

MIX DESIGN 1

- Designed following ACI 211.1, Chapter 6
- No modification to ACI-recommended design
- Test batch produced June 11th, 2015
- Tested (as are all mixes) according to program above

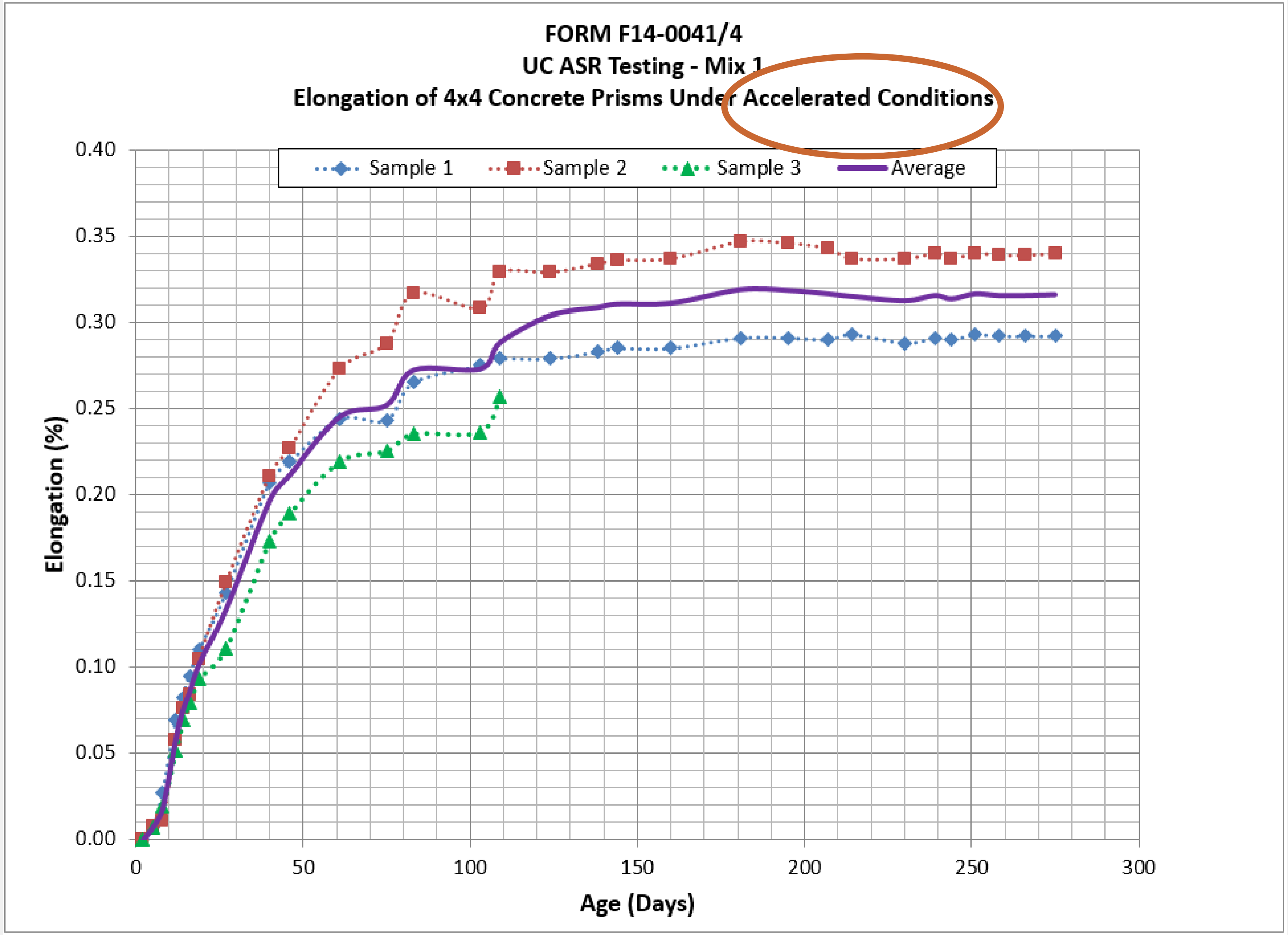
Estimate Concrete Mix Using ACI 211.1 Chapter 6			
Step 1: Choice of slump	Ref Table 6.3.1		
	Slump =	5	in
Step 2: Choice of maximum aggregate size	Clear spacing =	1.5	in
	Max CA size = 0.75*(Clear spacing)	1.125	in
	Available CA size =	0.75	in
Step 3: Estimate water and air	Ref Table 6.3.3		
	28-Day compressive strength	4000	lbs/in^2
	Water =	350	lbs/yd^3
	air =	1%	
Step 4: Select w/c ratio	Ref Table 6.3.4(a)		
	w/c =	0.57	
Step 5: Calculate cement content	Cement = Water / (w/c)	614	lbs/yd^3

Step 6: Estimate coarse aggregate content	oven dry-rodded unit wt of CA =	100.9	lbs/ft3
	Fineness modulus of FA =	2.5	ft^3
	Ref Table 6.3.6		
	Vol CA per unit vol concrete =	0.65	
	Vol CA per yd^3 = (Vca/unit)*27	17.6	ft^3/yd^3
	CA = (Vca/yd^3)*(unit wt CA)	1771	lbs/yd^3
Step 7: Estimate fine aggregate content (6.3.7.1)	Ref Table 6.3.7.1		
	Weight of concrete =	3960	lbs/yd^3
	FA =(Weight concrete) - W - C - CA	1225	lbs/yd^3

Refine FA by Volume Method (6.3.7.2)	Vwater = W / 62.4	5.61	ft^3/yd
	specific gravity of cement =	3.15	
	Vcement = C / (s.g. C * 62.4)	3.12	ft^3/yd
	specific gravity of CA =	2.641	
	Vca = CA / (s.g. CA * 62.4)	10.7	ft^3/yd
	Air (~1%) = .01*27	0.27	ft^3/yd
	Vw + Vc + Vca + Vair	19.7	ft^3/yd
	Vfa = 27 – (Vw + Vc + Vca + Vair)	7.3	ft^3/yd
	Specific gravity of FA =	2.623	
	FA = (Vfa * s.g. FA*62.4)	1187	lbs/yd

Material	lbs/yd3	kg/m3
Portland Cement, Type I/II, (0.53% Na_2O)	614	365
Fine Aggregate: Manufactured Sand	1187	705
Coarse Aggregate: 3/4" Crushed Rock	1771	1052
Water	350	208
w/c	0.57	0.57

Concrete Test Results : Mix 1	
Temperature of freshly-mixed concrete (°F)	77
Ambient temperature (°F)	75
Slump (in)	6.25
Air Content (%)	0.7%
Unit Weight (lbs/ft^3)	147.6
Compressive strength (8 days)	4170
Compressive strength (28 days)	4430


FORM F14-0041/4
UC ASR Testing - Mix 1
Elongation of 4x4 Concrete Prisms Under Accelerated Conditions
Sample 1
Sample 2
Sample 3
Average
Elongation (%)
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
50
100
150
200
250
300
Age (Days)

MIX 1 CONCLUSION

Curing Conditions	Elongation	Age
80°C, 1M NaOH	0.247%	65 days

- Mechanical properties acceptable
- ASR expansion fails to meet goal

MIX DESIGN 2, REACTIVE

- Attempt to increase expansion
- Used higher-alkalinity cement (0.91% as Na_2o)
  - Cement provided by Holcim of Maryland
- Added $NaOH_{(s)}$ to boost alkalinity to 1.25% as Na_2O

