# Feasibility of Non-Proprietary Ultra-High Performance Concrete (UHPC) for use in Highway Bridges in Montana: Phase II Field Application

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# Scope

- Introduction/Background
- Literature Review
  - Non-proprietary UHPC and Bond Strength Testing
- Constituent Materials
  - Properties, Sources, Gradation, Moisture Content
- Field Application
  - Strength Gain vs. Time, Batch Size, Temperature, Mixing Time, Aggregate Moisture Content
- Rebar Bond Strength
  - FHWA Recommendations, Embedment Length, Bar Size, Bar Spacing, Bar Side Cover
- Summary & Conclusions

# Background

- 20 ksi 28-day compressive strength
- 1.2 ksi 28-day flexure strength
- MDT interested in field-cast joints between precast bridge deck panels
- Cost Prohibitive
- Previous research at MSU developed a non-proprietary UHPC mix design
  - Local Materials
  - Lower cost

# METHODS

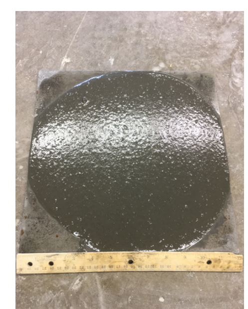
# Mixing Procedure

- Small laboratory mixtures produced in an industrial benchtop Hobart A200 mixer in 0.20-ft3 batches

- Larger-scale mixes produced in an IMER Mortarman 360 high-shear horizontal mortar mixer

# Mixing Procedure

- Combine fine aggregate and silica fume
  - Mix for 5 minutes on low speed
- Add cement and fly ash to mixer
  - Mix for 5 minutes on low speed
- Combine water and HRWR in separate container
  - Mix thoroughly
- Add water & HRWR to mixing bowl
  - Mix on low speed until mix becomes fluid  (typically around 3-6 minutes)
- Add steel fibers
  - Mix for approximately 3 minutes
- Flow Test

# Specimen Preparation

- 3-by-6-in compression test cylinders prepared for each mix
  - ASTM C1856 Standard Practice for Fabricating and Testing Specimens of Ultra-High Performance Concrete
- Filled with single lift and leveled
- Tops wrapped with plastic wrap to avoid surface drying
- Removed from molds after 48 hours
- Diamond-blade tile saw used to remove uneven top surface
- Ground using an automatic cylinder end grinder
- Placed in temperature-controlled cure room at 100% humidity

# Compression Testing

- ASTM C 1856 Standard Practice for Fabricating and Testing Specimens of Ultra-High Performance Concrete
- At least three 3-by-6-in cylinders loaded to failure
- Testmark CM Series hydraulic compression load frame
  - 400,000-pound capacity
- Loaded at a target rate of 975-1075 lbs/second (138-152 psi/s)
- Maximum load at failure was recorded
- Average compressive strength calculated from all specimens

# Flexure Testing

- ASTM C78 -- Standard Test Method for Flexural Strength of Concrete
- Flexural tensile strength calculated as the average of two 20-by-6-by-6 inch prisms
- Steel fibers allow to carry load beyond the formation of an initial crack
- Initial cracking was determined from the recorded force-deformation response of each specimen
  - First point at which there was a sudden reduction in applied load and a distinct reduction in stiffness

# Materials

- Cement (top right)
- Silica Fume (top left)
- Fly Ash (bottom right)
- Fine Aggregate (bottom left)
- High Range Water Reducer (HRWR)
- Steel Fibers (middle)

# Mix Design

| w/c Ratio | HRWR/c Ratio | Sand/c Ratio | SF/FA Ratio | SCM/c Ratio | Fiber Content | Paste Content |
|---|---|---|---|---|---|---|
| 0.28 | 0.05 | 1.40 | 0.75 | 0.50 | 2% | 62% |

| Item | Item Type | Amount (lbs) |
|---|---|---|
| Water | - | 27.66 |
| HRWR | CHRYSO Fluid Premia 150 | 5.96 |
| Portland Cement | Type I/II Trident | 120.32 |
| Silica Fume | BASF MasterLife SF 100 | 25.78 |
| Fly Ash | Trident Genesee | 34.38 |
| Fine Aggregate | O.D. BBB&T Concrete Sand | 144.11 |
| Steel Fibers | Bekaert Dramix OL 13/0.20 | 24.34 |

# SENSITIVITY TO MATERIAL VARIABILITY

# Effect of Cement Source

- Trident cement
  - Type I/II/IV cement
  - GCC cement plant in Trident, MT
  - Compressive strengths 10% higher at 7 days and 4% higher at 28
- Ash Grove cement
  - Type I/II cement
  - Ash Grove cement plant in Clancy, MT
  - Delayed turnover time
    - Higher water demands

| Cement Source | Flow (in.) | Compressive strength, f'c (ksi) | |
|---|---|---|---|
| | | 7-day | 28-day |
| Trident (May 2018) | 8.50 | 14.7 | 17.5 |
| Ash Grove | 5.88 | 13.3 | 16.8 |

# Effect of Fly Ash Source

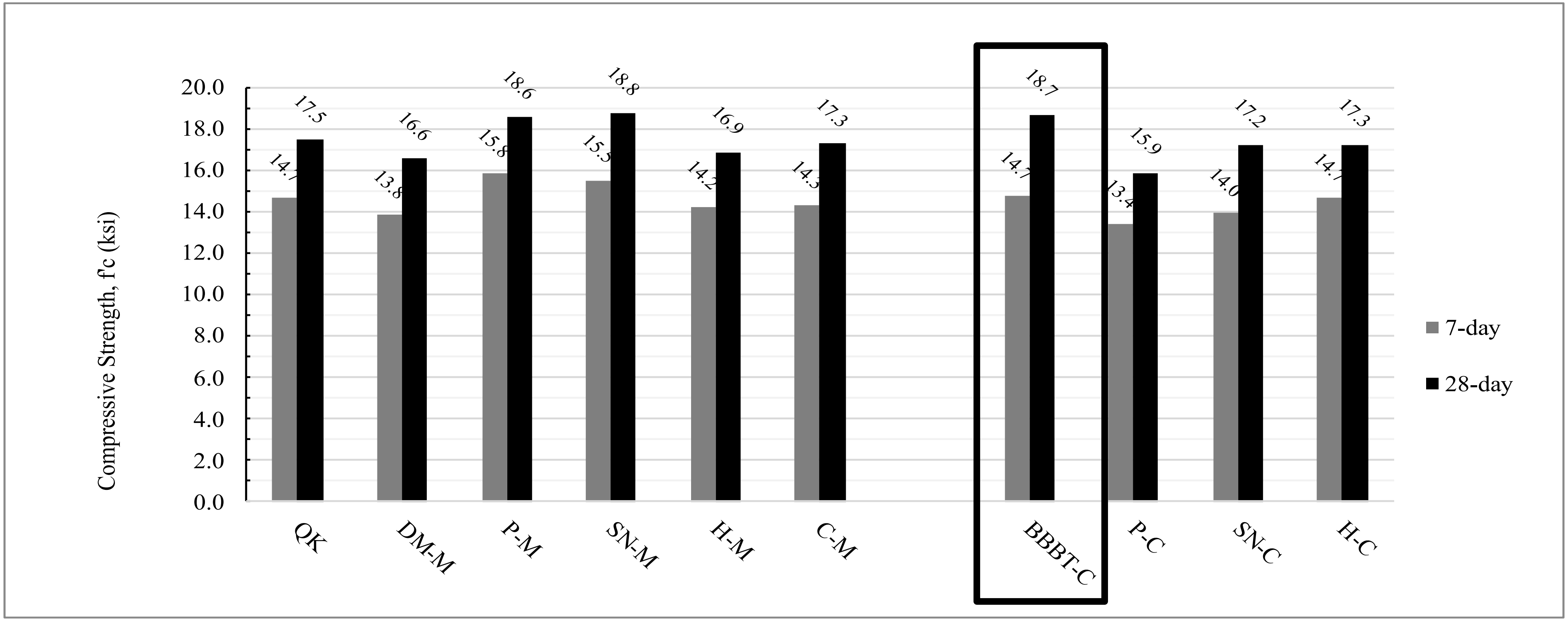
- Coal Creek ash
  - Coal Creek power plant in Underwood, North Dakota
- Genesee fly ash
  - Genesee Generating Station near Warburg, Alberta, and was supplied by the GCC cement plant near Trident, MT
- Sheerness fly ash
  - Ash Grove cement plant and obtained from the Sheerness Generating Station in Hanna, Alberta

