Development, Characterization & Applications of Non-Proprietary Ultra High Performance Concretes for Highway Bridges

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So, what is UHPC?

- ACI 239 voted on a definition
  - "Concrete that has a minimum specified compressive strength of 150 MPa (22 ksi) with specified durability, tensile ductility and toughness requirements using reproducible test methods; fibers are generally included to achieve specified requirements"
- A cementitious composite material
  - Properly selected and optimized reactive components
  - Optimally graded granular constituents
  - A water-to-cementitious materials ratio less than 0.22
  - Contains discontinuous fiber reinforcement
  - Has a discontinuous pore structure

Proprietary Material is Expensive

- Sold by LaFarge and marketed as *Ductal*.
  - Others include Densit, Cemtec
- Proprietary materials are much more expensive than regular concretes.
- Construction requires specially certified contractors and costly construction processes.

Non-proprietary UHPC

- In 2008, we published the mix ingredients and mixing process for non-proprietary UHPC.

Optimizing Ultra-High-Performance Fiber-Reinforced Concrete

Mixtures with twisted fibers exhibit record performance under tensile loading

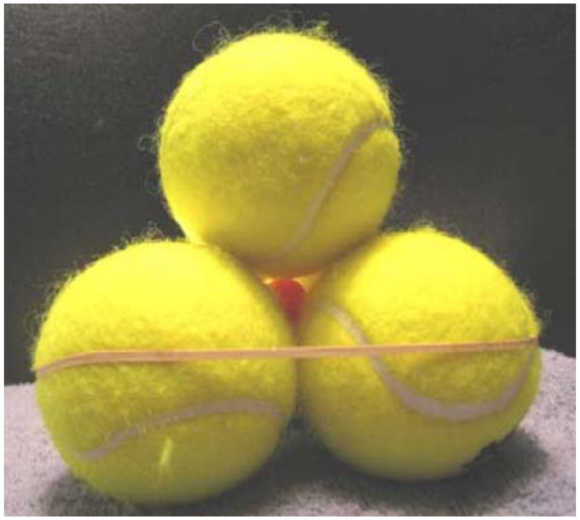
by Kay Wille, Antoine E. Naaman, and Sherif El-Tawil

Ultra-high-performance concrete (UHPC) has attracted the attention of researchers and practitioners since its introduction in the mid-1990s, not only because of its high compressive strength

Making the Material

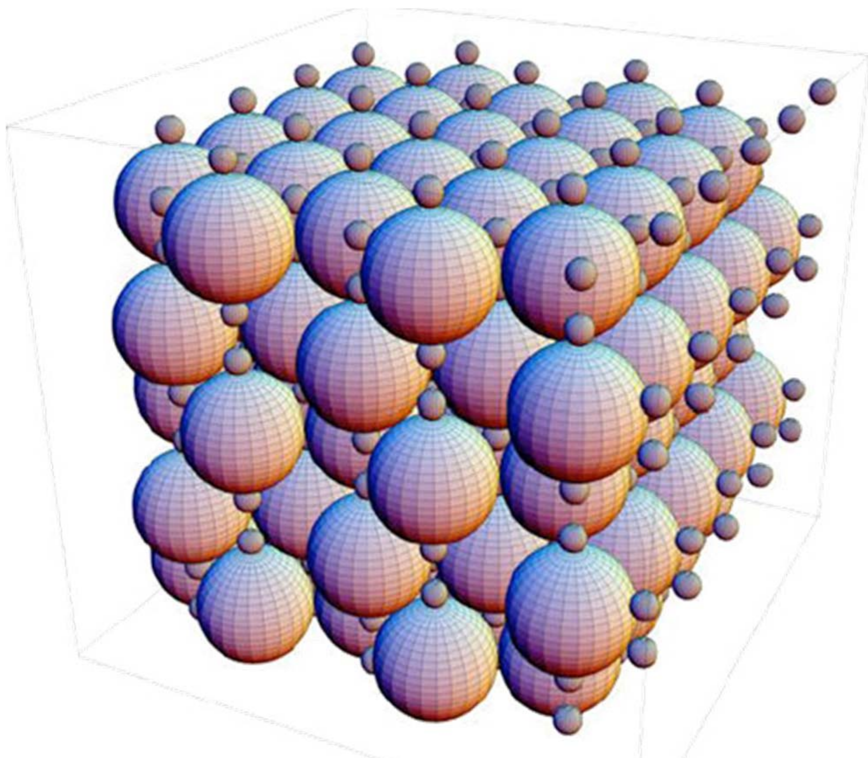
- Step 1: Selected Reactive Components
  - Cement, silica fume, HRWR.
- Step 2: Stable and Optimized Packing

Tetrahedral Arrangement

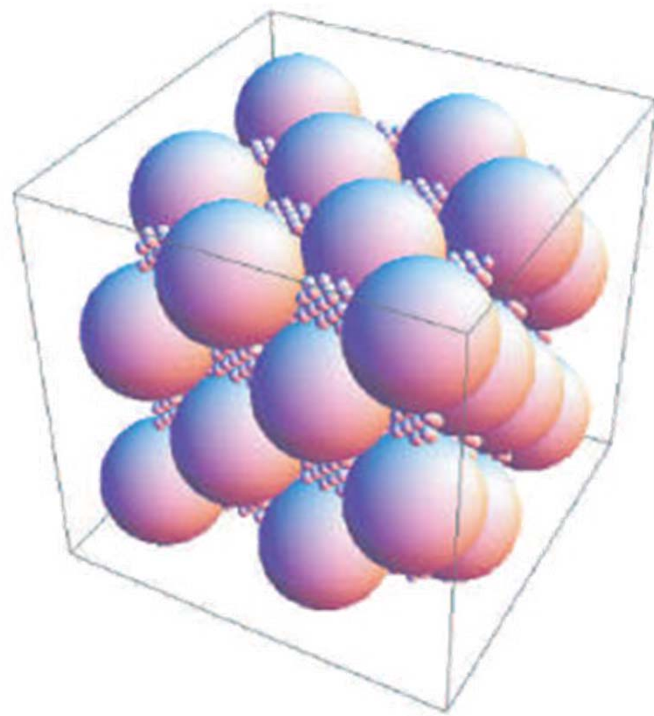


Tetrahedron with sphere in void

How is Packing Optimized?



Ordered Tetrahedral Arrangement[1]



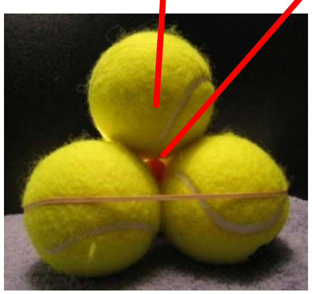
Increased packing density using two sizes of spheres[2]

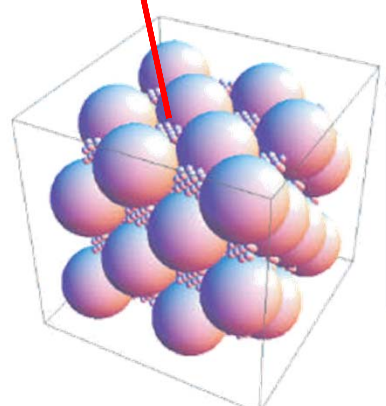
[1]*Jacobson, Alec, "Sphere Packing Lattice Generation," August 16, 2007, 21 pages. Web publication (http://alecjacobson.com/programs/sphere-packing/).*

[2]Yamada, S., Kanno, J., and Miyauchi, M., "Multi-Sized Sphere Packing," 7th Japan Conference on Computational Geometry and Graphs, November 11-13, 2009, Kanazawa, Ishikawa, Japan.

How is Packing Optimized?

r_1 Sand 1	r_2 Sand 2	r_3 Glass powder and SF	r_4	r_5
0.5 mm = 500 microns (diameter = 1 mm)	113 microns (diameter = 0.225 mm)	0.73 microns (diameter = 1.46 microns)	25 microns (diameter = 50 microns)	0.037 micron 37 nano-m (diameter = 0.074 microns)
0.25 mm (diameter = 0.5 mm in case study with UHP-FRC)	56 microns (diameter = 0.113 mm)	0.18 microns (diameter = 0.36 microns)	12.7 microns (diameter = 25 microns)	0.0092 micron 9 nano-m (diameter = 0.018 microns)



