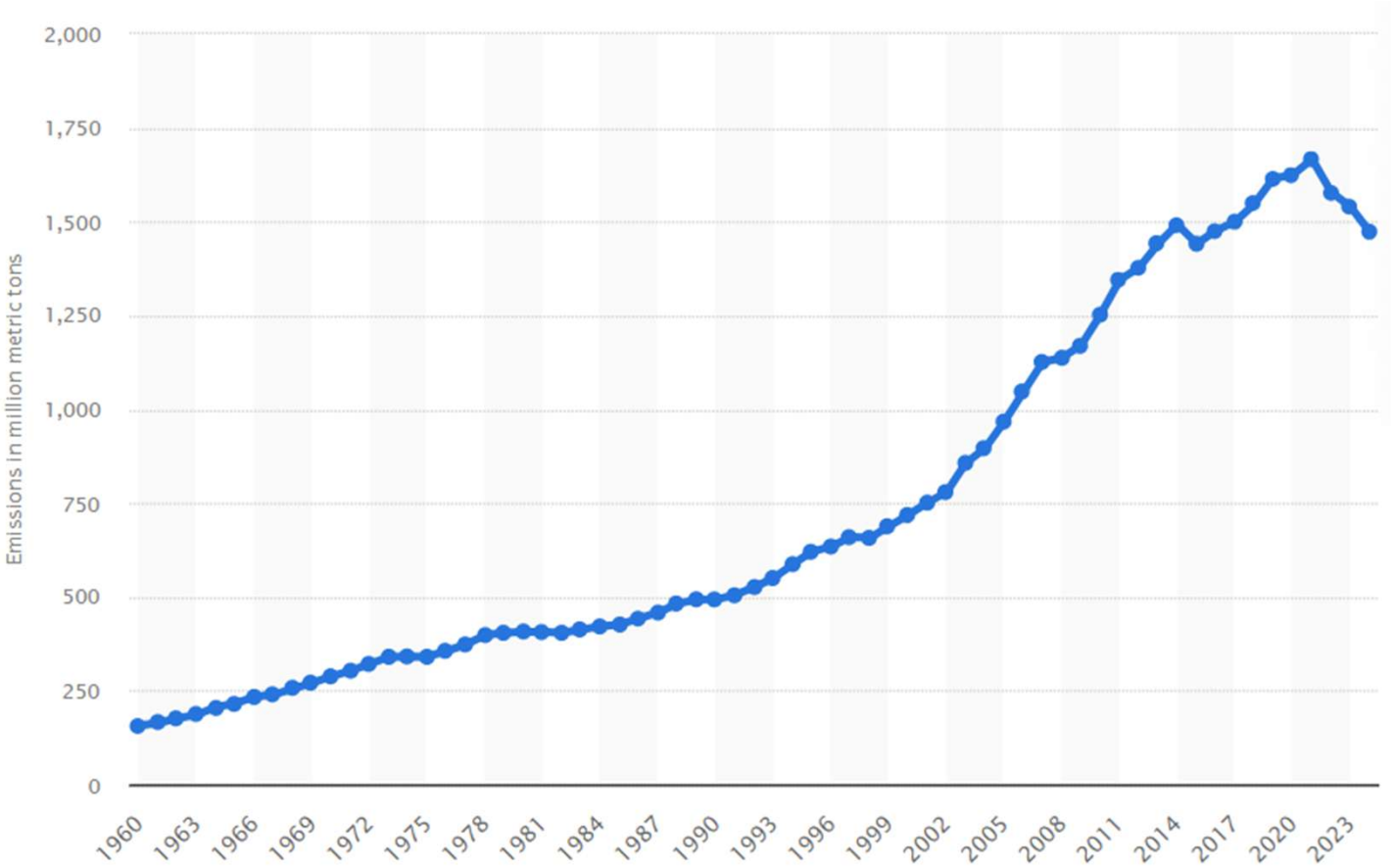
Testing Variability, Overdesign, and the Carbon Impact of Concrete

Glenn Schaefer
Vice President, Research & Technical Services
National Ready Mixed Concrete Association

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Carbon dioxide emissions from the manufacture of cement worldwide from 1960 to 2024



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Low Carbon Concrete

- Concrete has one of the lowest carbon footprints of any material… but…
  - We used ~4.5 billion tons world-wide in 2020 and projected to double by 2050
  - ~1 cy/person/year

- Concrete greenhouse gas (GHG)
  - ~1.5% acquiring raw materials
  - ~9.5% concrete production
  - ~89% cement production
    - ~37% from burning fuel
    - ~46% from calcination

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Paths to Less Cement (reduced clinker factor)

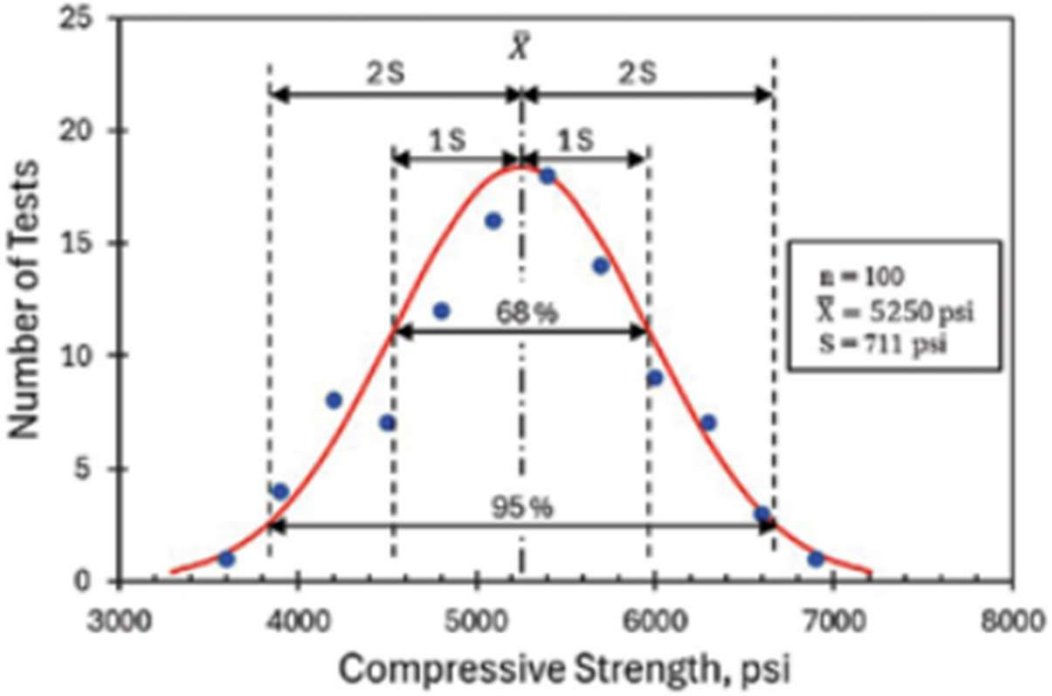
- Improve aggregate gradation and packing density
- Reduce paste volume and maximize aggregate efficiency
- Use blended cements
- Alternative cement
- SCMs
- Admixtures to lower cement demand
- Optimize air and workability without excess paste
- Shift to performance-based specifications
- Right-size strength requirements
- Accept slower early strength where feasible