| Fly Ash Source | Flow (in.) | Compressive strength, f'c (ksi) 7-day | Compressive strength, f'c (ksi) 28-day |
|---|---|---|---|
| **Genesee** | 9 | 14.6 | 18.2 |
| **Coal Creek** | 10 | 15.2 | 18.2 |
| **Sheerness** | 11 | 14.9 | 18.1 |

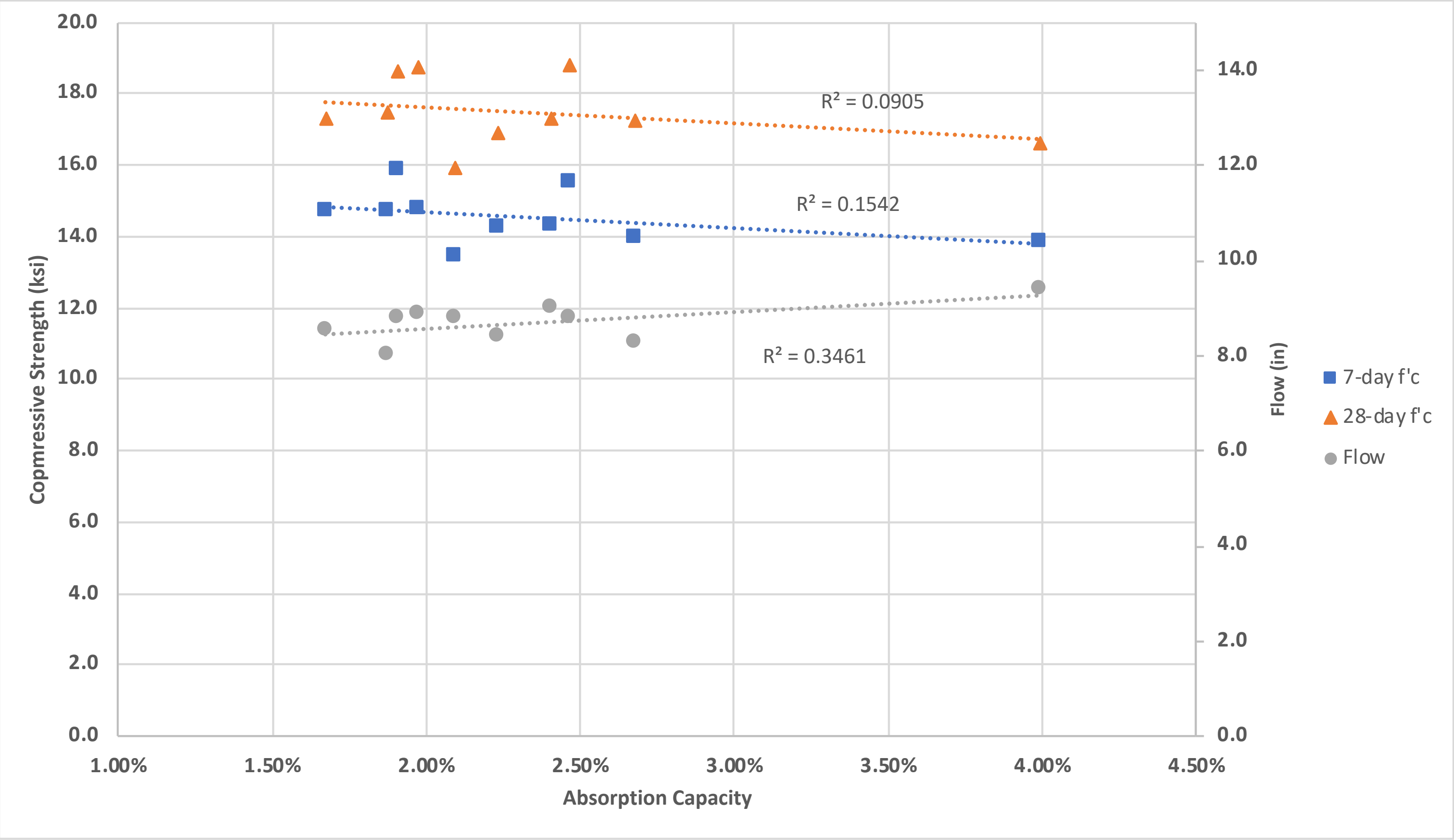
# Effect of Fine Aggregate

| Fine Aggregate Source | Supplier | Location | Flow (in) | Compressive Strength (ksi) 7-day | Compressive Strength (ksi) 28-day |
|---|---|---|---|---|---|
| **QUIKRETE-Masonry** | QUIKRETE | Billings, MT | 8.0 | 14.7 | 17.5 |
| **Diamond Mountain-Masonry** | BBB&T | Frenchtown, MT | 9.4 | 13.8 | 16.6 |
| **Pioneer-Masonry** | Pioneer Concrete & Fuel | Butte, MT | 8.8 | 15.8 | 18.6 |
| **S&N-Masonry** | S&N Concrete & Materials | Anaconda, MT | 8.8 | 15.5 | 18.8 |
| **Helena-Masonry** | Helena Sand & Gravel | Helena, MT | 8.4 | 14.2 | 16.9 |
| **Capital-Masonry** | Capital Concrete | East Helena, MT | 9.0 | 14.3 | 17.3 |
| **BBB&T-Concrete** | BBB&T | Bozeman, MT | 8.9 | 14.7 | 18.7 |
| **Pioneer-Concrete** | Pioneer Concrete & Fuel | Butte, MT | 8.8 | 13.4 | 15.9 |
| **S&N-Concrete** | S&N Concrete & Materials | Anaconda, MT | 8.3 | 14.0 | 17.2 |
| **Helena-Concrete** | Helena Sand & Gravel | Helena, MT | 8.5 | 14.7 | 17.3 |