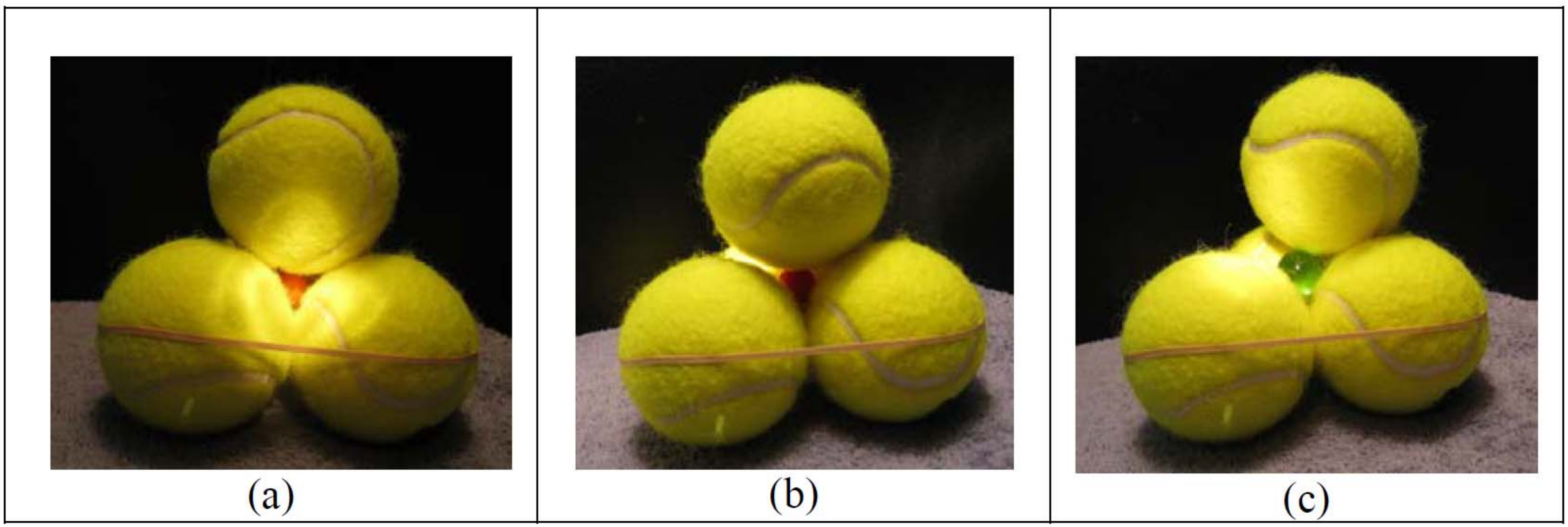


Close in size to Cement Particles

Future: Nano Materials

Ensuring Flowability

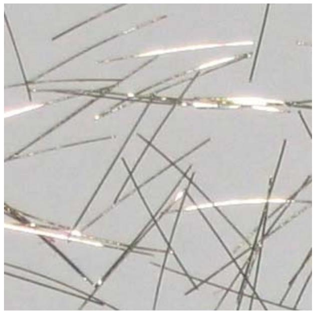
- Hexagonal arrangement is very stable.
  - Not favorable for spreading or flowing
- Exceed theoretical r_2 to create instability.



Step 3: Select Fiber Types

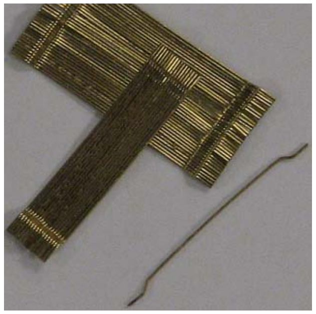
Undeformed

Straight



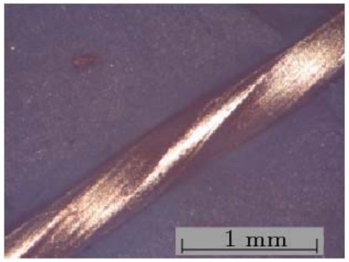
Deformed

End hooked

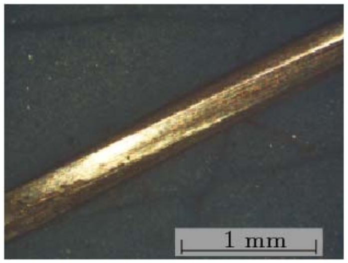


Twisted along the fiber

High twist ratio



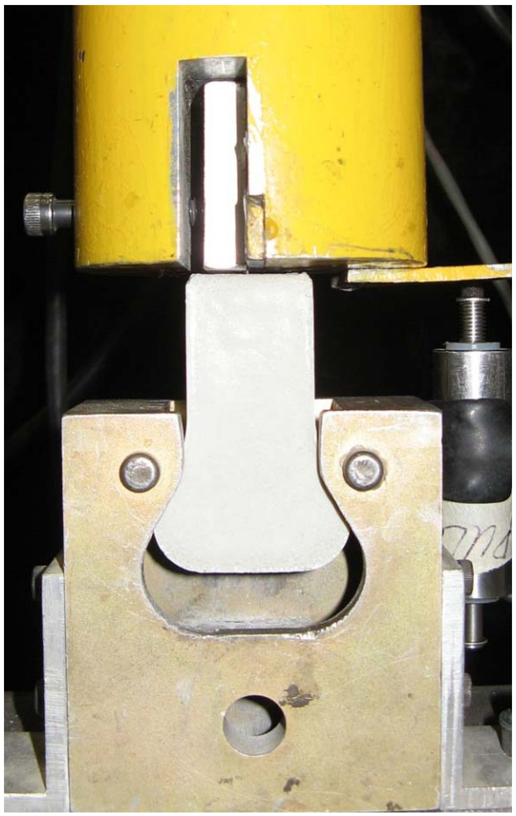
Low twist ratio

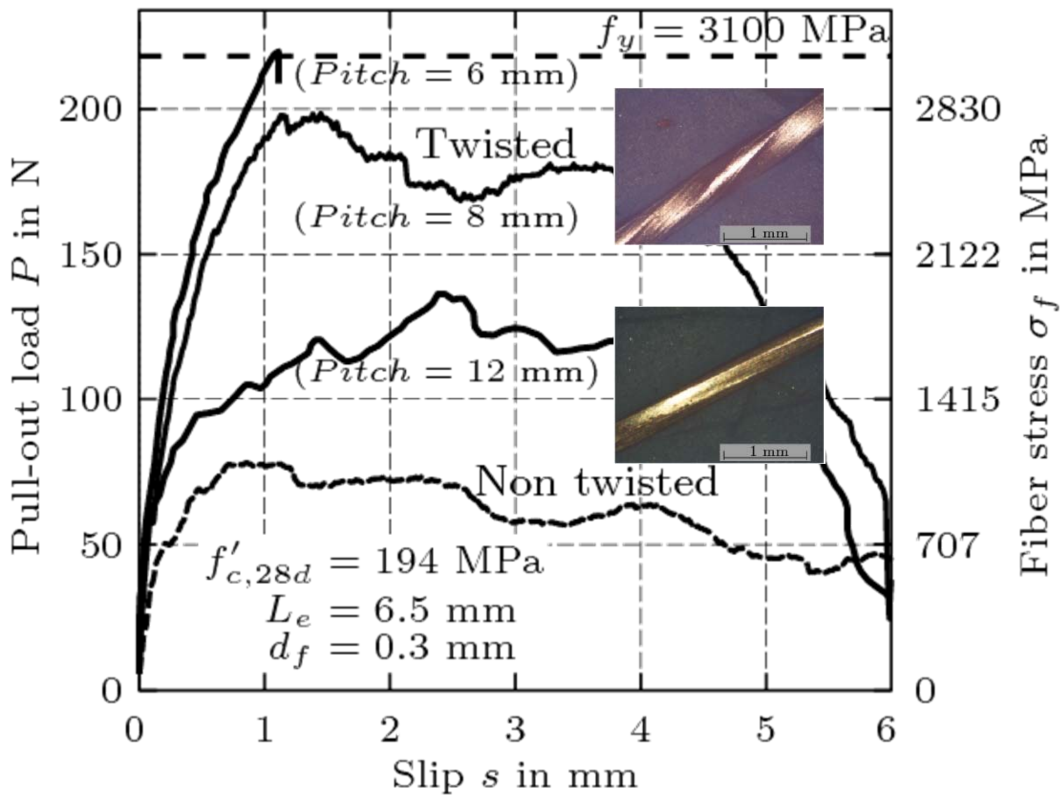


Volume Fraction:

