U.S. Department of Transportation
Federal Highway Administration
Turner-Fairbank
Highway Research Center

Portland Limestone Cement Variability

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Source: FHWA.

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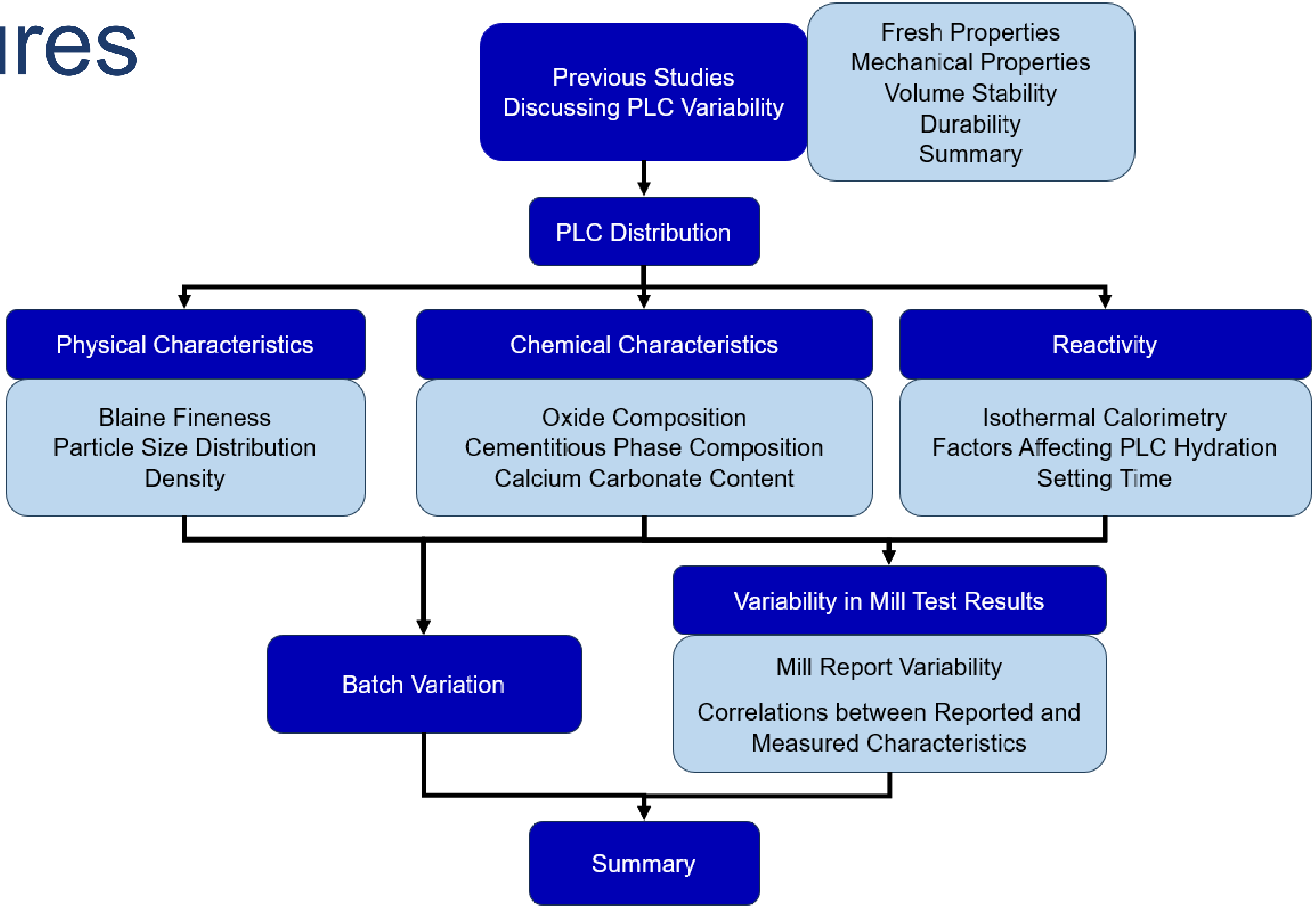
Acronyms

AASHTO	American Association of State Highway and Transportation Officials
BR	bulk resistivity
CNS1	colloidal nanosilica number 1
CNS2	colloidal nanosilica number 2
CS	colloidal nanosilica
cwt	100 lb of cement by weight
$D_{average}$	average particle size diameter
$D_{(xx)}$	particle size diameter at xx percentile
FHWA	Federal Highway Administration
H_u	ultimate heat of hydration
IL(xx)	Type I and limestone blended cement with xx percent limestone content
LOI	loss-on-ignition
LWA	lightweight aggregate
M1	mixture 1
M2	mixture 2
NT	Nordic Test
OPC	ordinary portland cement
PLC	portland limestone cement
QXRD	quantitative X-ray diffraction
SCM	supplementary cementitious material
SR	surface resistivity
SRA	shrinkage reducing admixture
TGA	thermogravimetric analysis
w/c	water-to-cement ratio
w/cm	water-to-cementitious materials ratio
wt. %	weight percentage

Chemical Notations

Al_2O_3	aluminum oxide
C_2S	dicalcium silicate
C_3A	tricalcium aluminate
C_3S	tricalcium silicate
C_4AF	tetracalcium aluminoferrite
$CaCO_3$	calcium carbonate
CaO	calcium oxide
Cr_2O_3	chromium (Ⅲ) oxide
Fe_2O_3	iron oxide
K_2O	potassium oxide
MgO	magnesium oxide
Mn_2O_3	manganese (Ⅲ) oxide
Na_2O	sodium oxide
P_2O_5	phosphorous pentoxide
SiO_2	silicon dioxide
SO_3	sulfur trioxide
SrO	strontium oxide
TiO_2	titanium dioxide
ZnO	zinc oxide

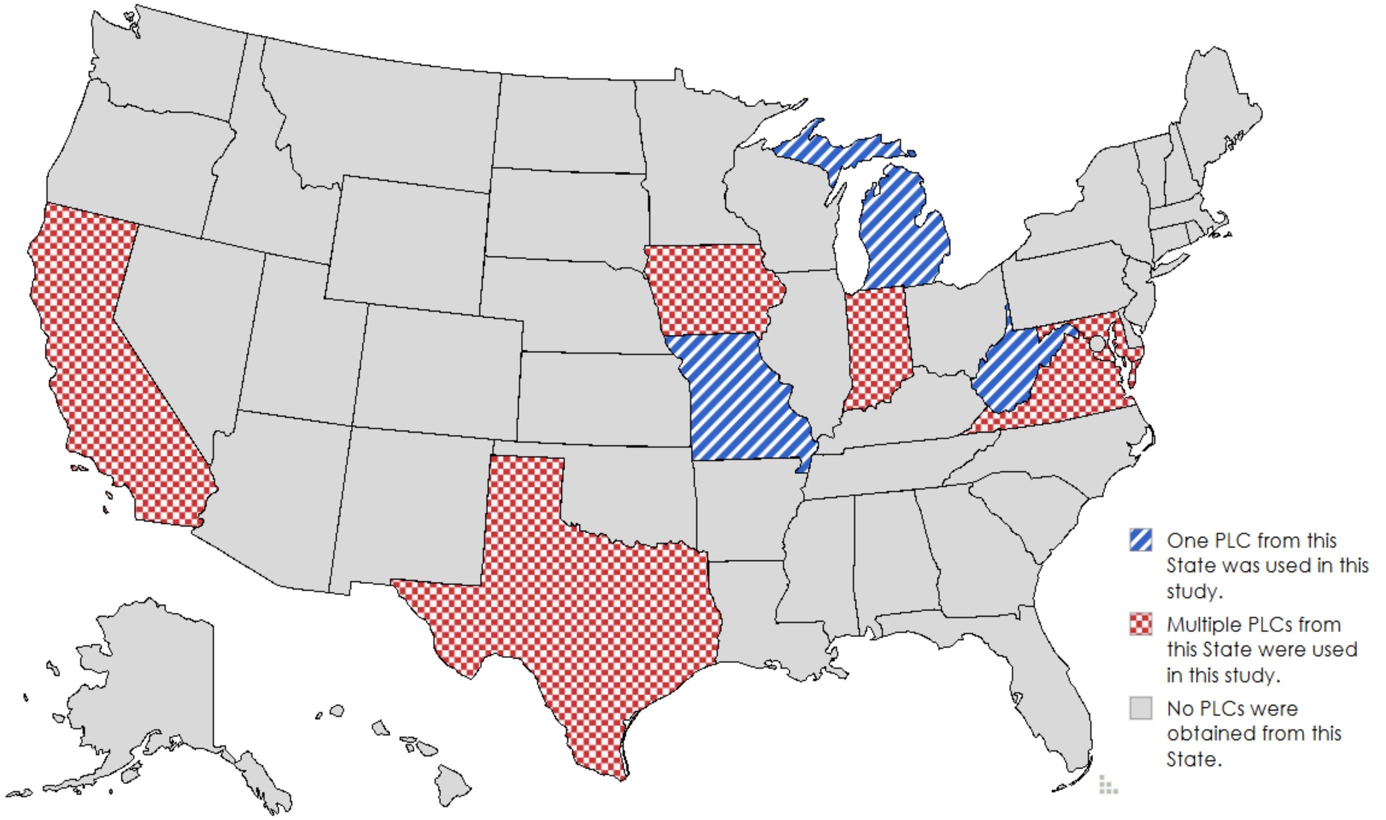
Study Features



Source: FHWA.

PLCs

- Eighteen PLC samples were collected from 13 cement plants in 9 States.
- PLCs include different production methods, raw material sources, geology, and grinding aids.
- Four PLC samples were obtained from one cement plant to provide indications of batch-to-batch variability.