- **Minimize overdesign**

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Normal Distribution

Concrete strength follows a statistical "normal" distribution

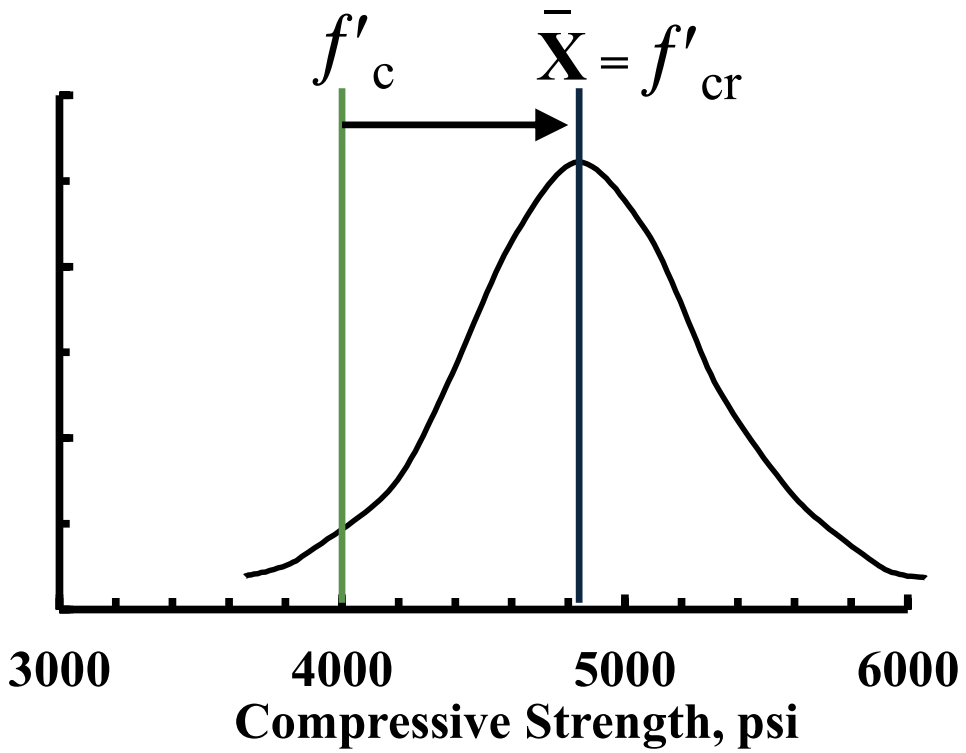


Standard deviation is a measure of the spread or variability of around the average

- ±1 standard deviation includes about 68% of the data
- ±2 standard deviations (2s) includes about 95% of the data
- ±3 standard deviations (3s) includes about 99.7% of the data

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What is Overdesign?

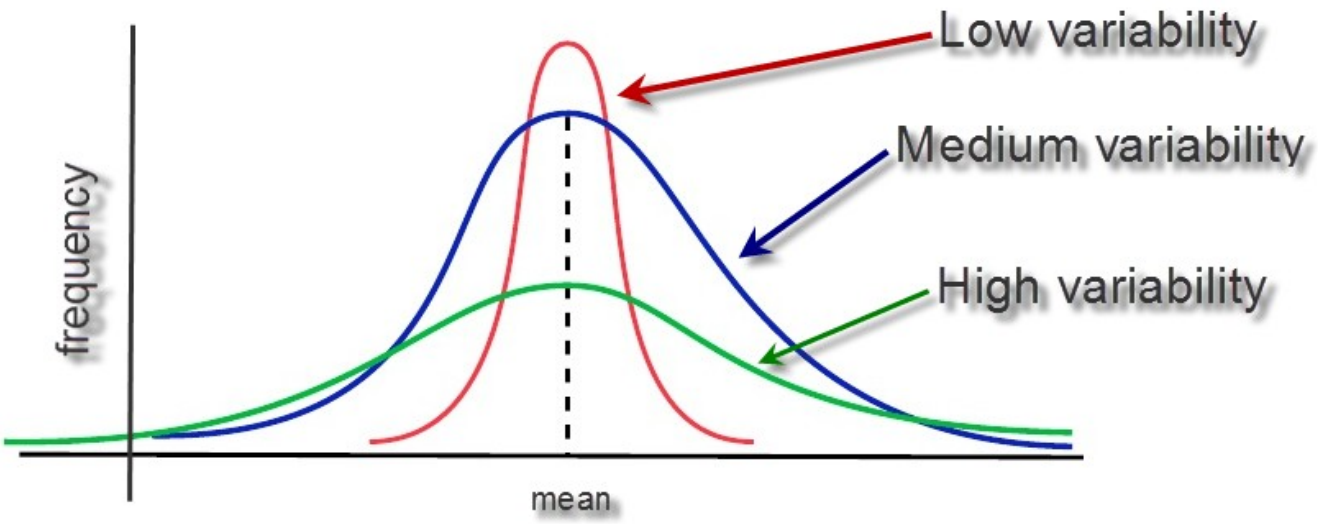


- **f'c** = specified (required) strength
- **f'cr** = required average strength to ensure compliance
- The gap (f'cr – f'c) = **overdesign margin**

- ACI 318 requirements (<5000 psi)
  - No individual test below f'c by more than 500 psi
  - Avg of 3 no lower than f'c

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Variability



Increased variability raises the standard deviation of strength test results.

A higher standard deviation increases the required average strength (f'cr) to ensure compliance.

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Source of Variability

- Materials
  - Cement chemistry and fineness
  - Aggregate gradation, shape, moisture, and cleanliness
  - Variability in SCMs like fly ash or slag
  - Admixture dosage and compatibility
  - Water quality and water content
- Mixing and batching
  - Incorrect batching proportions
  - Moisture corrections not applied correctly
- Production and delivery
  - Variations between loads
  - Transit time and agitation
  - Temperature changes during delivery
  - Slump adjustments in the field

How are these related ?

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Testing Variability

Challenges in Concrete Field Testing

- Inconsistent adherence to **ASTM testing standards**
- Variability introduced during **sampling, handling, and curing**

Workforce & Training Gaps

- Untrained or underqualified testing personnel
- Lack of certification (e.g., ACI Field/Lab Technician)
- Inconsistent techniques between technicians and labs

Laboratory & Equipment Issues

- Poorly controlled curing environments (temperature, moisture)
- Inadequate or uncalibrated equipment
- Variability between different labs testing the same material

Field Practice Limitations

- Improper cylinder fabrication and consolidation
- Delays or mishandling during transport to lab
- Non-standard curing conditions (jobsite vs lab)

Key Message

- Poor testing practices **can't be "managed" by producer** and create "noise" in the data—driving unnecessary cost and carbon through overdesign

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Key Practices in ASTM C31 That Impact Results

Sampling & Timing

- Obtain a **representative sample** (ASTM C172)
- Mold cylinders **within 15 minutes** of sampling
- Avoid segregation and loss of mortar during handling

Cylinder Fabrication

- Proper consolidation (rodding or vibration as required)
- Correct number of layers and rodding per layer
- Strike off and finish surface properly
- Prevent voids, honeycombing, or overworking

Initial Curing (Critical)

- Maintain **60–80°F (16–27°C)** for first 24–48 hours
- Protect from **temperature extremes, sun, wind, and vibration**
- Keep cylinders **moist (prevent moisture loss)**
- Store in a controlled curing box or enclosure

Transportation to Lab

- Prevent **jarring, impact, or disturbance**
- Maintain temperature and moisture during transport
- Avoid premature handling or stripping

Sampling & Timing

- **Final Curing (Lab)**
- Standard curing at **73.5 ± 3.5°F (23 ± 2°C)**
- Continuous moisture (lime-saturated water or moist room)
- Ensure consistent curing conditions across all samples

Common Failure Points

- Poor temperature control during initial curing
- Improper consolidation (too much or too little)
- Moisture control
- Mishandling

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Factors Affecting Strength

NRMCA Publication No. 179

Review of Variables that Influence Measured Concrete Compressive Strength

By David N. Richardson

TABLE 1. Measured Strength Reduction by Nonstandard Conditions

Variable (1)	Strength loss (%) (2)	Lab (L) or field (F) (3)
Convex ends	up to 75	L
Insufficient consolidation	up to 61	F
Immediate freezing for 24 hours	up to 56	F
Rubber cap, no restraint	up to 53	L
Weak, soft capping compound	up to 43	L
Flat particle vertical orientation	up to 40	F
Concave ends	up to 30	L
Rough end before capping	up to 27	F
Seven days in field, warm temperature	up to 26	F
Reuse of plastic molds	up to 22	L
Cardboard mold	up to 21	F
Seven days in field at 73° F, no added moisture	up to 18	F
Plastic mold	up to 14	F
Rough end, air gaps under cap	up to 12	F
Convex end, capped	up to 12	F
Eccentric loading	up to 12	L
Out-of-round diameter	up to 10	F
Ends not perpendicular to axis	up to 8	F
Rough handling	up to 7	F
Three days at 37° F, mixed at 73° F	up to 7	F
One day at 37° F, mixed at 46° F	up to 7	F
Excessive tapping	up to 6	F
Thick cap	up to 6	L
Sloped end, leveled by cap	up to 5	F
Wet mix subjected to vibrations	up to 5	F
Chipped cap	up to 4	L
Rebar rodding	up to 2	F
Insufficient cap cure	up to 2	L
Slick end cap	up to 2	L
Slow loading rate	up to 2	L