1 % to 2.5%

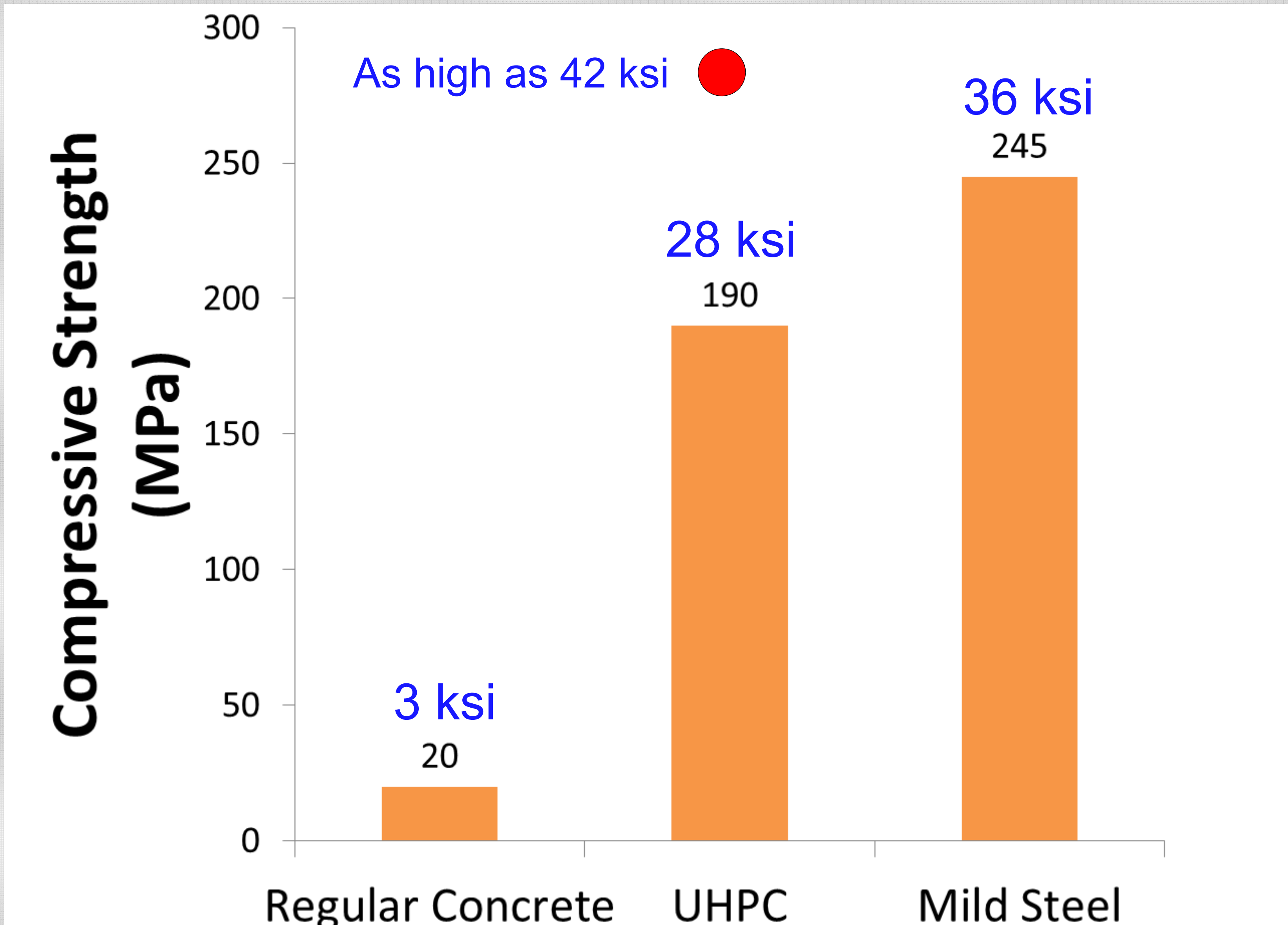
Step 4: Tailor Bond Properties





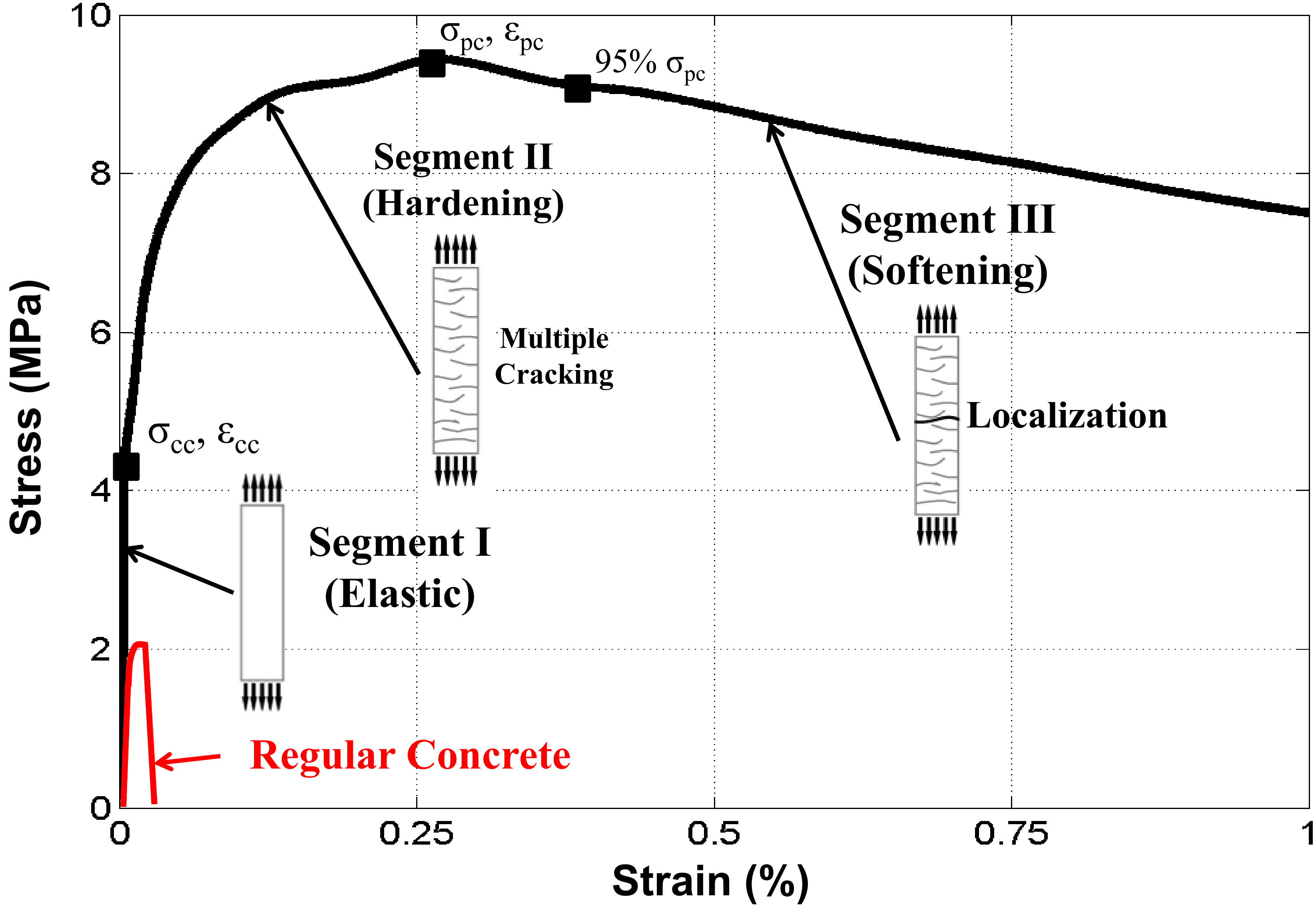
Test setup **Typical pull out response**

Mixing of Non-Proprietary UHPC



Compressive Strength (MPa)
300
250
200
150
100
50
0
As high as 42 ksi
3 ksi
20
28 ksi
190
36 ksi
245
Regular Concrete
UHPC
Mild Steel

UHPC Tensile Stress-Strain Response



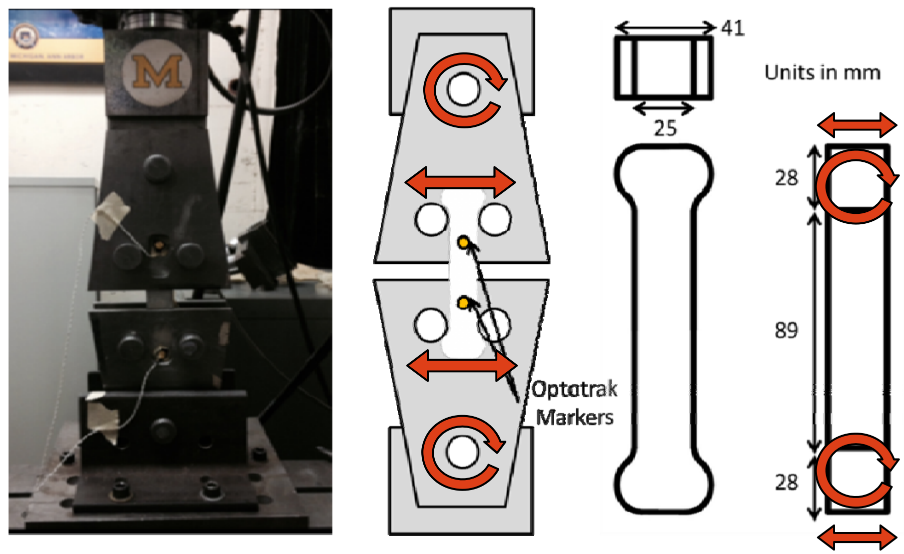
MDOT-Funded Project

- Current materials are expensive
  - Cost must be reduced!
- All of the literature compiled on UHPC has been on the proprietary blends, Ductal® and Cemtec Multiscale®
- Data on short and long-term behavior on UHPC
  - Only available for proprietary blends
- Data on bond between UHPC and deformed bars
  - Only available for proprietary blends
- Work on UHPC joint connections have been limited to a select few FHWA projects