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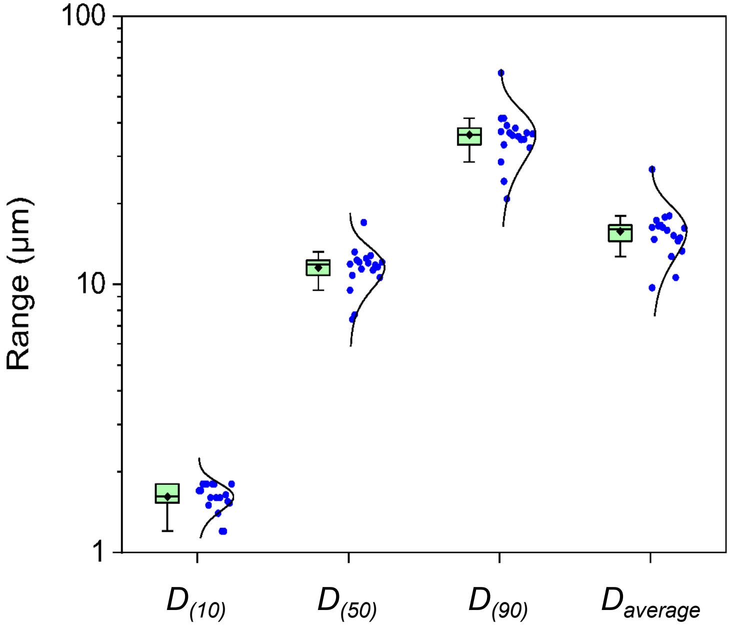
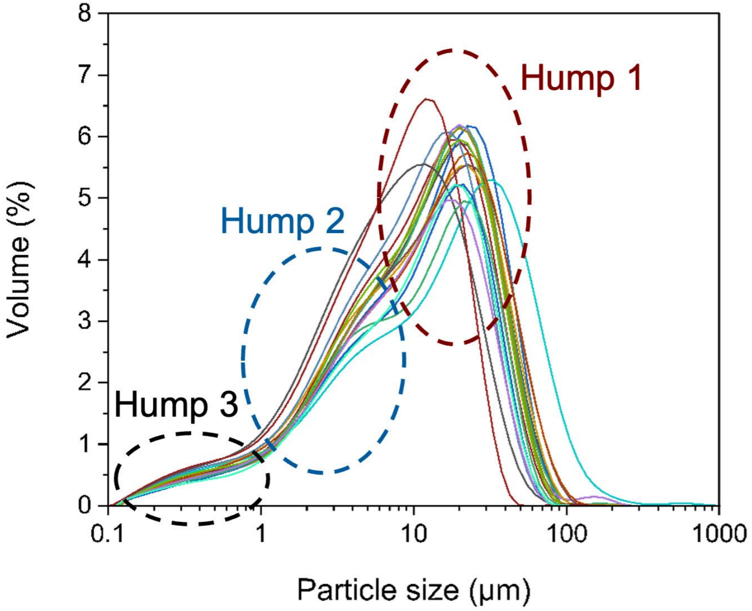
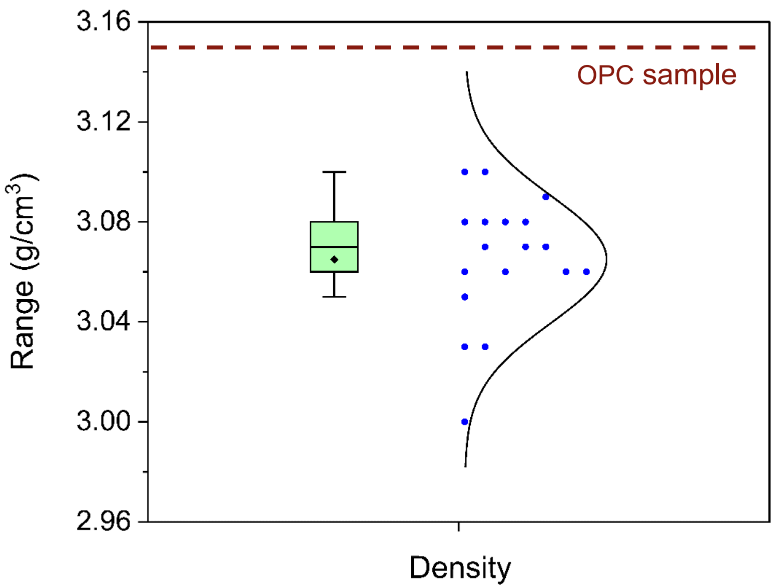
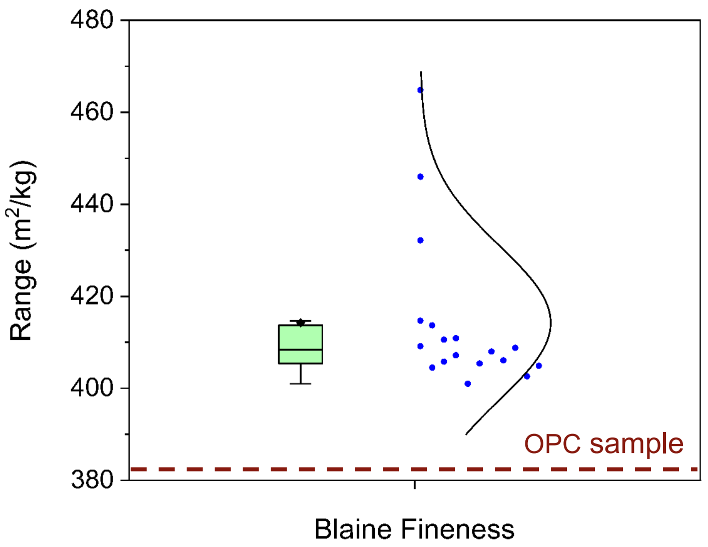
Physical PLC Variability

- The finer portions of the PLCs exhibited narrower variability (variability of $D_{(10)} < D_{(50)} < D_{(90)}$).
- All PLCs featured three distinct particle size groupings.
- Fifteen out of 18 PLCs exhibited Blaine fineness values ranging from 400 to 415 m^2/kg.
- Fifteen out of 18 PLCs exhibited densities ranging from 3.05 to 3.10 g/cm^3.









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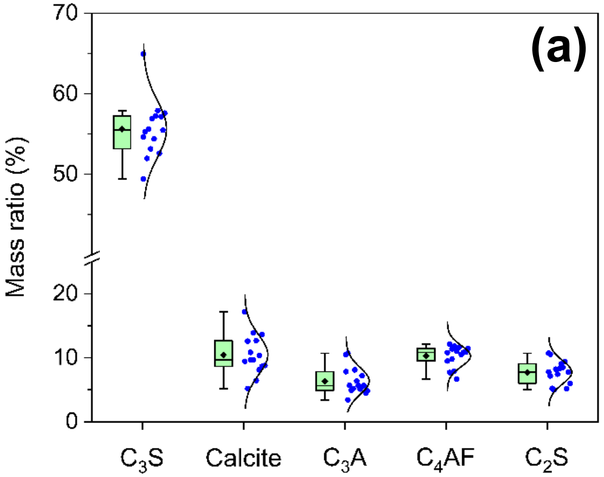
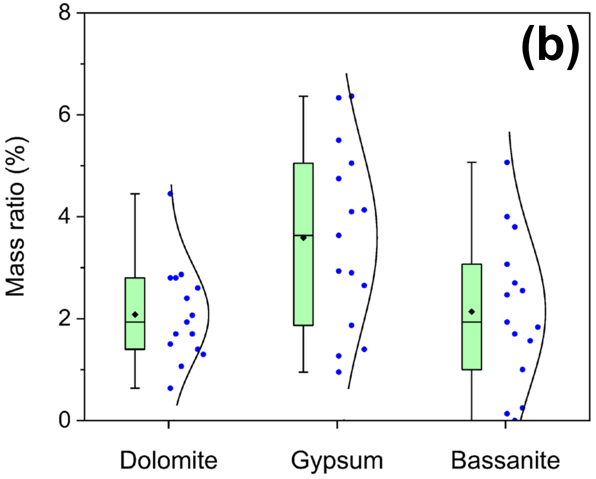
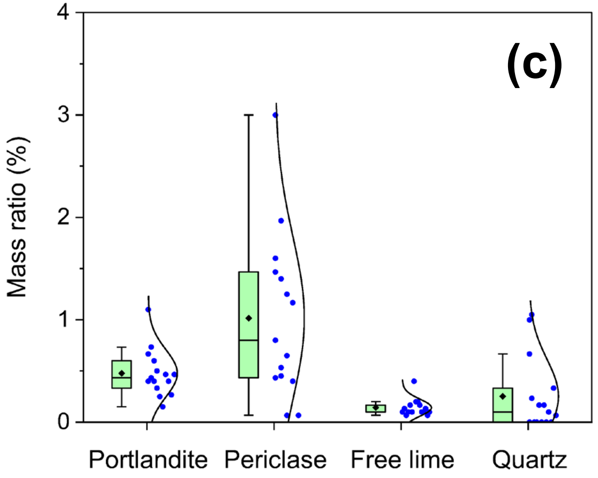
PLC Phase Composition Variability