ALKALI DOPING CALCULATION

$$Alkali_{cement} = \frac{measured\ alkali\ \%}{100} W_c$$

$$Alkali_{required} = \frac{desired\ alkali\ \%}{100} W_c$$

$$Alkali_{additional} = (Alkali_{cement}) - (Alkali_{required})$$

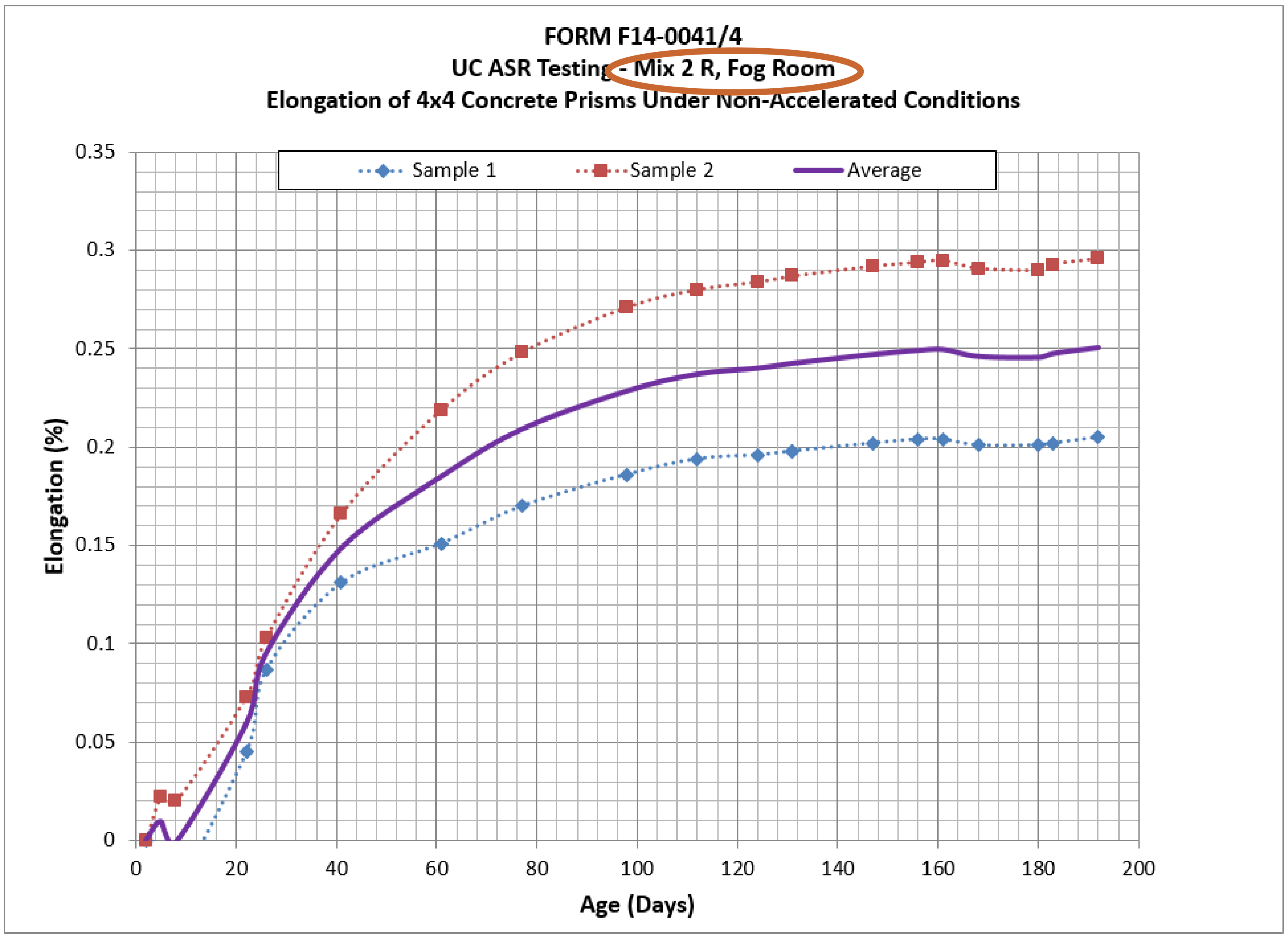
$$Na_2O_{(s)} + H_2O_{(l)} \rightarrow 2NaOH_{(aq)}$$

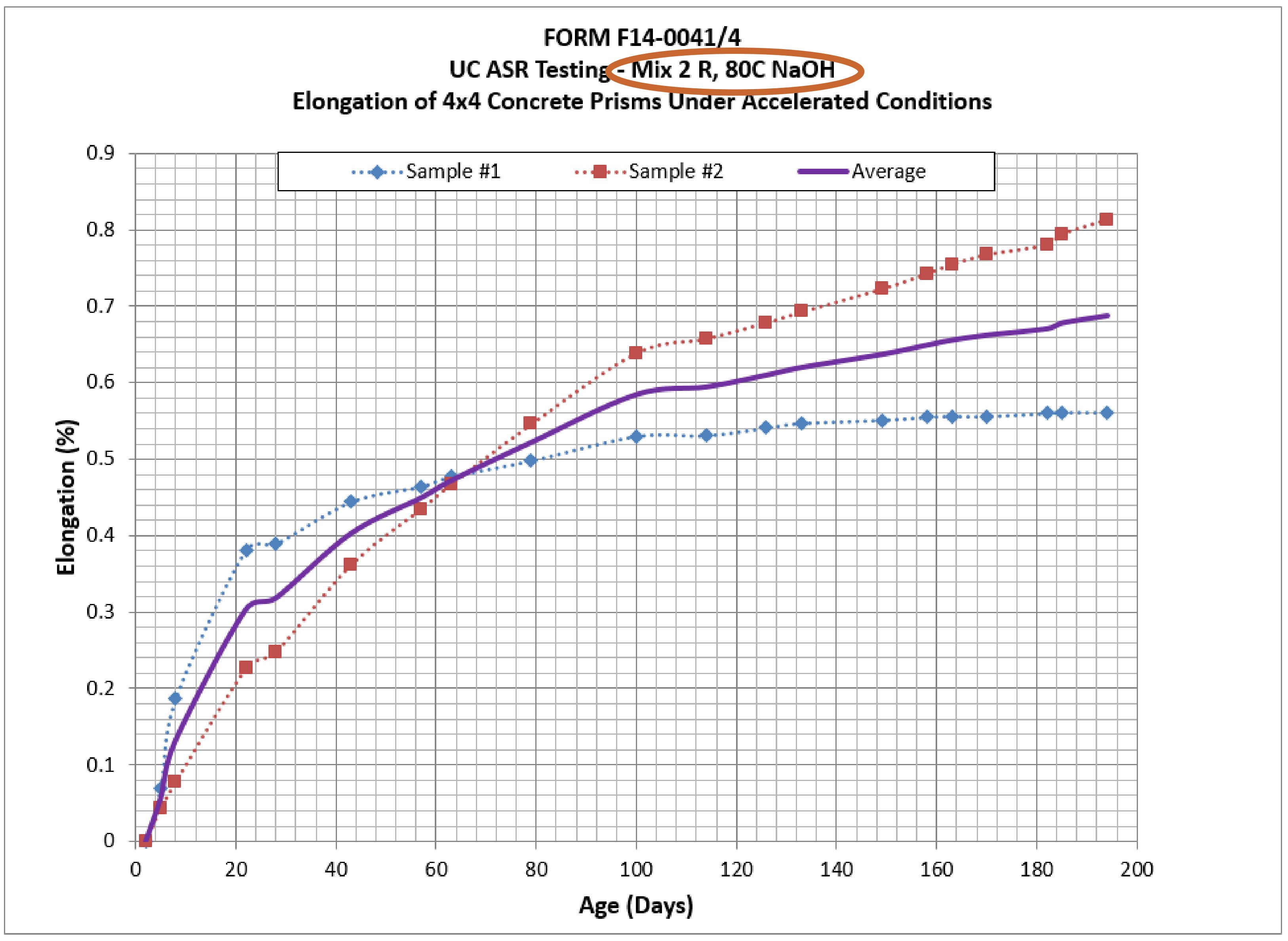
$$\left(\frac{2\ mol\ NaOH}{1\ mol\ Na_2O}\right)\left(\frac{1\ mol\ Na_2O}{61.98\ g\ Na_2O}\right)\left(\frac{39.997\ g\ NaOH}{1\ mol\ NaOH}\right) = 1.291\left(\frac{NaOH}{g\ Na_2O}\right)$$

$$NaOH_{additional} = (1.291)Alkali_{additional}$$

Material	lbs/yd^3	kg/m^3
Portland Cement, Type I/II, (0.91% as Na_2O)	614	365
Fine Aggregate: Manufactured Sand	1,205	716
Coarse Aggregate: 3/4" Crushed Rock	1,753	1,041
Water	350	208
w/c	0.57	0.57
Admixtures	**kg/yd^3**	**kg/m^3**
NaOH(s) Doping Additive (1.25% as Na_2O)	1.22	1.6

Concrete Test Results : Mix 2R	
Temperature of freshly-mixed concrete (°F)	83.4
Ambient temperature (°F)	78.2
Slump (in)	8.3
Air Content (%)	2.1%
Unit Weight (lbs/ft^3)	145.7
Compressive strength (8 days)	3920
Compressive strength (28 days)	4760


FORM F14-0041/4
UC ASR Testing - Mix 2 R, Fog Room
Elongation of 4x4 Concrete Prisms Under Non-Accelerated Conditions
Sample 1
Sample 2
Average
Elongation (%)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0
20
40
60
80
100
120
140
160
180
200
Age (Days)


