Slag Characterization and Concrete Durability

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Current Specifications for Slag Cement

- ASTM C989 separated slag into 3 grades:

Grade	7-Day Slag Activity Index, min%	28-Day Slag Activity Index, min%
80	--	75
100	75	95
120	95	115

- Fineness: amount retained on 45 µm sieve (wet-sieved) ≤ 20%
- Air content of slag mortar ≤ 12%
- Limit on sulfide content ≤ 2.5%

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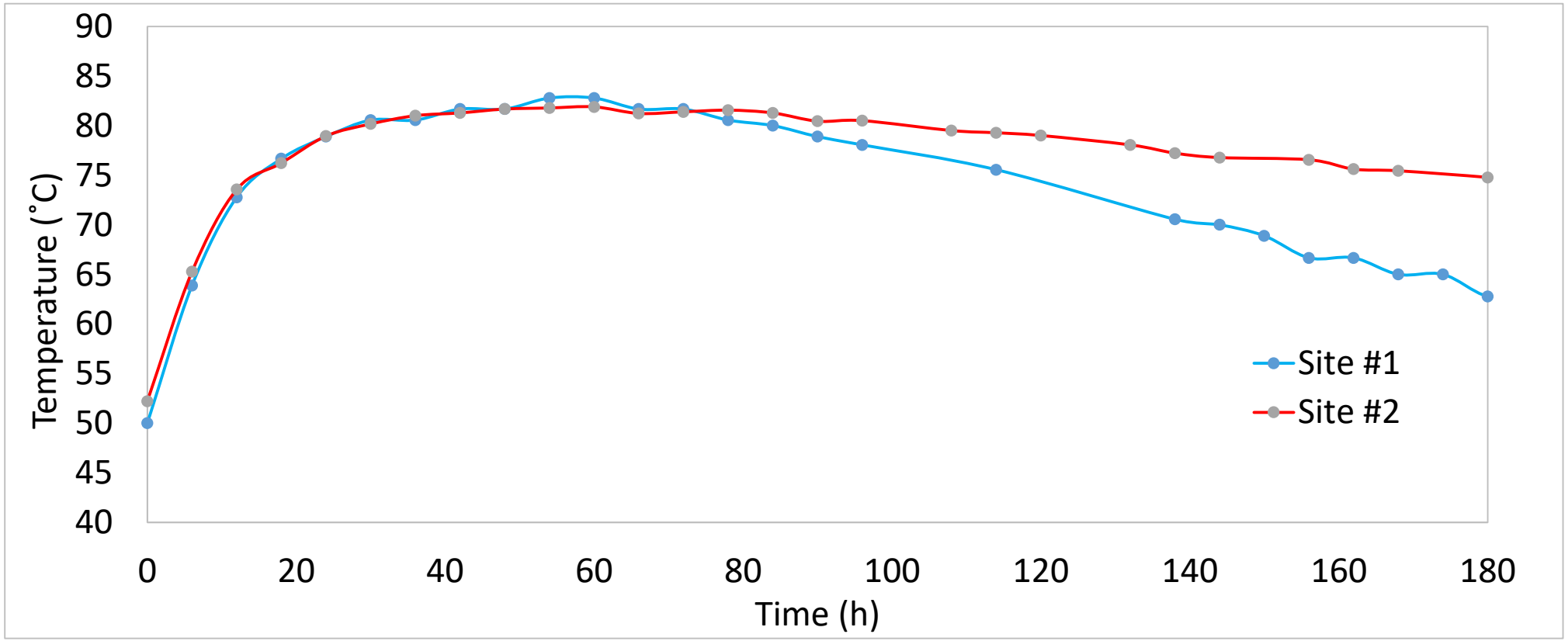
Field Temperature Profiles



Objective: Compare chemical and physical characteristics of granulated blast furnace slag available in the United States and their effect on cracking indices for mass concrete

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Reactivity of Ground Granulated Blast Furnace Slag

- Parameters affecting slag reactivity:
  - Elemental oxide composition (CaO/SiO_2 ratio, Al_2O_3, MgO)
  - Mineralogical composition (amorphous vs crystalline content)
  - Blaine fineness / particle size distribution
- Proposed hydraulic moduli from the literature:
  - CaO/SiO_2
  - Al_2O_3/SiO_2
  - $(CaO + MgO + Al_2O_3)/SiO_2$
  - $(CaO + MgO + 1/3\ Al_2O_3)/ (2/3\ Al_2O_3 + SiO_2)$

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As-Received Materials Characterization

- Materials used in this study:
  - 7 slags with variable Al_2O_3, MgO content, and fineness
  - 2 cements with variable C_3A
- Methodology for as-received materials characterization:
  - X-ray fluorescence (XRF)
  - X-ray diffraction (XRD)
  - 27Al NMR (slag only)
  - Blaine fineness
  - Particle size analysis

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Concrete Mixture Proportions

Material	Control A/B	Slag mixes
Cement (kg)	395	158
Slag (kg)	0	237
Coarse aggregate (SSD) (kg)	1047	1047
Fine aggregate (SSD) (kg)	696	696
Air-entrainer (ml/100 kg)	6.5	6.5
w/b	0.385	0.385

*Superplasticizer dosage was adjusted to maintain workability
w/b= water/binder

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Methodology for Performance Assessment

- Isothermal calorimetry at 30˚C
  - TAM Air 8-channel calorimeter, internal mixing
- Semi-adiabatic calorimetry
- Rigid cracking frame (RCF)
- Free shrinkage frame (FSF)
- Nitrogen adsorption porosity measurements

Rigid Cracking Frame

- Center cross section of concrete specimen: 100 x 100 mm
- Length: 1041 mm
- Frame is insulated
- Connected to a programmable water bath

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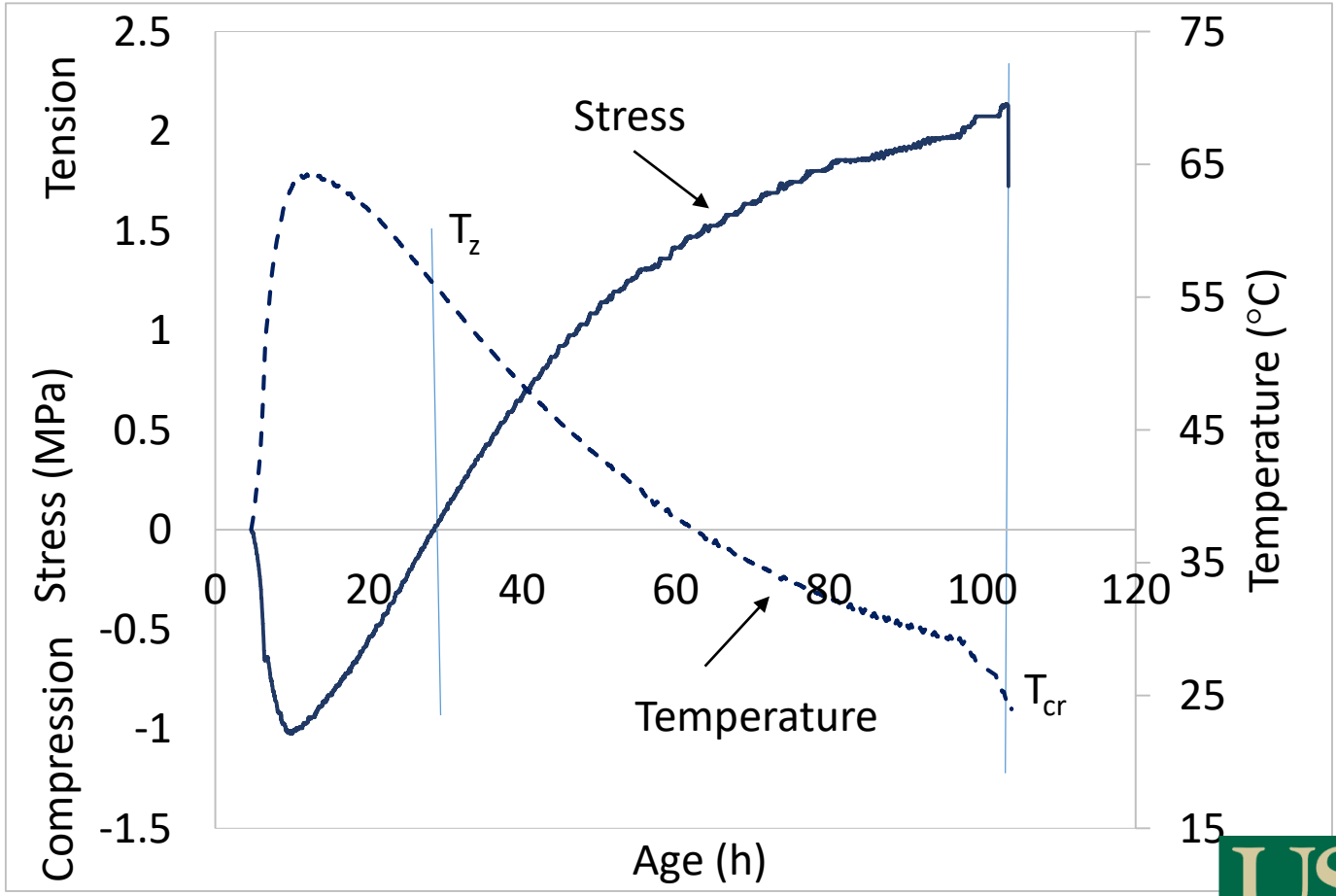
Thermal Cracking Potential

Cracking Indices:

- T_z – 2nd zero stress temperature
- t_z – 2nd zero stress time
- T_{cr} – cracking temperature
- t_{cr} – cracking time



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Slag Chemical, Physical and Mineralogical Analyses

	S8	S8F	S11F	S11C	S14	S14S	S16
CaO	38.11	39.52	41.93	37.41	41.06	41.48	37.98
SiO_2	38.59	38.61	35.67	36.15	35.44	33.7	32.86
Al_2O_3	8.09	7.73	10.82	10.71	14.25	13.67	16.29
MgO	10.83	10.40	7.9	11.27	5.25	5.33	8.88
SO_3	2.21	2.25	1.91	2.33	1.99	3.02	2.61
Na_2O_{eq}	0.55	0.51	0.44	0.51	0.40	0.42	0.66
CaO/SiO_2	0.99	1.02	1.18	1.03	1.16	1.23	1.16
Amorphous content	98.9	98.6	98.8	98.3	97.0	97.6	99.0
Mean particle size (µm)	9.2	8.0	8.4	10.9	11.2	12.3	11.8
Blaine fineness (m^2/kg)	642	698	680	589	574	595	466

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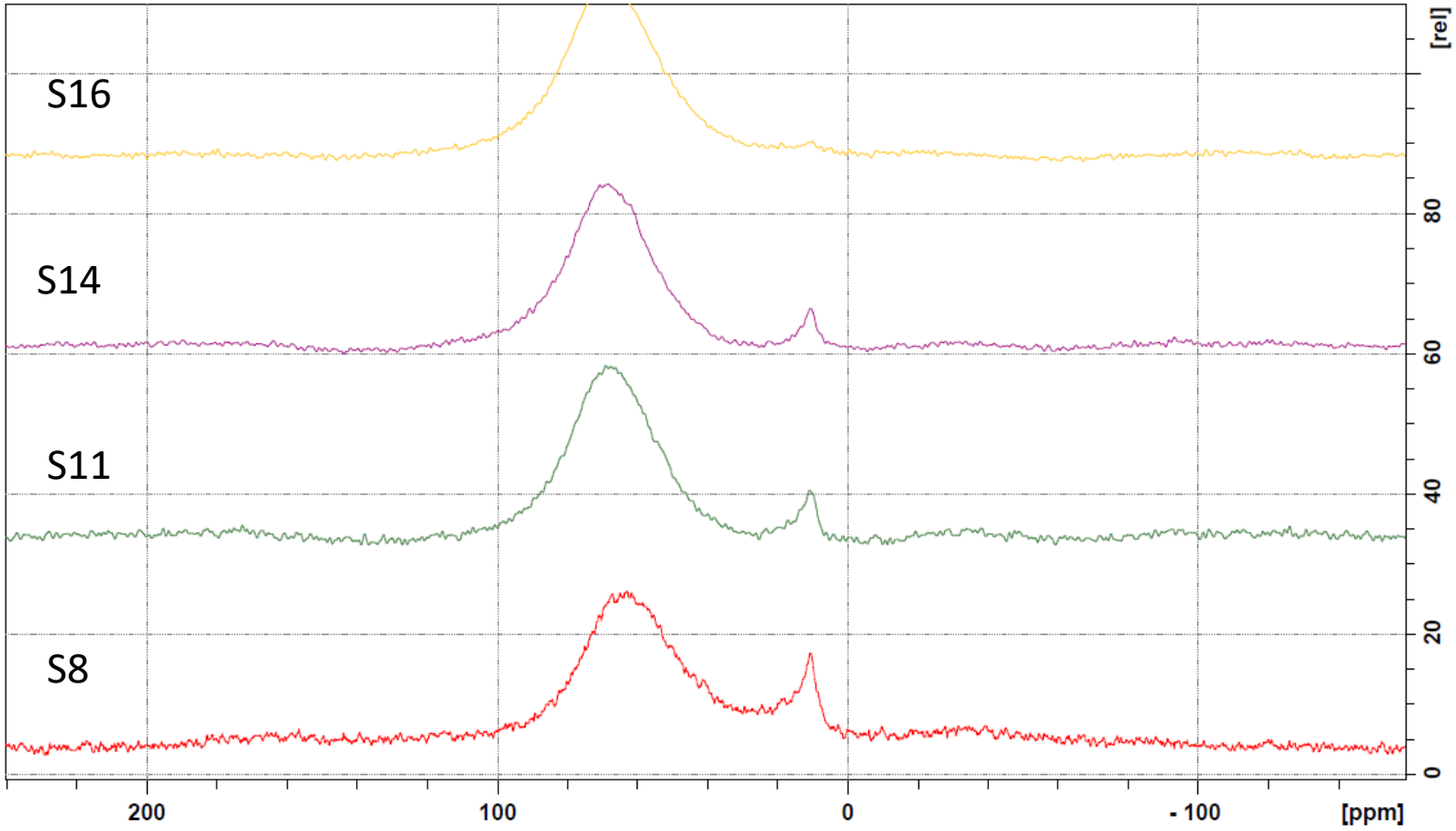
27Al NMR Results



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Cement Physical and Mineralogical Analyses

	Cement A	Cement B
Alite	48.1	54.0
Belite	23.1	17.3
C_3A	5.5	8.4
Ferrite	9.9	5.6
Gypsum	2.6	4.3
Hemihydrate	1.5	1.4
Na_2O_{eq}	0.35	0.39
Blaine fineness (m^2/kg)	485	474