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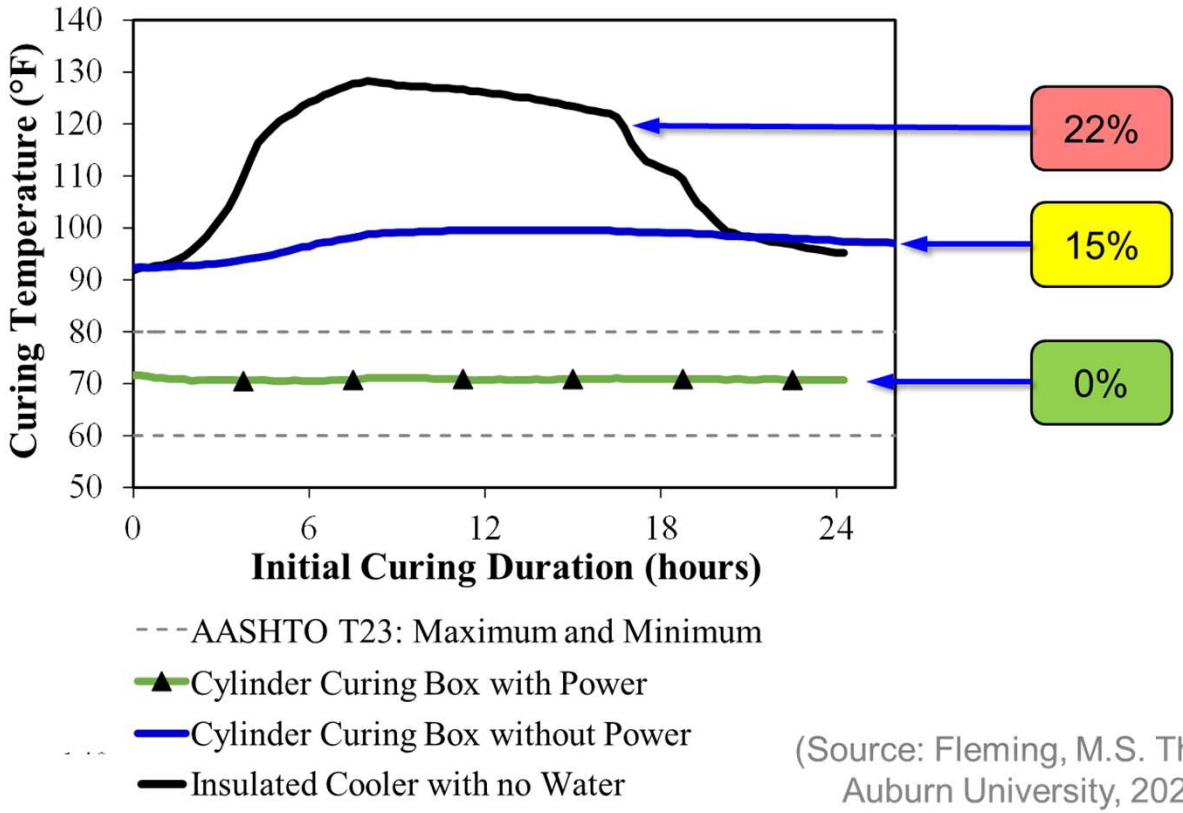
Impact of Initial Curing of Cylinders on Concrete Strength

- Looking only at temps in “Lab” Setting
  - Circulator
  - Copper pipes
  - Curing tank with internal water circulating pump



Anton Schindler, PhD, PE, F.ASCE, F.ACI
Professor and HRC Director
Department of Civil and Environmental Engineering
Auburn University

How hot does it get?





(Source: Fleming, M.S. Thesis, Auburn University, 2023)

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Experimental Design

- **6 Initial Curing Temperatures:**
  - **60 °F**
  - **68 °F** (Control)
  - **78 °F**

  } **In Spec.**

  - **84 °F**
  - **90 °F**
  - **100 °F**

  } **Out of Spec.**
- **3 Initial Curing Durations:**
  - **24 Hours**
  - **48 Hours**

  } **In Spec.**

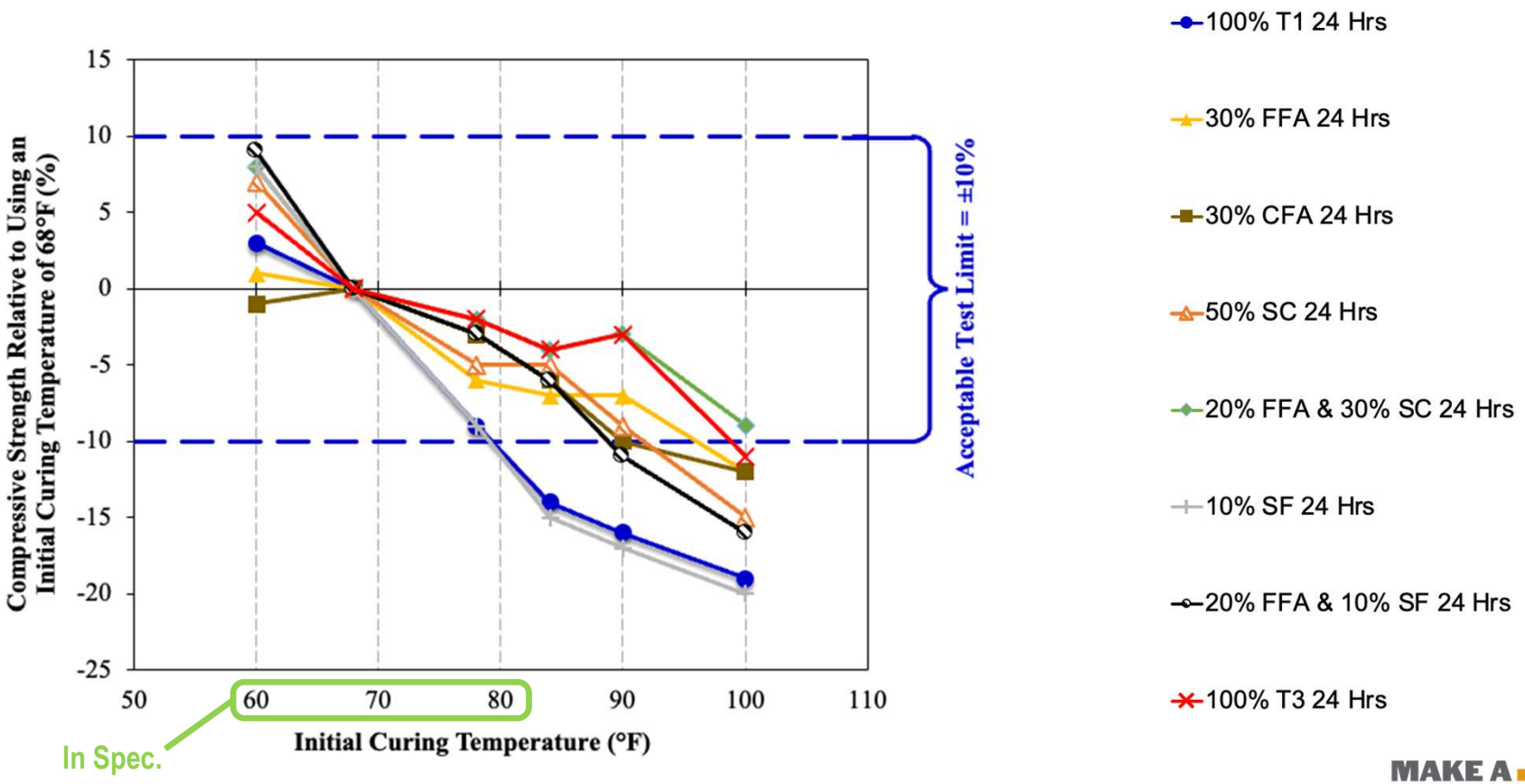
  - **72 Hours**

  } **Out of Spec.**
- **Final Curing:**
  - **73.5 ± 3.5 °F and 100% RH** for remainder of 28 days

- **8 Concretes:**
  - 100% Type I
  - 30% Class F Fly Ash
  - 30% Class C Fly Ash
  - 50% Slag Cement
  - 10% Silica Fume
  - 20% Class F Fly Ash & 30% Slag
  - 20% Class F Fly Ash & 10% Silica
  - 100% Type III
- **Compressive Strength:**
  - Test at 28 days
  - Range: 4300 to 8900 psi