FORM F14-0041/4
UC ASR Testing - Mix 2 R, 80C NaOH
Elongation of 4x4 Concrete Prisms Under Accelerated Conditions
Sample #1
Sample #2
Average
Elongation (%)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
120
140
160
180
200
Age (Days)

MIX 2R CONCLUSION

Curing Conditions	Elongation	Age
80°C, 1M NaOH	0.478%	65 days
21°C, Fog Room RH > 90%	0.191%	65 days

- Mix 2R rejected on basis of slump
- ASR expansion just fails to meet goal at 65 days
- Ultimate expansion beyond target

- Unaccelerated bars were kept in hot NaOH for days before until 8 days after casting

MIX DESIGN 2, NONREACTIVE

- Evaluate effectiveness of $LiNO_3$ at controlling ASR
- Objective is similar mechanical properties to Mix 2R with negligible expansion
- If successful, will use for control concrete

$LINO_3$ DOSING CALCULATION

- GCP Rasir (30% $LiNO_3$) dose calculation

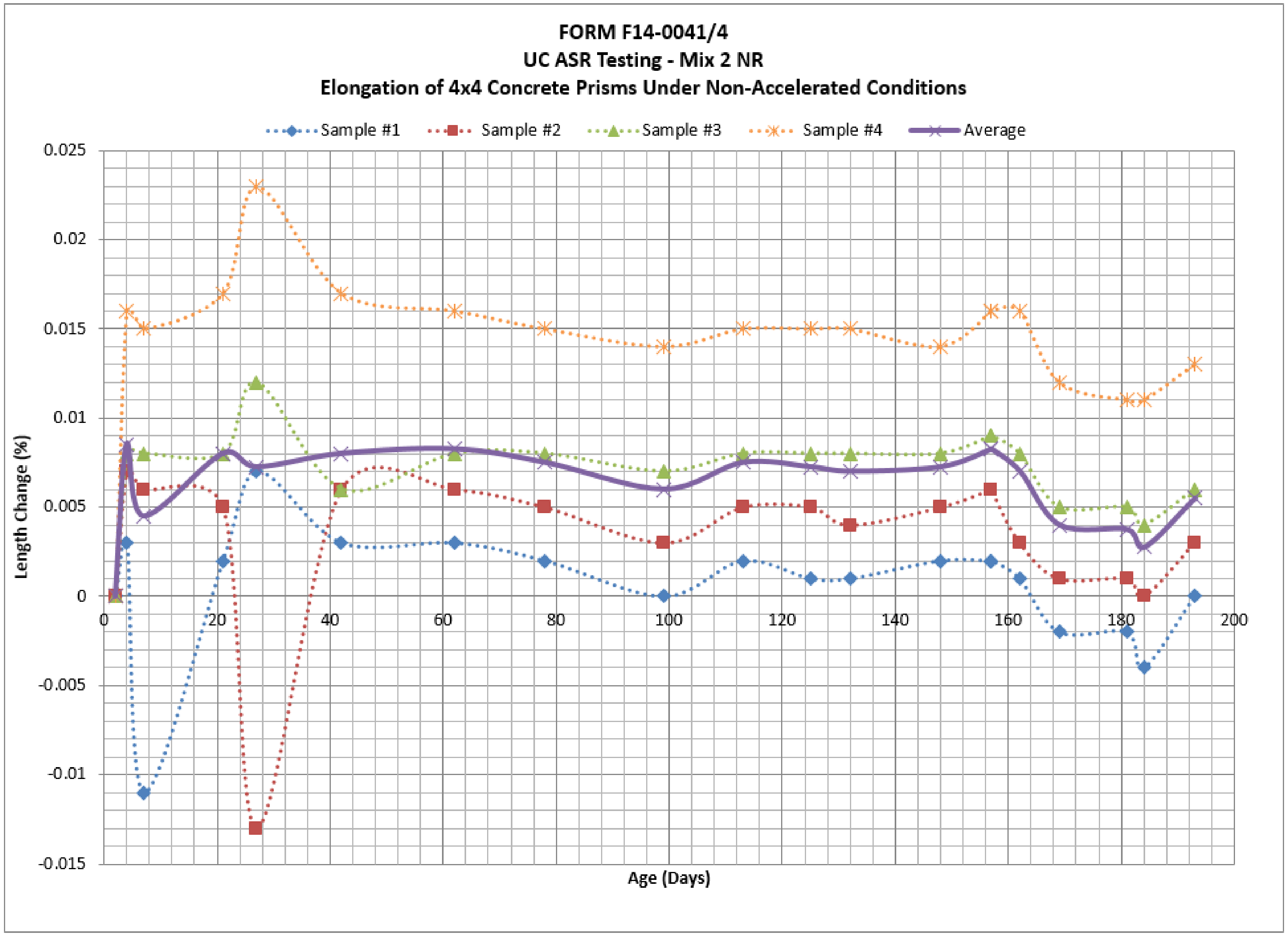
$$multiplier = 4.6\ for\ L/m^3$$

$$LiNO_3\ dose(L/m^3) = 4.6\, W_c\ \frac{Alkalinity\ \%\ of\ cement}{100}$$

$$W_{w\ reduced} = W_w - 0.84(LiNO_3\ dose)$$

Material	lbs/yd^3	kg/m^3
Portland Cement, Type I/II, (0.91% as Na_2O)	614	365
Fine Aggregate: Manufactured Sand	1,227	716
Coarse Aggregate: 3/4" Crushed Rock	1,786	1,041
Water	329	208
w/c	0.57	0.57
Admixtures	**L/yd^3**	**L/m^3**
Lithium Nitrate, 30%	11.7	15.3

Concrete Test Results : Mix 2NR	
Temperature of freshly-mixed concrete (°F)	61.6
Ambient temperature (°F)	82.1
Slump (in)	7.0
Air Content (%)	1.7%
Unit Weight (lbs/ft^3)	145.4
Compressive strength (8 days)	4,160
Compressive strength (28 days)	5,030


FORM F14-0041/4
UC ASR Testing - Mix 2 NR
Elongation of 4x4 Concrete Prisms Under Non-Accelerated Conditions
Sample #1
Sample #2
Sample #3
Sample #4
Average
Length Change (%)
0.025
0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
0
20
40
60
80
100
120
140
160
180
200
Age (Days)

MIX 2NR CONCLUSION

Curing Conditions	Elongation	Age
21°C, Fog Room RH > 90%	0.006%	65 days

- Expansion of unaccelerated specimens reduced 96.9%
- Expansion of accelerated specimens reduced 98.7%

- 28-day compressive strength increased 5.7%
- Slump reduced 15.7%

- Conclusion: $LiNO_3$ ideal for production of control

MIX DESIGN 3

- Attempt to further boost reactivity of Mix 2R by following:

1. Increase fine aggregate content to 34.5% as volume
   - Fine aggregate exposes greater surface area to alkali attack
   - Mortar bar results indicate that sand particle size large enough to avoid pessimum size effect.
2. Increase alkali even further to 1.6% as Na_2O
3. Reduce w/c to 0.50 to offset strength reduction of extra sand
4. Reduce slump slightly

Material	lbs/yd^3	kg/m^3
Portland Cement, Type I/II, (0.91% as Na_2O)	614	365
Fine Aggregate: Manufactured Sand	1,525	716
Coarse Aggregate: 3/4" Crushed Rock	1,536	1,041
Water	310	208
w/c	.50	0.57
Admixtures	**kg/yd^3**	**kg/m^3**
NaOH(s) Doping Additive (1.60% as Na_2O)	2.48	3.25

- Calculation error on testing day
- Incorrectly corrected for moisture content of aggregates