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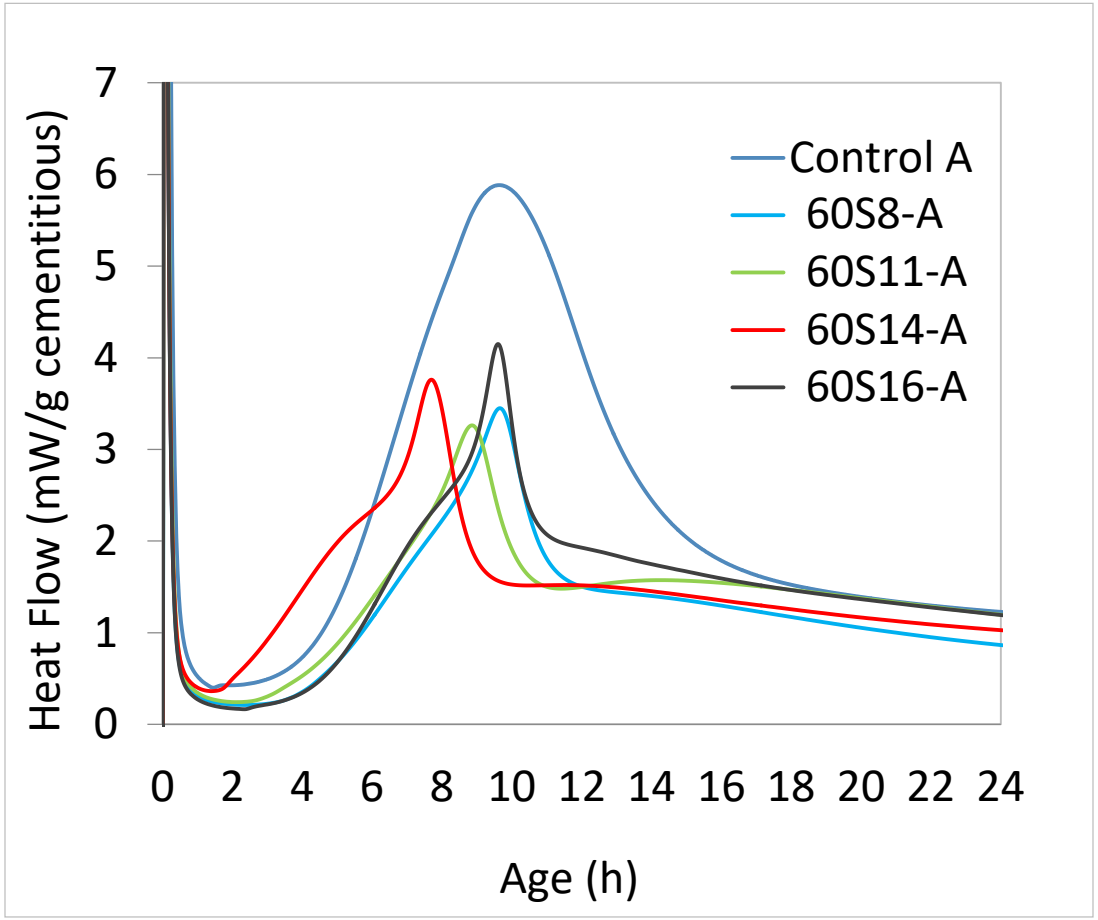
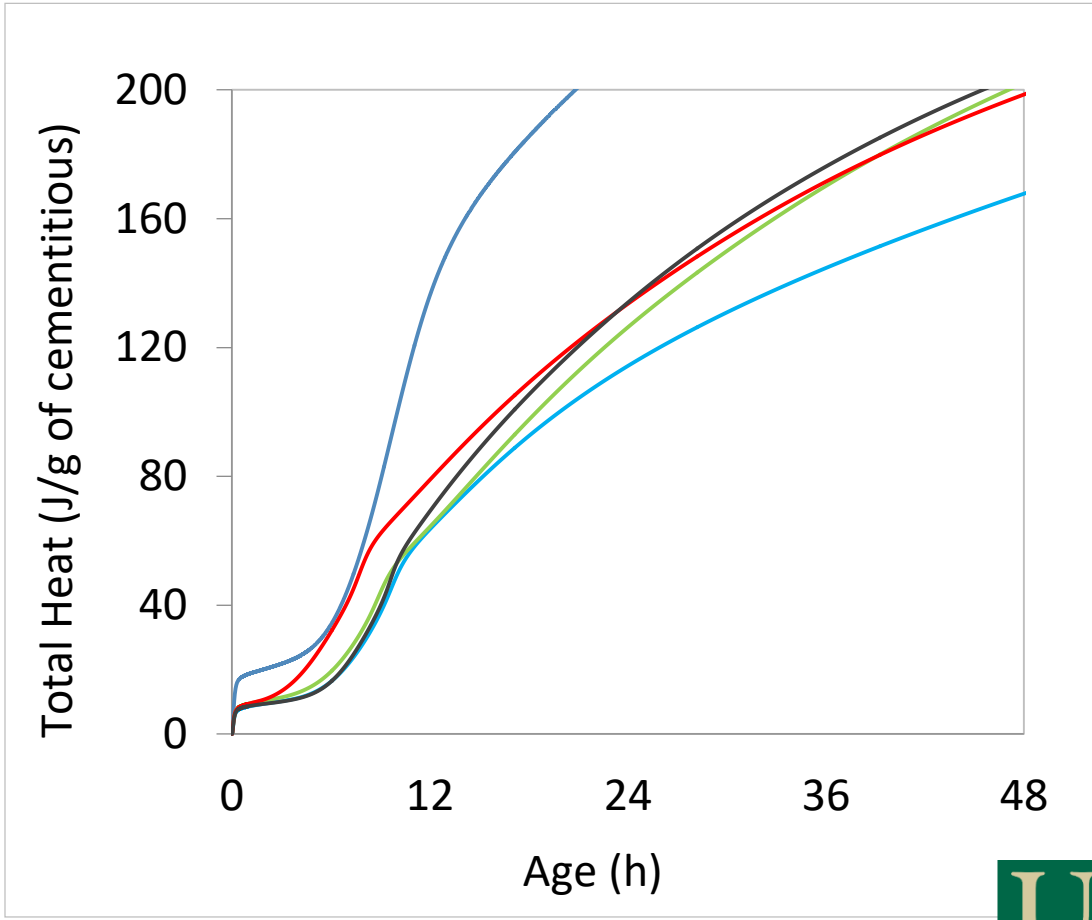
Isothermal Calorimetry





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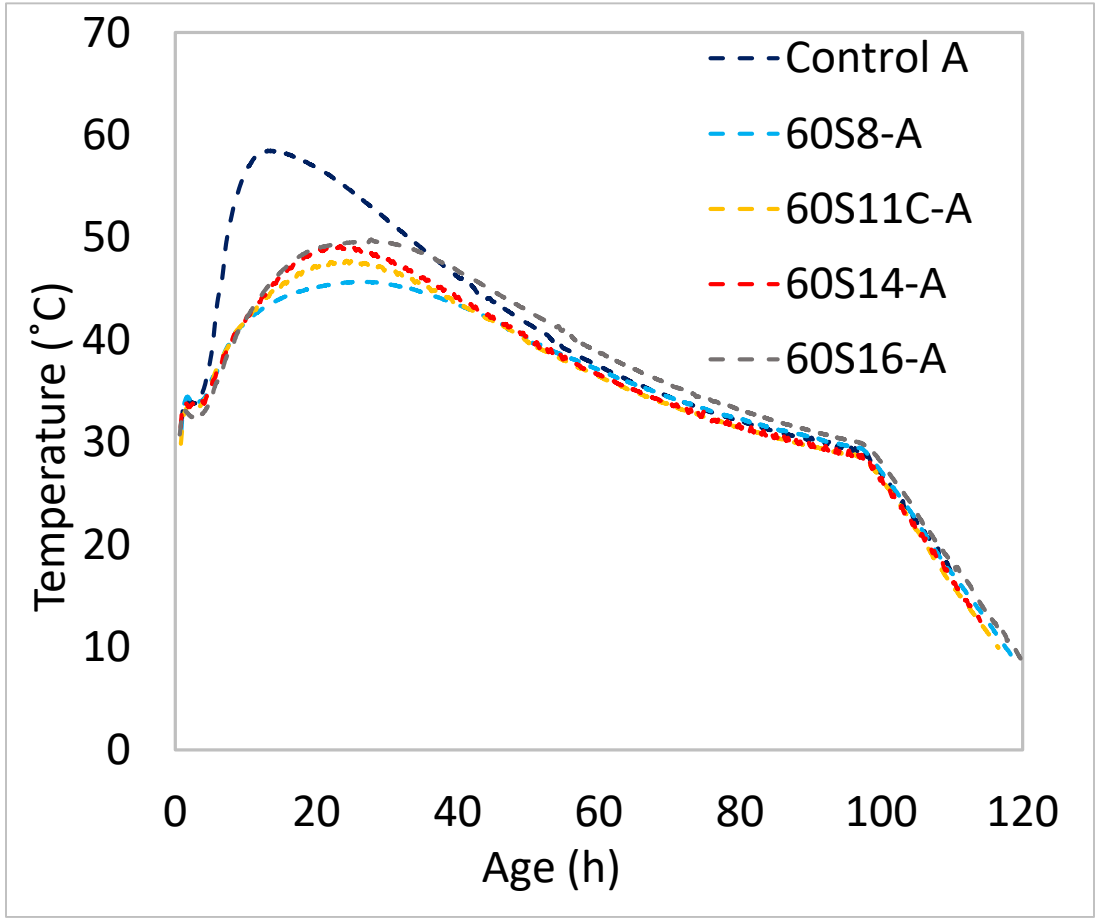
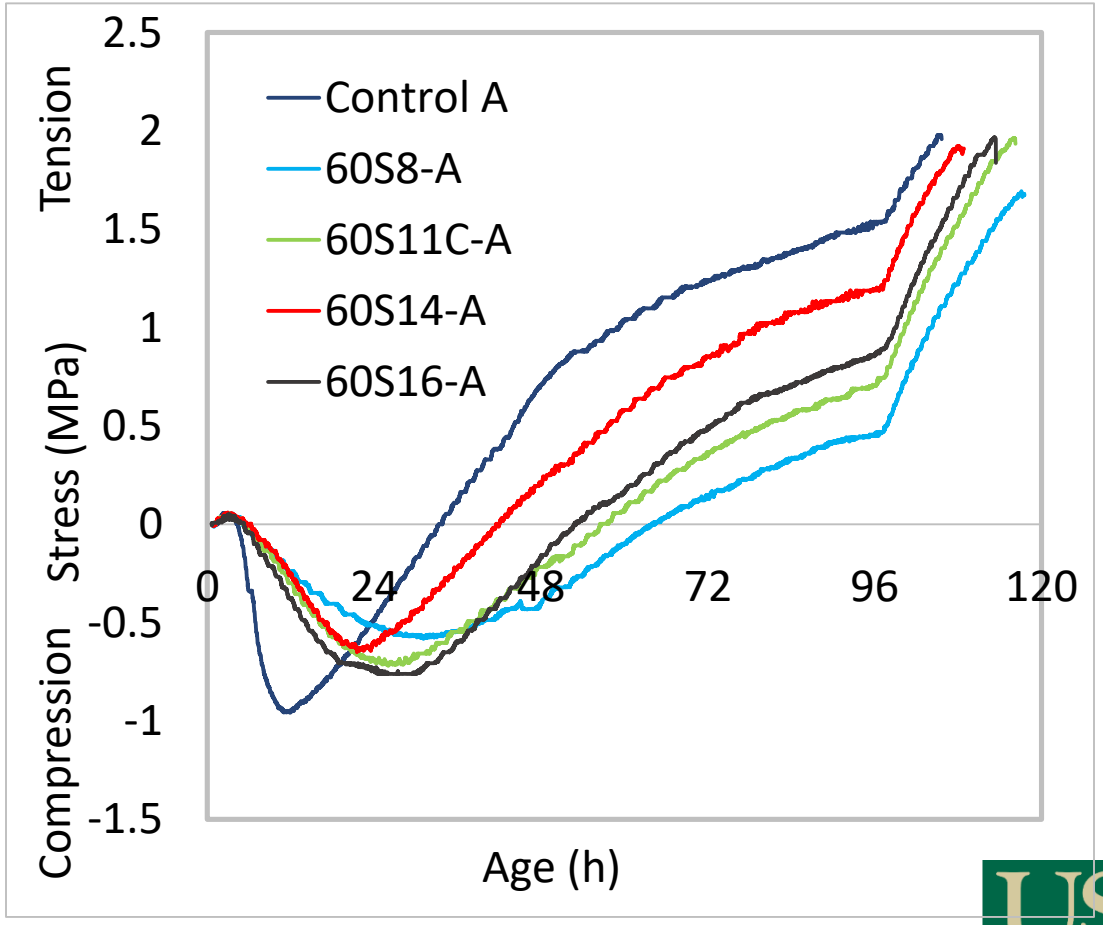
Temperature and Stress Development with Cement A





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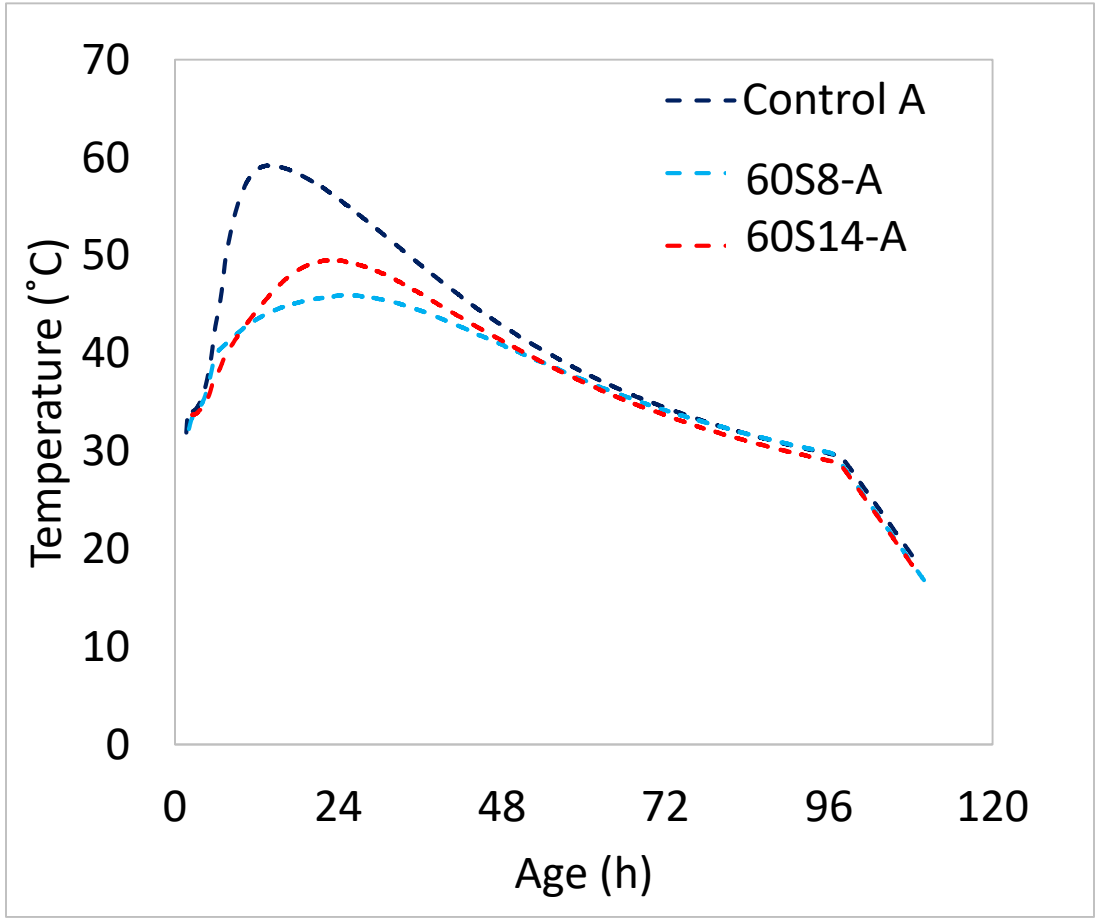
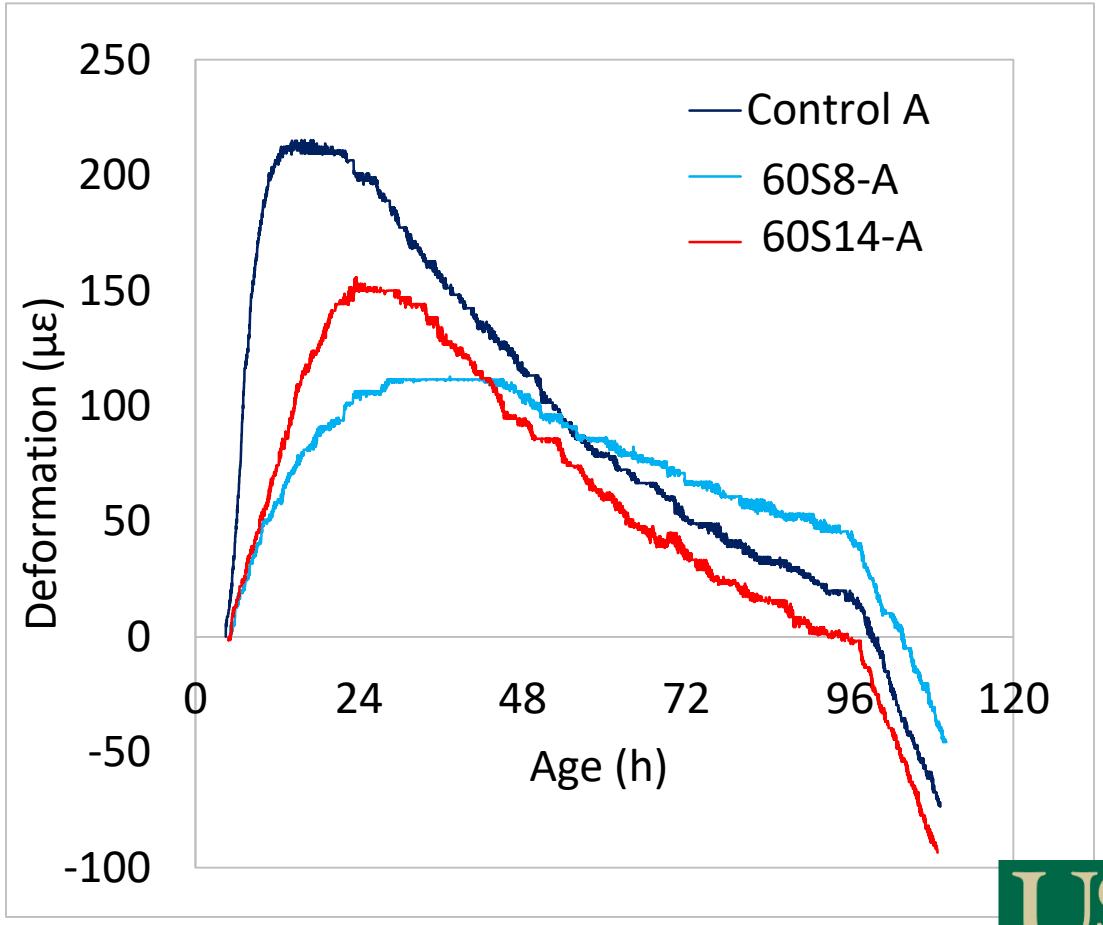
Free Deformation