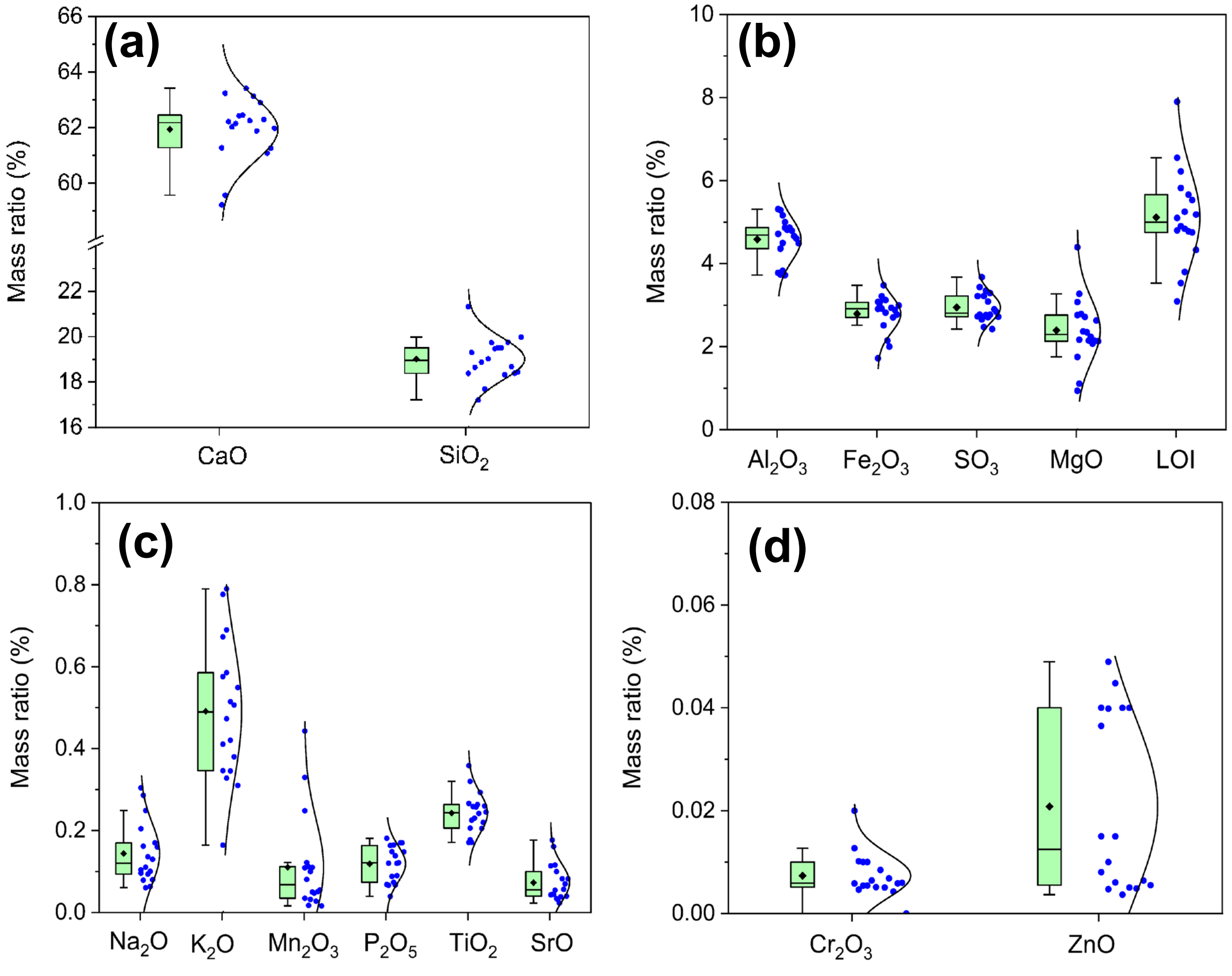


	Alite (C_3S)	Calcite ($CaCO_3$)	Dolomite ($CaMg(CO_3)_2$)	Aluminate (C_3A)	Ferrite (C_4AF)	Belite (C_2S)	Portlandite ($Ca(OH)_2$)	Gypsum ($CaSO_4.2H_2O$)	Bassanite ($CaSO_4.1/2H_2O$)	Total sulfate	Periclase (MgO)	Free lime (f-CaO)	Quartz (SiO_2)
1-d cumulative heat (J/g PLC)	* 0.48	-0.2	-0.4	* 0.46	0.2	-0.3	-0.2	-0.3	0.1	-0.3	-0.4	0.2	* 0.56
3-d cumulative heat (J/g PLC)	* 0.49	-0.3	* 0.50	0.1	-0.4	-0.4	0.2	-0.3	0.2	-0.2	-0.4	0.3	* 0.57
7-d cumulative heat (J/g PLC)	0.2	-0.2	* 0.42	0.2	* -0.38	-0.3	0.2	-0.1	-0.1	-0.1	-0.2	0.2	* 0.38
H_u (J/g PLC)	-0.2	0.1	-0.4	0.3	-0.4	-0.1	0.2	0.3	-0.4	0.2	-0.2	-0.1	0.2

- Alite and dolomite have high variability and moderate correlation with reactivity.
- Aluminate had low variability and moderate 1-d reactivity.
- Gypsum and bassanite have high variability and low correlation with reactivity.

All images source: FHWA.

PLC Oxides Variability



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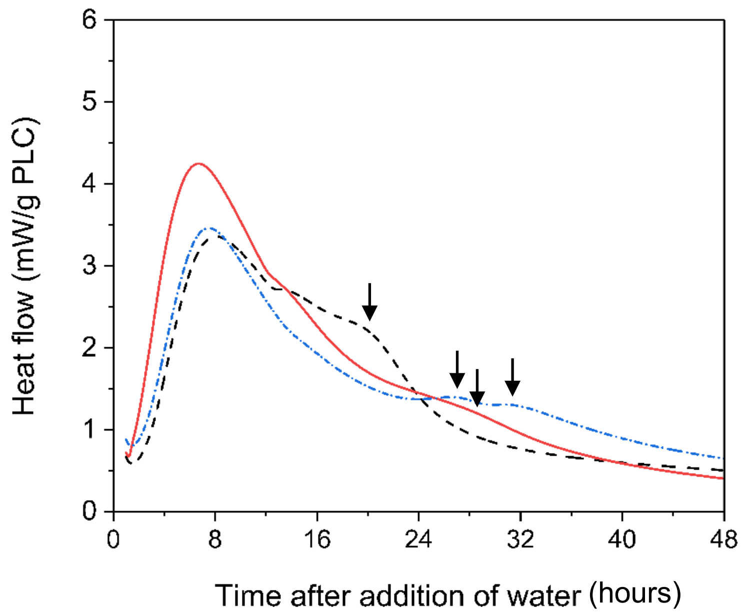
	Al_2O_3	SiO_2	CaO	SO_3	MgO	Na_2O	K_2O	Na_2O_{eq}	$CaO + SiO_2$	$CaO + Al_2O_3$	$CaO + SiO_2 + Al_2O_3$
1-d cumulative heat (J/g PLC)	* -0.42	0.2	-0.1	* 0.45	* -0.39	0.3	* 0.59	* 0.62	0.2	-0.2	-0.1
3-d cumulative heat (J/g PLC)	-0.2	0.2	0.3	0.2	-0.3	* 0.52	0.3	* 0.40	0.2	0.2	0.2
7-d cumulative heat (J/g PLC)	-0.2	0.2	0.2	-0.1	-0.2	* 0.40	0.2	0.2	0.2	0.2	0.2
Hu (J/g PLC)	0.1	0.2	0.1	-0.2	-0.2	0.2	-0.2	-0.2	0.2	0.2	0.2

	$CaO + Al_2O_3 + SO_3$	$CaO + SiO_2 + Al_2O_3 + SO_3$	$SiO_2 + Al_2O_3$	$SiO_2 + Al_2O_3 + SO_3$	$CaO + MgO$	$SiO_2 + MgO$	$CaO + SiO_2 + MgO$	$Al_2O_3 + MgO$	$CaO + Al_2O_3 + MgO$	$CaO + Al_2O_3 + SO_3 + MgO$	$CaO + Al_2O_3 + SiO_2 + MgO$
1-d cumulative heat (J/g PLC)	-0.2	0.2	-0.2	0.2	* -0.45	-0.2	-0.2	* -0.48	* -0.46	-0.3	-0.2
3-d cumulative heat (J/g PLC)	0.2	0.3	-0.2	0.3	-0.3	0.1	-0.1	* -0.36	-0.2	-0.1	0.1
7-d cumulative heat (J/g PLC)	0.2	0.3	0.3	0.3	-0.2	0.2	0.2	-0.3	-0.2	-0.1	0.1
Hu (J/g PLC)	-0.1	-0.2	0.3	0.3	-0.2	0.2	0.2	-0.2	-0.1	-0.2	0.1

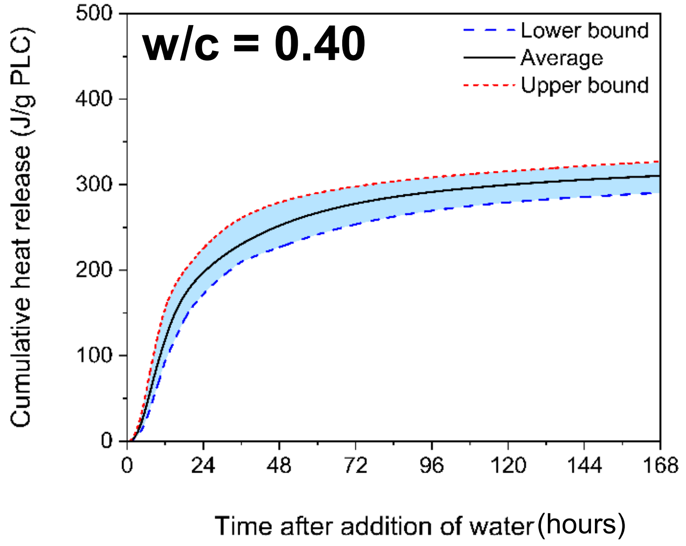
- Moderate variability shown in MgO and moderate correlation with 1-d reactivity.
- SO_3 has tight variability and moderate correlation with 1-d reactivity.
- Alkalis have high variability and high correlation with reactivity.

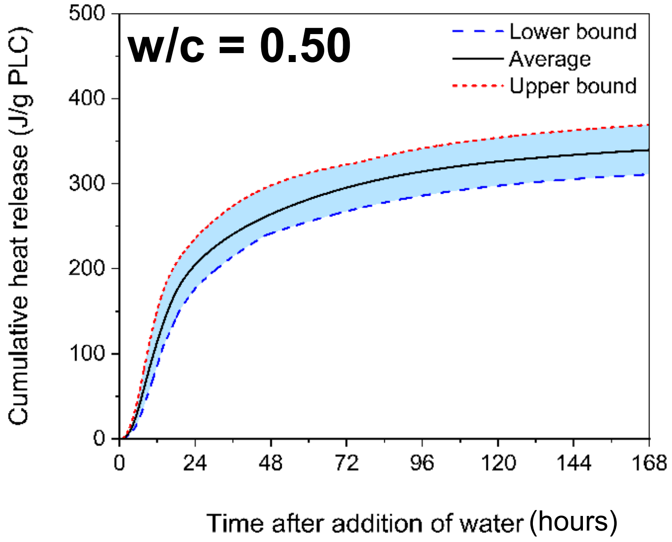
PLC Reactivity Variations

- Renewed aluminate peaks occurred at varying intervals within PLC hydration, ranging from immediately after the alite peak to 32 h after water contact.



- Cumulative heat release was relatively similar across PLCs when using same w/c.