- Should have added 13 lbs of water, but only added 10 lbs

MOISTURE COMPENSATION

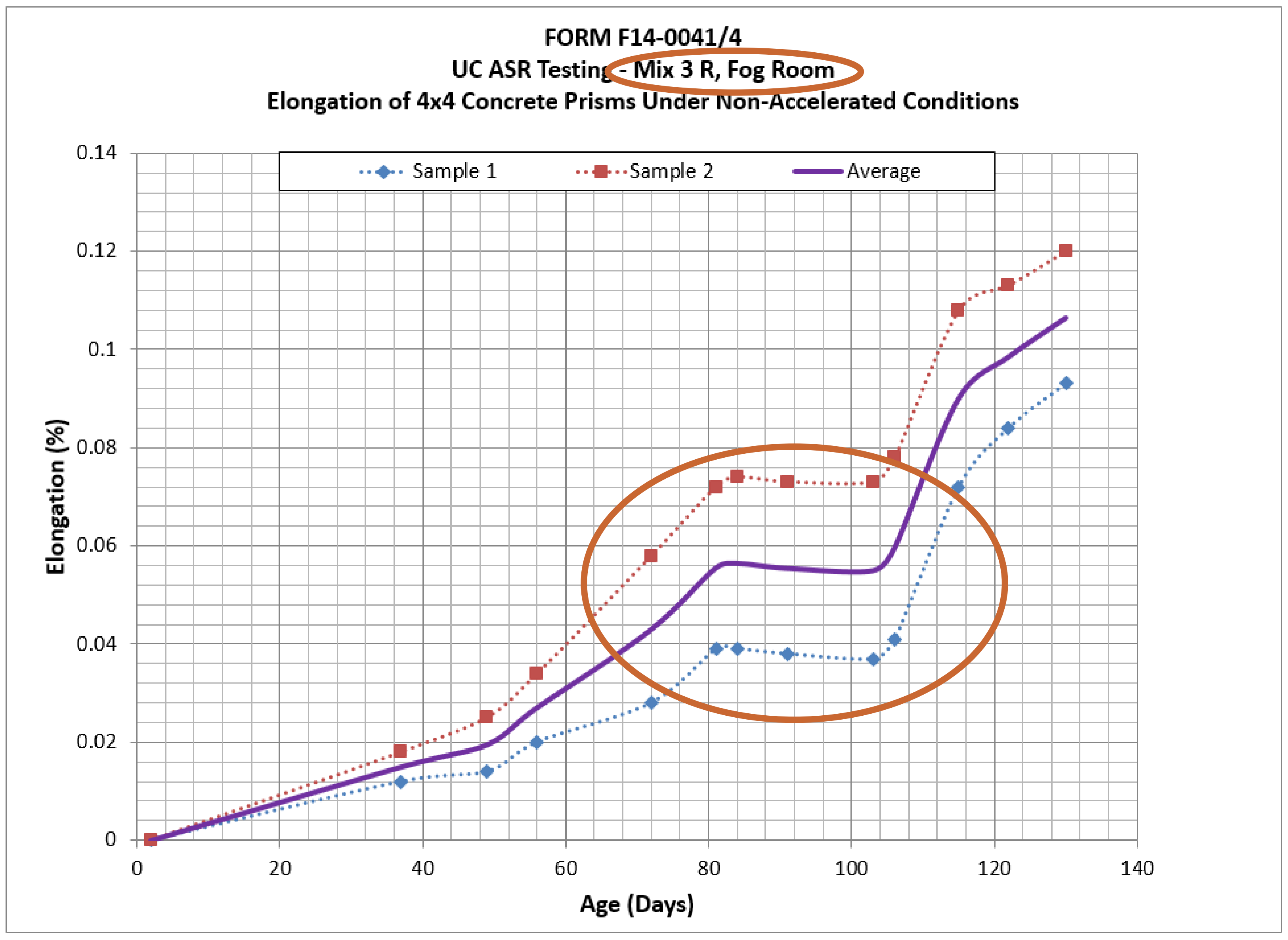
ACI 211.1 6.3.8

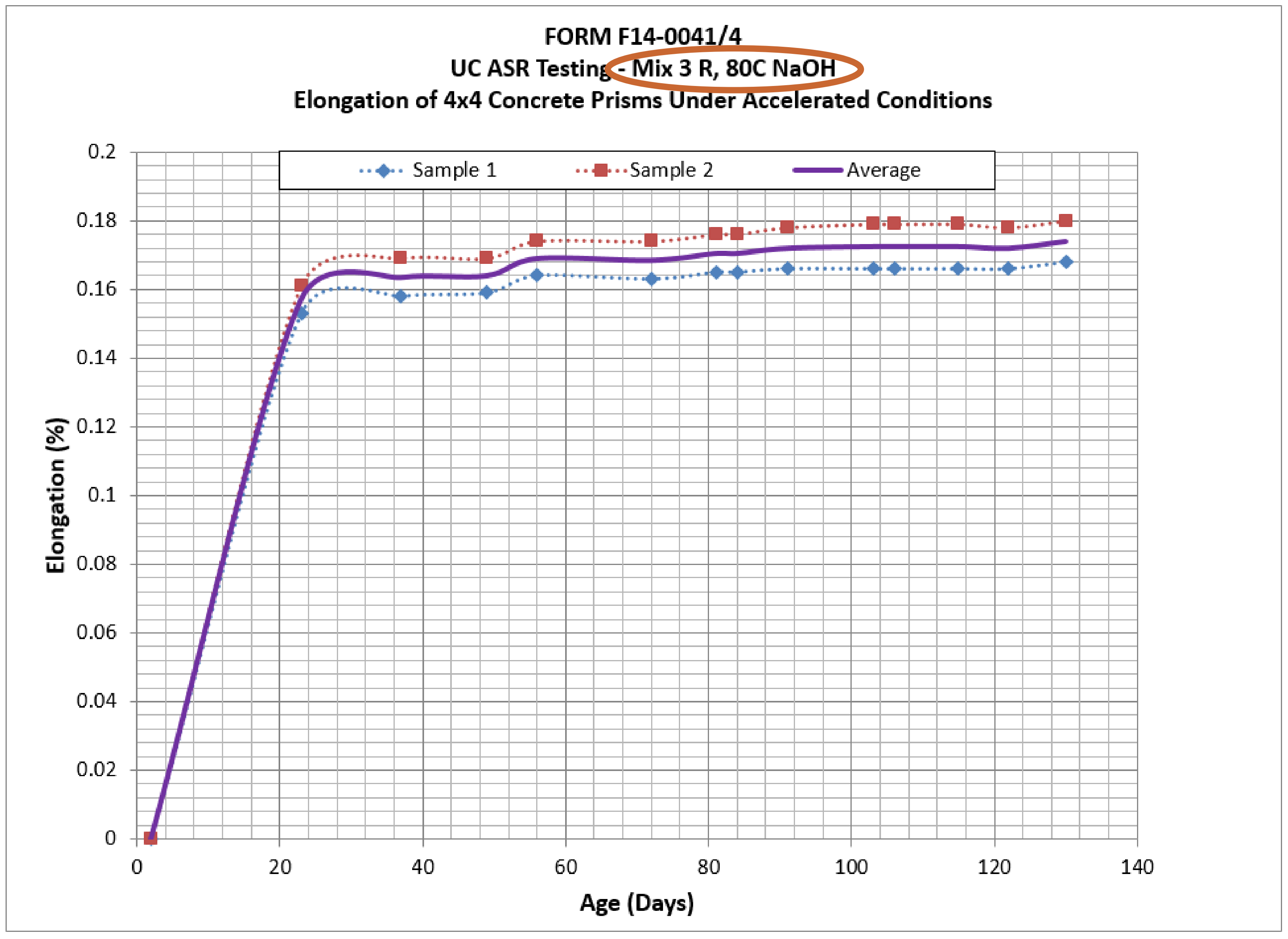
$$(Surface\ Mositure) = (Moisture\ Content) - (Absorbance)$$

$$W_{agg\ adjusted} = W_{agg\ design}(1 + SM)$$

$$W_{W\ adjusted} = W_{w\ design} - W_{FA}(SM_{FA}) - W_{CA}(SM_{CA})$$

Concrete Test Results : Mix 3	
Temperature of freshly-mixed concrete (°F)	68
Ambient temperature (°F)	65
Slump (in)	2.5
Air Content (%)	2.8%


FORM F14-0041/4
UC ASR Testing - Mix 3 R, Fog Room
Elongation of 4x4 Concrete Prisms Under Non-Accelerated Conditions
Sample 1
Sample 2
Average
Elongation (%)
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
20
40
60
80
100
120
140
Age (Days)


FORM F14-0041/4
UC ASR Testing - Mix 3 R, 80C NaOH
Elongation of 4x4 Concrete Prisms Under Accelerated Conditions
Sample 1
Sample 2
Average
Elongation (%)
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
0
20
40
60
80
100
120
140
Age (Days)