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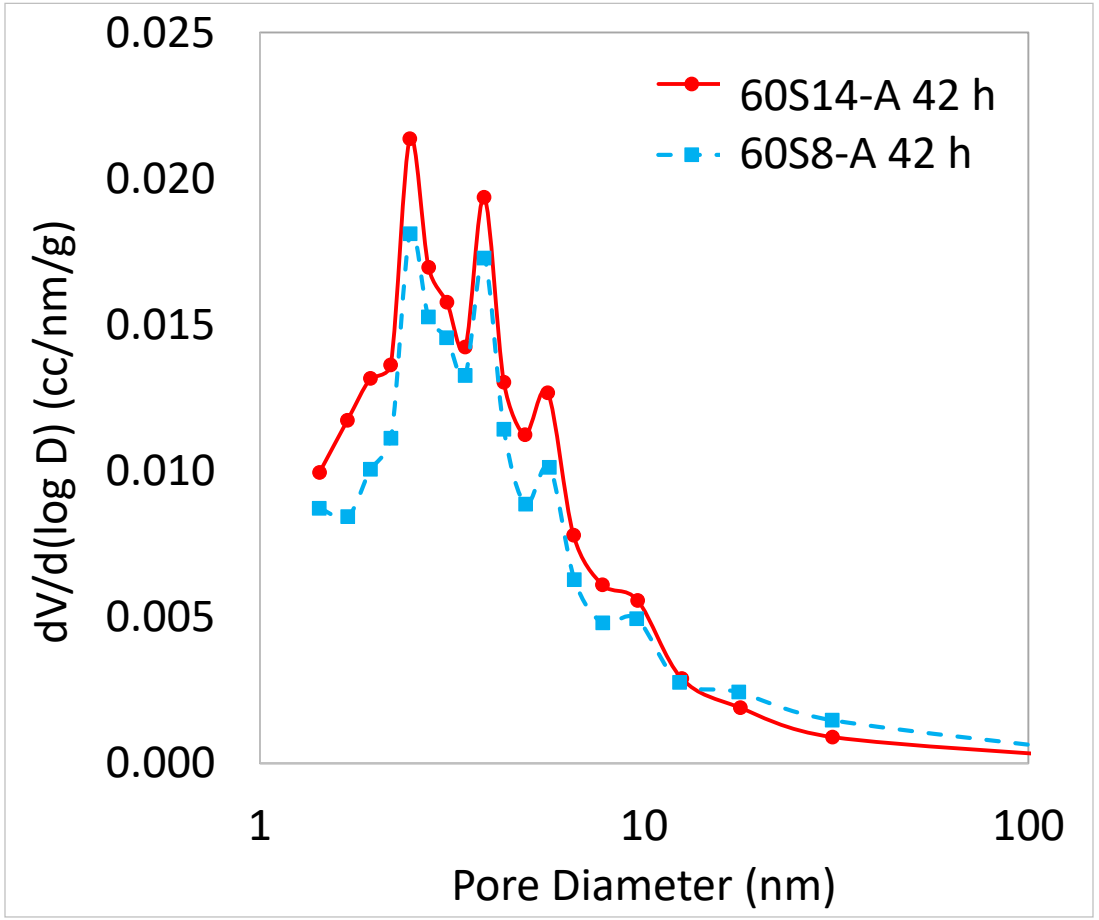
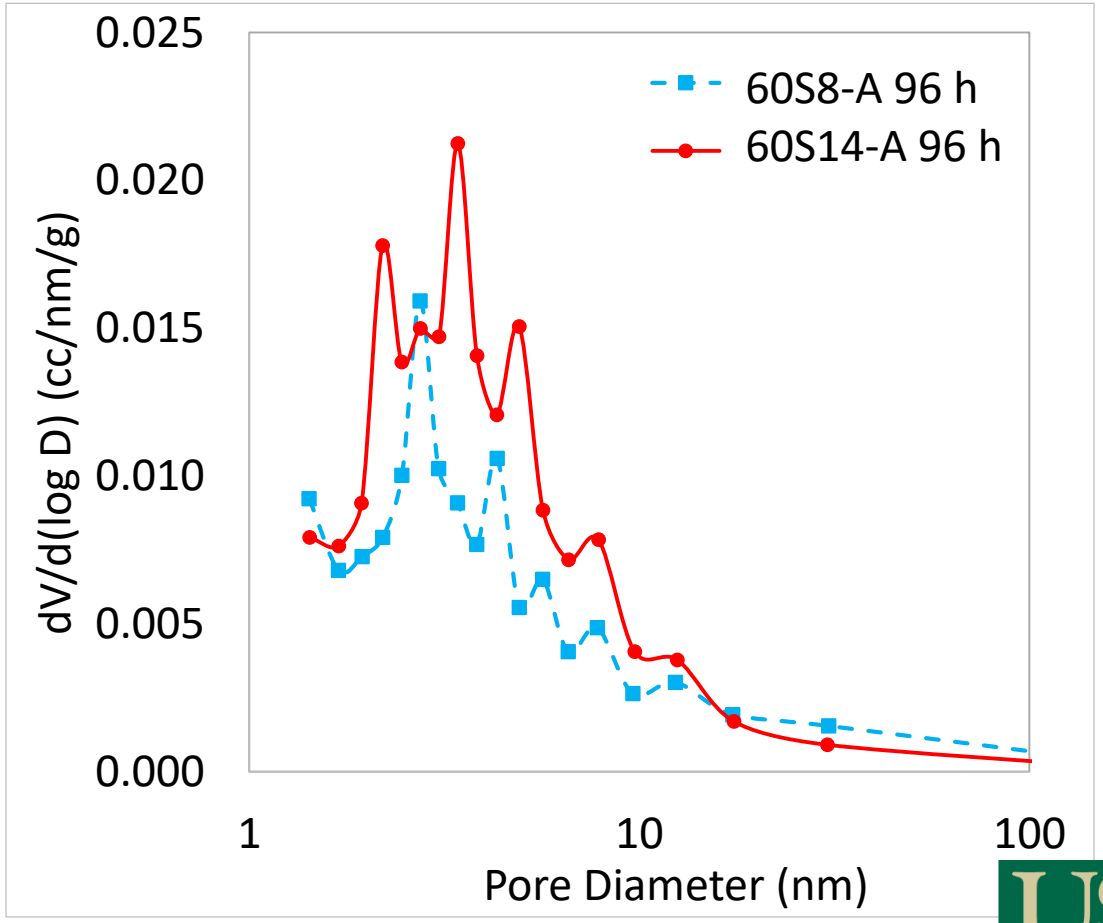
Pore Size Distribution





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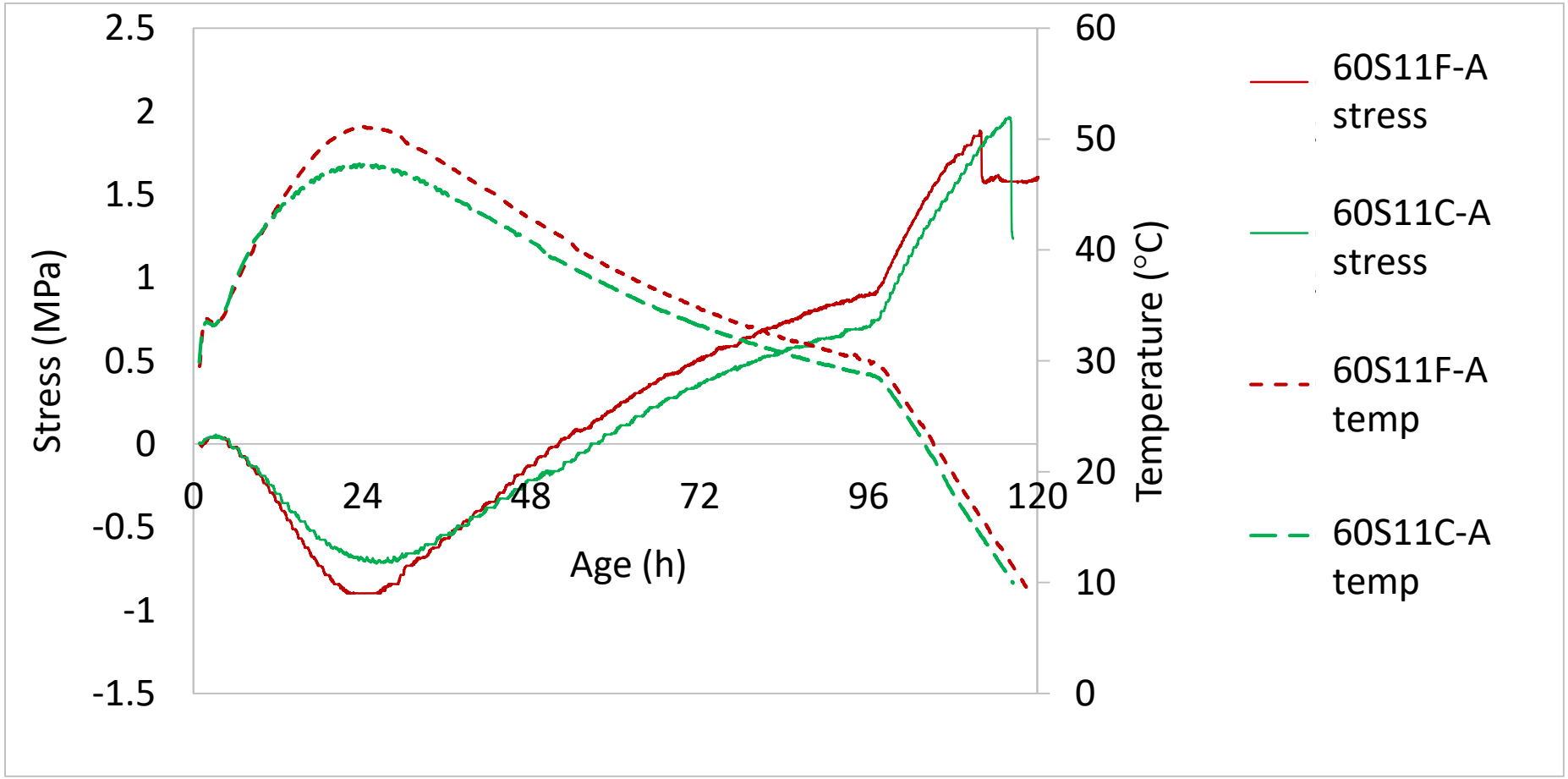
Effect of Fineness



MPS:
S11F – 8.4 µm
S11C – 10.9 µm

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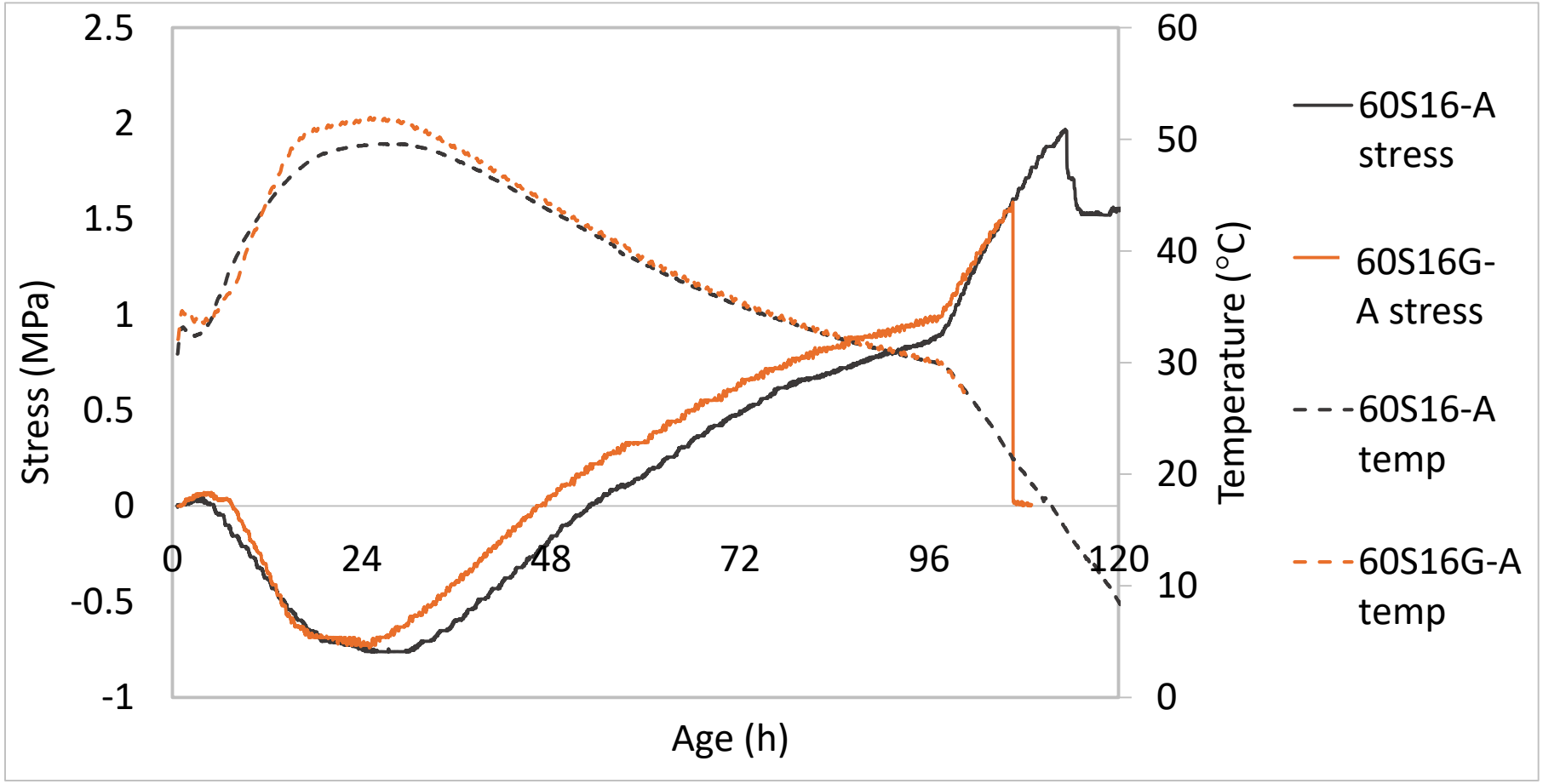
Effect of Fineness