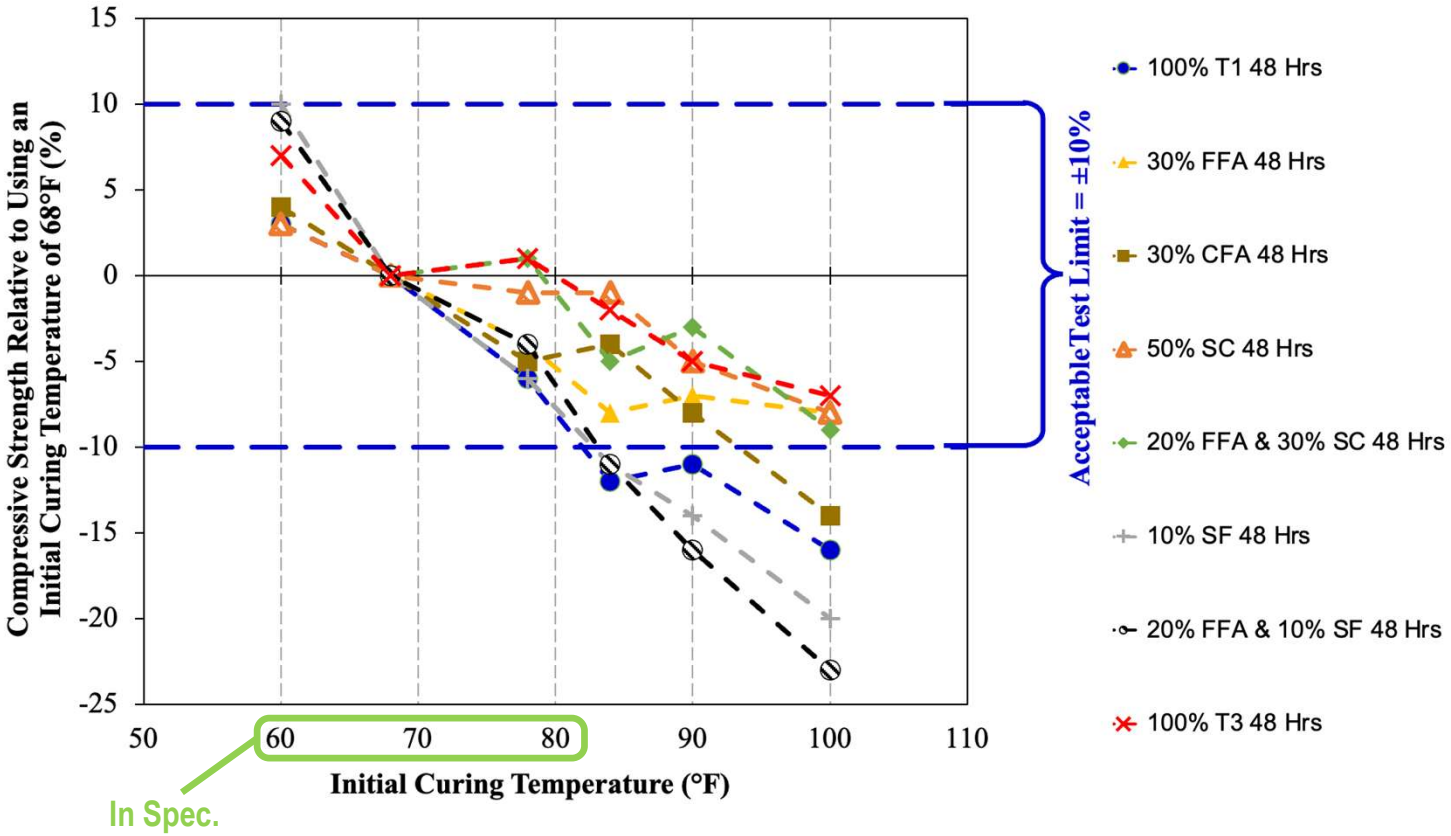
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24-Hour Initial Curing: Strength Differences



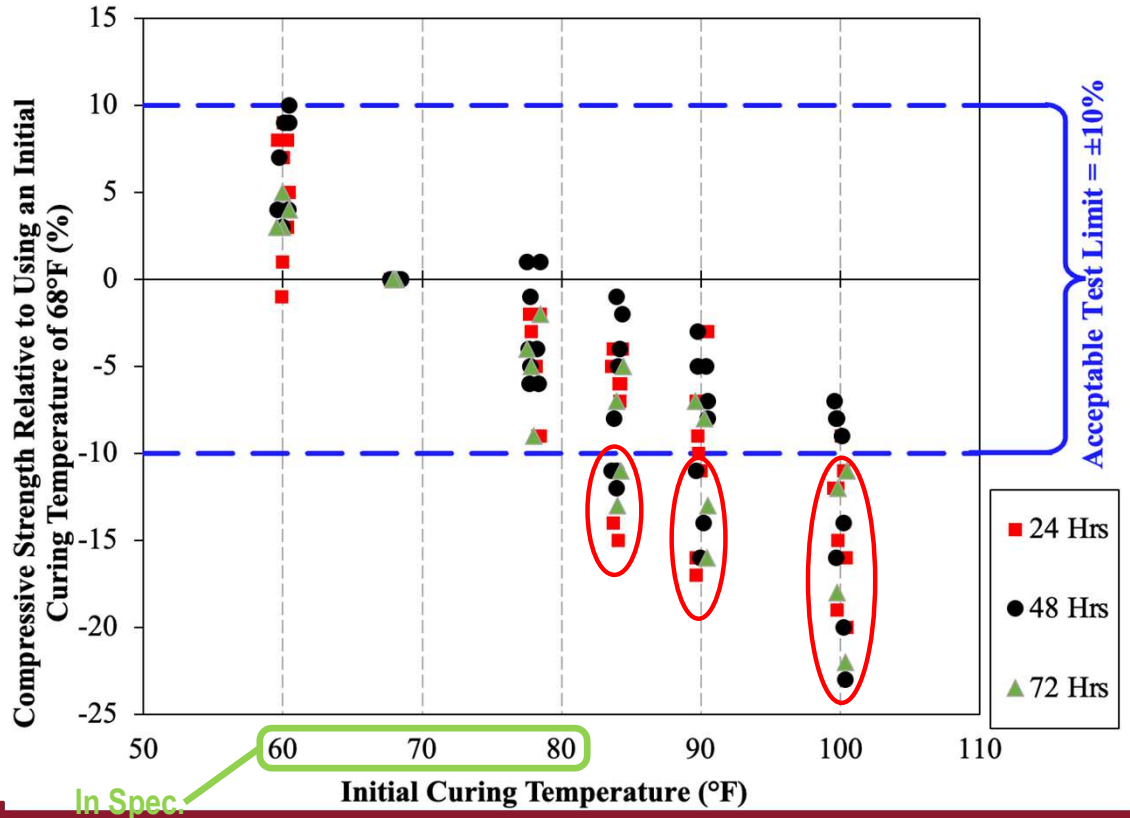
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48-Hour Initial Curing: Strength Differences



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Comparative Initial Curing: Strength Differences



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Concrete Field Testing IMPACT REPORT 2026

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Impact Scenarios

Control
All procedures were followed as per CSA A23.2-3C including casting, initial curing and transportation

Initial Hot & Cold Weather Curing
Properly cast cylinders exposed to hot and cold weather conditions without protection

Incorrect Sampling
Concrete left in the wheelbarrow for 60 minutes and cylinders were cast without remixing the sample

Cylinder Disturbance
Freshly cast cylinders were disturbed by being driven in the back of a pickup truck for 5 minutes

No Rodding
Cylinders were cast without rodding, leading to improper consolidation

96-Hour Demoulding
Delayed demoulding simulated by leaving cylinders in moulds for 96 hours