MIX 3 CONCLUSION

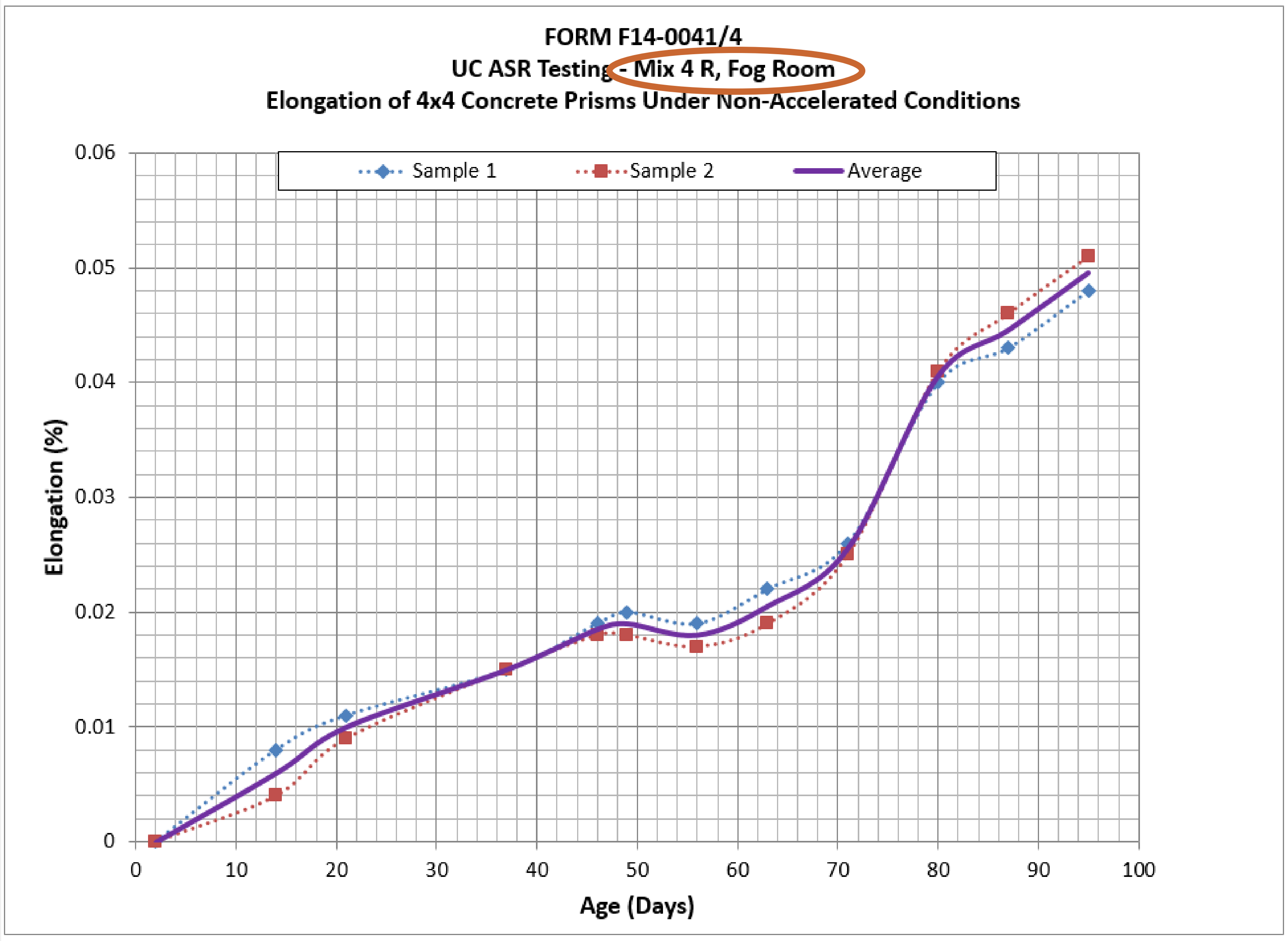
- Mix 3 must be rejected due to calculation error
- Accelerated prisms behaving unexpectedly:
  - Rapid expansion to 0.17%, then plateau
- Hydrofogger failure at Fall Line results in stalled expansion of unaccelerated prisms

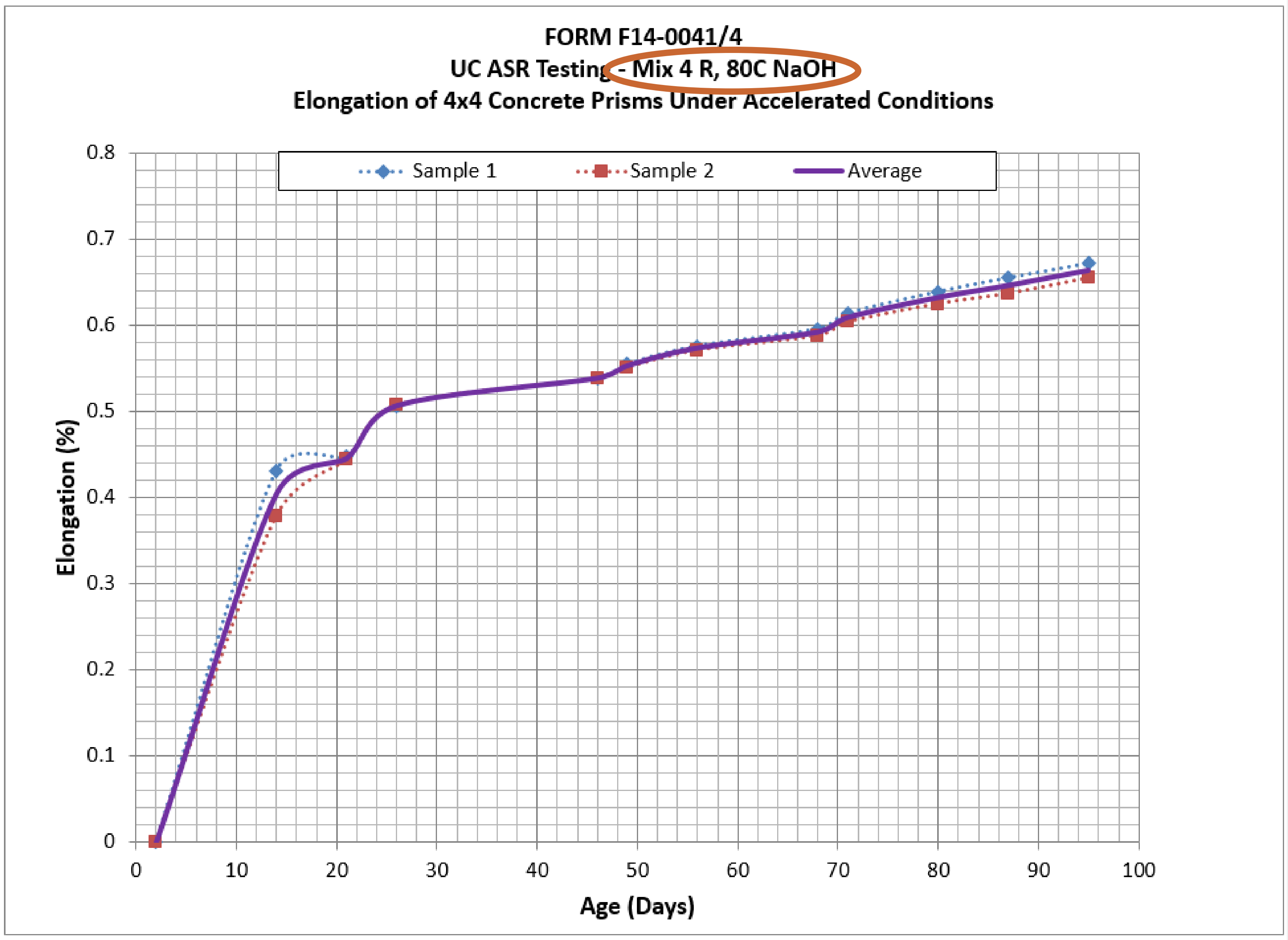
MIX DESIGN 4

- Correct mistakes with Mix 3
- Increased water content and adjusted w/c to be more in line with Mix 2R

Material	lbs/yd³	kg/m³
Portland Cement, Type I/II, (0.91% as Na_2O)	636	378
Fine Aggregate: Manufactured Sand	1,585	941
Coarse Aggregate: 3/4" Crushed Rock	1,362	809
Water	350	208
w/c	0.55	0.55
Admixtures	**kg/yd³**	**kg/m³**
NaOH(s) Doping Additive (1.6% as Na_2O)	2.57	3.37

Concrete Test Results : Mix 4	
Temperature of freshly-mixed concrete (°F)	69.8
Ambient temperature (°F)	64.2
Slump (in)	4.5
Air Content (%)	2.7%
Unit Weight (lbs/ft^3)	144.7
Compressive strength (8 days)	3500
Compressive strength (28 days)	3958


FORM F14-0041/4
UC ASR Testing - Mix 4 R, Fog Room
Elongation of 4x4 Concrete Prisms Under Non-Accelerated Conditions
Sample 1
Sample 2
Average
Elongation (%)
0.06
0.05
0.04
0.03
0.02
0.01
0
0
10
20
30
40
50
60
70
80
90
100
Age (Days)


FORM F14-0041/4
UC ASR Testing - Mix 4 R, 80C NaOH
Elongation of 4x4 Concrete Prisms Under Accelerated Conditions
Sample 1
Sample 2
Average
Elongation (%)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
10
20
30
40
50
60
70
80
90
100
Age (Days)

MIX 4 CONCLUSION

Curing Conditions	Elongation	Age
80°C, 1M NaOH	0.587%	65 days
21°C, Fog Room RH > 90%	0.030%	65 days

- Mix 4 fails strength criterion
- ASR expansion exceeds target at 65 days
- Ultimate expansion well beyond goals.