MPS:
S16 – 11.8 µm
S16G – 4.8 µm

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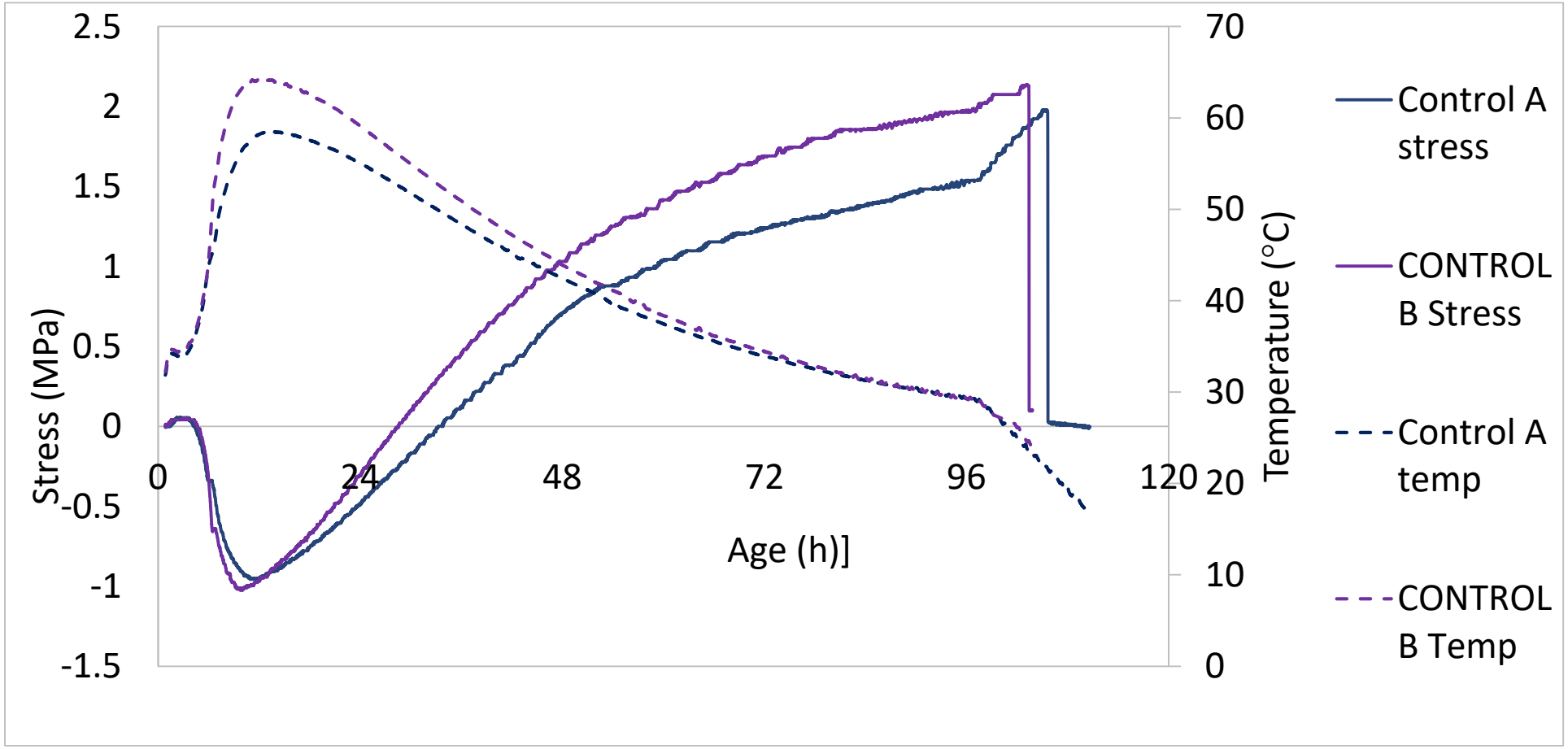
Effect of Cement Composition



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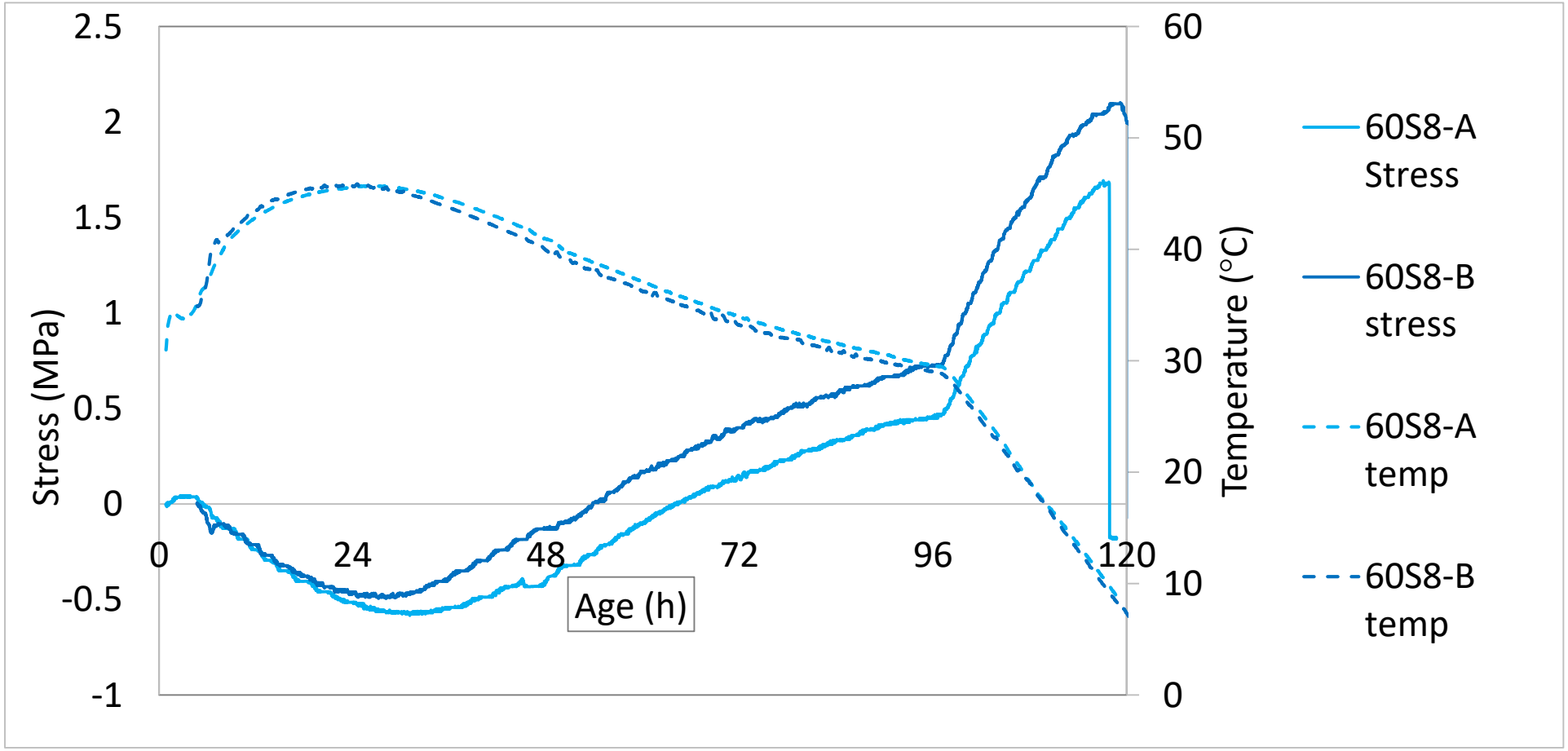

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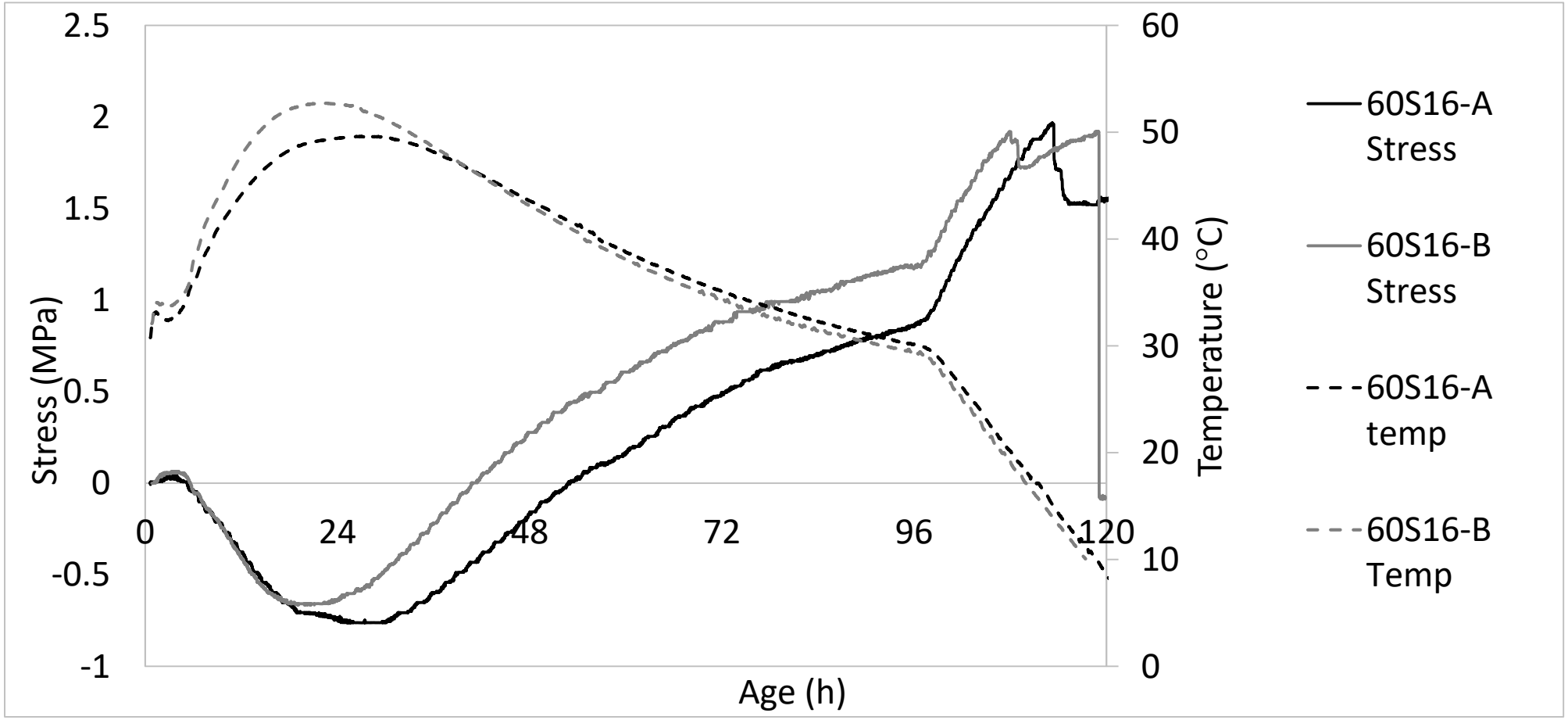

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Cracking Indices – Cement A Mixes

Mix #	Tz (˚C)	Tcr (˚C)
Control A	49.6	21.6
60S8-A	35.9	10.5
60S8F-A	36.1	13.5
60S11C-A	37.4	10.2
60S11F-A	41.3	15.8
60S14-A	43.4	16.3
60S14S-A	42.2	15.4
60S16-A	41.6	15.0
60S16G-A	44.7	21.6

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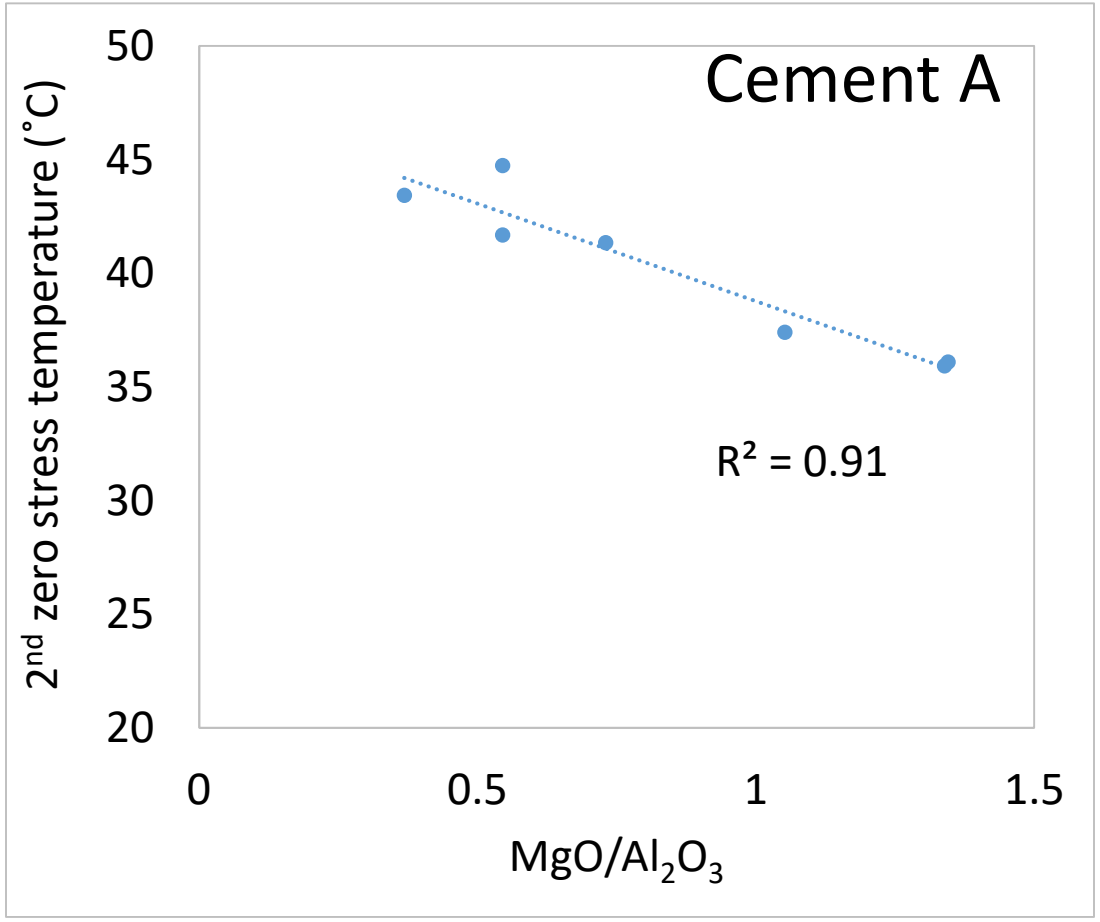
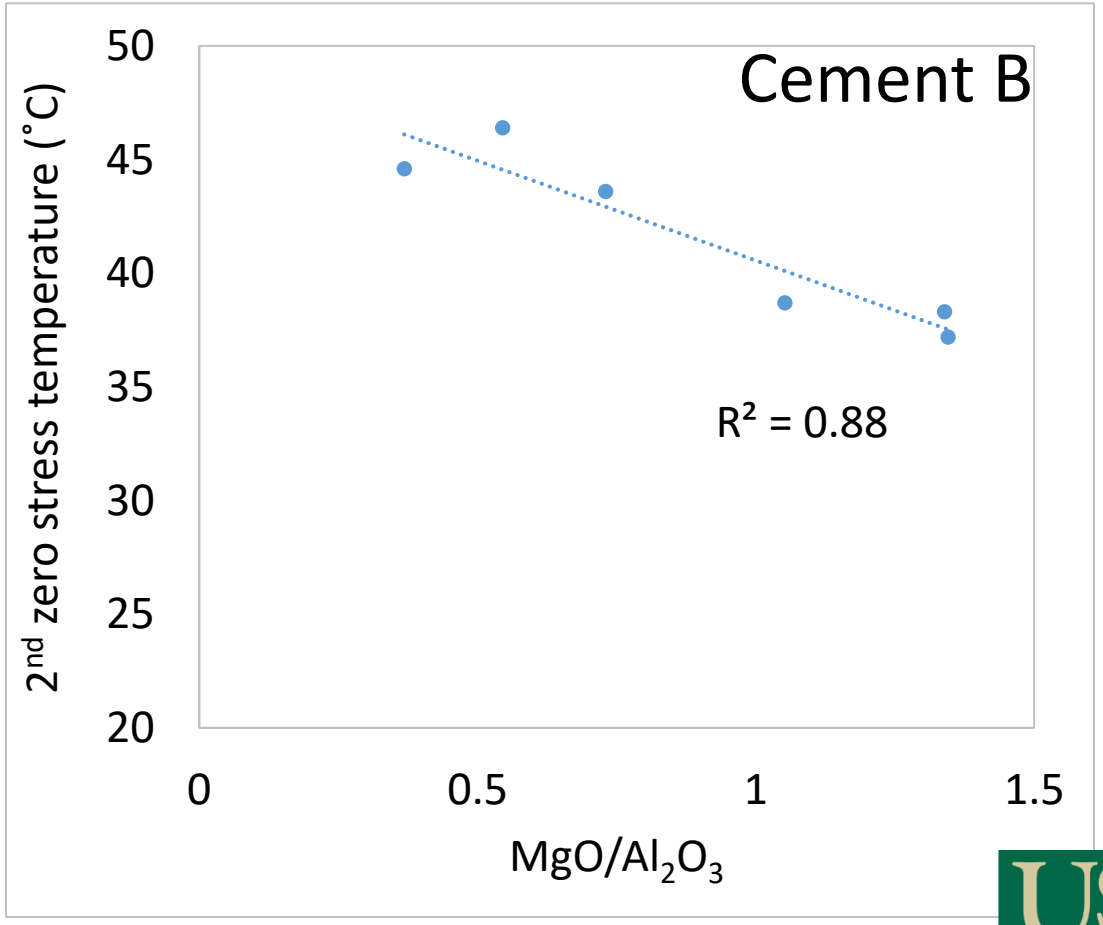
Cracking Indices – Cement B Mixes