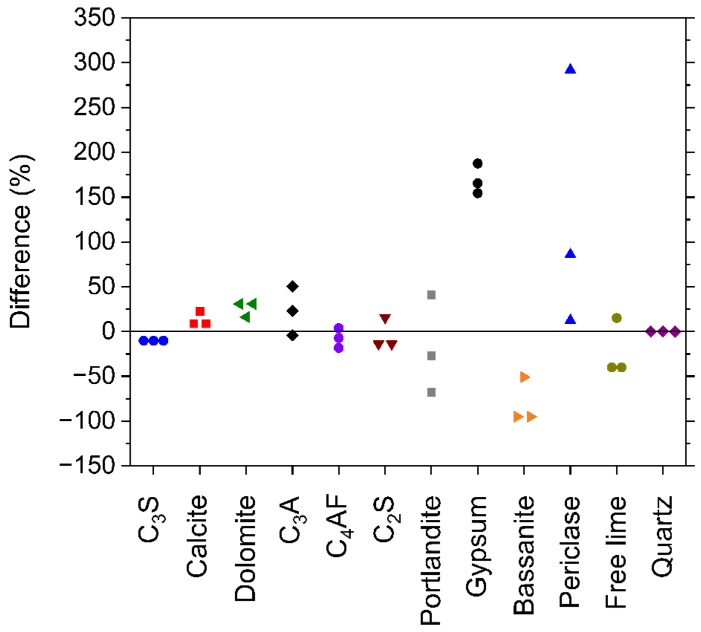


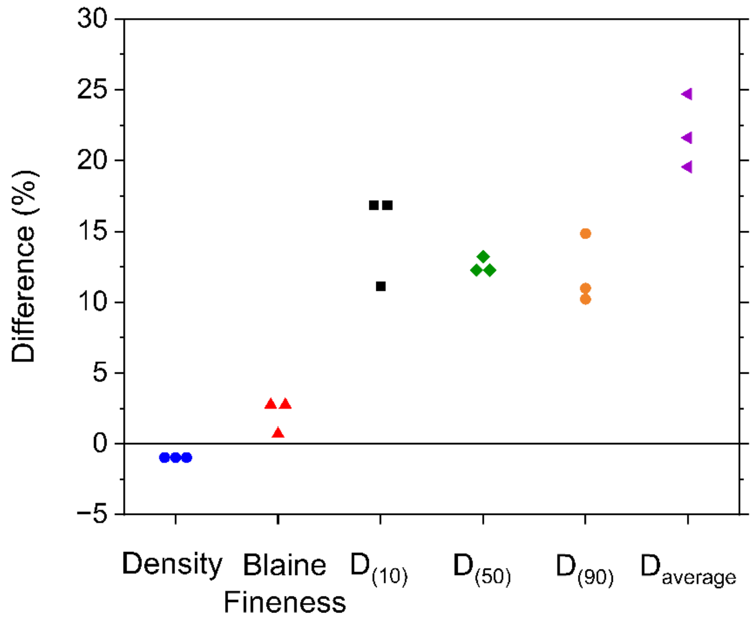


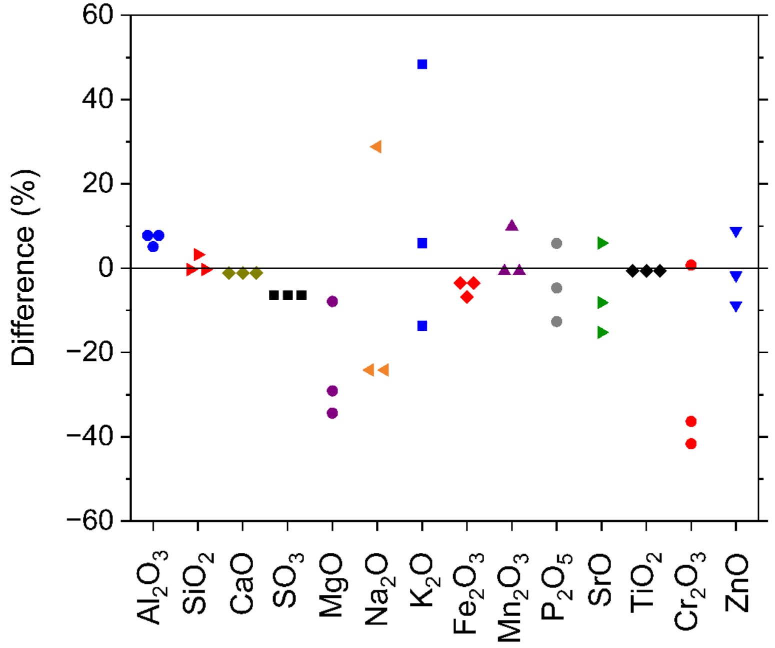
All images source: FHWA.

Batch-to-Batch Variability

- The PLCs exhibited minimal variation in early-age reactivity and early-age hydration (up to 7 d) of IL(10).
- Average particle size showed up to 25 percent variation.
- Major oxides (Al_2O_3, SiO_2, CaO, SO_3, and Fe_2O_3) showed up to 8 percent variation.
- Alite showed up to 10 percent variation.
- The final setting time exhibited greater variation than the initial setting time.



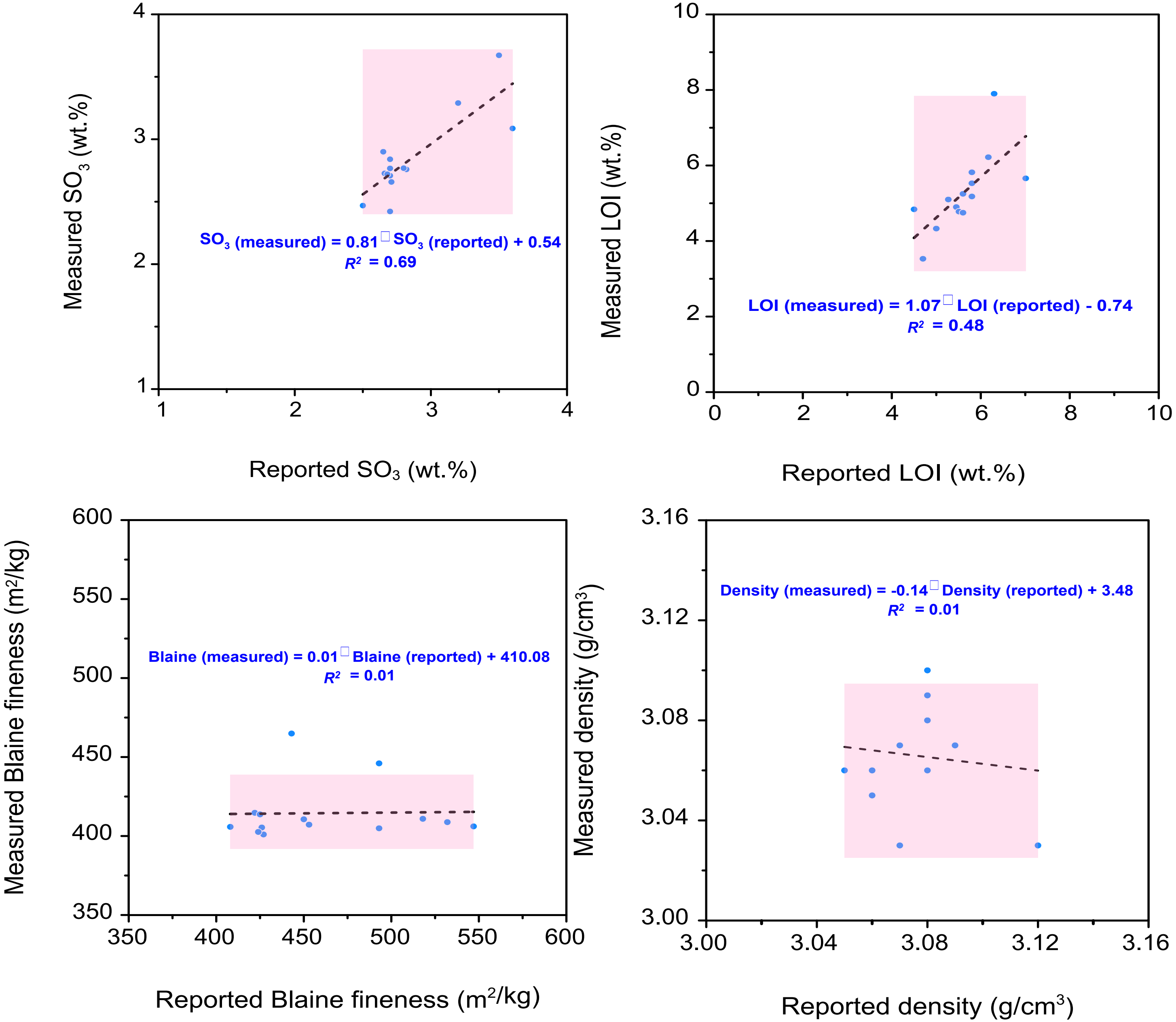




All figures source: FHWA.

Variability in Mill Test Results

- There was a positive correlation between measured and reported chemical characteristics of PLCs.
- There were low correlations between measured and reported physical characteristics.
- Blaine fineness is a poor metric for PLC.