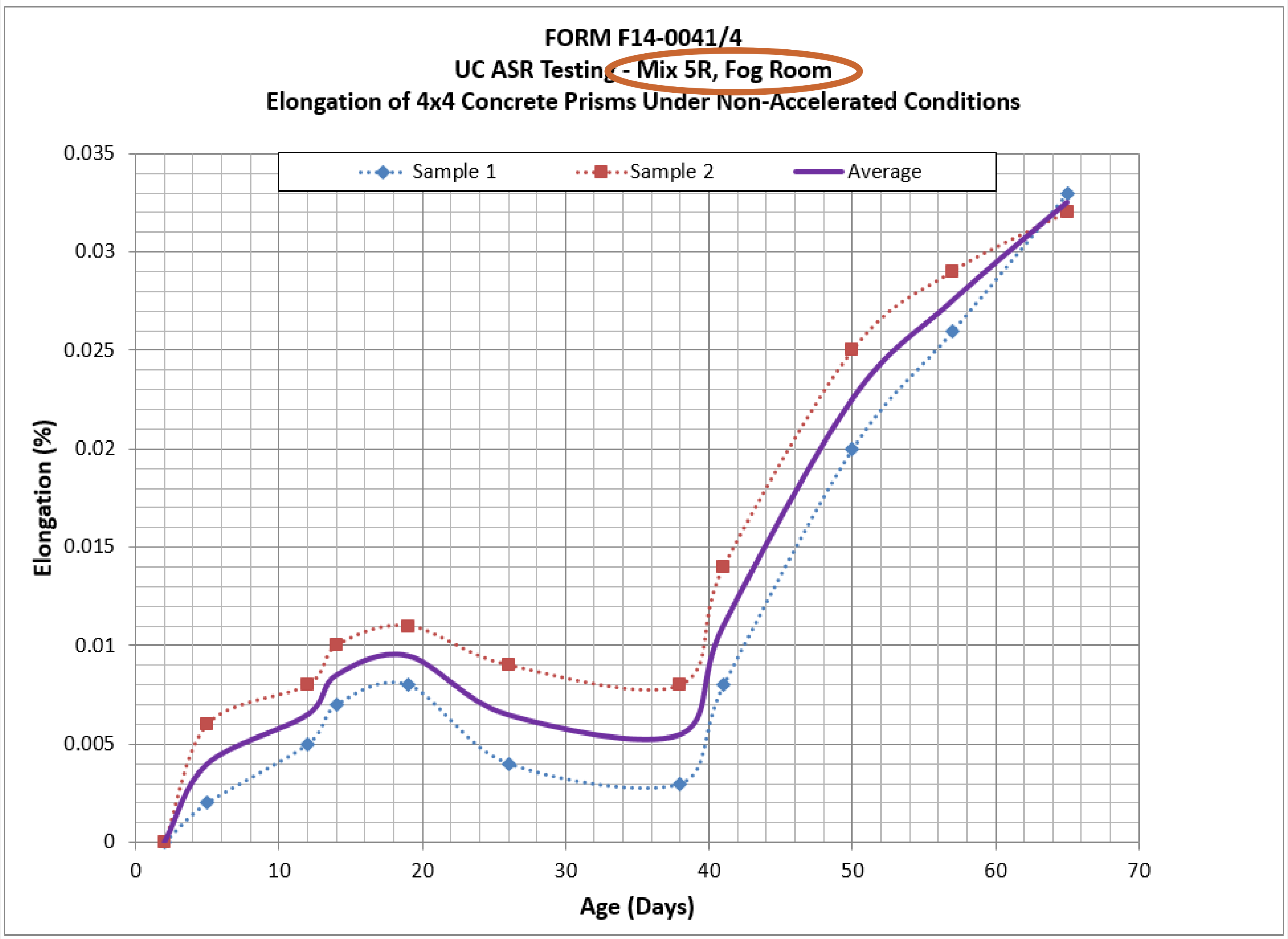
- Unaccelerated samples exhibit very small expansion; perhaps due to alkali leaching

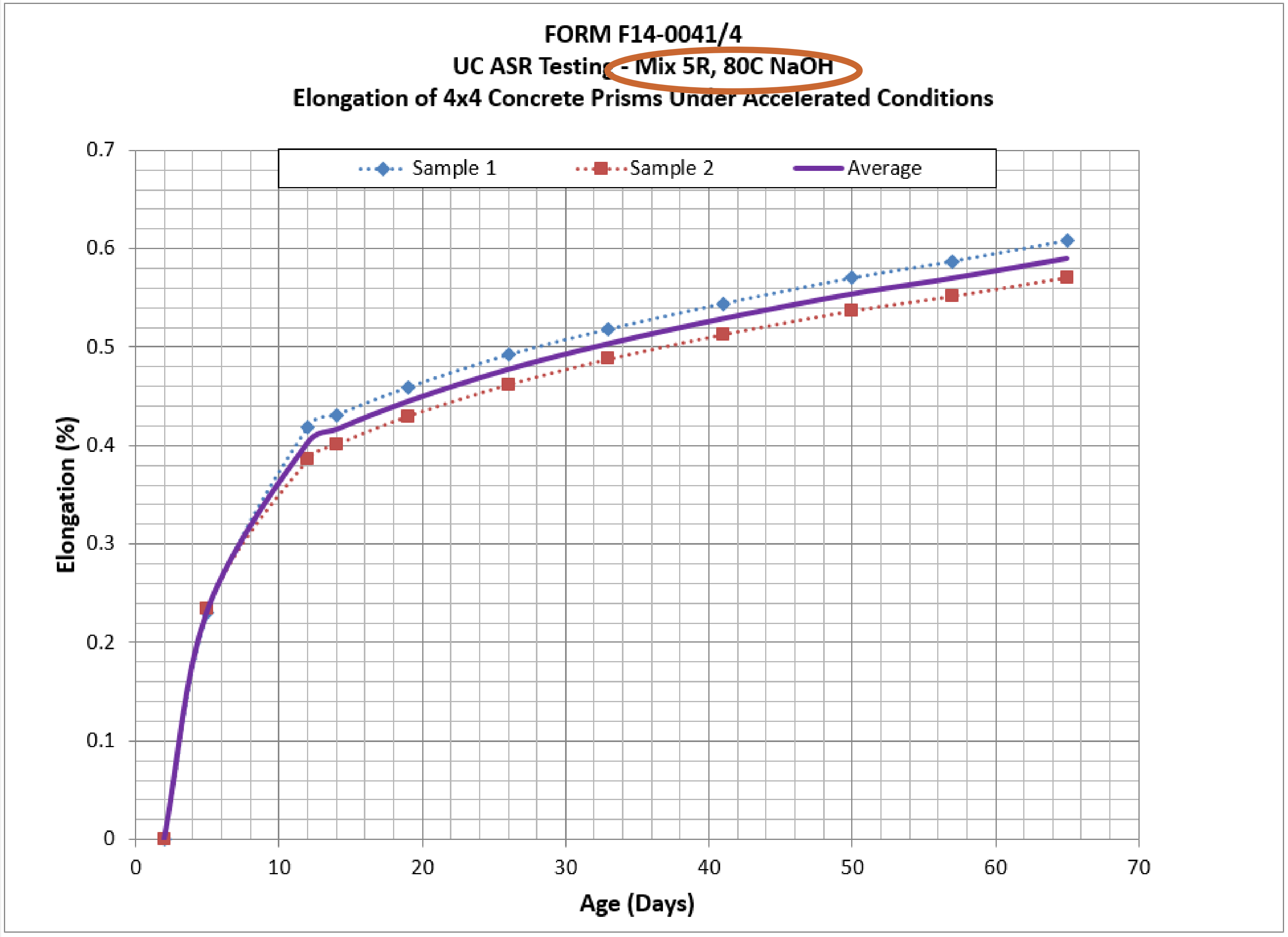
MIX DESIGN 5

- Correct strength deficit of mix design 4
- All other properties within acceptable bounds
- w/c ratio decreased

Material	lbs/yd³	kg/m³
Portland Cement, Type I/II, (0.91% as Na_2O)	666	396
Fine Aggregate: Manufactured Sand	1,552	922
Coarse Aggregate: 3/4" Crushed Rock	1,362	809
Water	353	210
w/c	.53	.53
Admixtures	**kg/yd³**	**kg/m³**
NaOH(s) Doping Additive (1.6% as Na_2O)	2.69	3.52