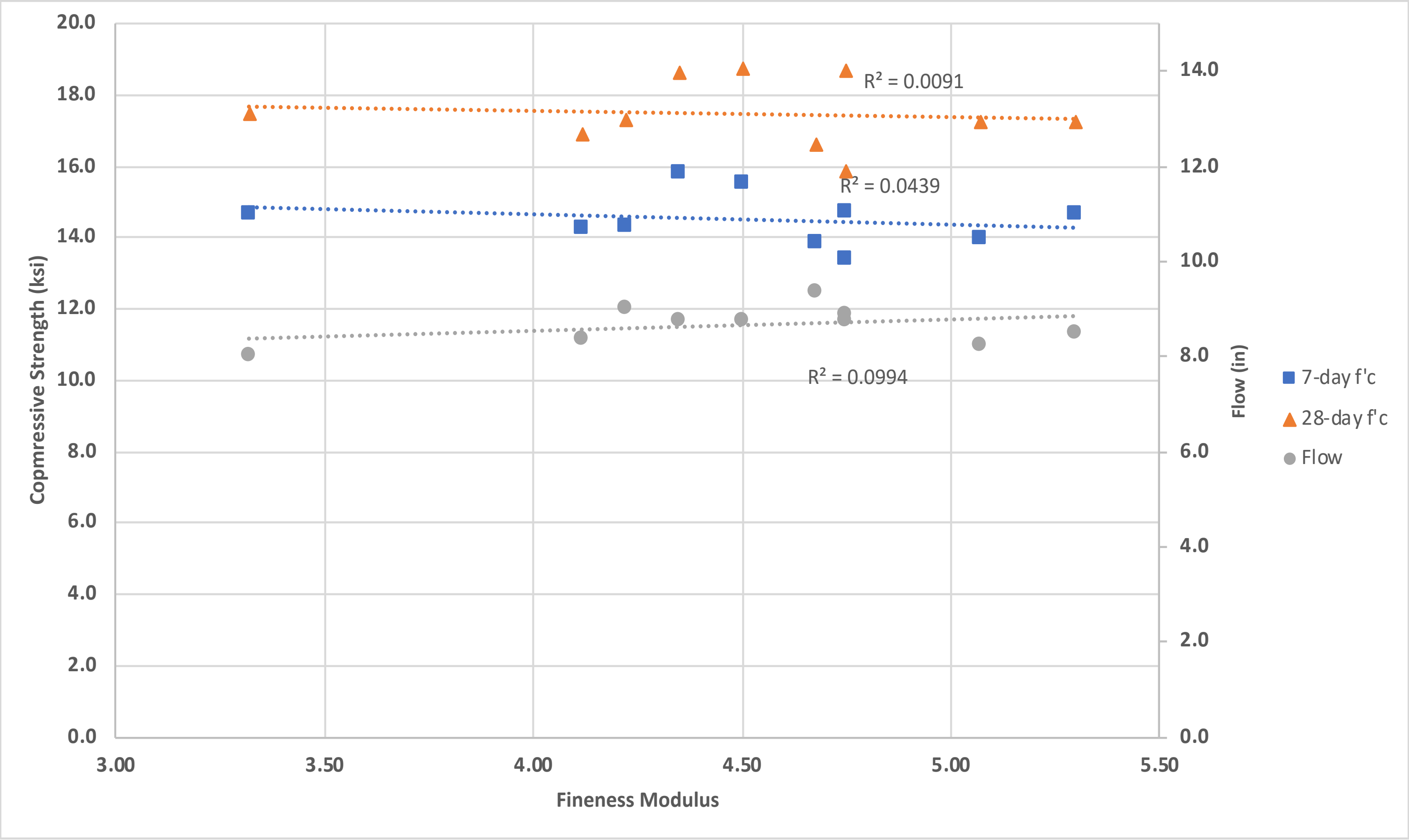
# Compressive Strengths



# Absorption Capacity



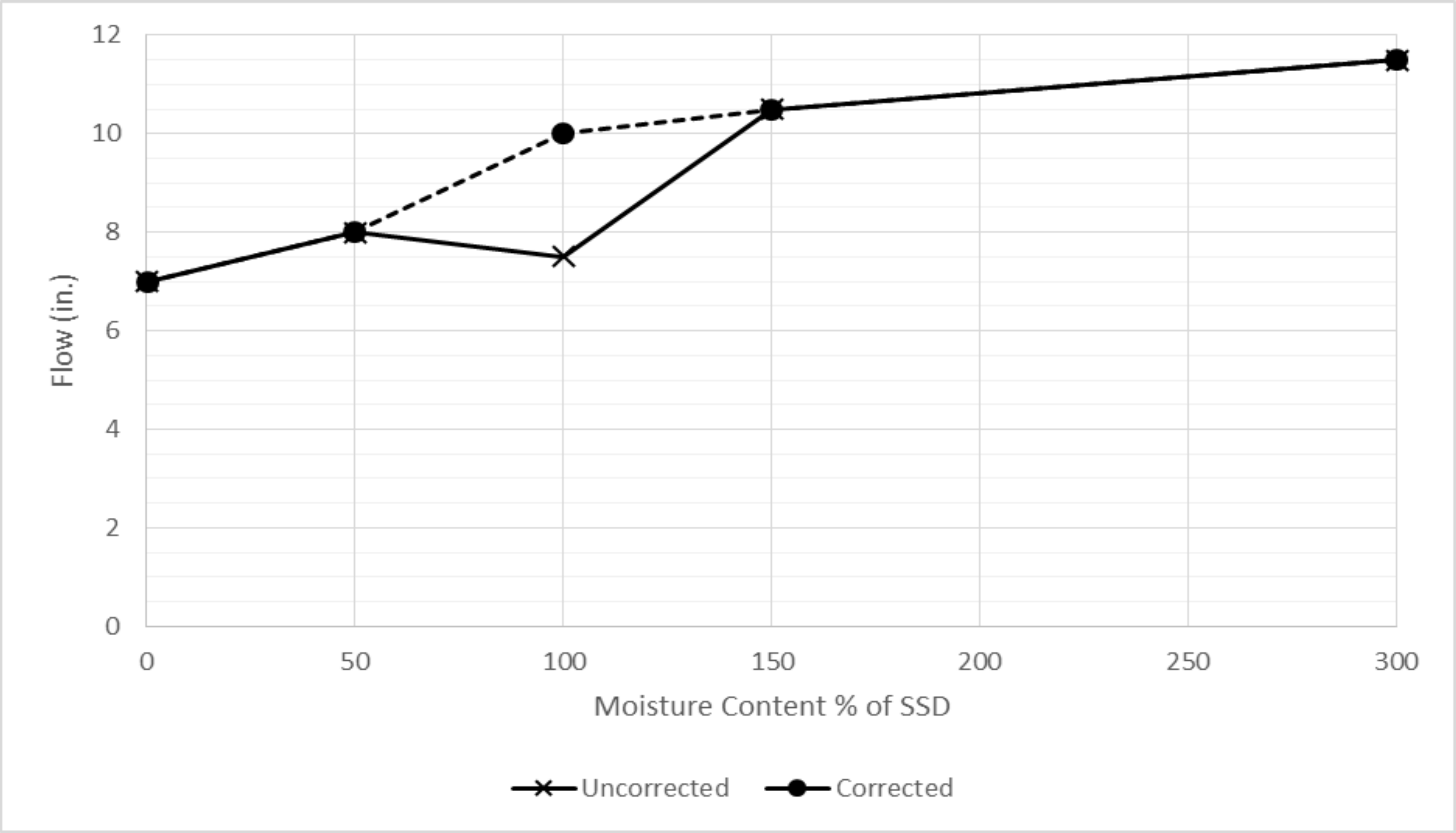
# Fineness Modulus



# Effect of Aggregate Moisture Content

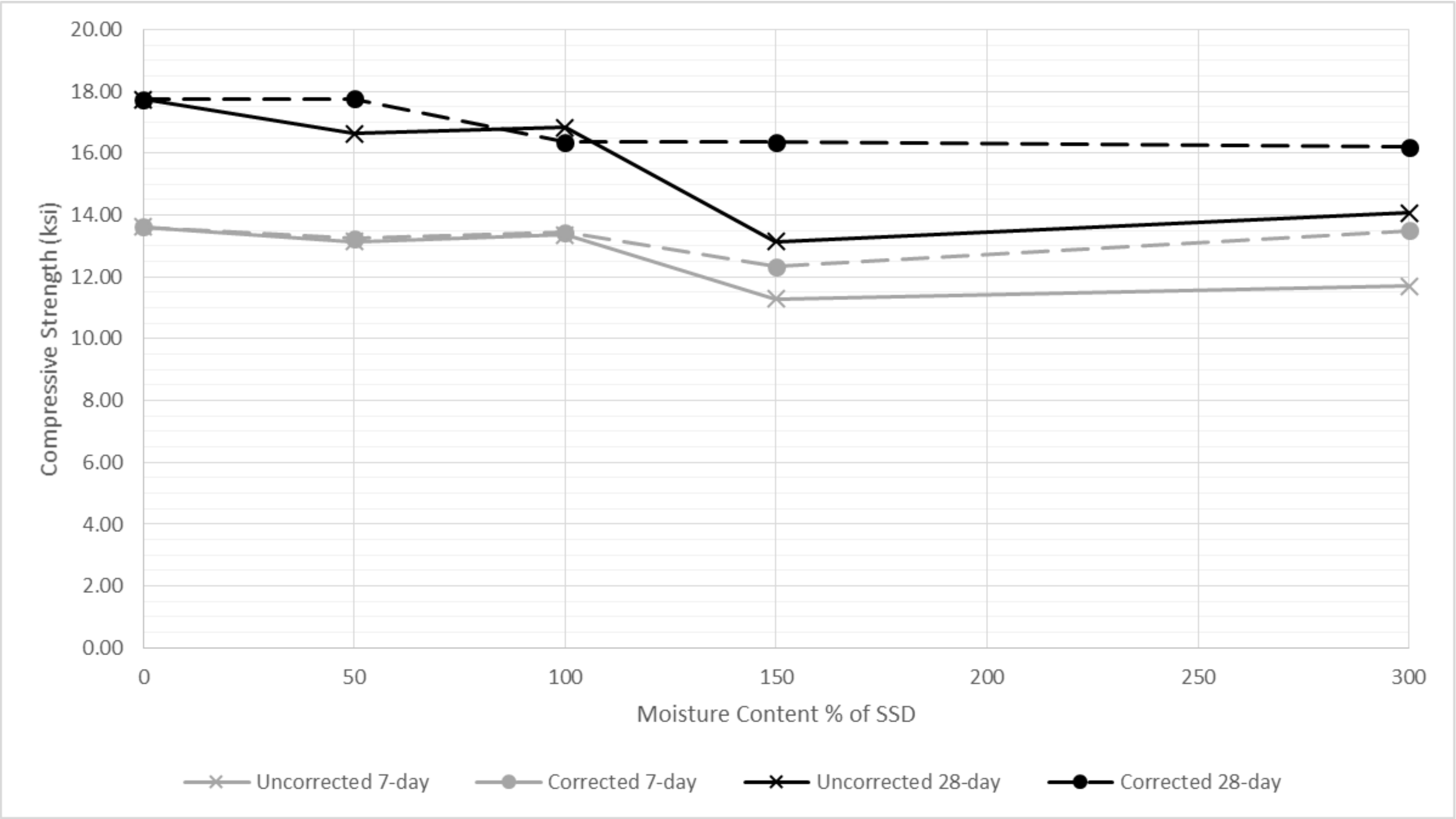
| Moisture Target | Flow (in.) | Compressive Strength, f'c (ksi) | |
|---|---|---|---|
| | | 7-day | 28-day |
| Oven Dried | 7 | 13.61 | 17.73 |
| 50% of SSD | 8 | 13.14 | 16.62 |
| 100% of SSD | 7.5 | 13.35 | 16.83 |
| 150% of SSD | 10.5 | 11.28 | 13.14 |
| 300% of SSD | 11.5 | 11.71 | 16.31 |
| 50% of SSD - MCC | 8 | 13.25 | 17.75 |
| 100% of SSD - MCC | 10 | 13.44 | 16.37 |
| 150% of SSD - MCC | 10.5 | 12.33 | 16.36 |
| 300% of SSD - MCC | 11.5 | 13.50 | 16.20 |
| Average: | 9.39 | 12.85 | 16.37 |
| C.O.V.: | 0.177 | 0.063 | 0.077 |

# FLOWS



12
10
8
6
4
2
0
Flow (in.)
0
50
100
150
200
250
300
Moisture Content % of SSD
Uncorrected
Corrected