Mix #	Tz (˚C)	Tcr (˚C)
Control B	55.9	24.6
60S8-B	38.3	7.9
60S11C-B	38.7	10.8
60S11F-B	43.7	18.9
60S14-B	44.6	17.7
60S16-B	46.4	19.1

Material Property-Performance Relationship





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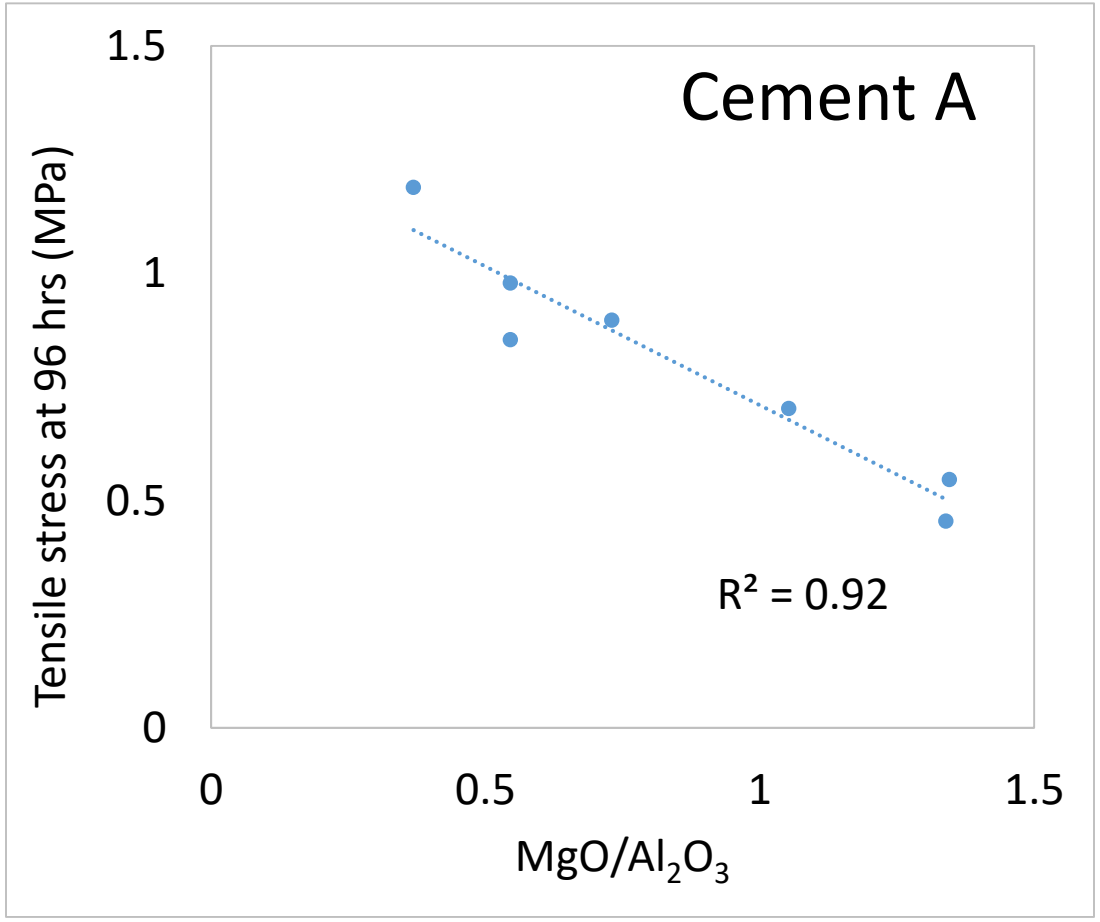

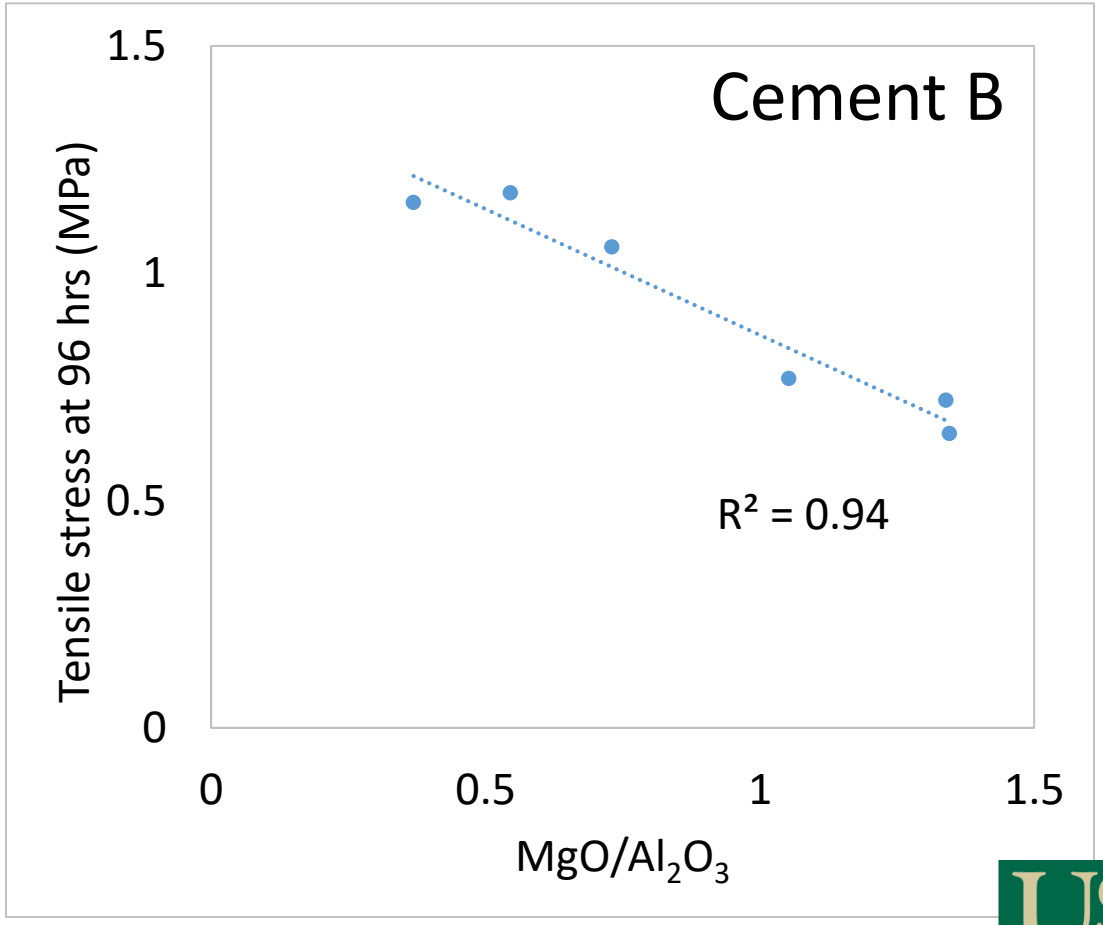

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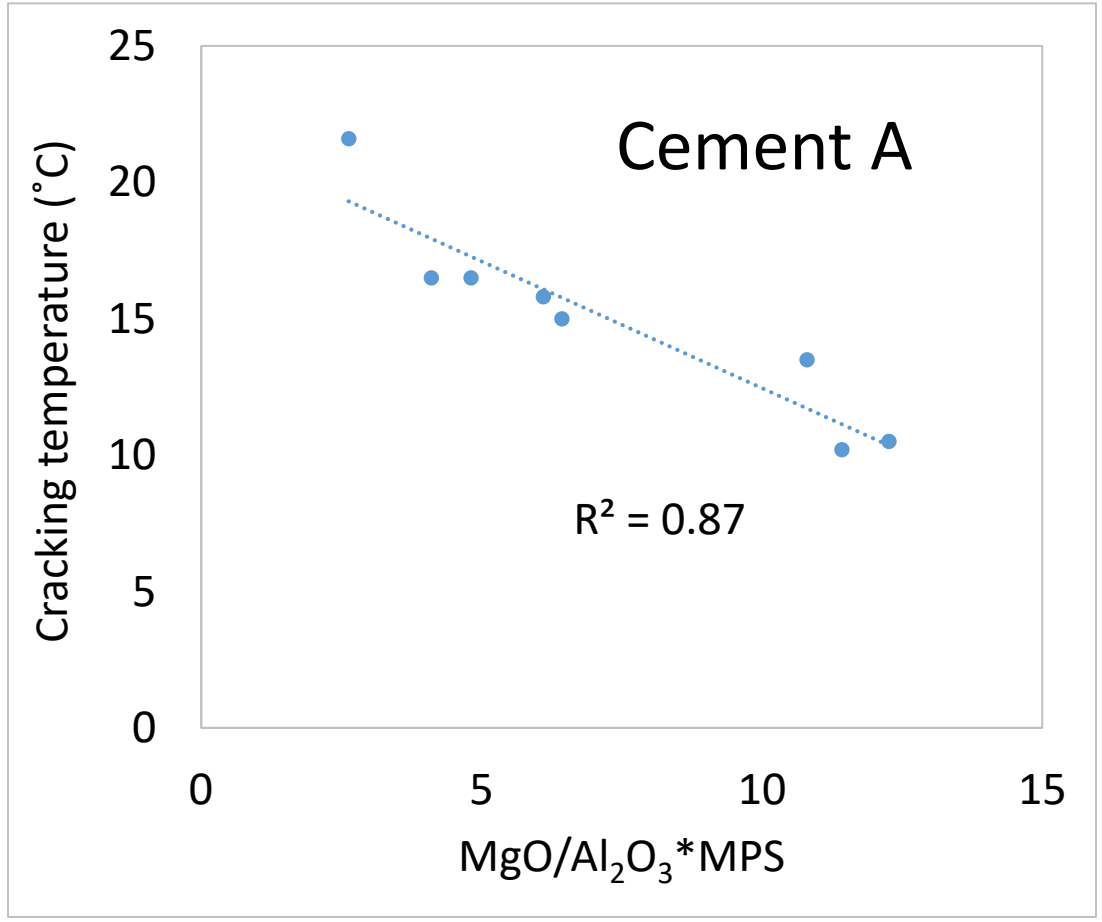
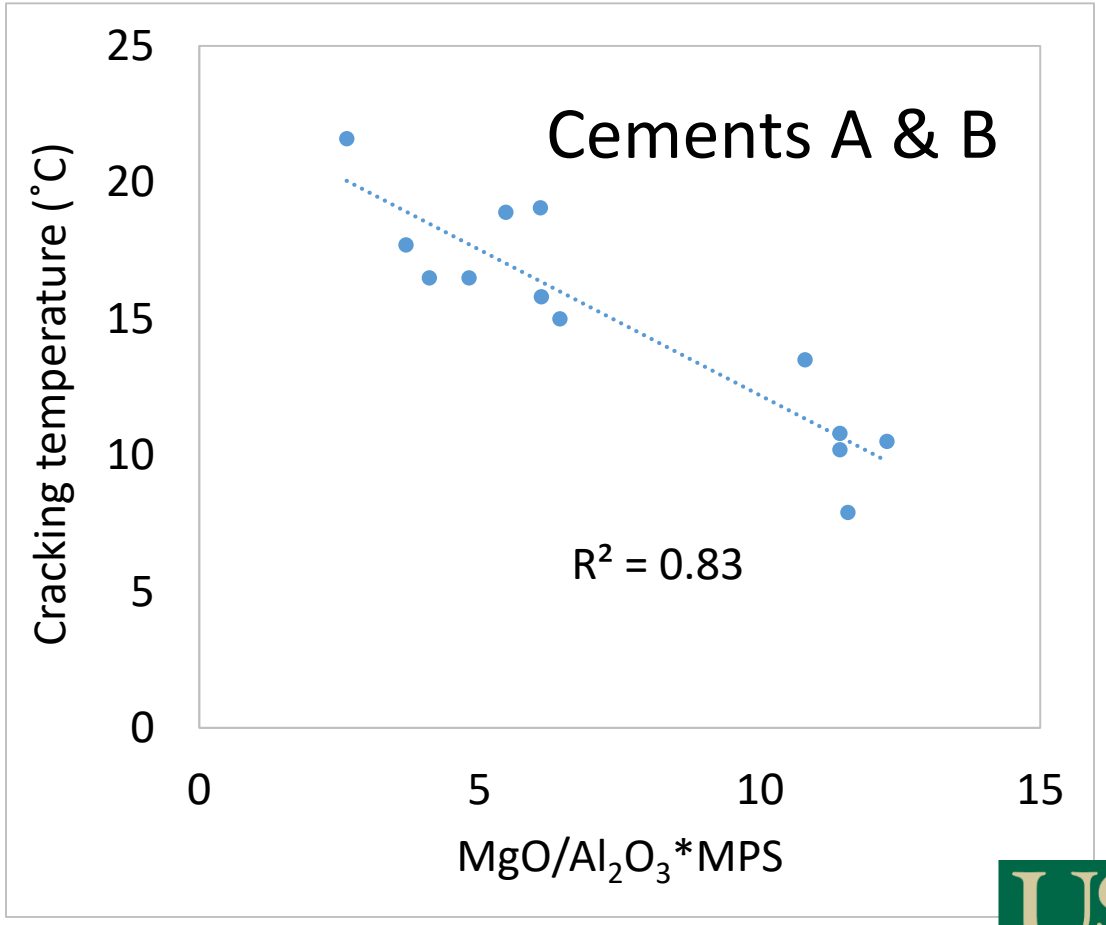
Material Property-Performance Relationship





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Summary

- Cement replacement with 60% slag reduced temperature rise and improved cracking resistance regardless of slag composition compared to the control
- However, cracking potential (in terms of RCF indices) varied between different slags
- Al_2O_3 and MgO content as well as fineness were identified as slag parameters affecting cracking potential
- Increasing MgO/Al_2O_3 ratio decreased T_z, which indicates an improvement in cracking resistance
- In addition to MgO/Al_2O_3 ratio, T_{cr} was affected by slag fineness
- Increasing MgO/Al_2O_3*MPS decreased T_{cr}, also indicating an improvement in cracking resistance