Test Series	Compressive Strength	First Cracking Strength σ_{cc}	Post Cracking Strength. σ_{pc}	Energy Absorption Capacity G	Strain Capacity ε_{pc}	Fiber Tensile Stress σ_{fpc}	Average Number of Cracks	Cost Index ($/$ Original Mix)*
	MPa	MPa	MPa	KJ/m^3	%	MPa	#	
W-25-25-1.5	192.7	6.6	9.48	30.20	0.19	698	7.8	1.0
W-30-20-0.5	144.7	3.5	6.1	3.3	0.05	1354	1.7	
W-30-20-1.0	163.5	3.8						
W-30-20-1.5	195.2	4.1						
W-35-15-0.5	144.1	3.6						
W-35-15-1.0	165.6	5.6						
W-35-15-1.5	195.4	7.2						
W-25-20-0.5	177.6	3.4						
W-25-20-1.0	187.8	4.6						
W-25-20-1.5	195.3	7.9						
W-25-15-0.5	181.0	3.8						
W-25-15-1.0	177.8	5.8						
W-25-15-1.5	192.7	6.6						
W-25-00-1.5	173.8	5.4						
PV-25-15-0.5	143.7	3.7						
PV-25-15-1.0	172.1	6.2						
PV-25-15-1.5	183.1	7.5						
PV-25-10-1.5	174.4	5.8						
PV-25-05-1.5	182.0	6.3						
PV-30-05-1.5	172.4	4.7	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
PV-35-05-1.5	177.2	4.6	7.2	20.2	0.24	534	10.5	0.68
PV-25-00-0.5	152.9	3.3	4.1	7.4	0.15	915	2.4	
PV-25-00-1.0	161.7	6.2	7.6	35.1	0.11	847	5.6	0.55
PV-25-00-1.5	174.0	6.3	9.0	35.1	0.11	666	8.1	
PV-25-25-1.5	190.0	5.7	8.8	18.7	0.15	651	10.0	0.82
GG-25-00-1.5	173.8	5.9	8.0	17.6	0.15	595	9.0	0.52
GG-25-15-1.5	180.6	5.7	8.6	24.2	0.21	633	10.5	0.69
GG-25-25-1.5	185.5	5.5	9.4	40.5	0.28	699	11.3	0.79

Mix GG-25-00-1.5 reduces material cost by 50%

Maintains UHPC performance in tension and compression

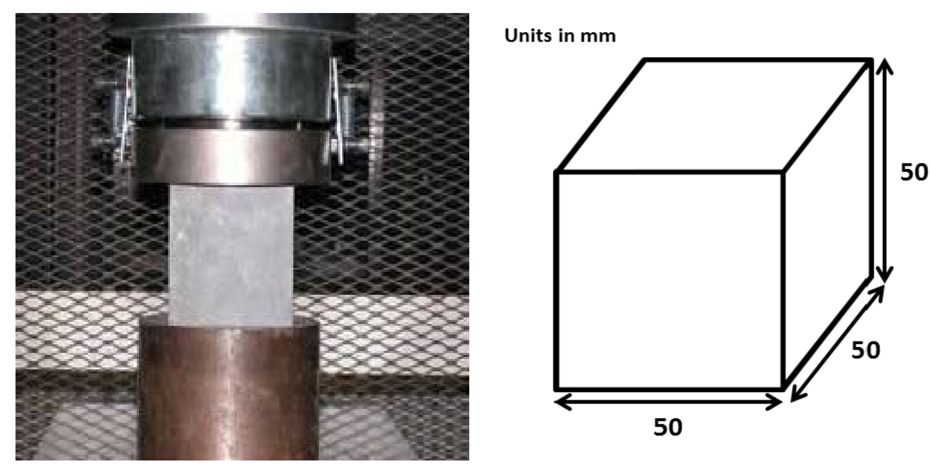


Tensile Test Set Up

(Custom Set Up)

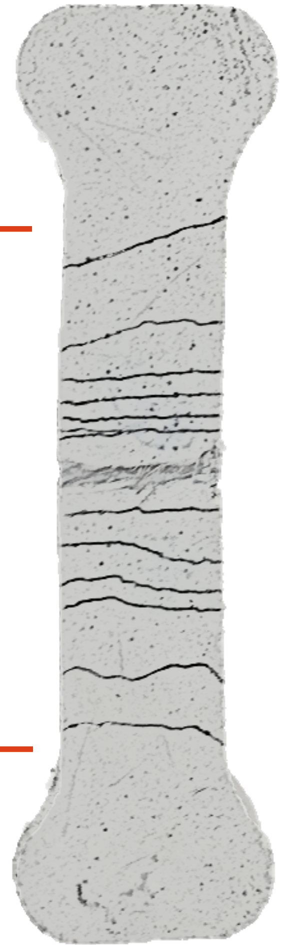
Compression Test Set Up

(ASTM C109)