# COMPRESSIVE STRENGTHS

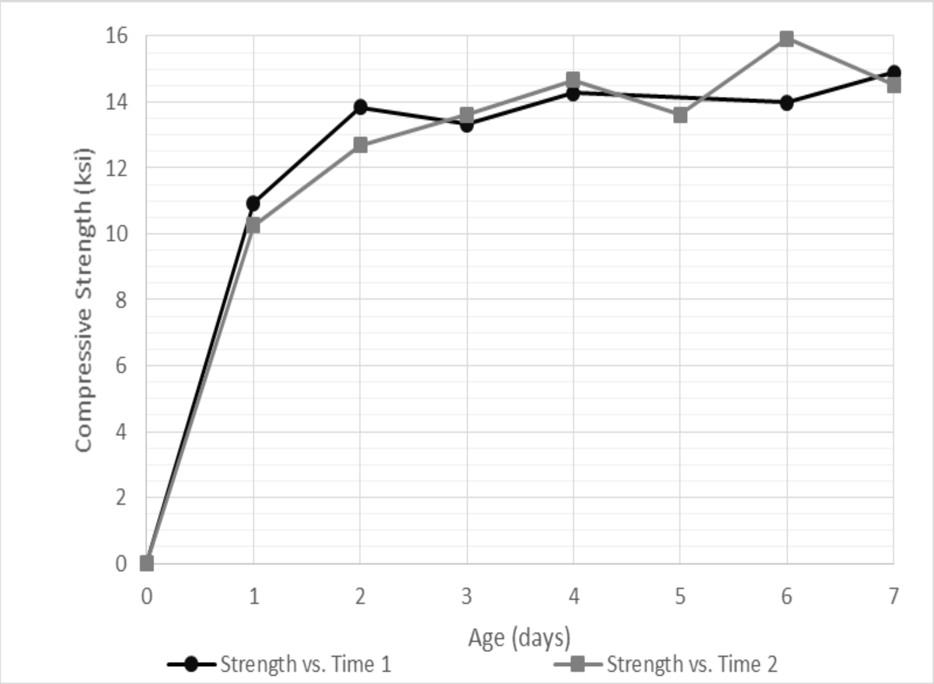


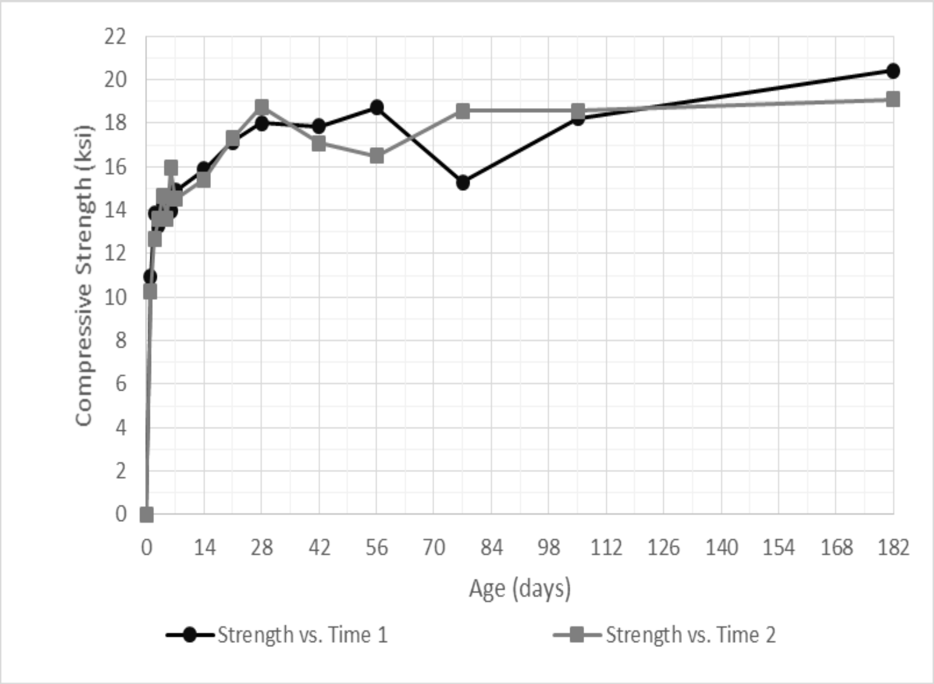
# Steel Fibers

| Properties | Nycon-SF Type I | Bekaert Dramix OL 13/0.20 |
|---|---|---|
| Length (mm) | 13 | 13.0 |
| Diameter (mm) | 0.2 | 0.2 |
| Aspect Ratio | 65 | 65.0 |
| Tensile Strength (ksi) | 285 | 399.0 |
| Elastic Modulus (ksi) | 29000 | 29000 |
| Coating | Copper | Copper |
| **Flow (in.)** | 8.5 | 10.0 |
| **7-day Comp. Strength (ksi)** | 14.7 | 13.9 |
| **28-day Comp. Strength (ksi)** | 17.5 | 17.3 |
| **Initial Cracking Strength (ksi)** | 1.98 | ? |
| **Ultimate Flexure Strength (ksi)** | 3.39 | 2.95 |