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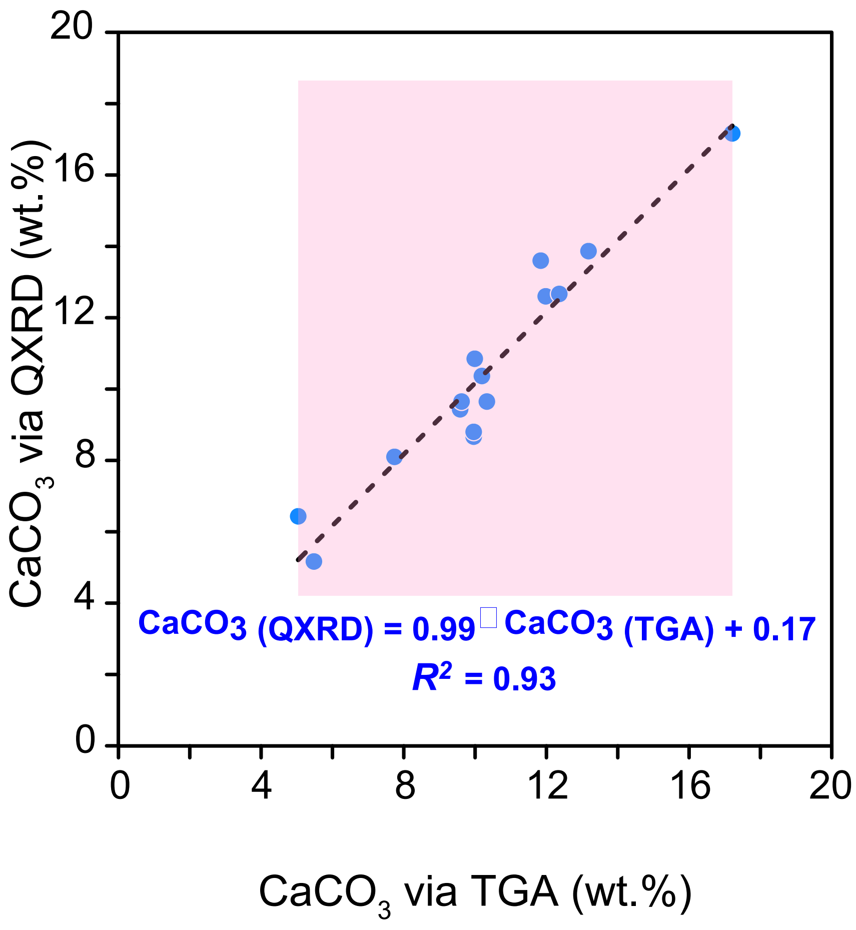
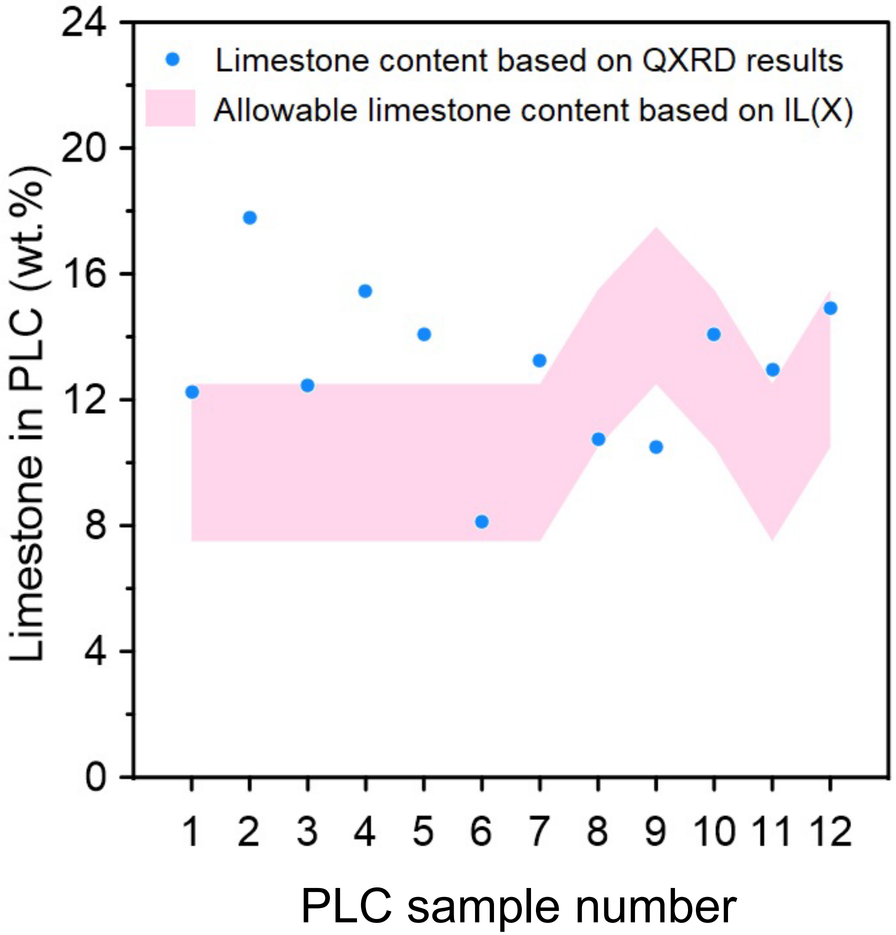
$CaCO_3$ and Estimated Limestone Content





Dolomitic limestone is likely used as feedstock for producing the studied PLCs based on negligible quartz content and dolomite presence.

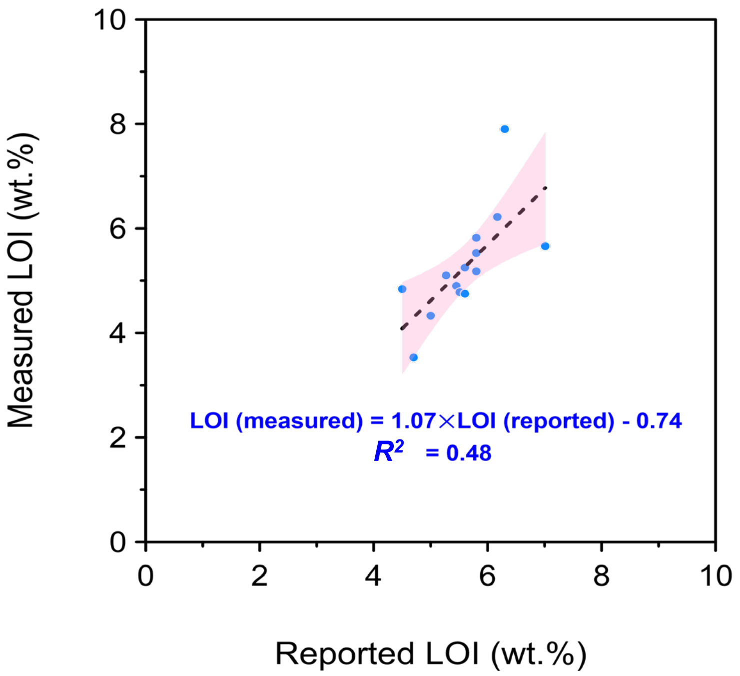
Based on this assumption, the PLC limestone mass content ranges from 7 to 18 percent.

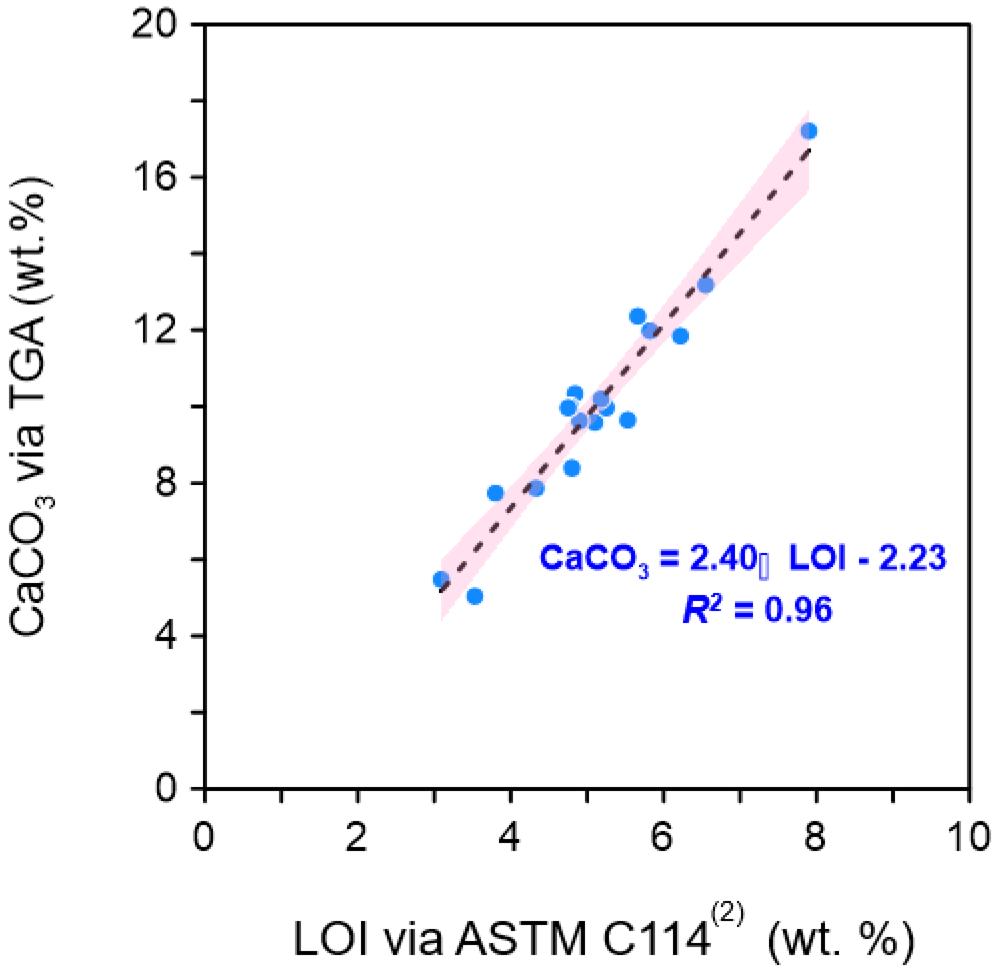
All images source: FHWA.

Using LOI for $CaCO_3$ Estimations

Reported and measured LOI were generally similar.

LOI can be used to estimate $CaCO_3$.





All figures source: FHWA.

Key Findings

- Reactivity of PLCs correlated well with chemical characteristics and correlated poorly with physical characteristics.
- $CaCO_3$ content in PLC can be estimated by measuring LOI using ASTM C114.[(2)]
- PLC characteristics were similar from batch-to-batch for three batches, with the fourth being more varied.
- Estimated limestone content and measured $CaCO_3$ content varied significantly for PLCs across the country.

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The Use of Electrical Durability Tests on Concretes with CS

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September 9, 2025

Source: FHWA.

Purpose

- Investigation 1: Determine if inclusion of commercial CS products in concrete mixtures affects electrical durability test methods differently than nonelectrical test methods.
- Investigation 2: Evaluate durability of concrete mixtures using raw CS products with different surface areas and amounts.
- Investigation 3: Measure autogenous shrinkage of various technologies, including CS, LWA, SRA, and latex.