Concrete Test Results : Mix 5		
Mechanical Property	**Observed**	**Target**
Temperature of freshly-mixed concrete (°F)	68.7	-
Ambient temperature (°F)	66.2	-
Slump (in)	6.5	4.5-6.5
Air Content (%)	1.7%	<3%
Unit Weight (lbs/ft^3)	146.4	-
Compressive strength (8 days)	3700	-
Compressive strength (28 days)	5100	4500


FORM F14-0041/4
UC ASR Testing - Mix 5R, Fog Room
Elongation of 4x4 Concrete Prisms Under Non-Accelerated Conditions
Sample 1
Sample 2
Average
Elongation (%)
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0
10
20
30
40
50
60
70
Age (Days)


FORM F14-0041/4
UC ASR Testing - Mix 5R, 80C NaOH
Elongation of 4x4 Concrete Prisms Under Accelerated Conditions
Sample 1
Sample 2
Average
Elongation (%)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
10
20
30
40
50
60
70
Age (Days)

MIX 5 CONCLUSION

Curing Conditions	Elongation	Age
80°C, 1M NaOH	0.590%	65 days
21°C, Fog Room RH > 90%	0.033%	65 days

- All mechanical properties acceptable
- ASR expansion of accelerated bars exceeds target expansion after 65 days
- Unaccelerated bars again expand much more slowly
- Conclusion: Mix 5 accepted for production of experimental specimens

PREDICTIONS

- Greatest expansion observed at 80°C
- Not feasible to heat university fog room to that temperature
- What is the effect of storage at 38°C?

- Temperature effects modelled by Larive equation (Larive,1998)

$$\varepsilon(t,T) = \frac{1 - e^{\left(\frac{1}{\tau_C(T)}\right)}}{1 + e^{\left(\frac{1-\tau_L(T)}{\tau_C(T)}\right)}}$$

- τ_L= latency time & τ_c= characteristic time are functions of temperature (Ulmet et al., 2000)

$$\tau_C(T) = \tau_C(T_0)e^{\left(U_C\left(\frac{1}{T}-\frac{1}{T_0}\right)\right)}$$

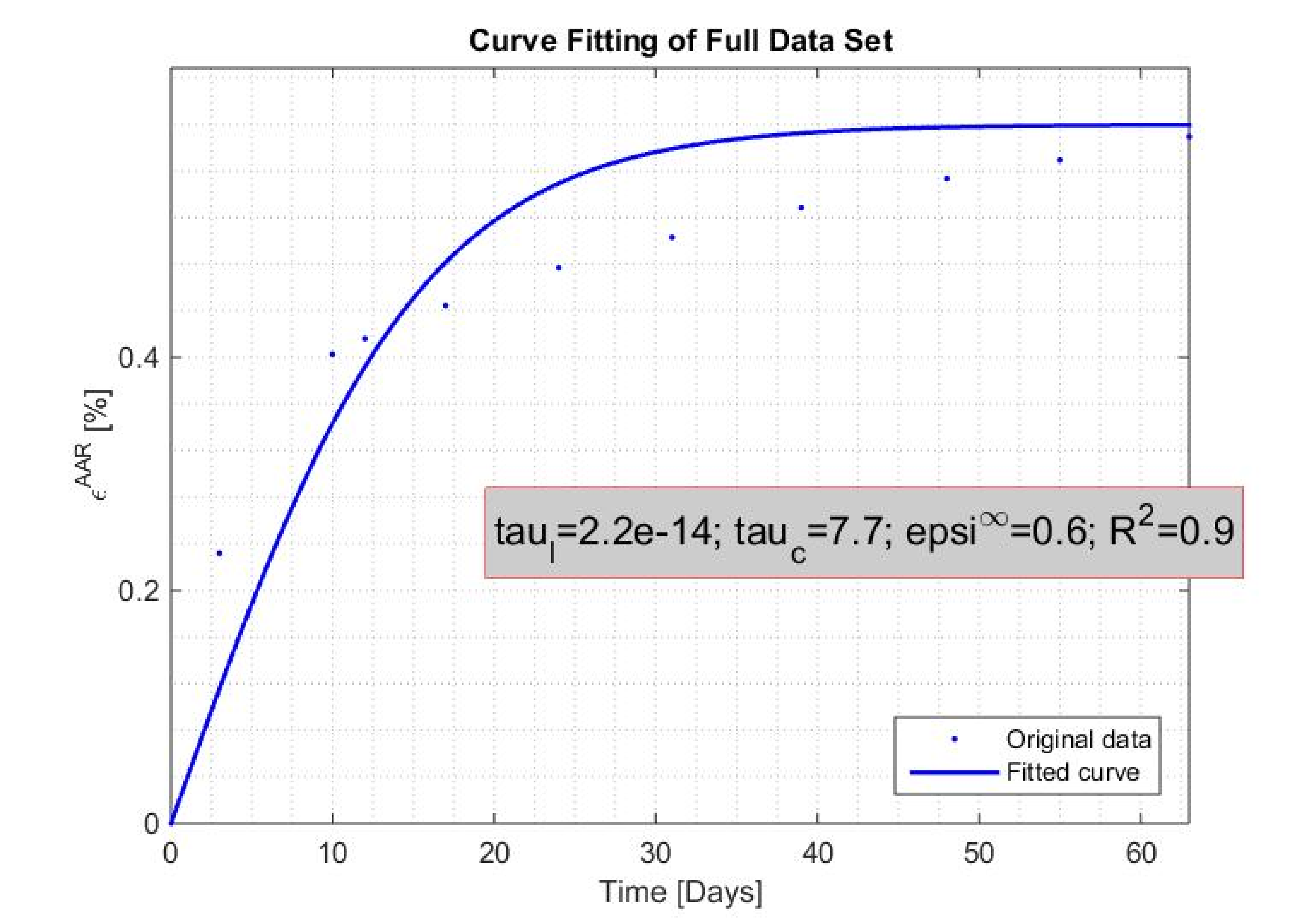
$$\tau_L(T) = \tau_L(T_0)e^{\left(U_L\left(\frac{1}{T}-\frac{1}{T_0}\right)\right)}$$

- U_L & U_C = activation energies, found by Larive.

$$U_L = 9400 \pm 500\ K$$

$$U_c = 5400 \pm 500\ K$$

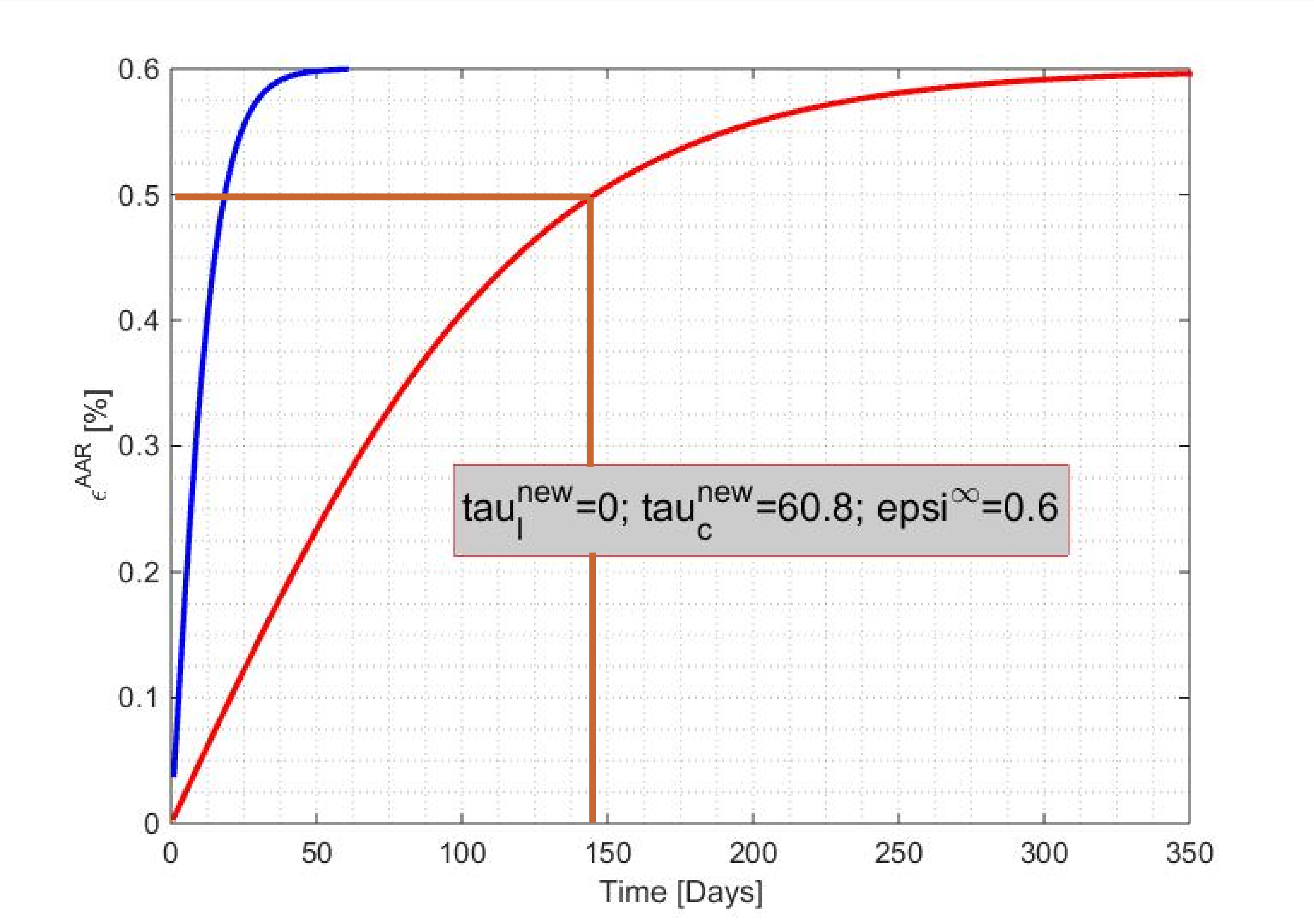
- Experimental data for Mix 5 (80°C, 1M NaOH)
- Curve-fitting yields τ_C(353K) & τ_L(353K)