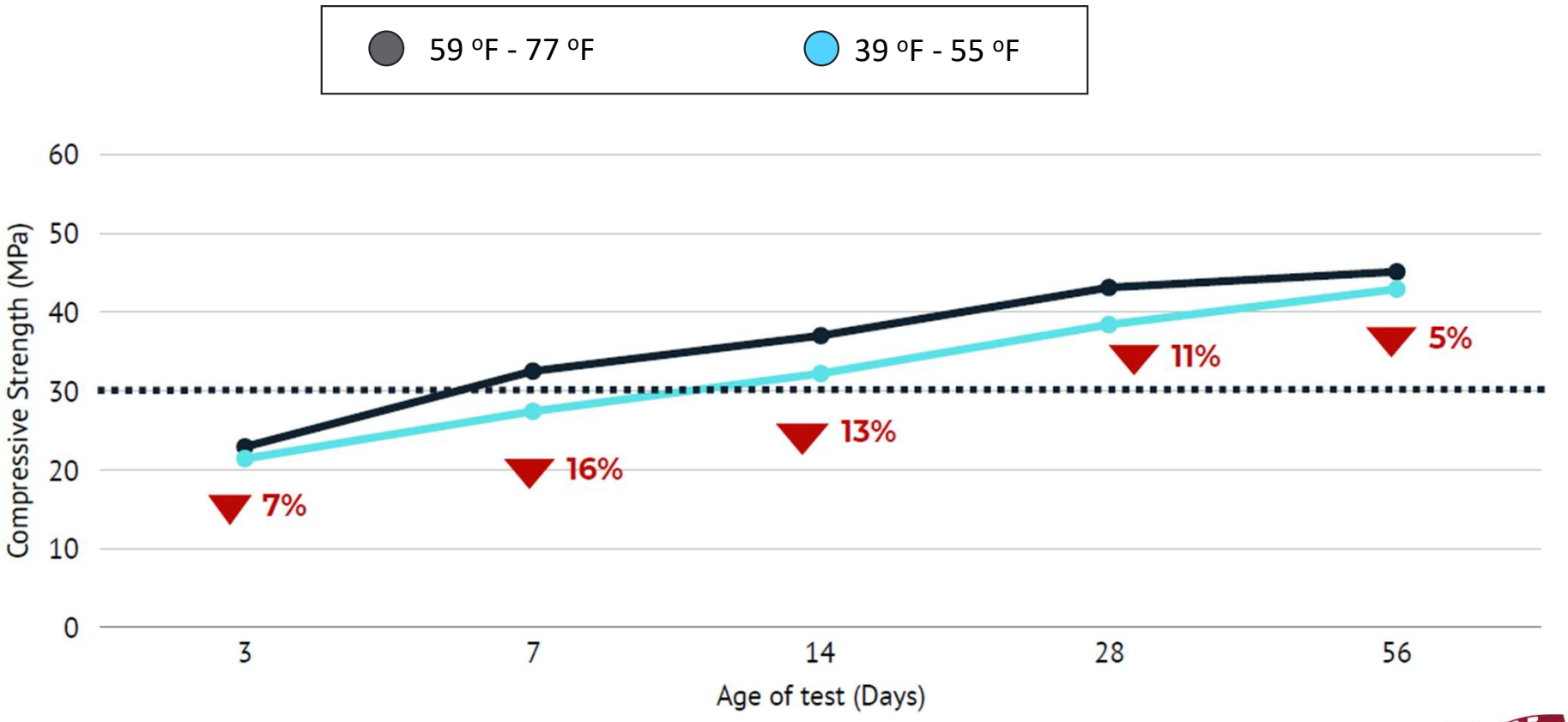
Water Addition
The ready-mix truck was allowed to sit for 1 hour before water was added

Submerged Cylinders
Cylinders were submerged in cold water within a cooler for initial curing

Site Trailer Disturbance
Site trailer vibration was simulated on properly cast cylinders

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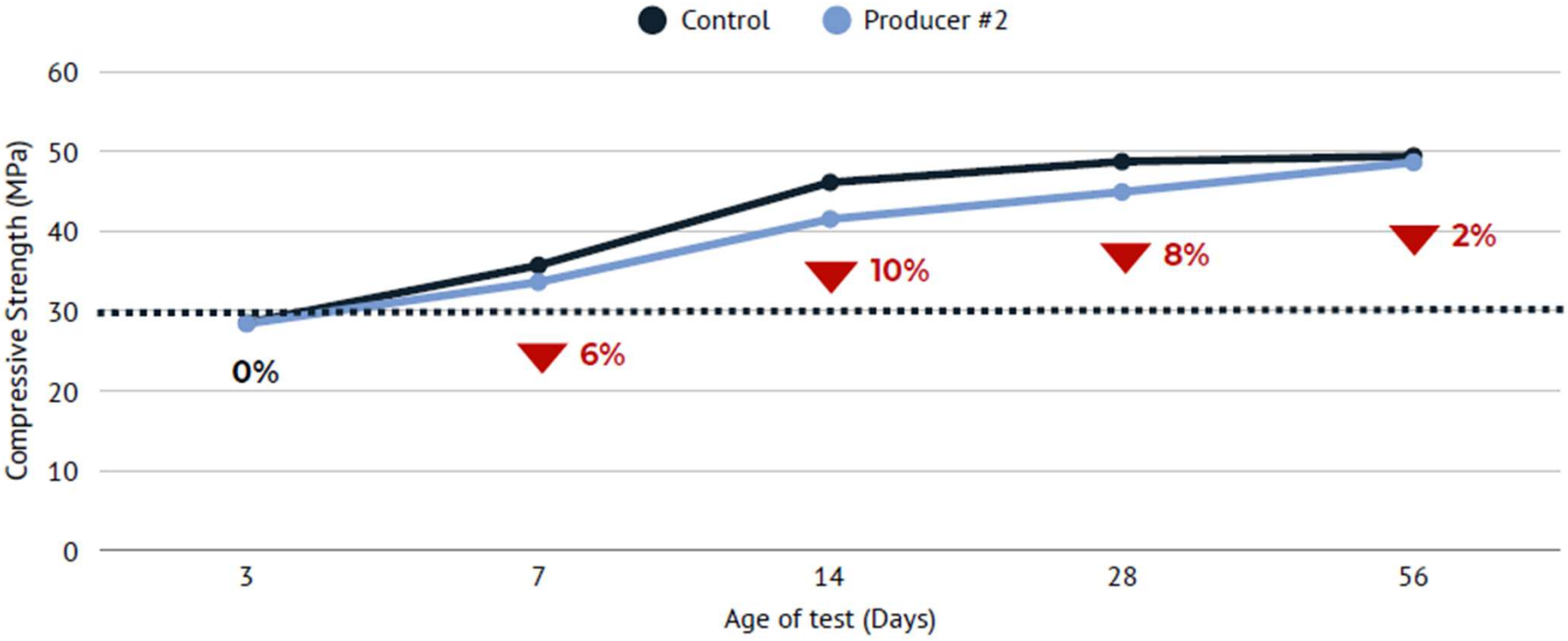
Impact Scenarios-Cool Ambient