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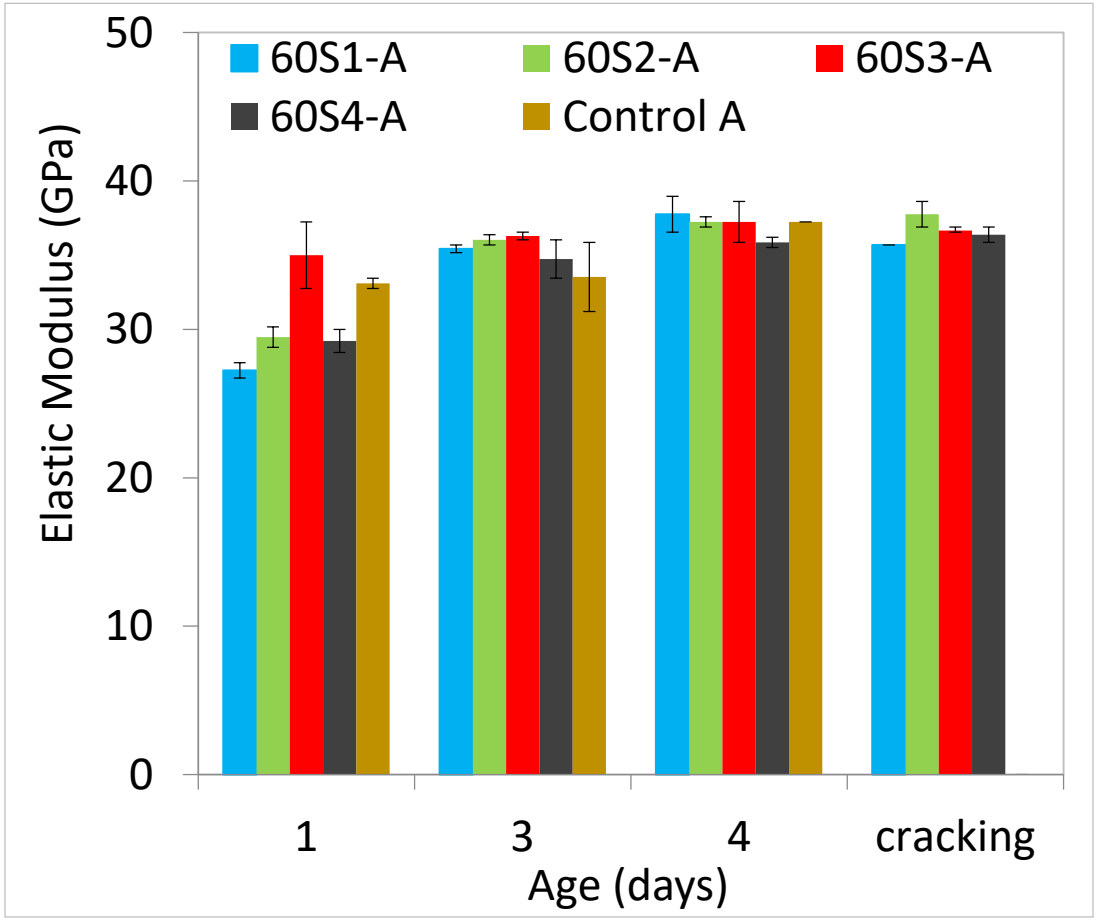
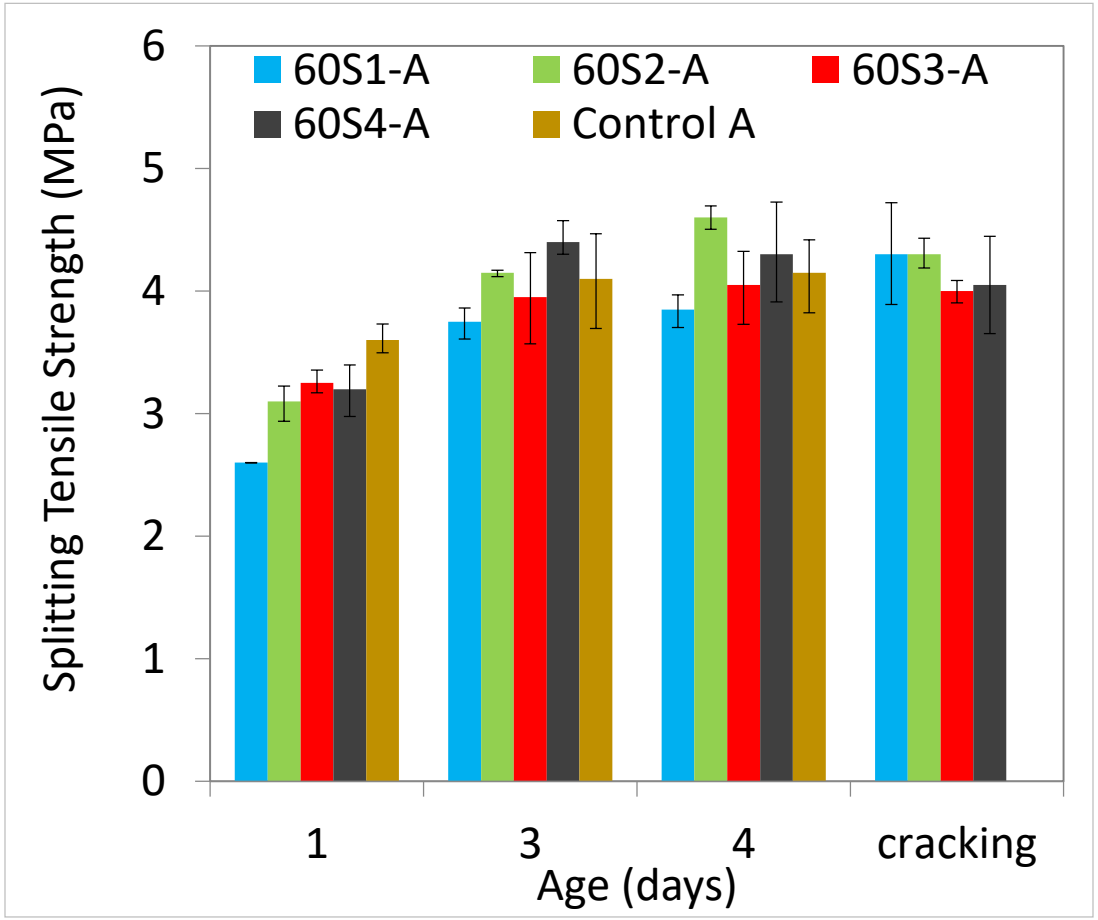
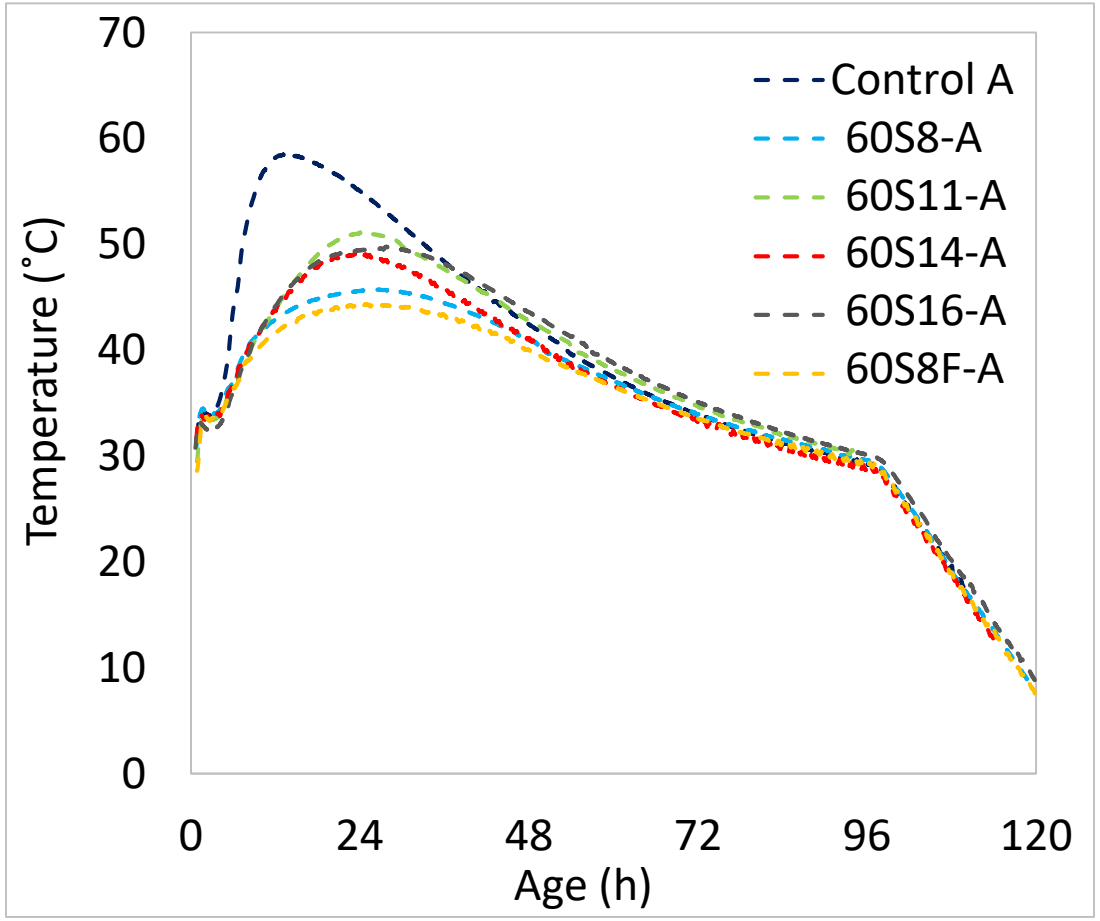
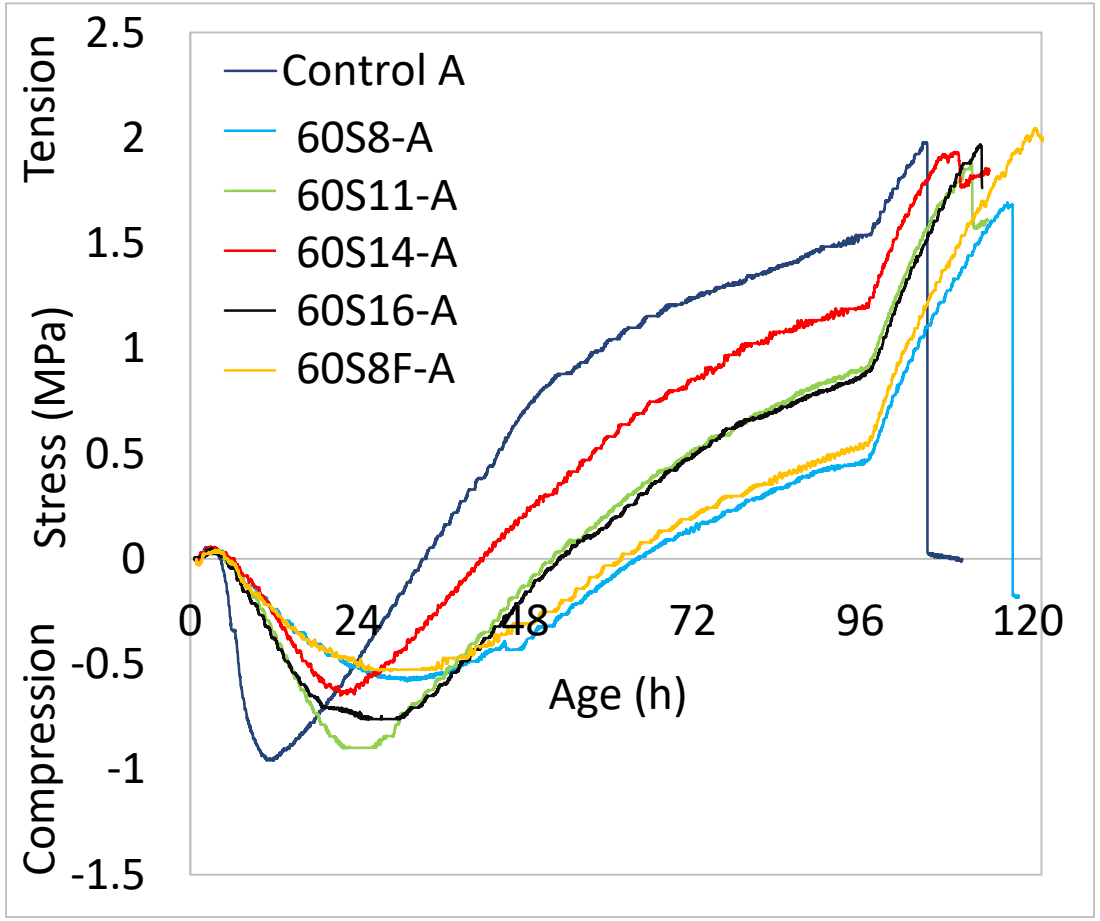
Mechanical properties