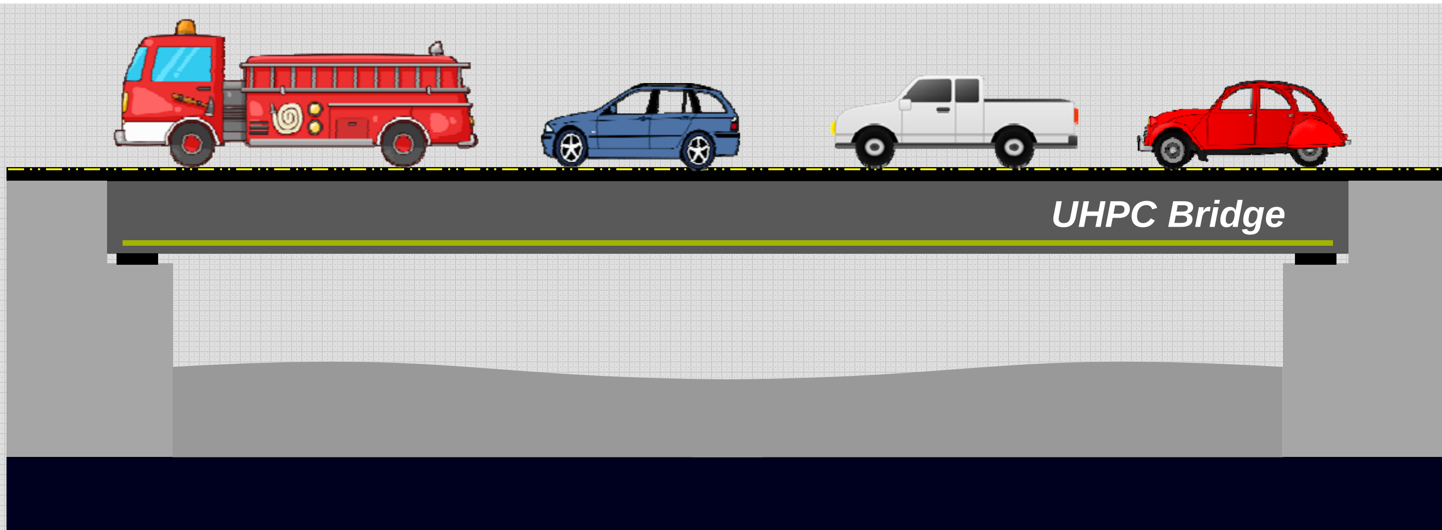


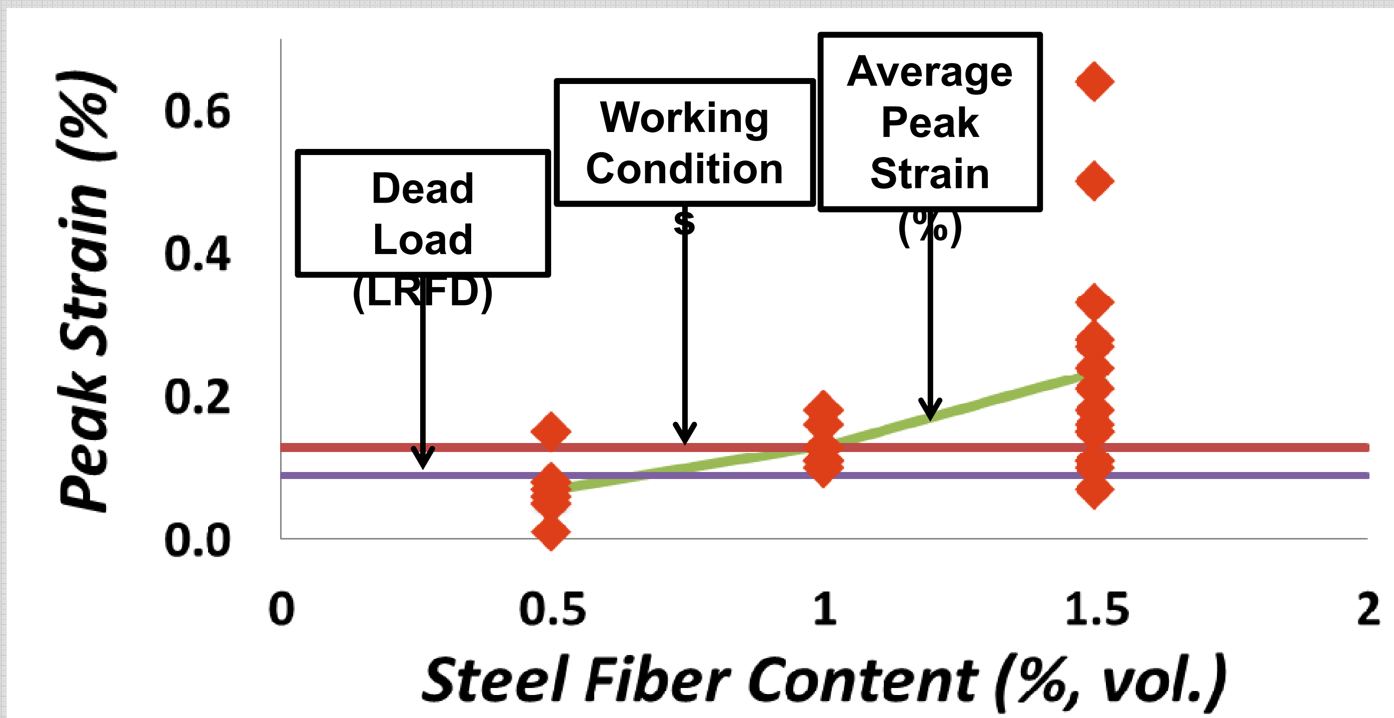
Post Test Tensile Specimen

Multiple Crack Development



Post Test Compression Specimen


UHPC Bridge

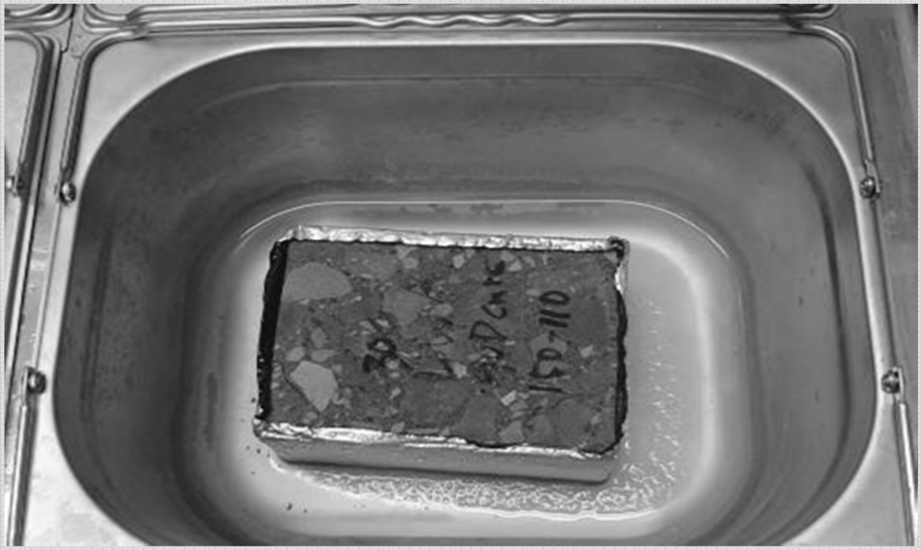

Peak Strain (%)
0.6
0.4
0.2
0.0
0
0.5
1
1.5
2
Steel Fiber Content (%, vol.)
Dead Load (LRFD)
Working Conditions
Average Peak Strain (%)

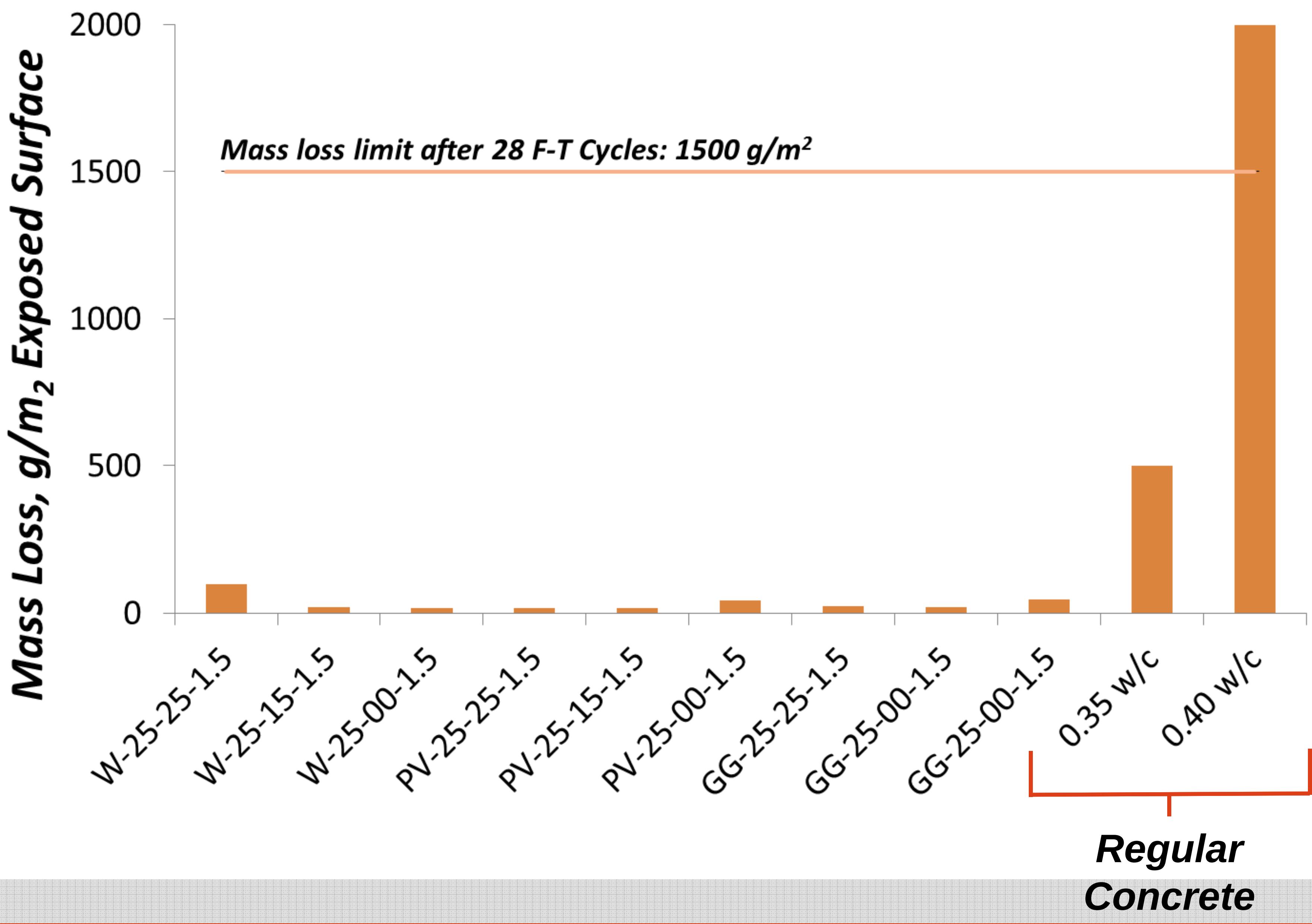
Long Term Performance of UHPCs

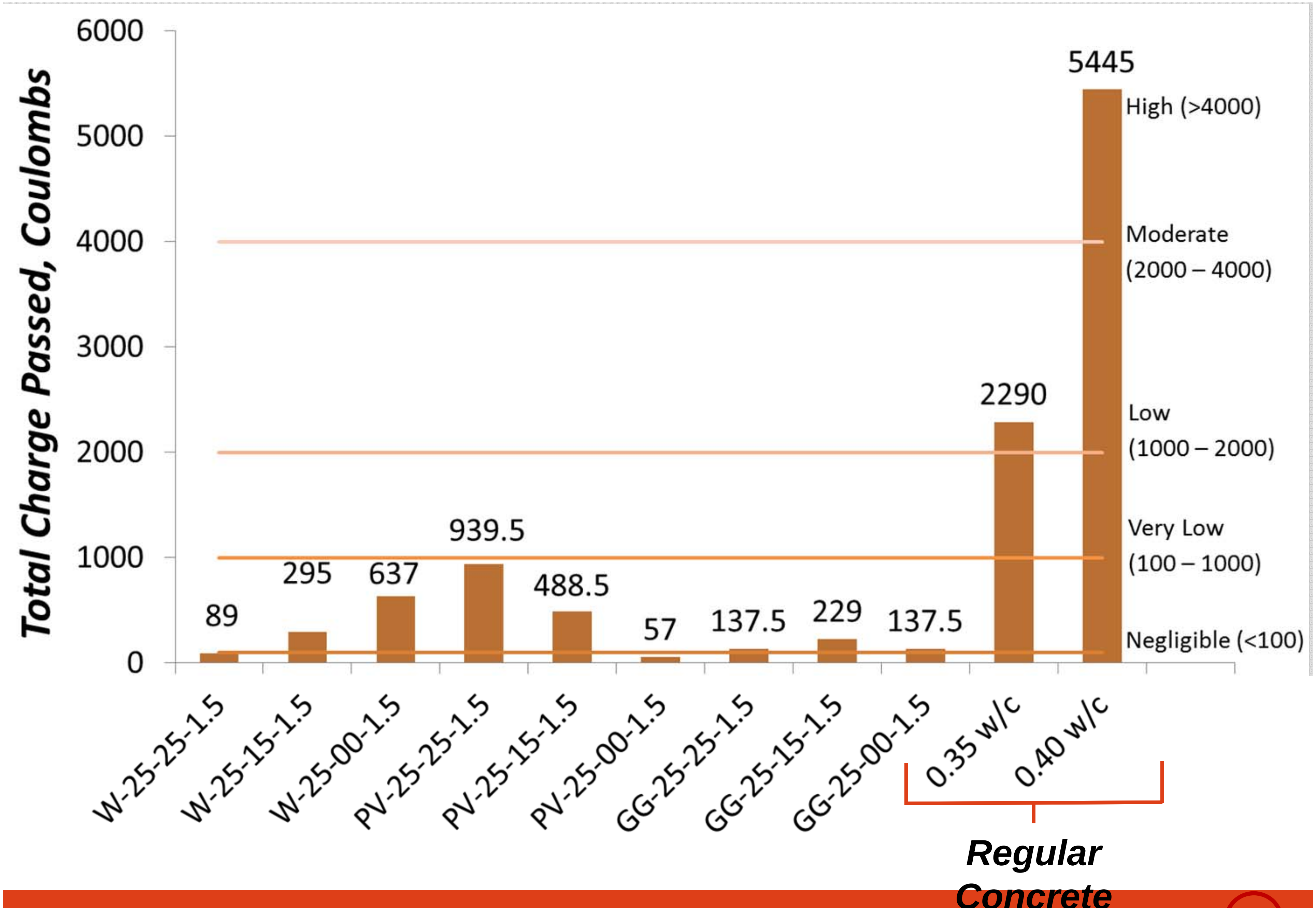
Alkaysi, M., El-Tawil, S., Liu, Z. and Hansen, W. (2016), “Effects of Silica Powder and Cement Type on Long Term Durability of Ultra High Performance Concrete (UHPC),”Cement and Concrete Composites 66 (2016): 47-56. Web.