3” Slump

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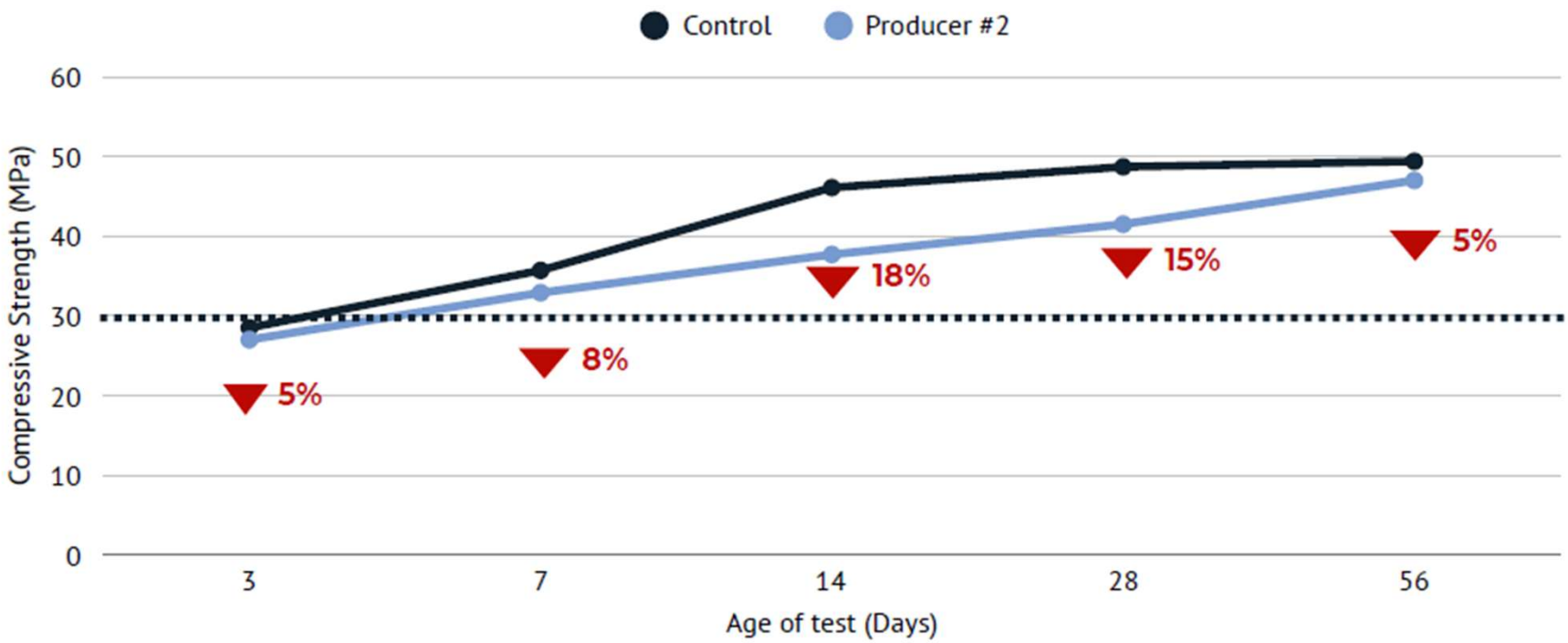
Impact Scenarios-Cylinder Disturbance



3" Slump

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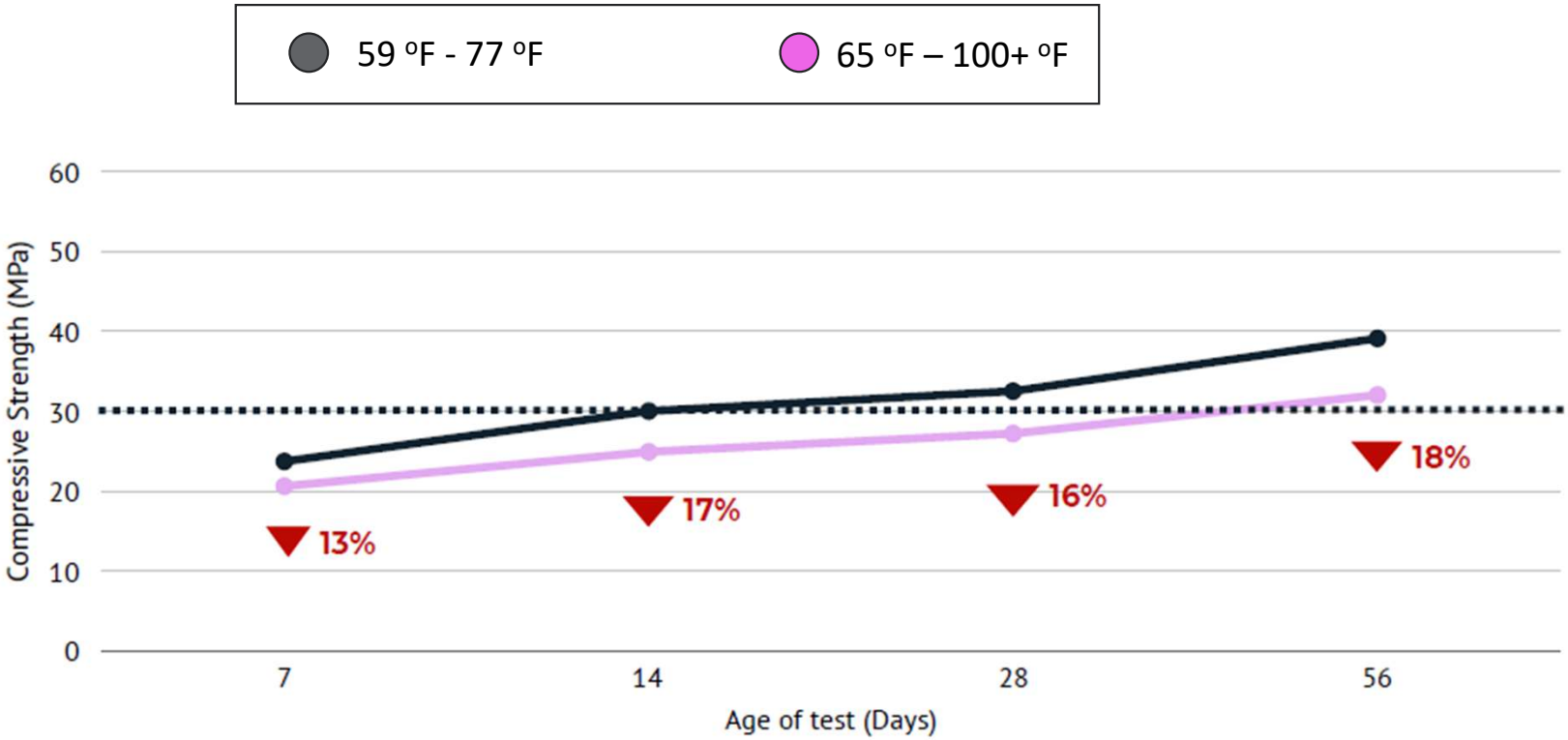
Impact Scenarios-No/Poor Consolidation



3” Slump

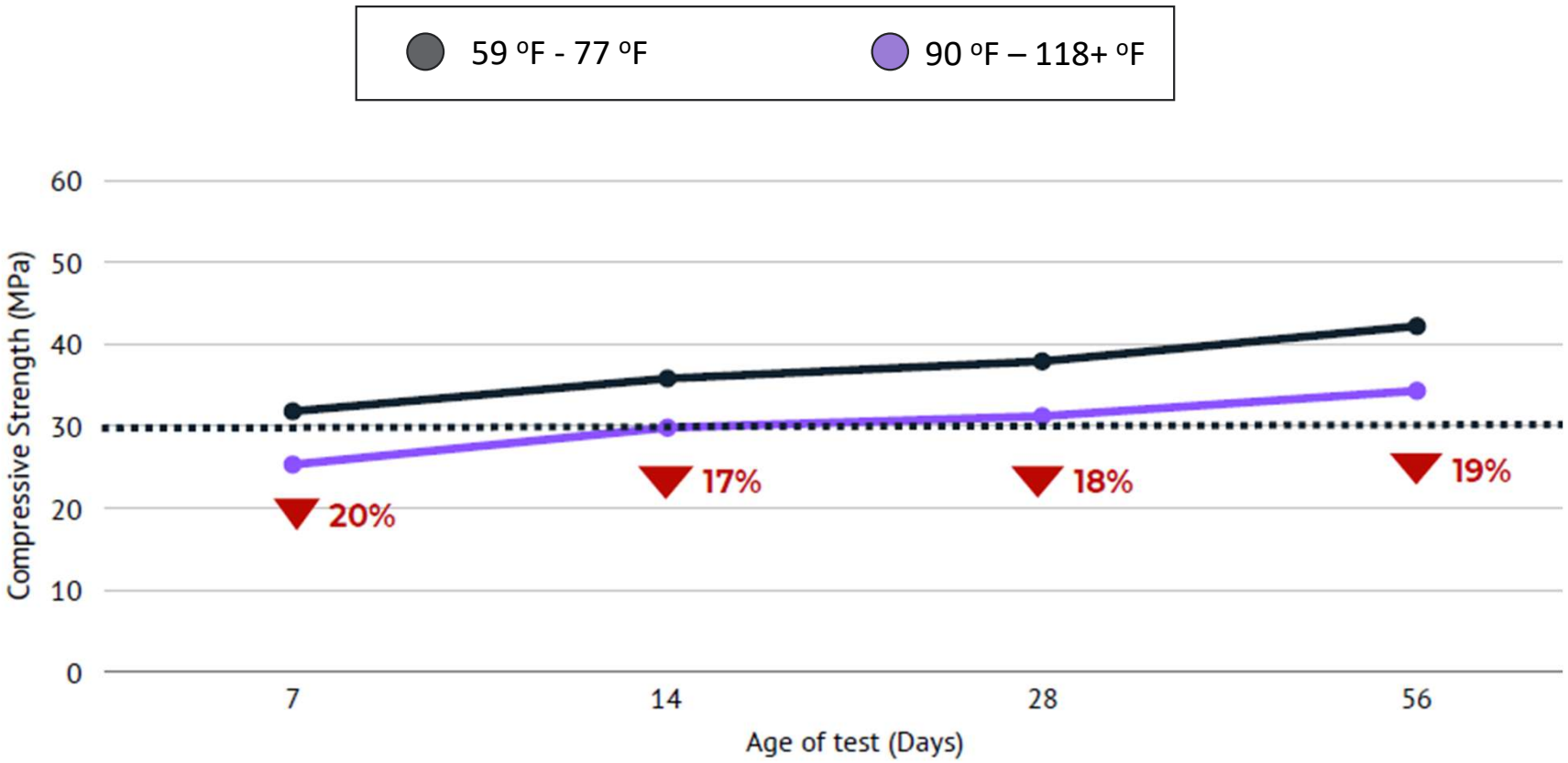
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Impact Scenarios-Hot Ambient (Outside)