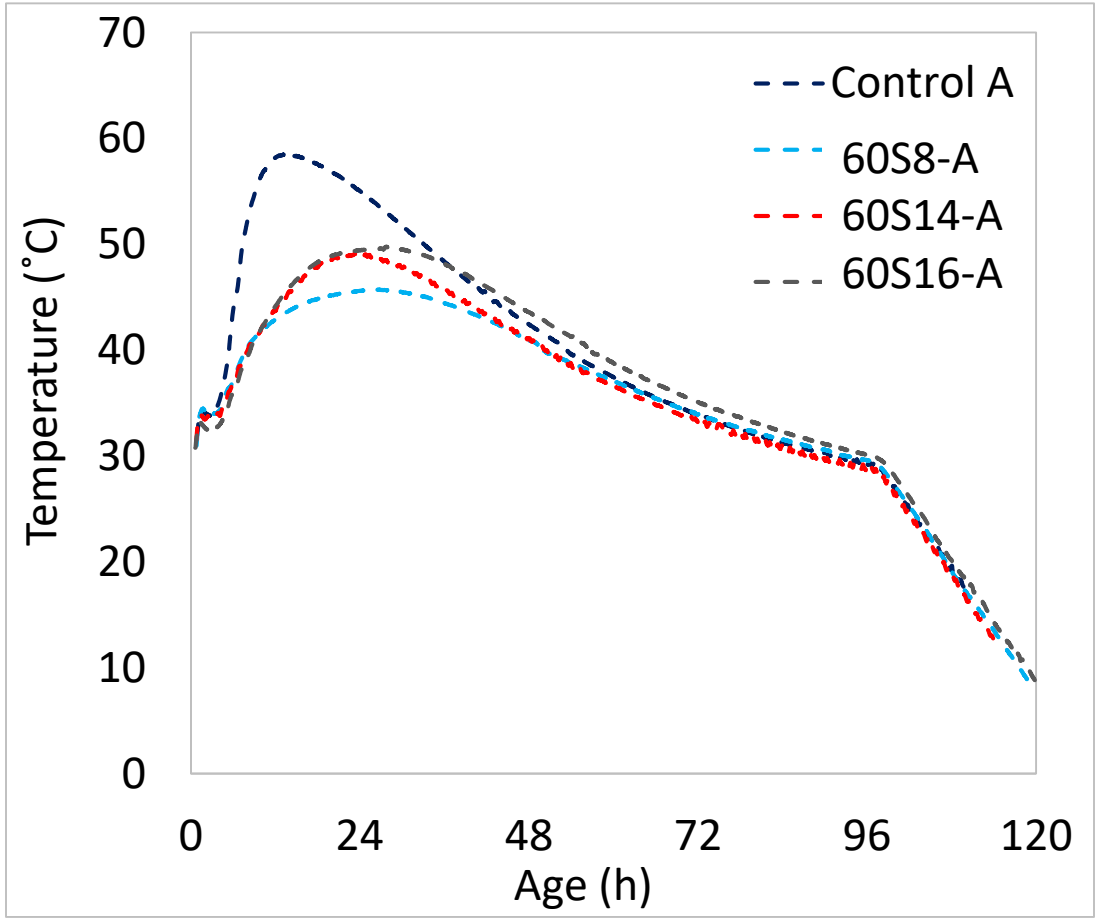


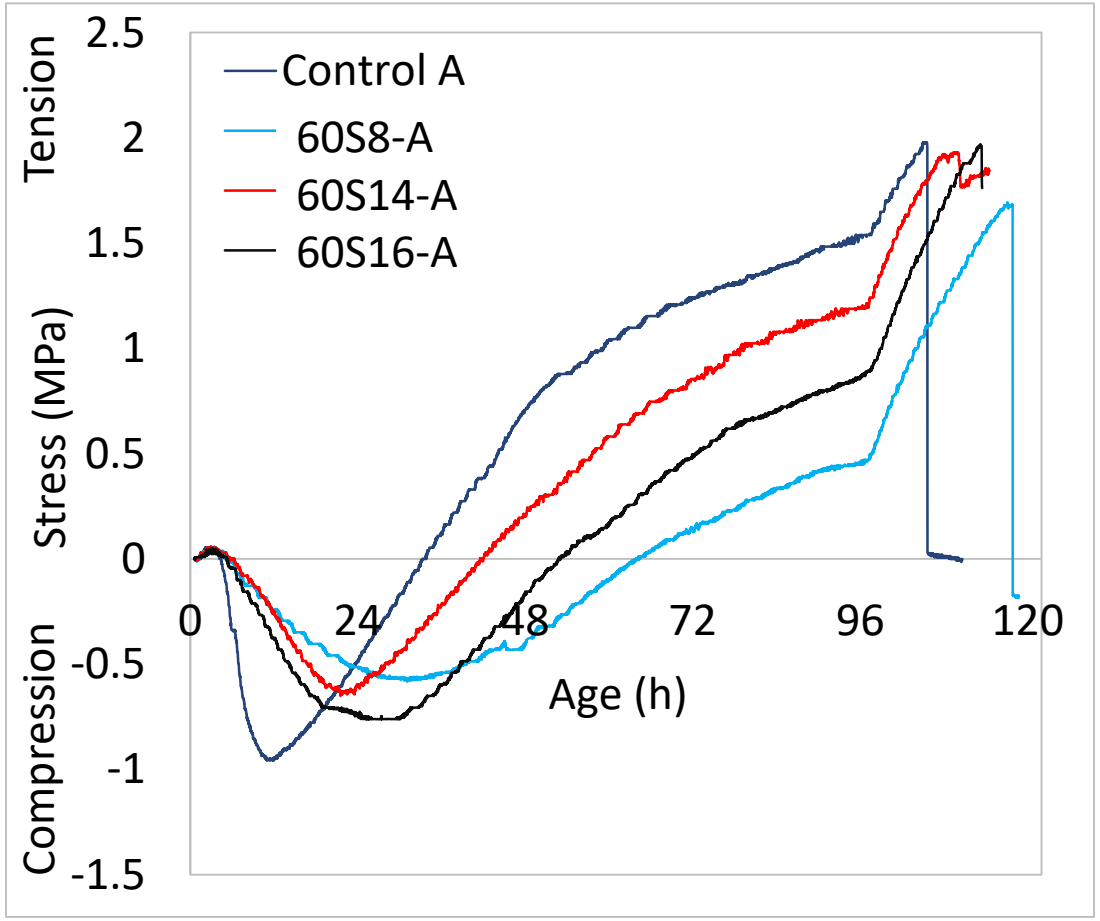
Temperature and stress development with Cement A



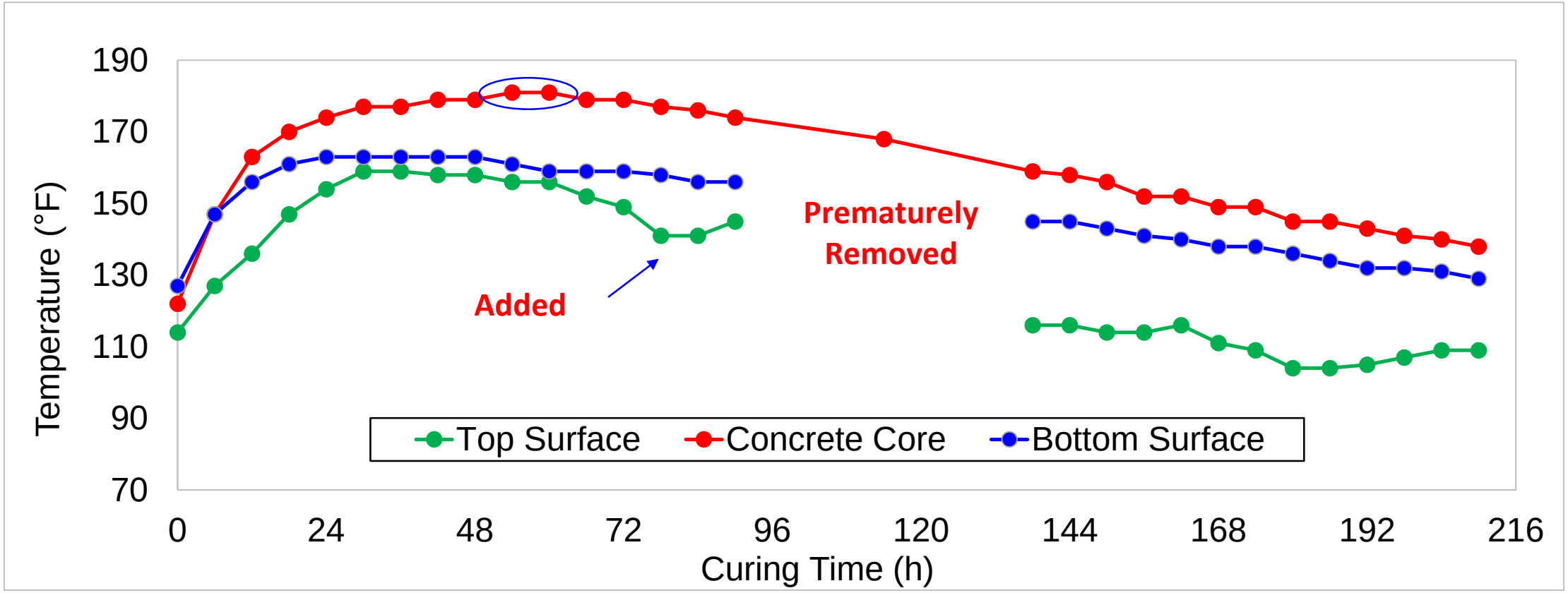


Temperature and stress development with Cement A

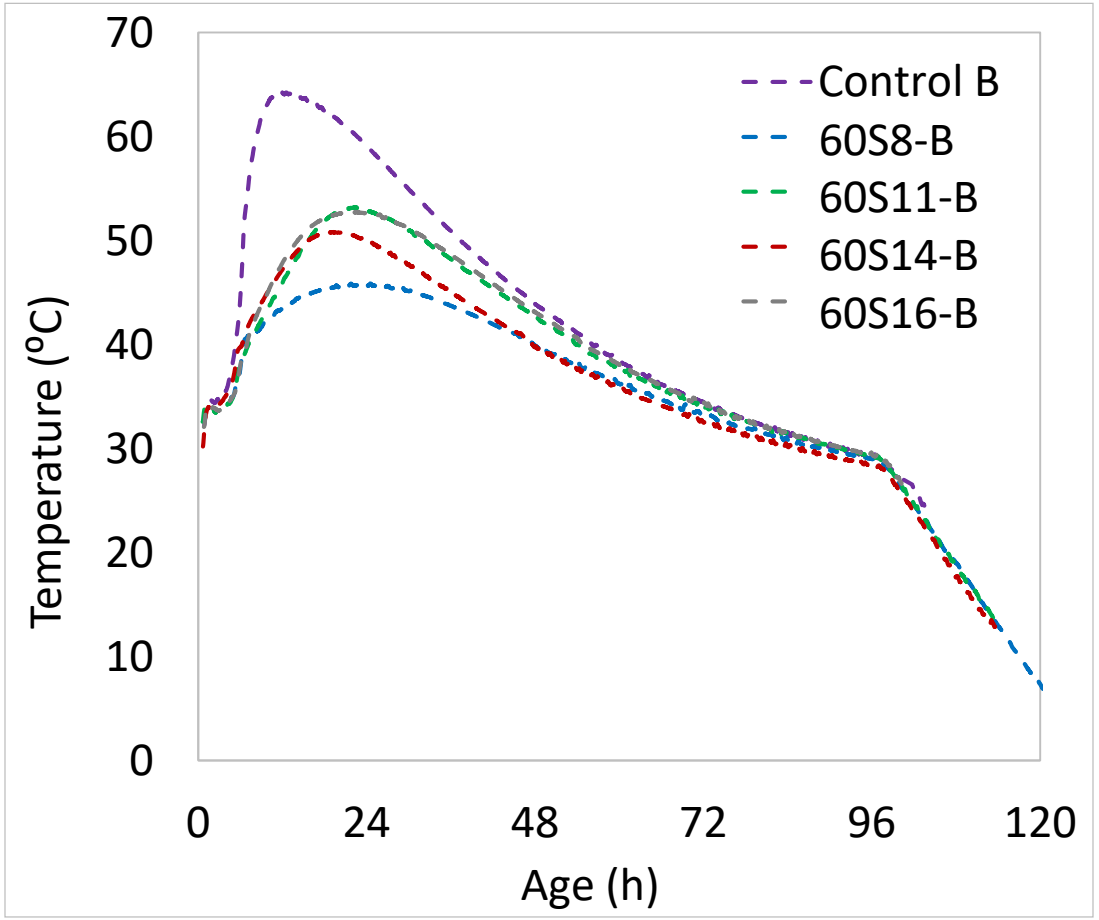


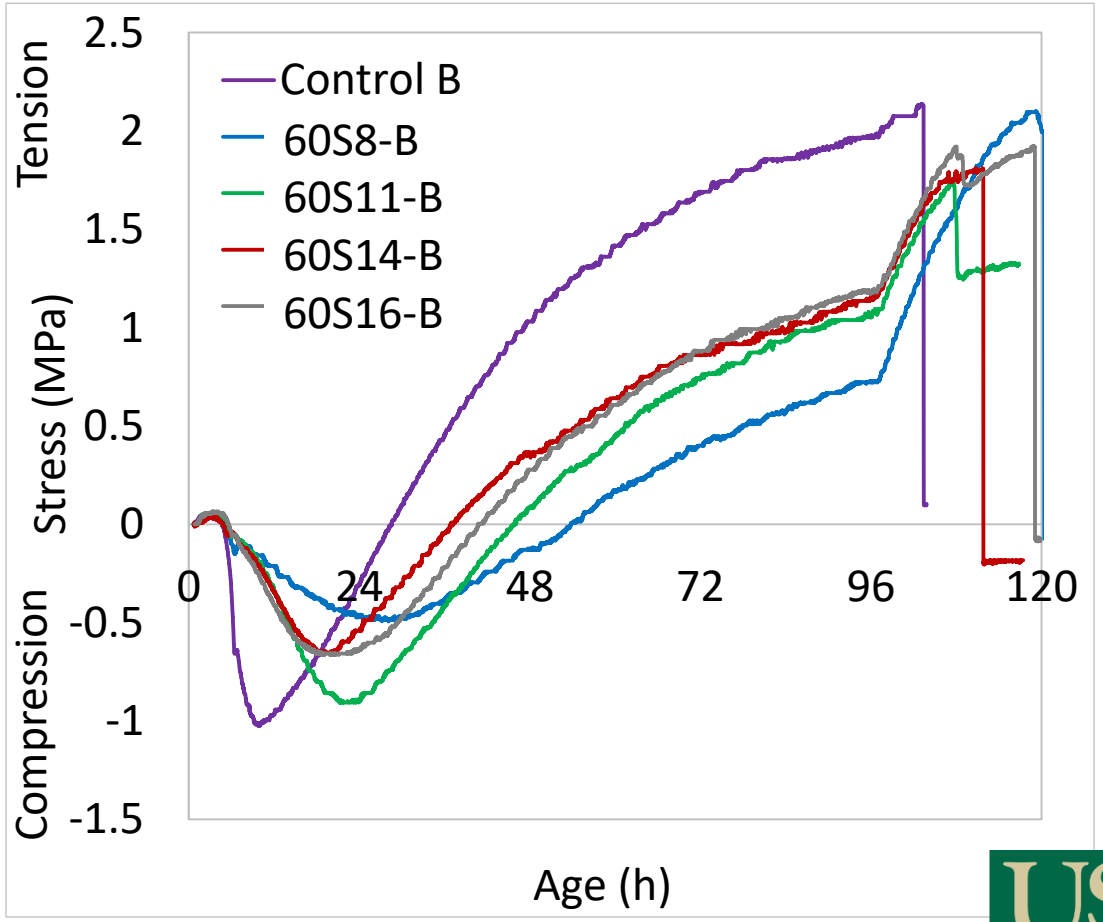


Field temperature profiles



Temperature and Stress Development with Cement B





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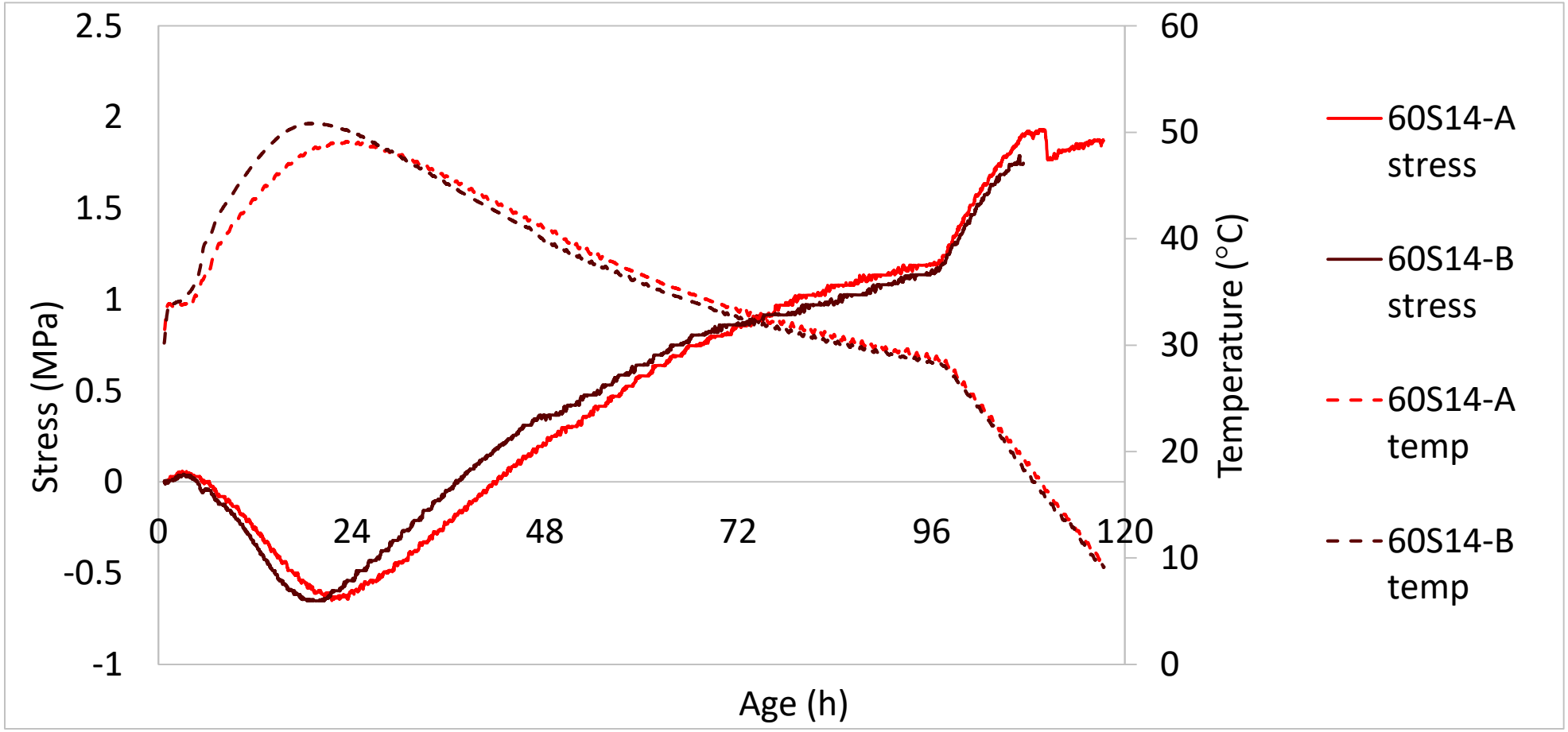
Effect of Cement Composition