Long Term Performance of UHPCs

Identify the key ***durability*** *parameters of the developed generic UHPC. Specifically, Resistance to* ***Chloride Ion Penetration*** *and* ***Freeze – Thaw***

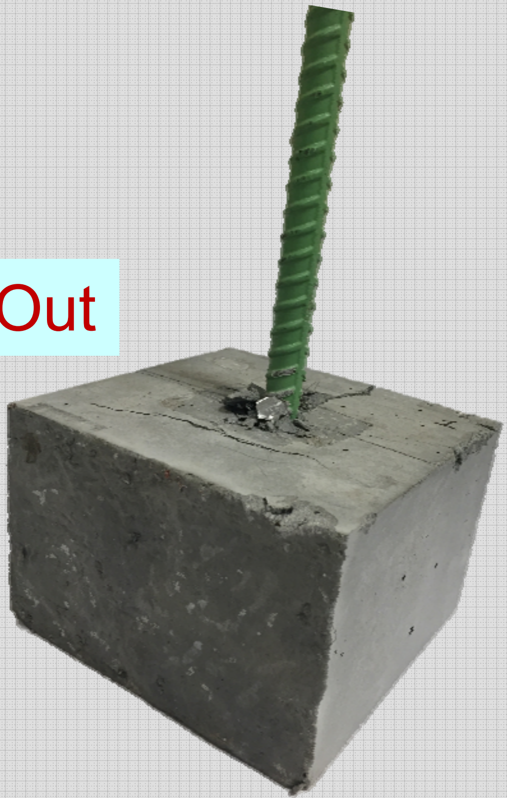


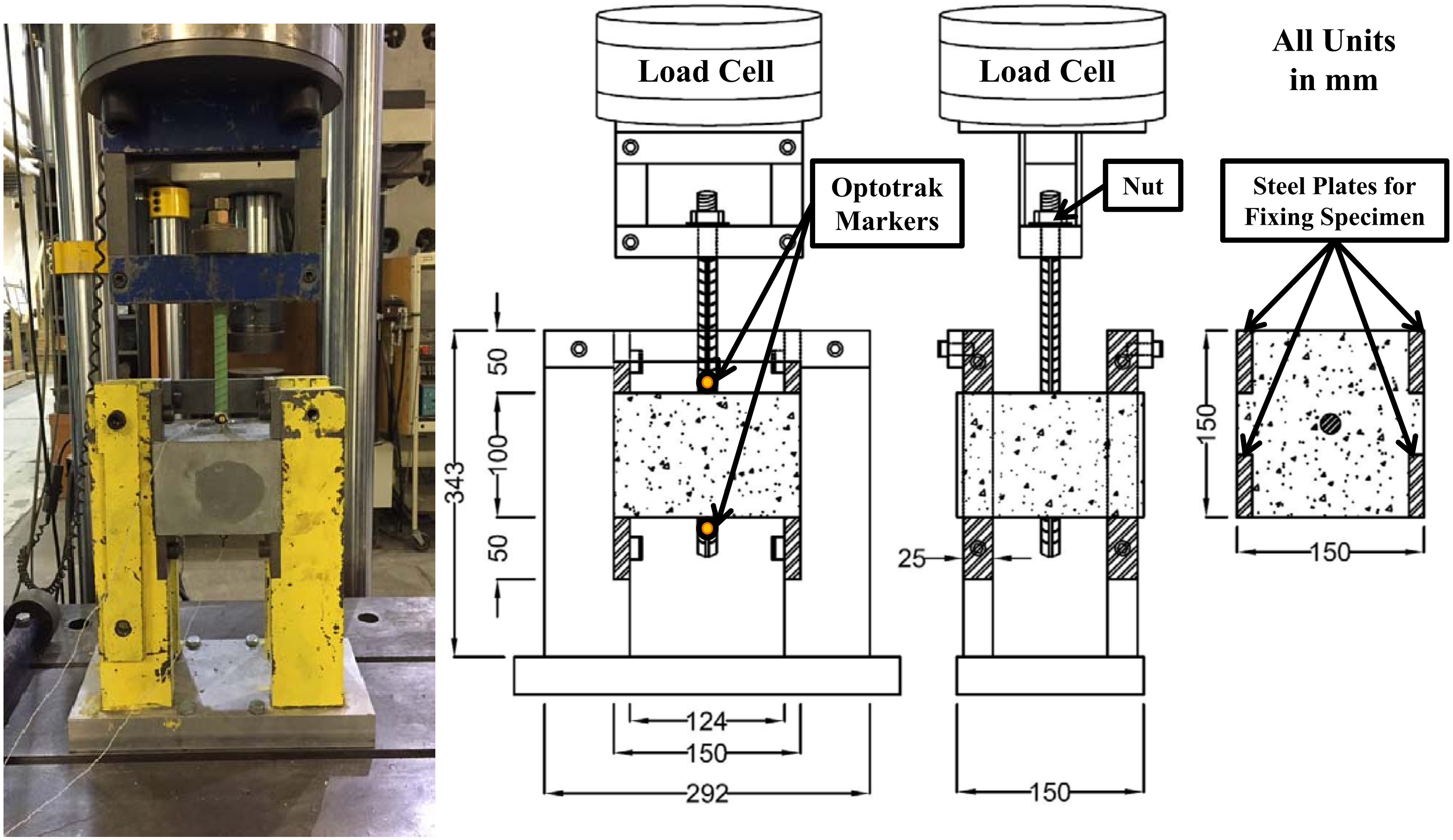

Mass Loss, g/m2 Exposed Surface
2000
1500
1000
500
0
Mass loss limit after 28 F-T Cycles: 1500 g/m2
W-25-25-1.5
W-25-15-1.5
W-25-00-1.5
PV-25-25-1.5
PV-25-15-1.5
PV-25-00-1.5
GG-25-25-1.5
GG-25-00-1.5
GG-25-00-1.5
0.35 w/c
0.40 w/c
Regular Concrete



ASTM C1202-12, "Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration"

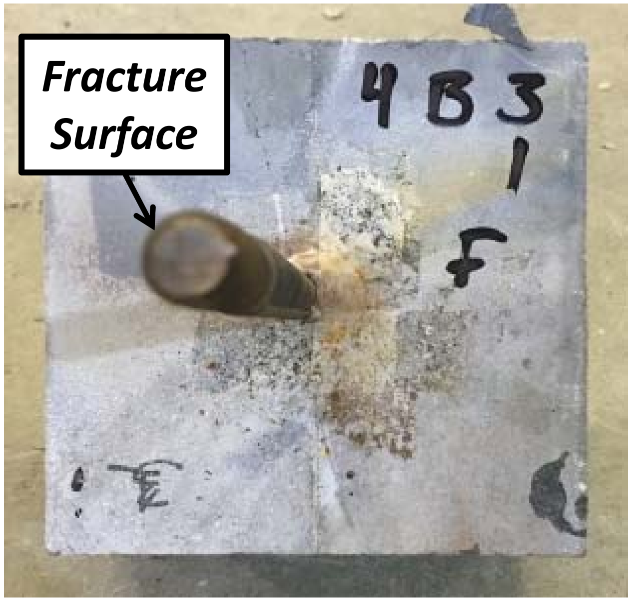
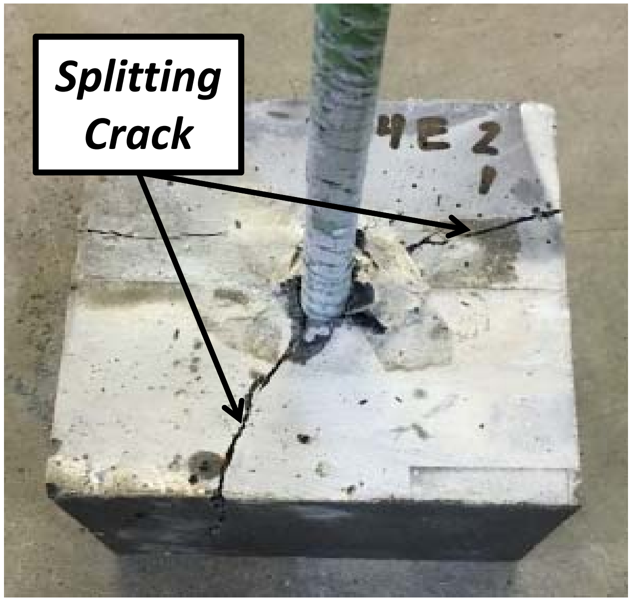
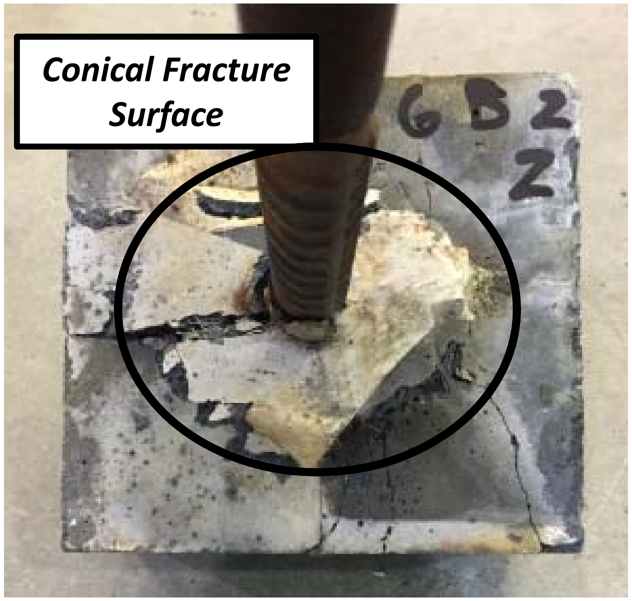
Structural Level