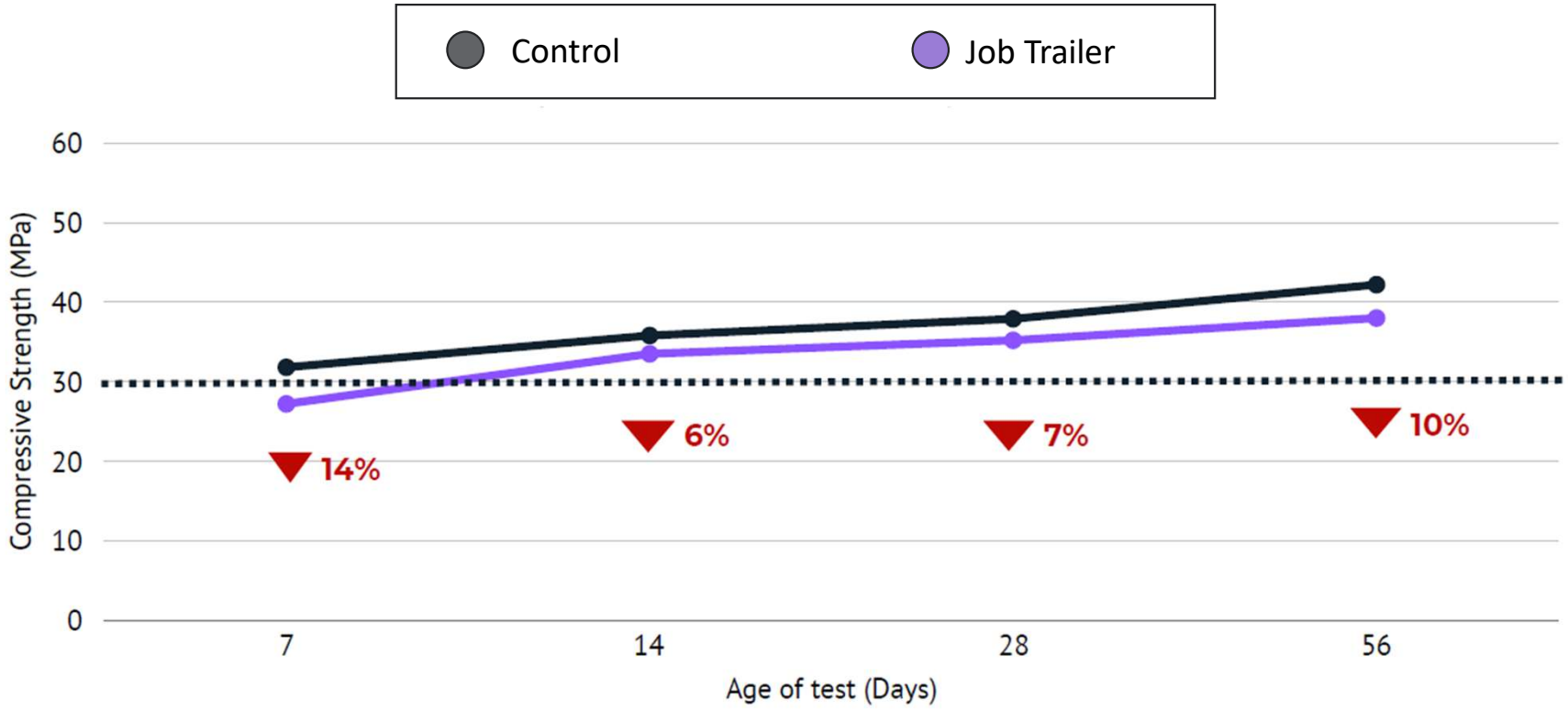
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Impact Scenarios-Dry Cooler (Hot)



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Impact Scenarios-Job Trailer



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Impact Scenarios

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30 MPa at 28 days, Non-air entrained			
Slump (mm)	**Testing Scenario**	**7 Day Impact (%)**	**28 Day Impact (%)**
80 ± 30	Cold Curing	▼ 6 - 16 ▼	▼ 11 - 12 ▼
	Incorrect Sampling	▼ 3 - 9 ▼	▼ 3 - 6 ▼
	Cylinder Disturbance	▼ 6 - 7 ▼	▼ 7 - 8 ▼
	No Rodding	▼ 8 - 15 ▼	▼ 10 - 15 ▼
	96-hour Demoulding	▲ 1 - 6 ▼	▼ 2 - 5 ▲
150 ± 30	Hot Curing - Outside	▼ 7 - 13 ▼	▼ 9 - 16 ▼
	Hot Curing - Dry Cooler	▼ 7 - 20 ▼	▼ 9 - 18 ▼
	Hot Curing - Submerged	▲ 1 - 4 ▼	▲ 1 - 4 ▼
	Water Addition	▼13 - 18▼	▼ 9 - 13 ▼
	Cylinder Disturbance	▼ 5 - 10 ▼	▼ 8
	Site Trailer Disturbance	▼ 14	▼ 7

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Concrete Field Testing Impact Report 2026

- What Drives the biggest Risk?
  - Temperature Control
    - Cold Weather: Reduced Strength at all ages
    - Hot Weather: Accelerated hydration & moisture loss;. Dry coolers often exceeded 100°F
  - Water Addition on Site
    - 7-day loss up to 18%; 28-day loss up to 13%
  - Consolidation and Handling
    - No rodding = 10–15% loss
    - Transport vibration amplified losses at higher slump
    - Site vibration caused up to 14% reduction

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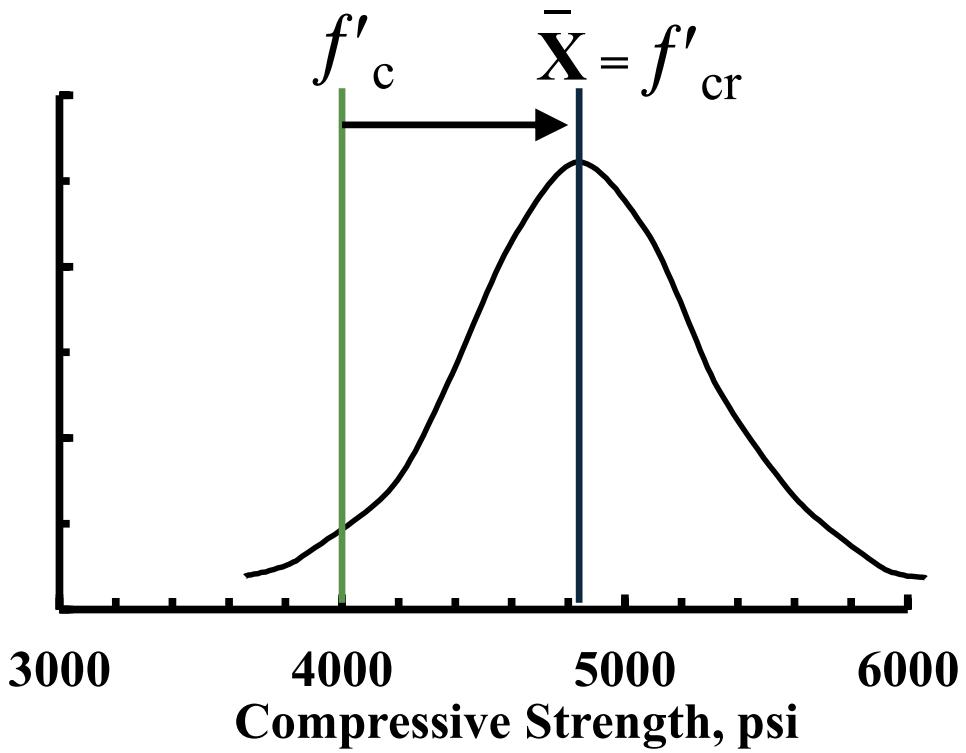
Testing- Concrete Field Testing Impact Report 2026