# SENSITIVITY TO MIXING VARIABILITY & FIELD CONDITIONS

# Strength Gain vs. Time

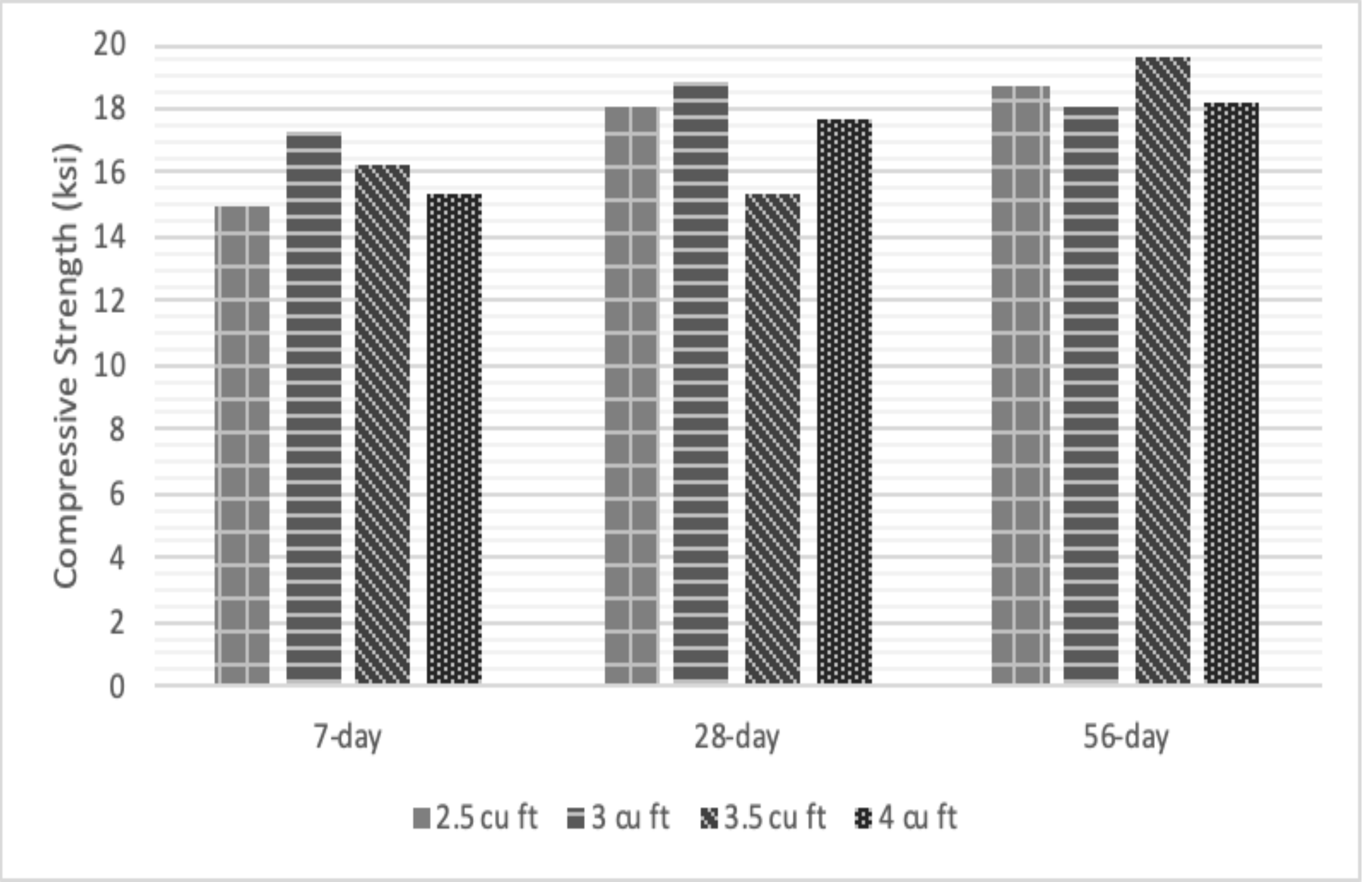


# Batch Size

| Mix Size (cu. ft.) | Flow (in.) | Compressive Strength, f'c (ksi) | | |
|---|---|---|---|---|
| | | 7-day | 28-day | 56-day |
| 2.5 | 9 | 14.90 | 18.01 | 18.71 |
| 3 | 9.5 | 17.29 | 18.81 | 18.01 |
| 3.5 | 7.5 | 16.25 | 15.97 | 19.57 |
| 4 | 8.5 | 15.38 | 17.73 | 18.24 |
| **Average:** | 8.63 | 15.95 | 17.63 | 18.63 |
| **C.O.V.:** | 8.6% | 5.7% | 5.9% | 3.2% |

# Batch Size

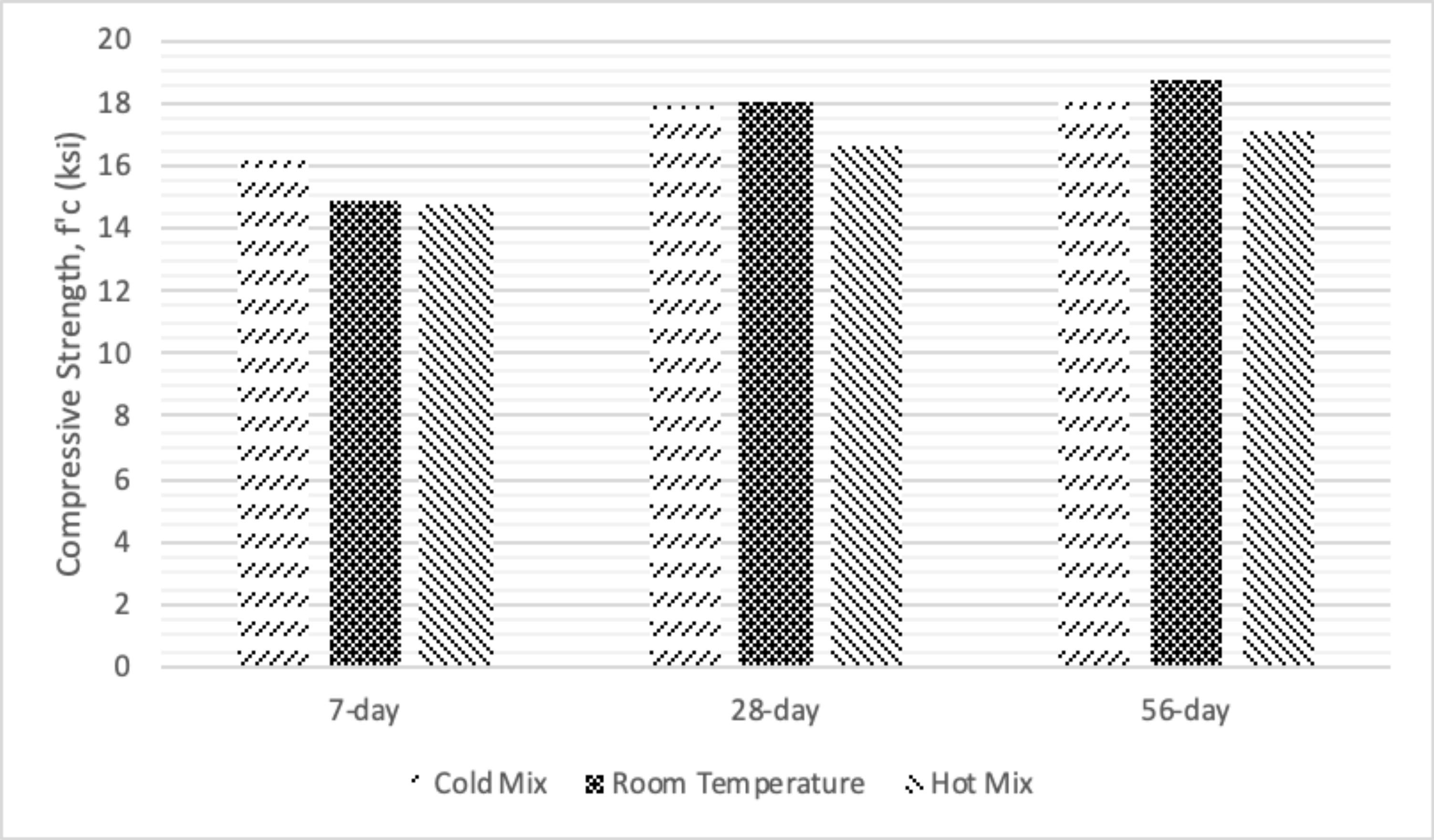


20
18
16
14
12
10
8
6
4
2
0
Compressive Strength (ksi)
7-day
28-day
56-day
2.5 cu ft
3 cu ft
3.5 cu ft
4 cu ft