Investigation 1

Electrical Durability Testing of Concretes with Commercial CS Projects

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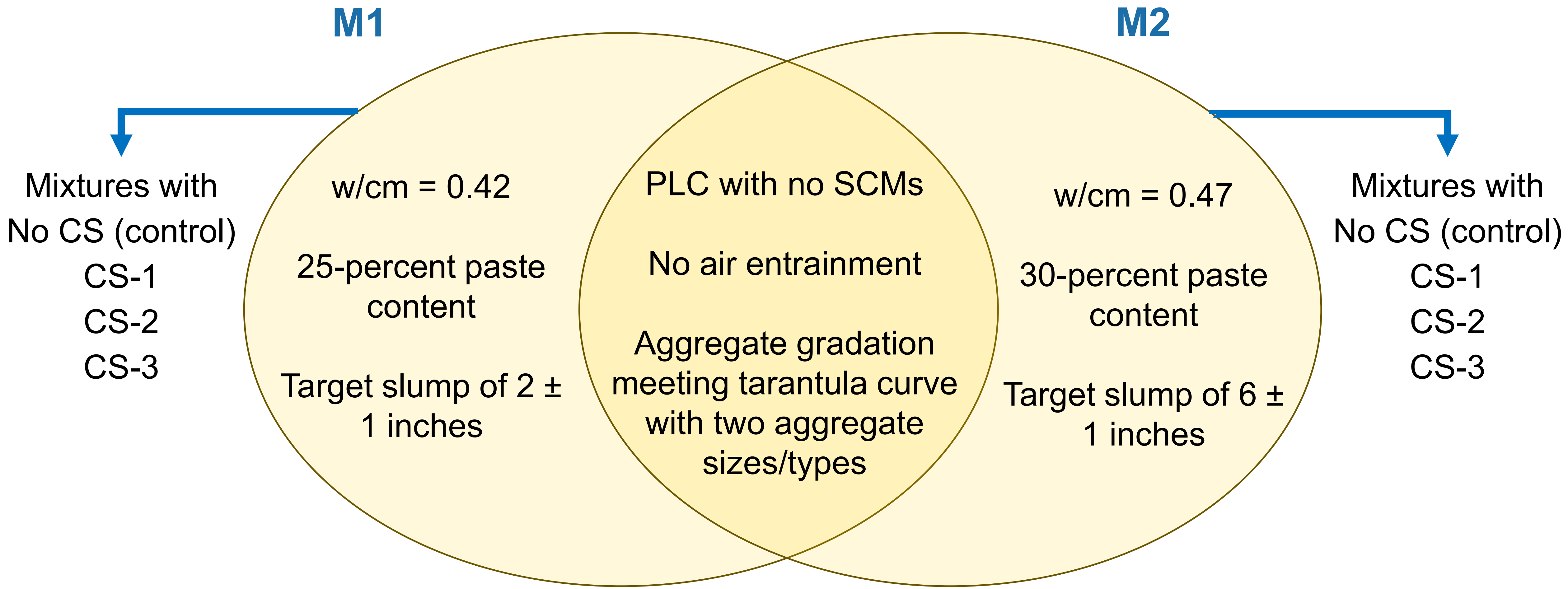
Mixture Overview



Source: FHWA.

Test Matrix

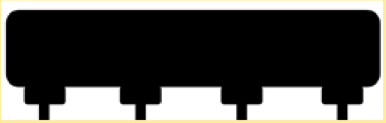
- **Admixture Properties**
  - Solids Content
  - Conductivity
  - Specific Gravity
- **Characterization**
  - Isothermal Calorimetry
- **Concrete Fresh Properties**
  - Slump
  - Total Air
  - Unit Weight
  - Temperature
  - Box Test
- **Concrete Mechanical Performance**
  - Compressive Strength (ASTM C39[3]):
    - 1 d
    - 28 d
    - 56 d
- **Concrete Durability Performance**
  - BR (modified AASHTO T 402[4]):
    - 1 d
    - 3 d
    - 28 d
    - 56 d
  - SR (AASHTO T 358[5]):
    - 1 d
    - 3 d
    - 28 d
    - 56 d
  - Chloride Migration (NT Build 492[6]): 56 d
  - Chloride Diffusion (ASTM C1556[7]): 56 d
  - Porosity

Source: FHWA.

Electrical Versus Physical Tests

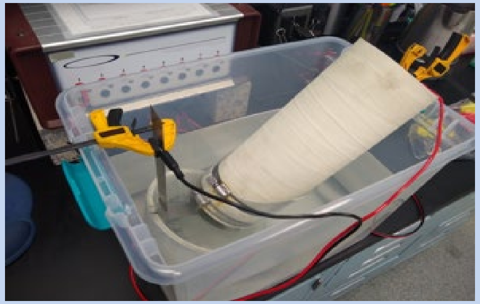
Electrical Tests

Apparent SR[5]



BR[4]

Semielectrical Tests



Chloride migration coefficient[6]

Physical Tests

Chloride diffusion coefficient[7]

Porosity

All figures source: FHWA.

Materials Dosage

The **highest** recommended dosages suggested by the manufacturers were used for all of the commercial products.

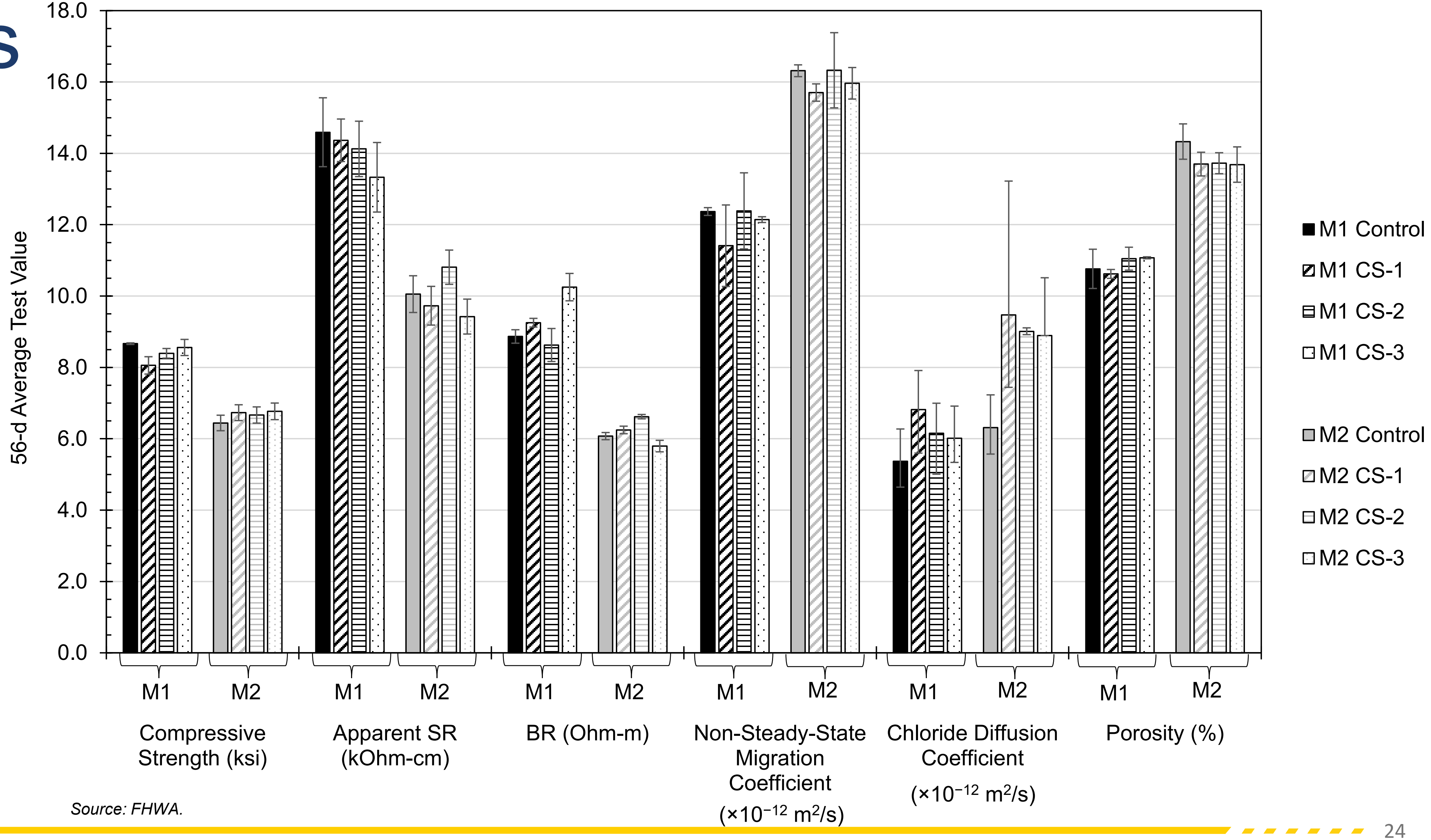
Materials	Manufacturer Recommended Dosage
CS-1	8–**20** fl oz per cwt
CS-2	4–**8** fl oz per cwt
CS-3	0.5–**1.5 percent** by weight of total cementitious materials content

Admixture Conductivity

The admixtures containing CS were not highly conductive.