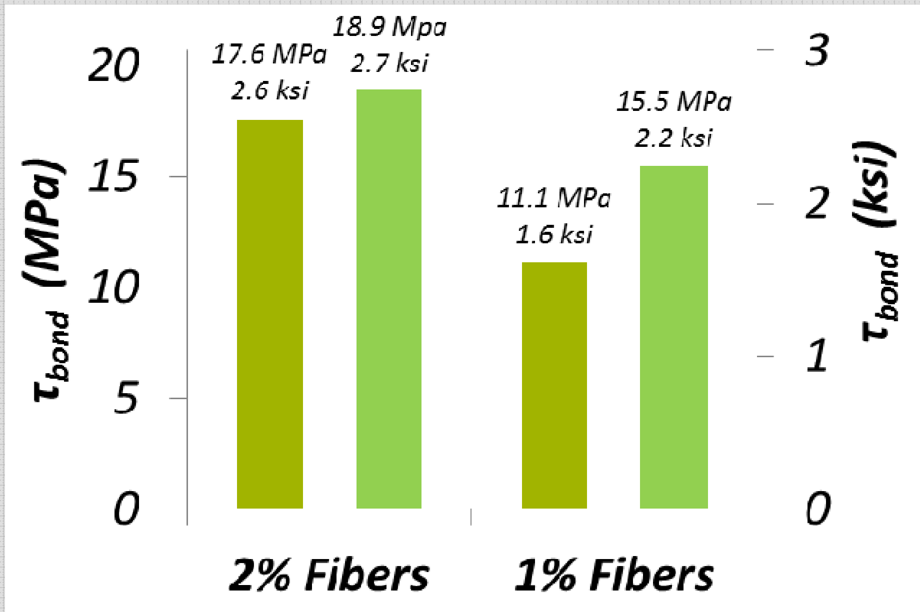




(a) Photo of Specimen Under Test (b) Front Elevation (c) Side Elevation (d) Plan View of Specimen

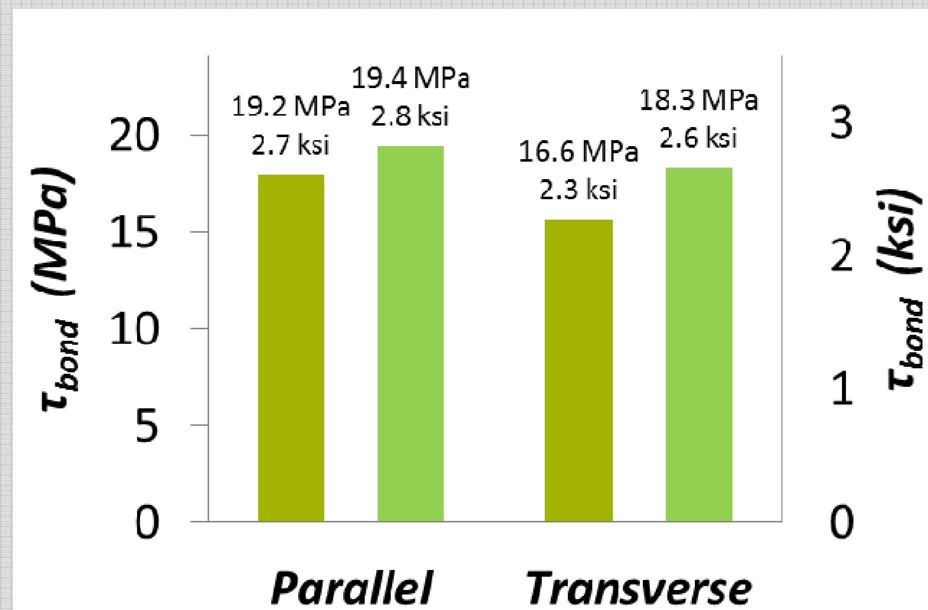
Peak Bond Strength: $$\tau_{bond} = \frac{F_{bar,max}}{\pi d_b l_d}$$

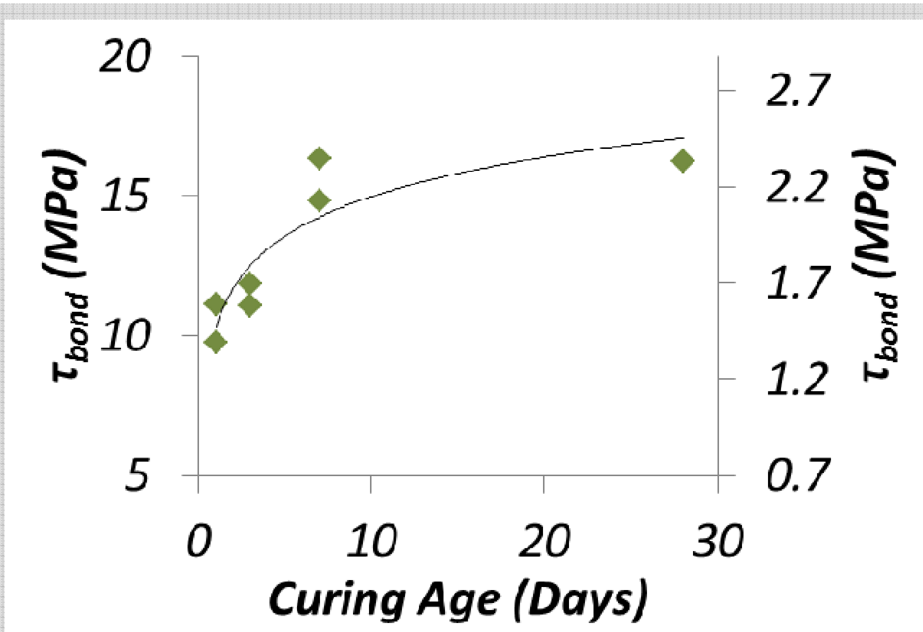
Bar Fracture	**Splitting Failure**	**Conical Concrete Failure**
		