# Effect of Temperature

| Mix | Outside Temp. | Material Temp. | Flow (in.) | Compressive Strength, f'c (ksi) | | |
|---|---|---|---|---|---|---|
| | | | | 7-day | 28-day | 56-day |
| Cold Mix | 45°F | 32°F | 10 | 16.15 | 17.89 | 17.98 |
| Lab Temp. | 70°F | 60°F | 9 | 14.9 | 18.01 | 18.71 |
| Hot Mix | 75°F | 90°F | 6.25 | 14.78 | 16.62 | 17.03 |
| | | **Average:** | 8.42 | 15.27 | 17.51 | 17.91 |
| | | **C.O.V.:** | 18.8% | 4.1% | 3.6% | 3.8% |

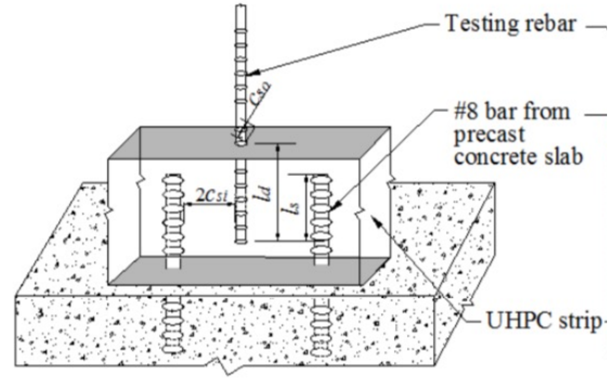
# Effect of Temperature



# BOND STRENGTH & PULLOUT TESTING

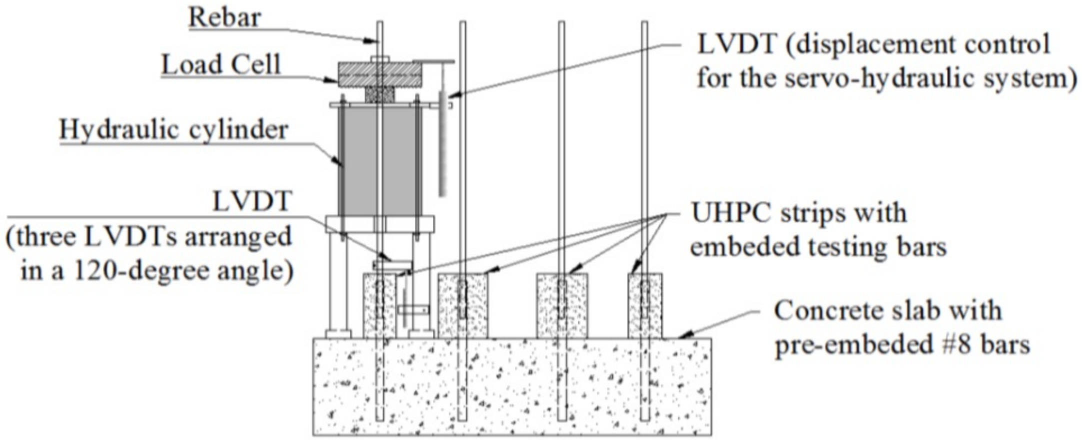
# Testing Setup

- Testing bar pulled out of 10 inch tall UHPC curbs
- Curbs running transversely across the top of conventional concrete slabs
- Connected through No. 8 Grade 60 bars
  - Extend 8 in. into the UHPC curbs and 11.5 in. inches into the conventional concrete slabs
- Testing bar located between #8 bars
- UHPC curbs cure for 28 days

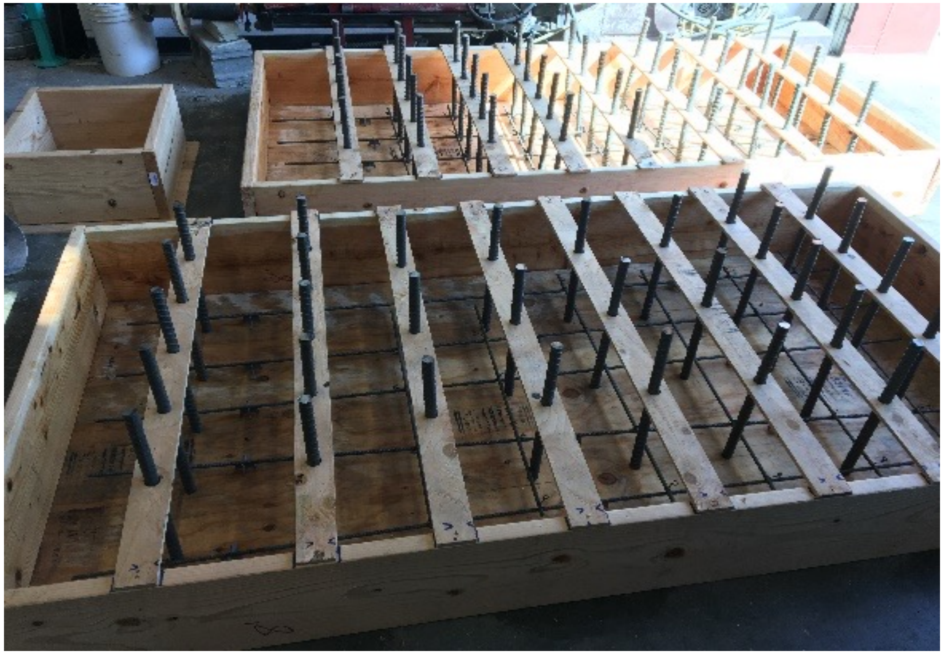



# Testing Setup

- Hydraulic jack on steel chair
- Testing bar pulled by hydraulic jack using bar chuck