(Plot provided by Dr. M. Hariri-Ardebili)

- Calculation of characteristic times for 38°C yields $\tau_C(311K)$ & $\tau_L(311K)$
- Plotting resultant expansion curve permits estimation of expansion.
- Estimate 145 days of cure time to reach 0.5% expansion

(Plot provided by Dr. M. Hariri-Ardebili)



ALKALI LEACHING PROTECTION

- Exposure to high-humidity fog room conditions exacerbates alkali leaching, reducing expansion
- Sprinkling specimens with aqueous NaOH solution resists alkali leaching by decreasing concentration gradient at surface
- What concentration to use?

- Specimens must be protected from the effects of alkali leaching and shrinkage
- Lindgård (2013) tested prisms wrapped in fabric soaked in caustic solution.
  - For pH 14.2, uptake of alkali by specimen
  - For pH 13.2, specimen lost alkali at approximately same rate as for tap water
- This observation aligns with results of this study

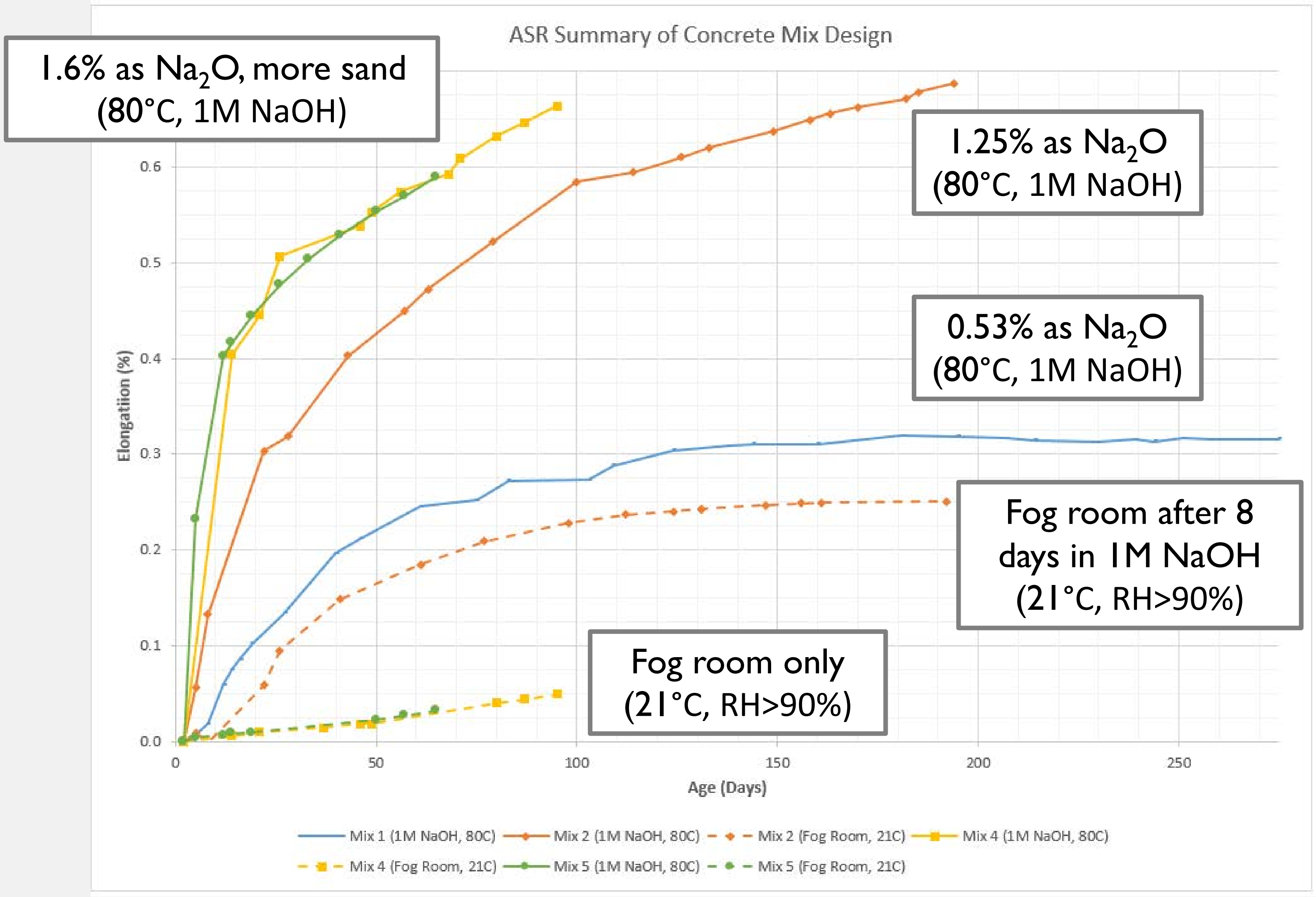
$$NaOH + H_2O \rightarrow Na^+ + OH^- + H_2O$$
$$1M\ NaOH \rightarrow 1M\ OH^-$$
$$pOH = -\log[OH^-]$$
$$pH = 14 - pOH$$
$$[OH^-] = 10^{14.2-14} = 1.58M\ NaOH$$

- Thus, recommend samples be sprinkled with 1.6M NaOH

CONCLUSIONS & RECOMMENDATIONS FOR FURTHER STUDY

- ASR expansion of concrete prisms highly dependent on environmental conditions

1. Higher temperatures accelerate expansion.
2. High humidity in the absence of surface alkalinity depresses expansion, likely due to alkali leaching
3. Increasing initial alkalinity improves expansion, but not enough to overcome leaching effects.
4. Increasing aggregate surface area (either by crushing or increasing proportion of reactive sand) increases expansion *(to pessimum limit)*
5. Drying shrinkage can mask ASR expansion.


ASR Summary of Concrete Mix Design
1.6% as Na_2O, more sand (80°C, 1M NaOH)
1.25% as Na_2O (80°C, 1M NaOH)
0.53% as Na_2O (80°C, 1M NaOH)
Fog room after 8 days in 1M NaOH (21°C, RH>90%)
Fog room only (21°C, RH>90%)
Elongatiion (%)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
Age (Days)
0
50
100
150
200
250
Mix 1 (1M NaOH, 80C)
Mix 2 (1M NaOH, 80C)
Mix 2 (Fog Room, 21C)
Mix 4 (1M NaOH, 80C)
Mix 4 (Fog Room, 21C)
Mix 5 (1M NaOH, 80C)
Mix 5 (Fog Room, 21C)

RECOMMENDATIONS

- Experimental storage conditions:
- Temperature ≈ 38°C
- RH > 90%
- Sprinkler supplying 1.5M NaOH wash
- Expose specimens to alkali wash as soon as practical (24 hours)
- Effects of confining reinforcement not evaluated. Monitor expansion using unconfined prisms.
- May be desirable to measure elastic modulus, as decrease shown to coincide with ASR. *(Esposito, 2016)*

QUESTIONS

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