- Major Take-Aways
  - Even minor deviations from CSA A23.2-3C procedures can cause double-digit strength reductions, potentially leading to:
    - Failed tests
    - Overdesigned mixes
    - Increased cement usage
    - Higher costs
    - Increased carbon footprint

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Back to Statistics and Overdesign



f'_c, psi	f'_{cr} psi
less than 3000	$f'_c + 1000$
3000 to 5000	$f'_c + 1200$
over 5000	$1.10f'_c + 700$

- 4000 psi specification
- $f'_c + 1200 = 5200$ psi

Process/Materials & Statistical Variation

with testing issue

- **6100 psi @ 15% strength loss = 5200 psi**

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"Cost" of "Extra Strength

6100 psi @ 15% strength loss = 5200 psi

- Financial
  - An extra "sack" of cement/yard
  - $160–$175 per ton
  - $8.00 of cement

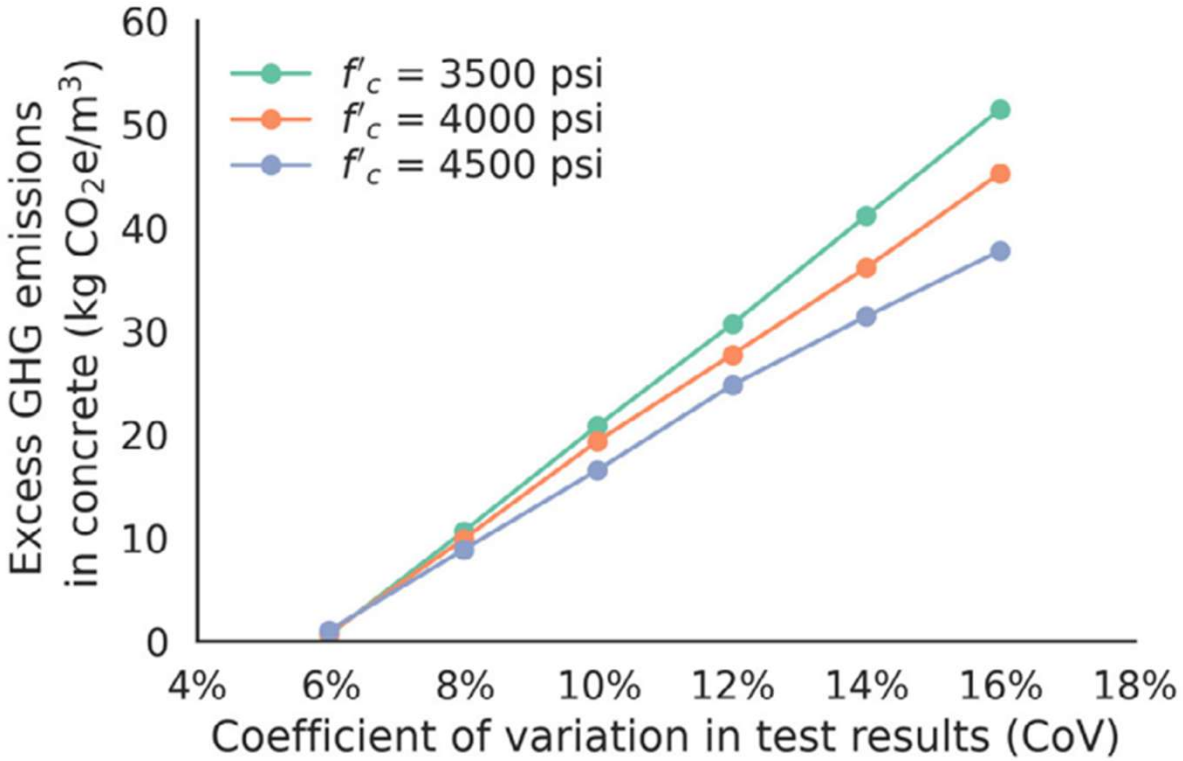
  - 20,000 CY project = $160,000 of extra cement

  - This added cost often brings no proportional performance benefit
  - Overdesign can also increase heat of hydration, shrinkage potential, and other technical challenges

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Environmental Impacts

CoV is Standard Deviation express as a %



MIT CSHub Research Brief
Soroush Mahjoubi,* Hessam AzariJafari, Randolph Kirchain, and Elsa Olivetti

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"Cost" of "Extra Strength

6100 psi @ 15% strength loss = 5200 psi

- Environmental
  - An extra "sack" (94 lbs) of cement/yard
  - Using recent NRMCA/PCA benchmark data, cement commonly carries roughly **809–993 kg CO_2e per short ton**, depending on region and source.

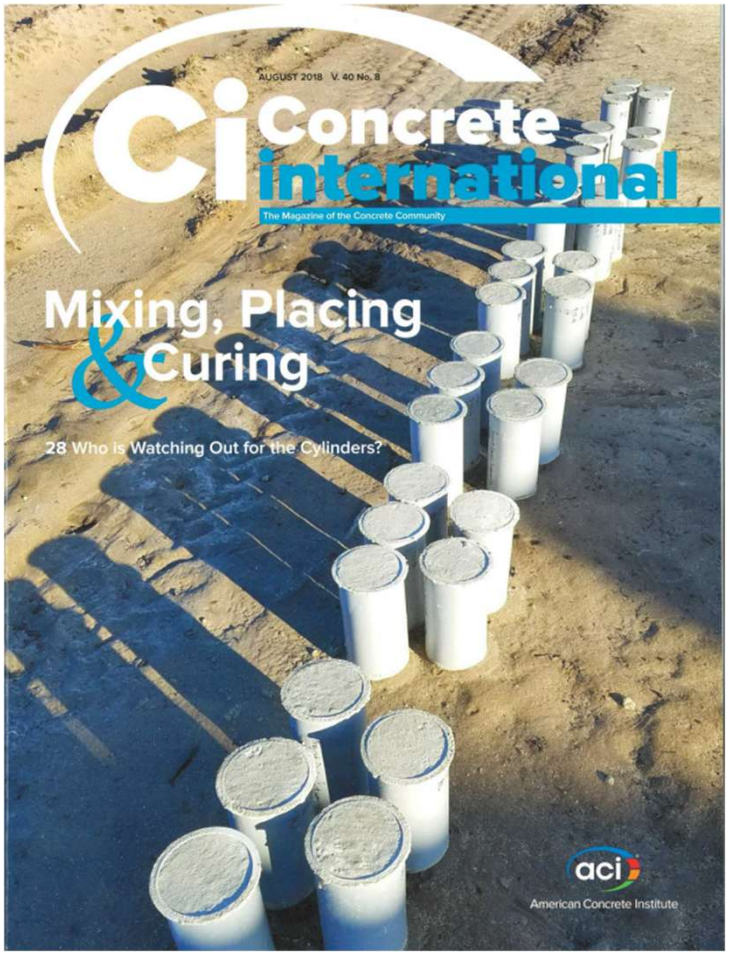
  - "Typical" CY of Concrete 200 kg CO_2e = 450 lbs kg CO_2e

  - 94 lb cement/CY = 0.047 short tons/CY
  - Added CO_2e ≈ 38–47 kg CO_2e per CY
  - 84–103 lb CO_2e per CY

  - Increases the total carbon footprint of that cubic yard by about 20–25%.

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Testing is Critically Important









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Key Takeaways

- Overdesigning concrete (extra cement) is often driven by uncertainty in testing
  - That "safety margin" comes at a real cost
- Concrete mixes are often overdesigned to "cover" variability, not because performance requires it
- The less confidence in testing results → the more cement gets added as insurance

The cheapest and most sustainable concrete is the one that meets performance — and nothing more."

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Thank You

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