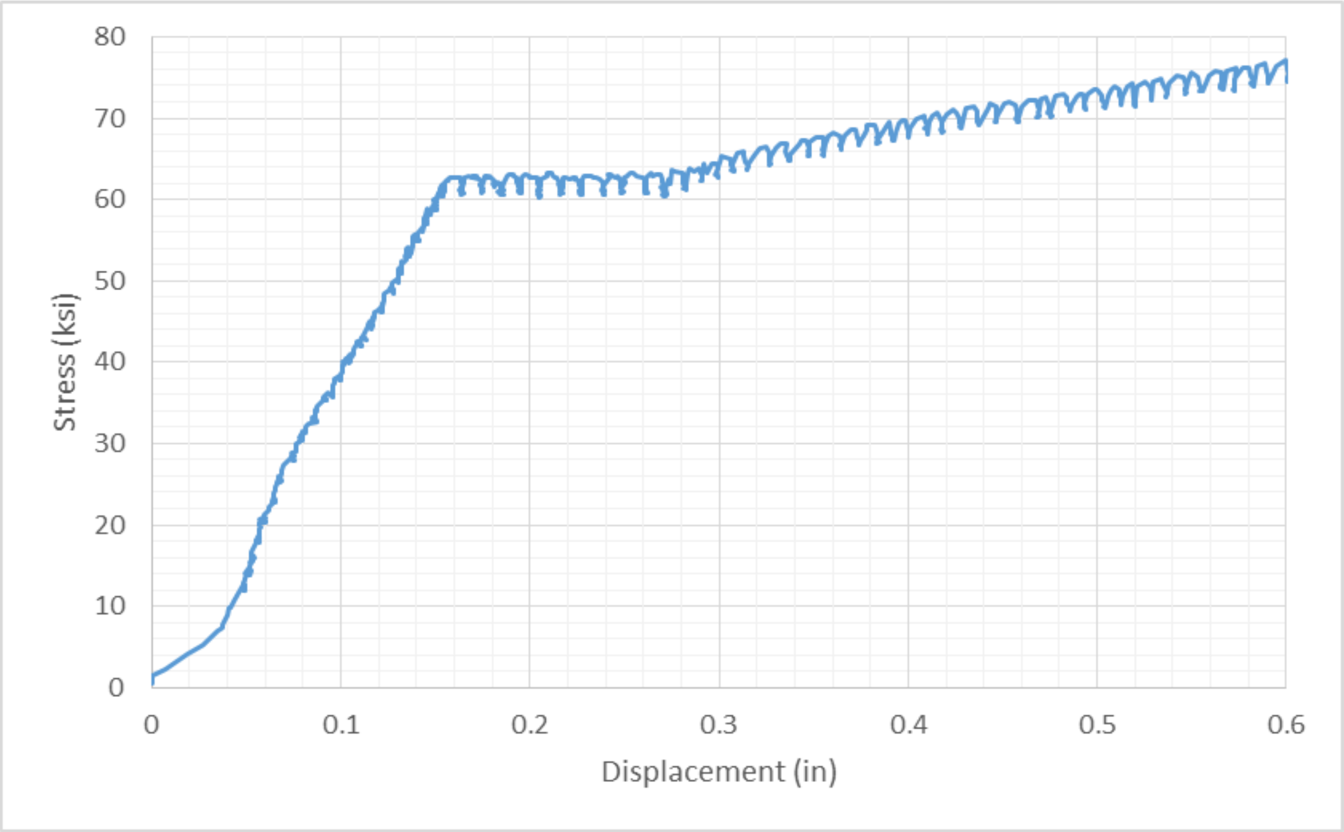

# Construction



# Pullout Testing

- Fifty-six total pullout tests were conducted
- Variables tested including bar size, bar embedment length, bar clear spacing, and bar clear cover
- Validate FHWA recommendations for development length
- No. 4, 5, 6, and 7 Grade 60 bars tested within the FHWA's recommended embedment, side cover, and bar spacing
- Each test bar was pulled beyond the rebar yielding limit to be sure the UHPC bond strength was above this maximum safe rebar loading

# Typical Stress-Displacement Plot



# FHWA Test Results

| Flow (in) | f'c, ksi | Bar Size | $l_d$, in | ls, in | $c_{so}$, in | $c_{si}$, in | Max. Stress (ksi) | Failure Mechanism |
|---|---|---|---|---|---|---|---|---|
| 11.0 | 17.34 | 4 | 4 | 2 | 1.5 | 3 | 80.79 | Yielding |
| 11.0 | 17.34 | 4 | 4 | 2 | 1.5 | 3 | 69.44 | Yielding |
| 11.0 | 17.34 | 4 | 4 | 2 | 1.5 | 3 | 92.08 | Yielding |
| 11.0 | 17.34 | 4 | 4 | 2 | 1.5 | 3 | 69.95 | Yielding |
| 9.5 | 16.59 | 5 | 5 | 3 | 1.875 | 3.1875 | 77.12 | Yielding |
| 9.5 | 16.59 | 5 | 5 | 3 | 1.875 | 3.1875 | 73.45 | Yielding |
| 9.5 | 16.59 | 5 | 5 | 3 | 1.875 | 3.1875 | 73.37 | Yielding |
| 9.5 | 16.59 | 5 | 5 | 3 | 1.875 | 3.1875 | 63.53 | Yielding |
| 11.0 | 17.34 | 6 | 6 | 4 | 2.25 | 3.125 | 77.35 | Yielding |
| 11.0 | 17.34 | 6 | 6 | 4 | 2.25 | 3.125 | 66.41 | Yielding |
| 11.0 | 17.34 | 6 | 6 | 4 | 2.25 | 3.125 | 86.34 | Yielding |
| 11.0 | 17.34 | 6 | 6 | 4 | 2.25 | 3.125 | 48.49 | Yielding |
| 9.5 | 16.59 | 7 | 7 | 5 | 2.625 | 3.0625 | 76.45 | Yielding |
| 9.5 | 16.59 | 7 | 7 | 5 | 2.625 | 3.0625 | 77.31 | Yielding |
| 9.5 | 16.59 | 7 | 7 | 5 | 2.625 | 3.0625 | 72.8 | Yielding |
| 9.5 | 16.59 | 7 | 7 | 5 | 2.625 | 3.0625 | 102.65 | Yielding |

# Conclusions

- Material Sensitivity
  - Material source variations had fairly minor effects on UHPC performance
  - Replacing materials sources can be admissible as long as materials with similar properties to the original mix constituents are used.
  - Aggregate Moisture Content effected behavior
    - With increasing moisture content, UHPC performance generally decreased
    - Flow generally increased with increasing moisture content and the 7- and 28-day compressive strengths generally decreased
    - Moisture content corrections only slightly helped the UHPC mixes
  - Trial batches should always be completed when using different materials or material sources

# Conclusions

- Sensitivity to Mixing Variability and Field Conditions
  - Mixes obtained high early strengths, exceeding 10 ksi in the first 24 hours
  - The mixes continued to gain strength over the duration of testing, ultimately reaching strengths of around 20 ksi at 182 days
  - Batch size was not observed to have a significant effect on flow or compressive strength
  - Larger scale mixes required 10% more water and HRWR
  - Flow was observed to decrease with increasing temperature
  - Compressive strengths for the hot mix were consistently the lowest
  - Care should be given while batching and mixing UHPC mixes at higher temperatures

# Conclusions

- Pullout and Bond Strength
  - When FHWA recommendations are followed, UHPC is satisfactory for the purposed pullout application
- Overall
  - All mixes in this study had a flow between 6 and 11 inches, and respective 7- and 28- day compressive strengths of at least 13 and 16 ksi despite the wide range of mixes completed
  - In terms of implementation, it is recommended doing multiple trial batches before use

# Acknowledgements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