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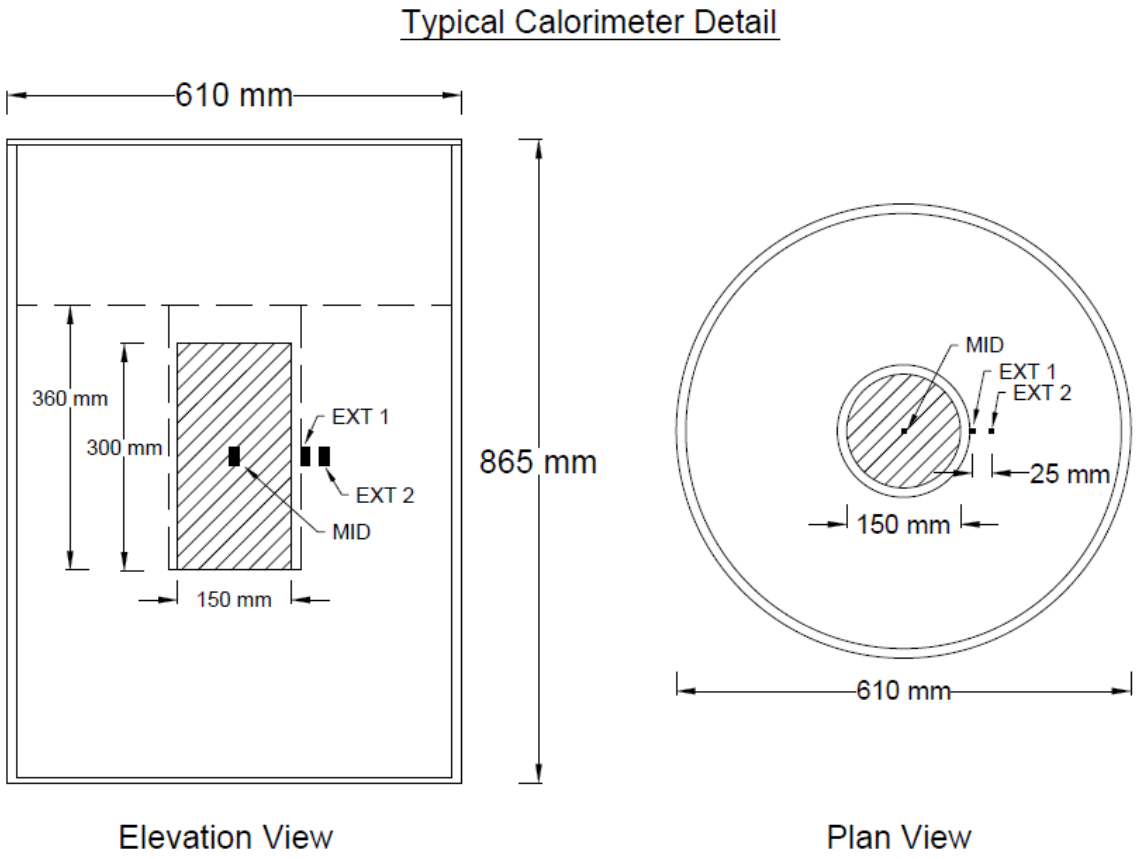
Semi-Adiabatic Calorimeter



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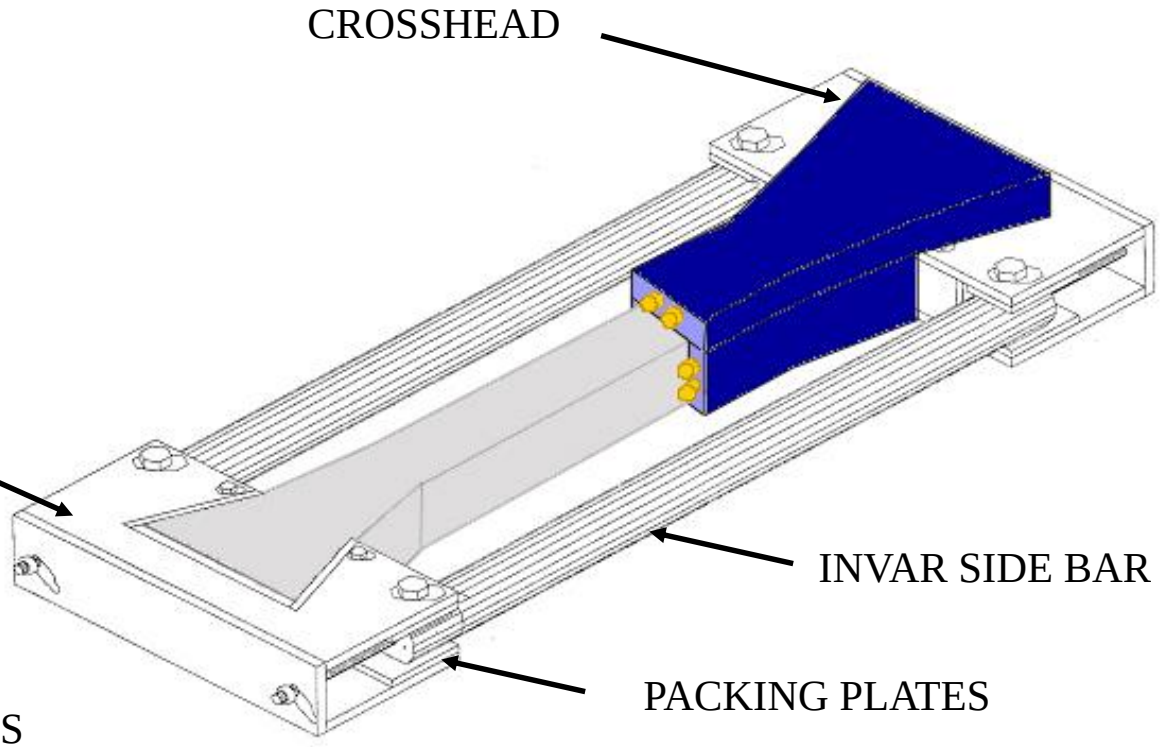
Rigid Cracking Frame



STRAIN GAUGES AND RTD PROBES
ARE MOUNTED ON INVAR SIDE BARS

Figures from Whigham 2005

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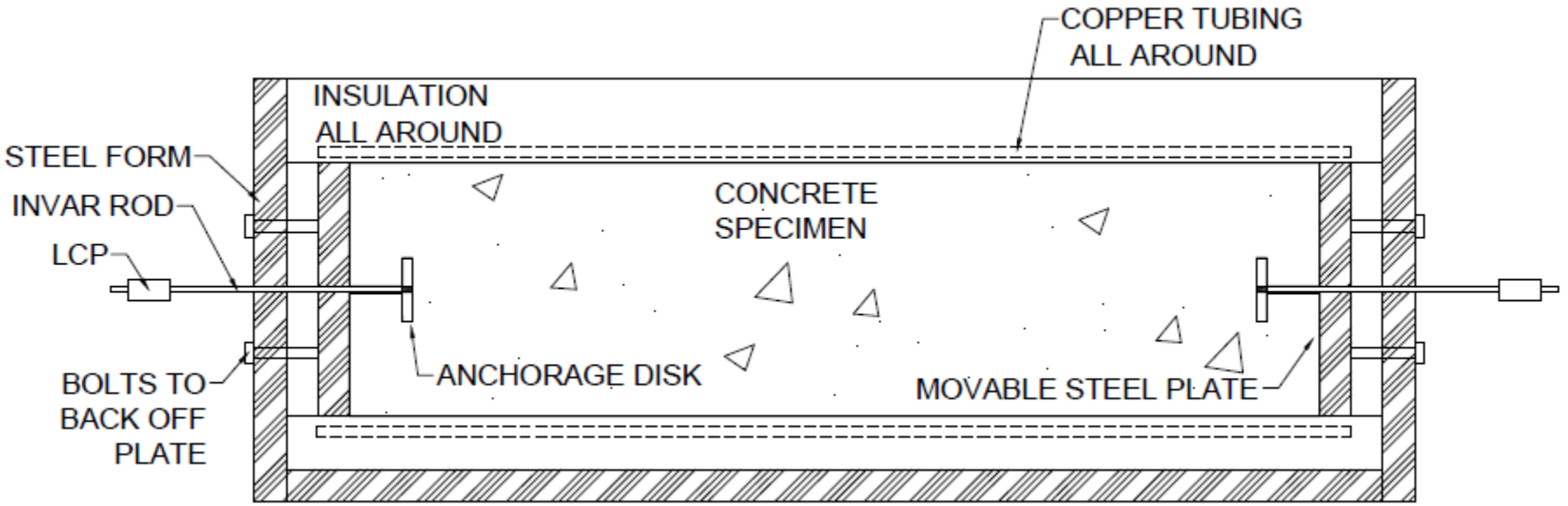
Free Shrinkage Frame



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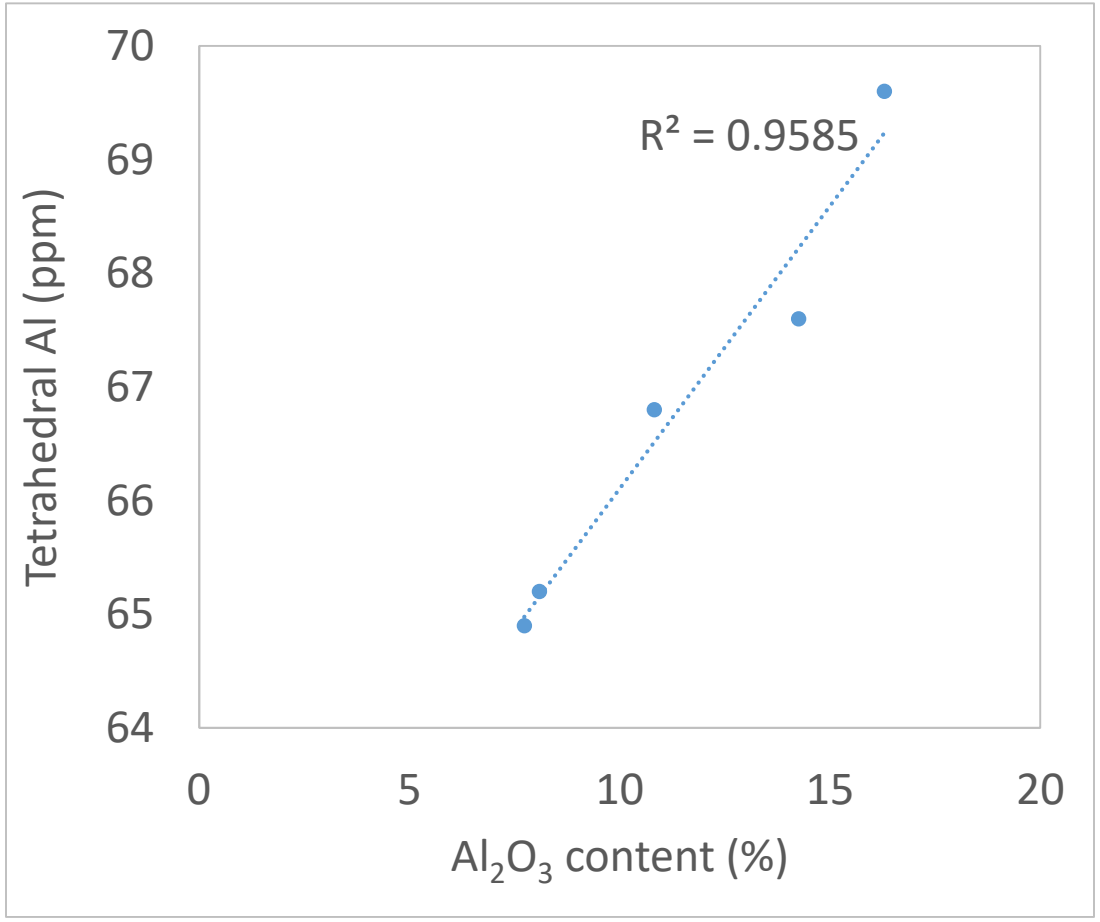
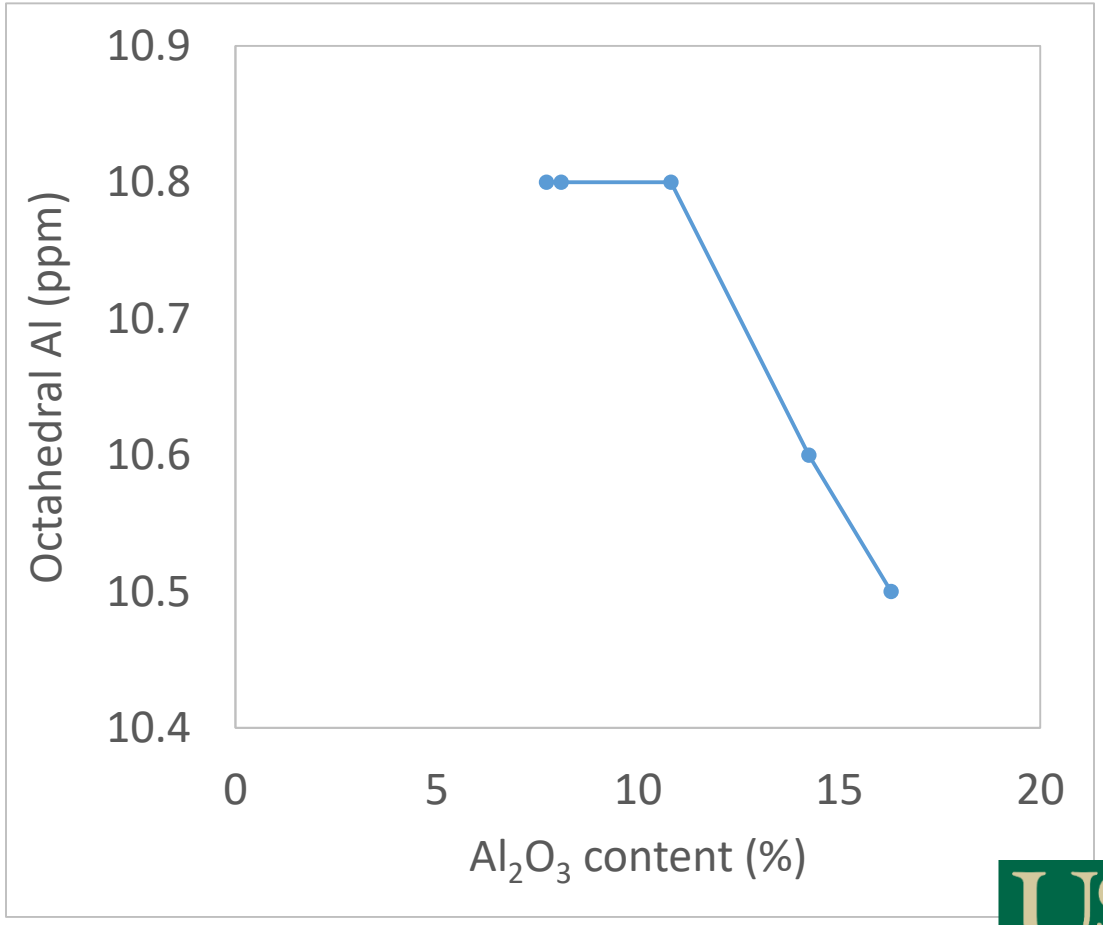
27Al NMR Results





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