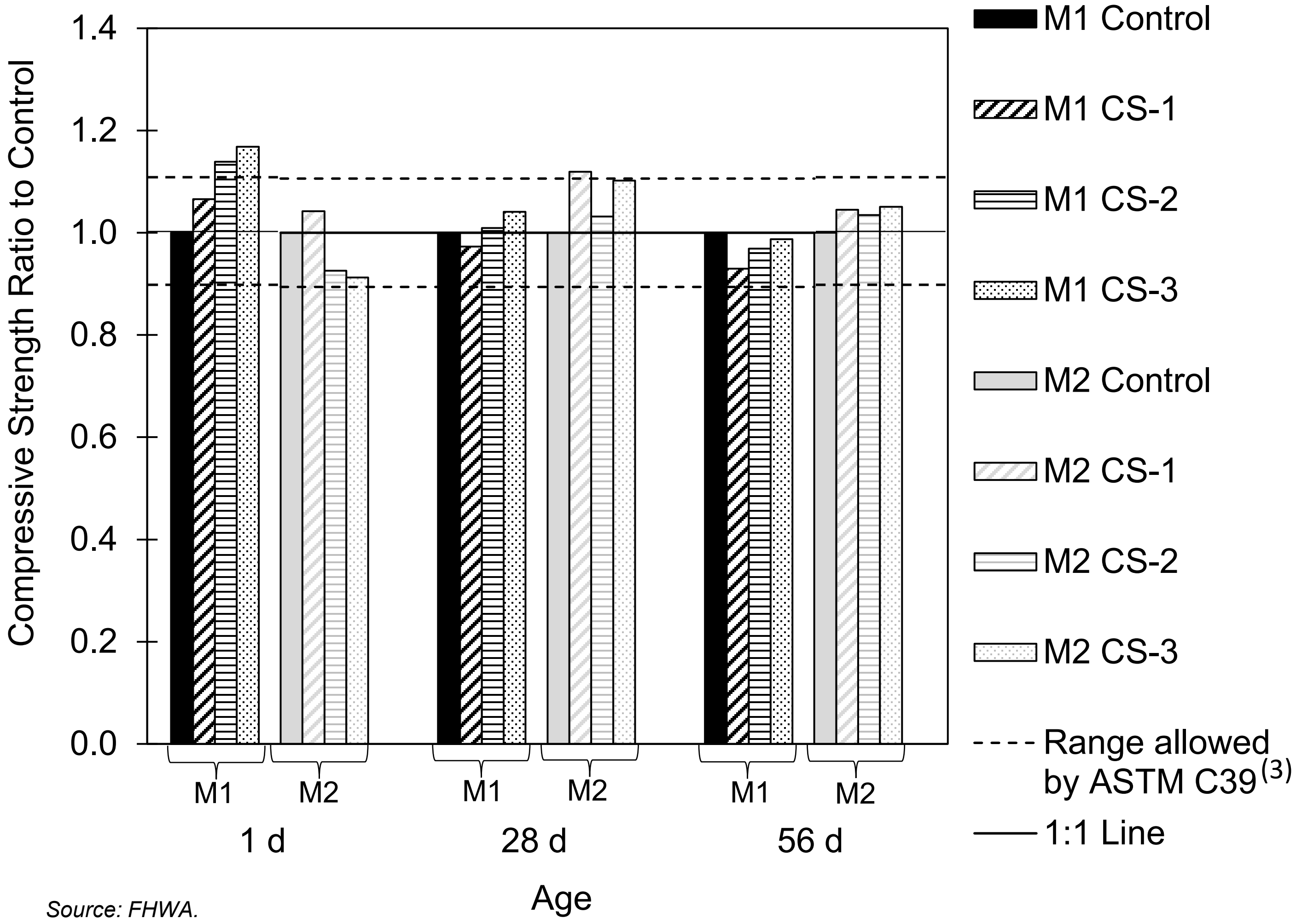
Materials	Conductivity (µS/cm)
CS-1	3,862 at 22.2 ℃
CS-2	2,580 at 22.0 ℃
CS-3	7,164 at 21.5 ℃
Limewater conditioning solution	12,100 at 23.0 ℃
Alkali–concentrated conditioning solution from AASHTO T 402[4]	92,700 at 23.0 ℃

Results



Source: FHWA.

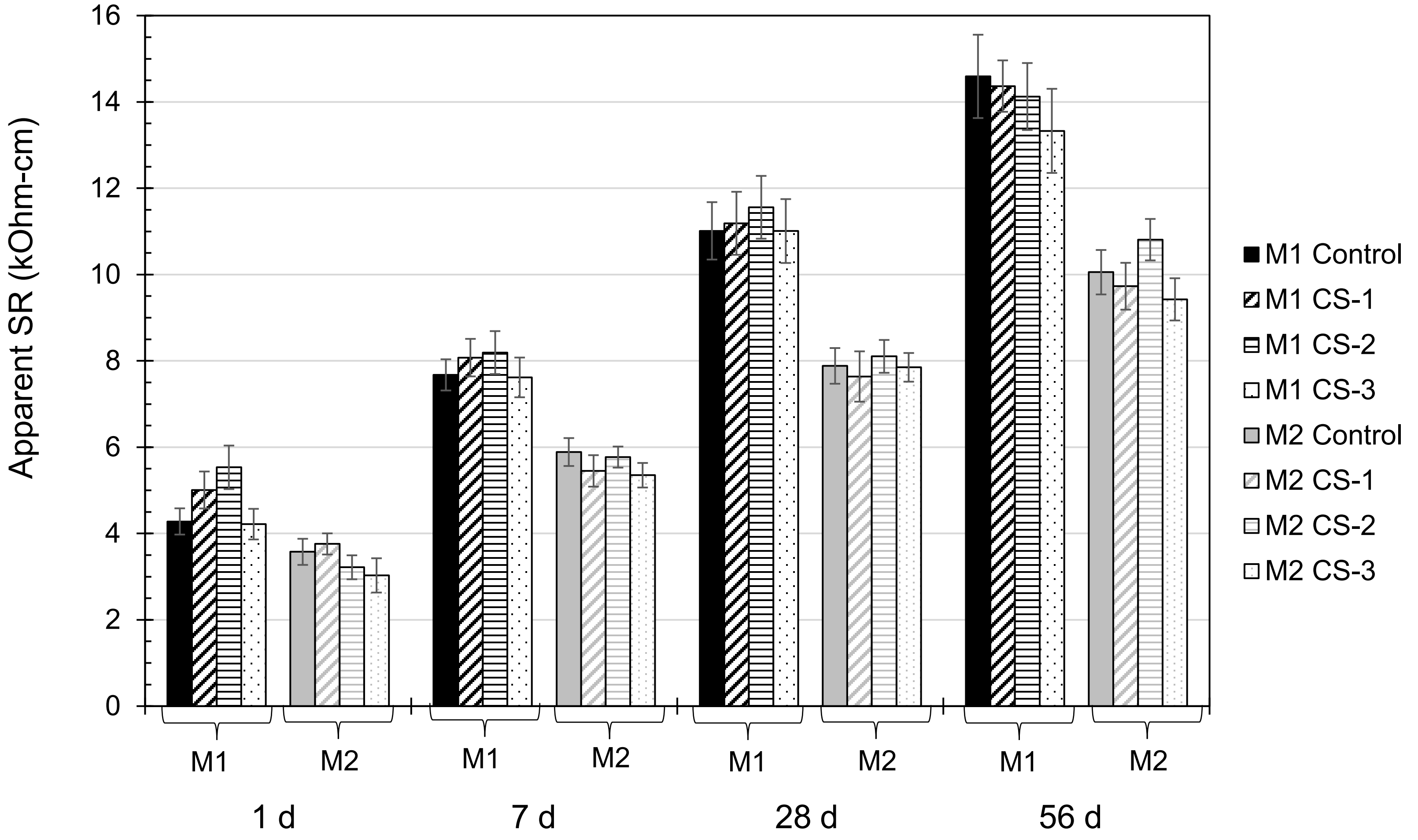
Compressive Strength Normalized



Source: FHWA.

- The compressive strengths of CS samples are within range of control samples.
- CS may increase compressive strength at 1 d for M1 with lower w/cm.
- CS has less influence on strength for M2 with higher w/cm.
- There is not a significant difference between control samples and samples with CS at 56 d.

Apparent SR

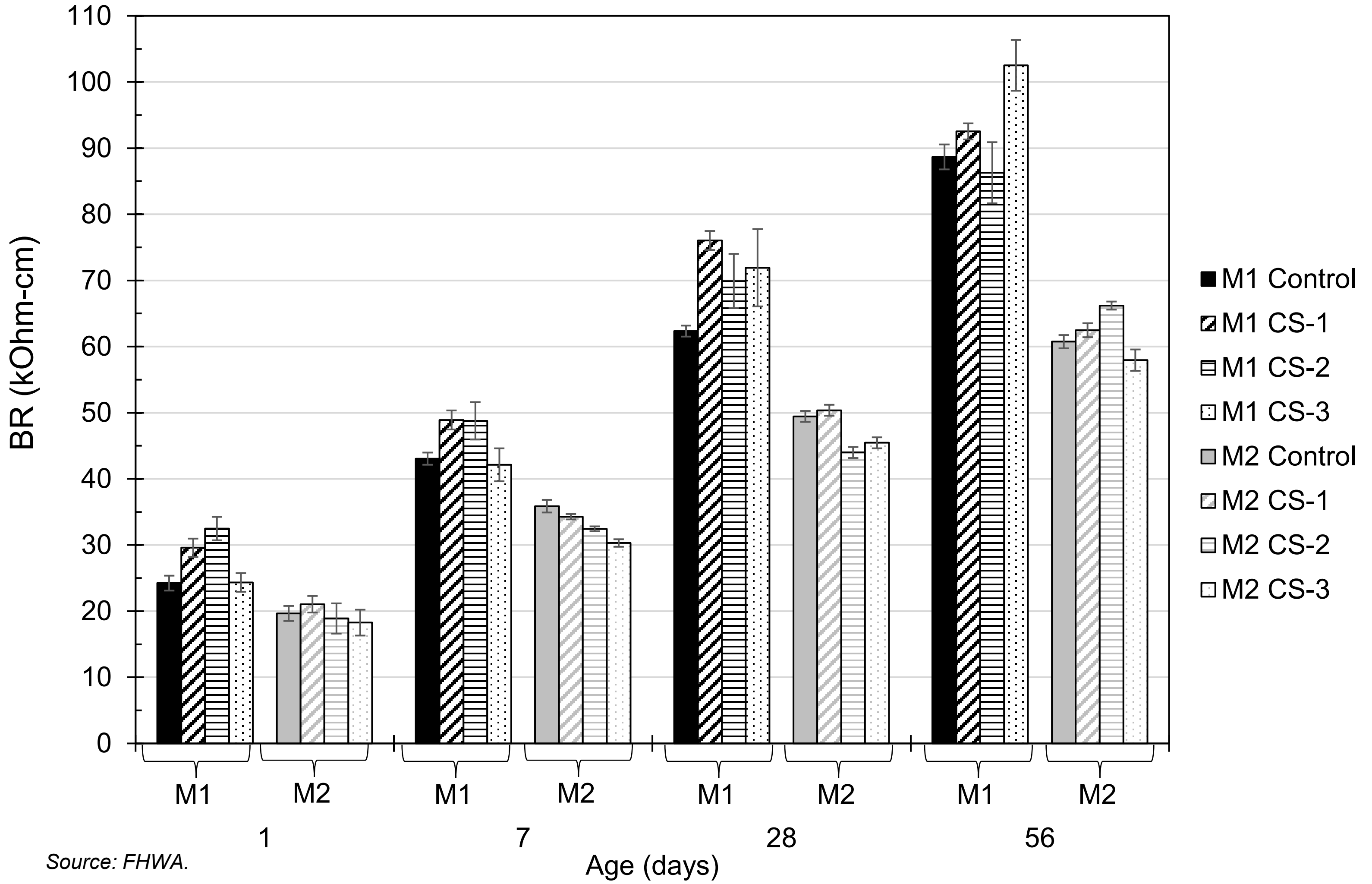


The apparent SR is not significantly different for the control samples without CS compared to those with CS after very early ages.

The apparent SR is higher for the M1 samples than for the M2 samples.

Source: FHWA.

BR



Source: FHWA.

- The BR of concrete with lower w/cm is more affected by the inclusion of CS.
- The M1 concrete samples have higher resistivity than the M2 concrete samples with or without CS.

Investigation 2

Durability for Concretes with Raw CS Products

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Mixture Identification

M2

- PLC with no SCMs
- No air entrainment
- Aggregate gradation meeting tarantula curve with two aggregate sizes/types
- w/cm = 0.47
- 30-percent paste content
- Target slump of 6 ± 1 inches

Mixtures

CS surface area

Manufacturers' recommended dosage for using commercial CS products

M2-130-R

M2-228-R

M2-360-R

M2-130-4R

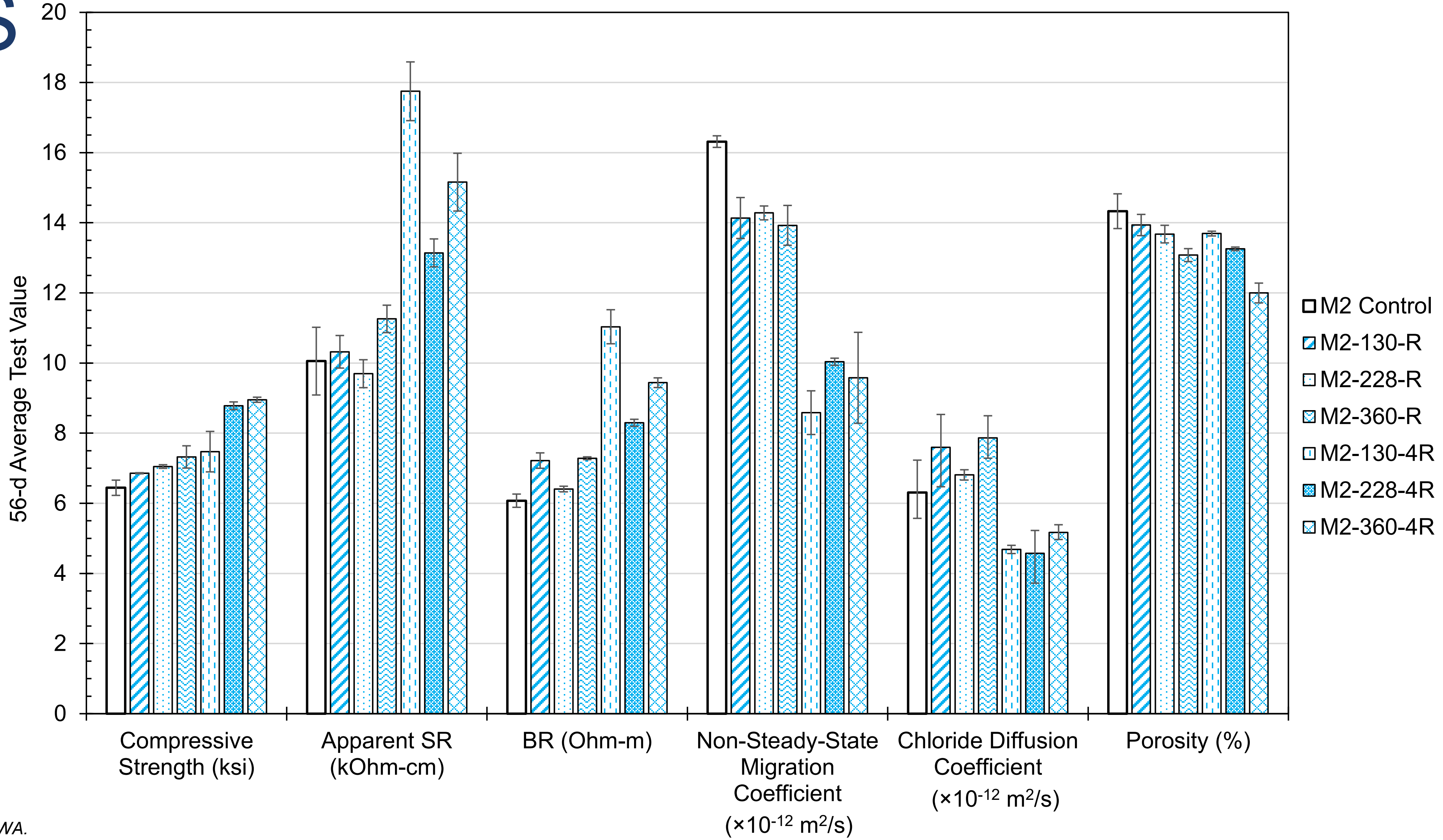
M2-228-4R

M2-360-4R

Four times the manufacturers' recommended dosage for using commercial CS products

Source: FHWA.

Raw CS



Source: FHWA.

Investigation 3

Autogenous Shrinkage

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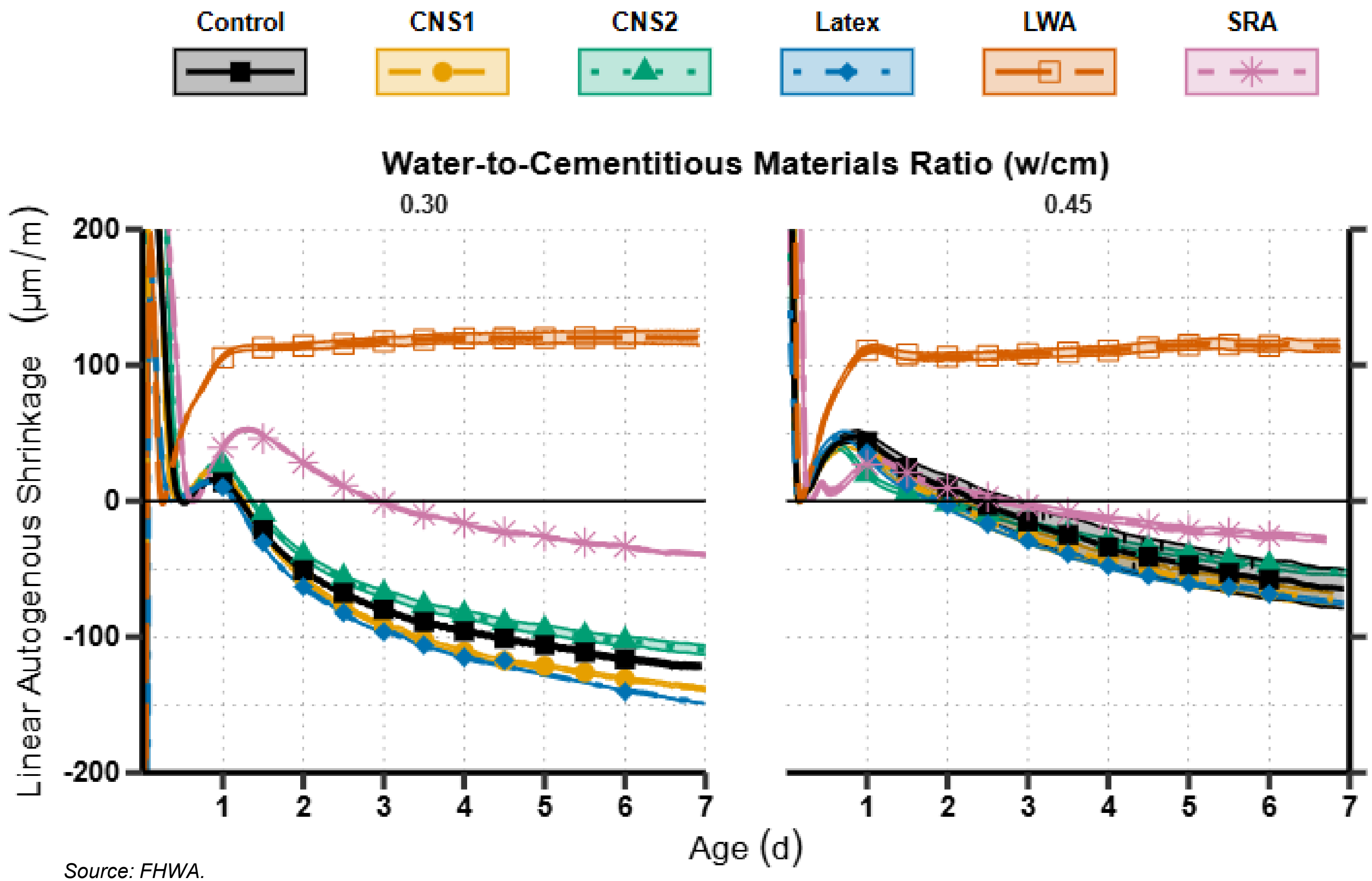
Autogenous Shrinkage



Source: FHWA.

- Internal curing stores water to reduce potential for self-desiccation that leads to autogenous shrinkage.
- LWA shows no autogenous shrinkage.
- SRA shows expansion and then shrinkage.
- CNS, latex, and control show similar autogenous shrinkage.

Key Takeaways

- Electrical tests can be used to indicate durability of concretes containing commercial CS products when used within the manufacturer's recommended dosages.
- If the owner is concerned about using electrical durability tests, bulk chloride diffusion can be performed to indicate transport of ions through the concrete.
- Commercial CS products do not reduce autogenous shrinkage.
- Suggest proper curing practices continue to be employed when placing concretes with CS.
- Suggest concrete durability continue to be improved through mixture design optimization.

References

1. MapChart. 2025. “MapChart” (website). https://mapchart.net, last accessed March 20, 2025.
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Questions?

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