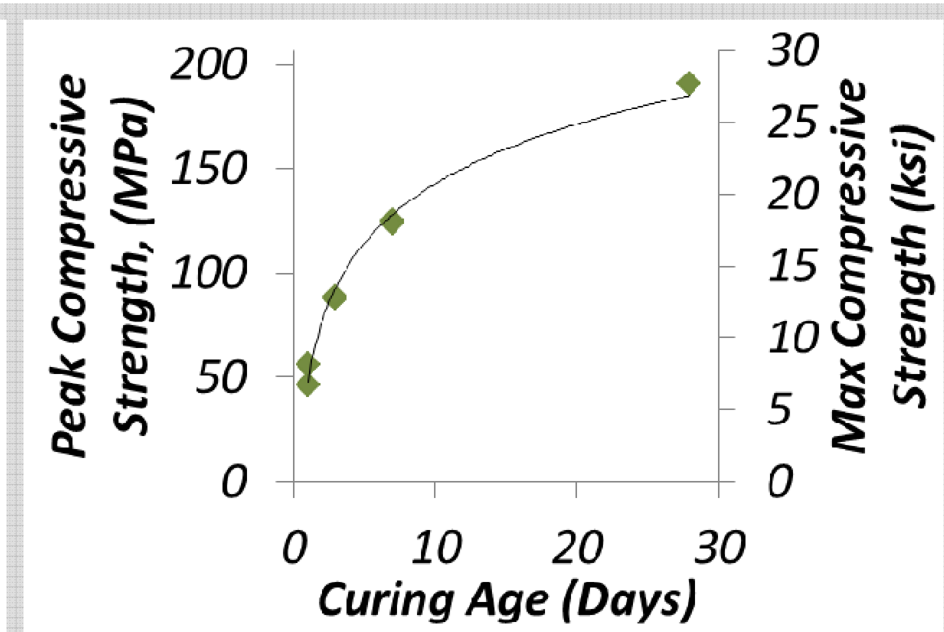


Effect of Fiber Volume Contents

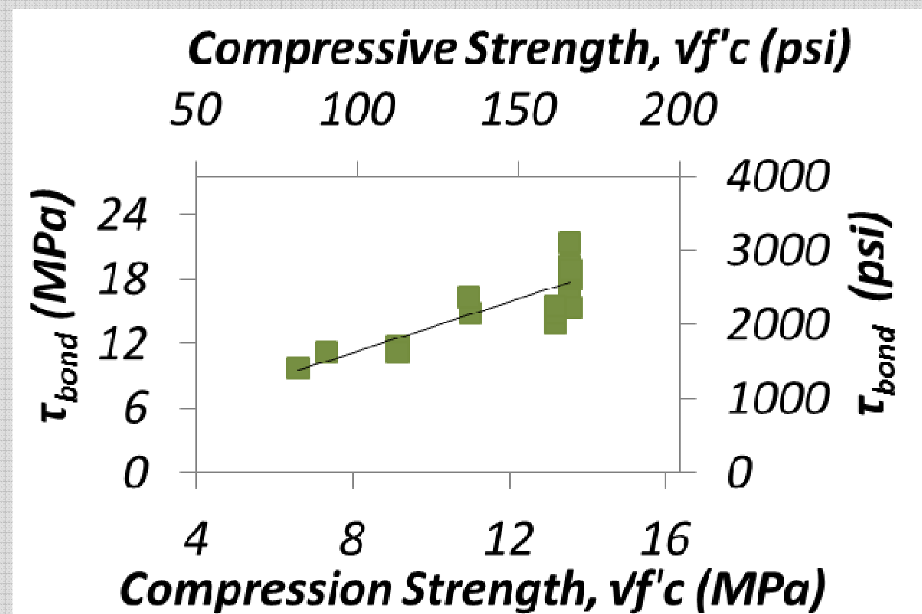
Effect of Fiber Casting Orientation

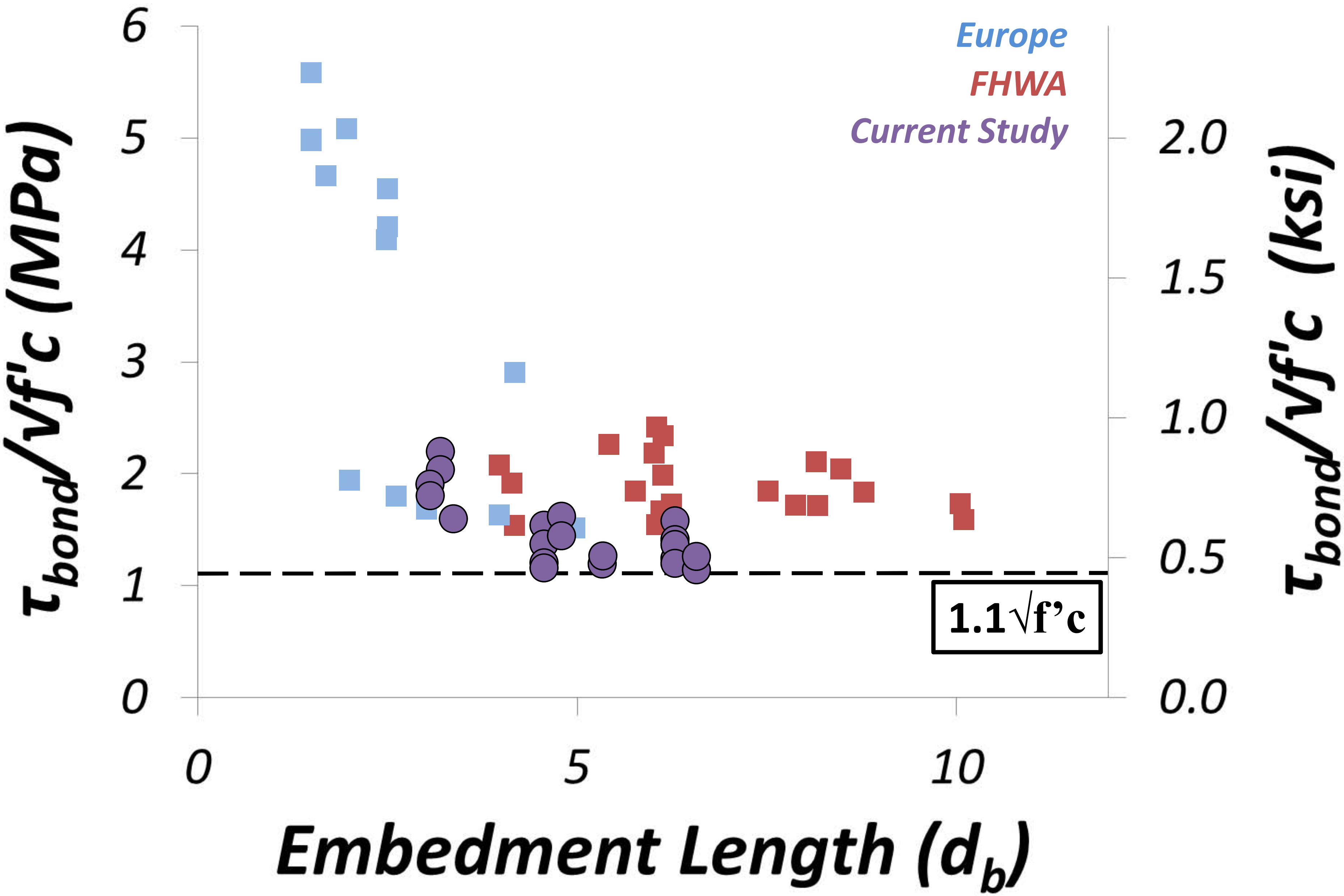






Effect of Curing Times



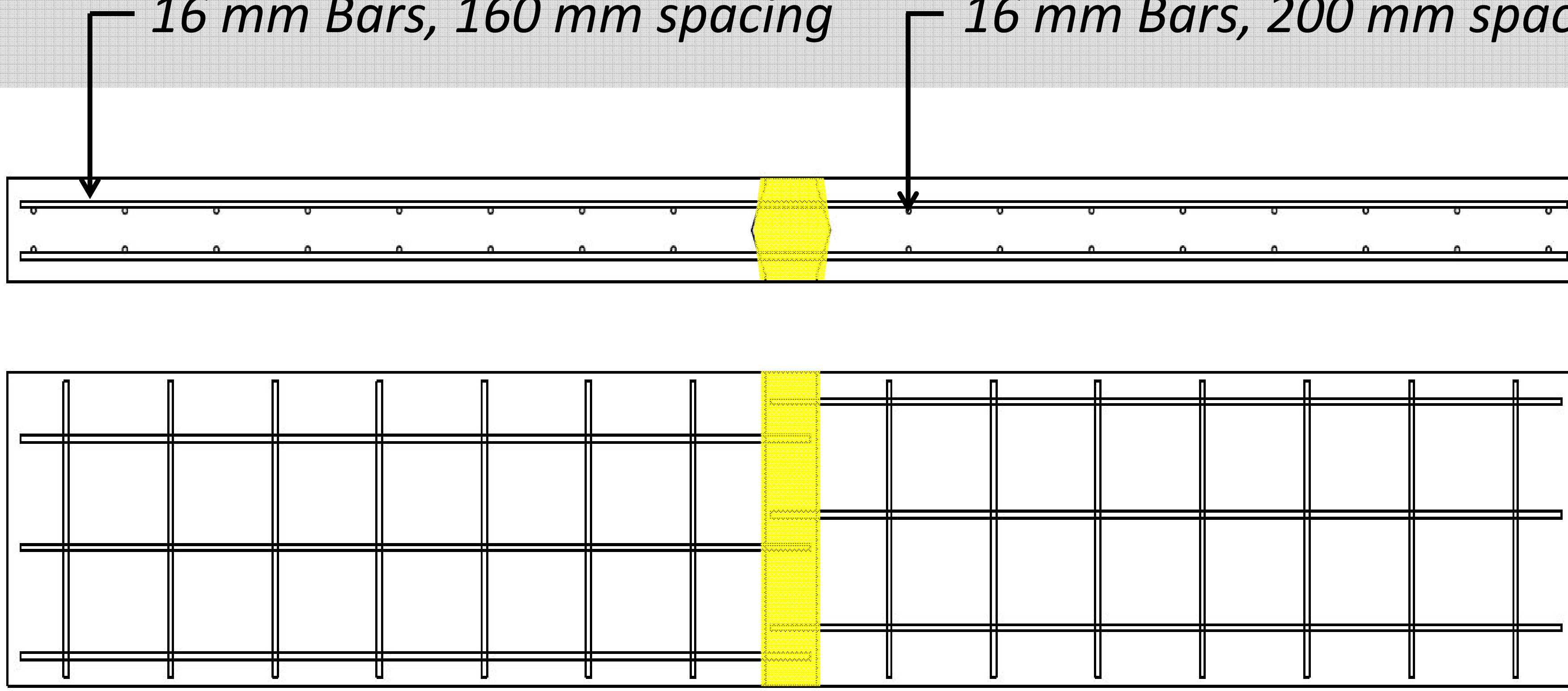


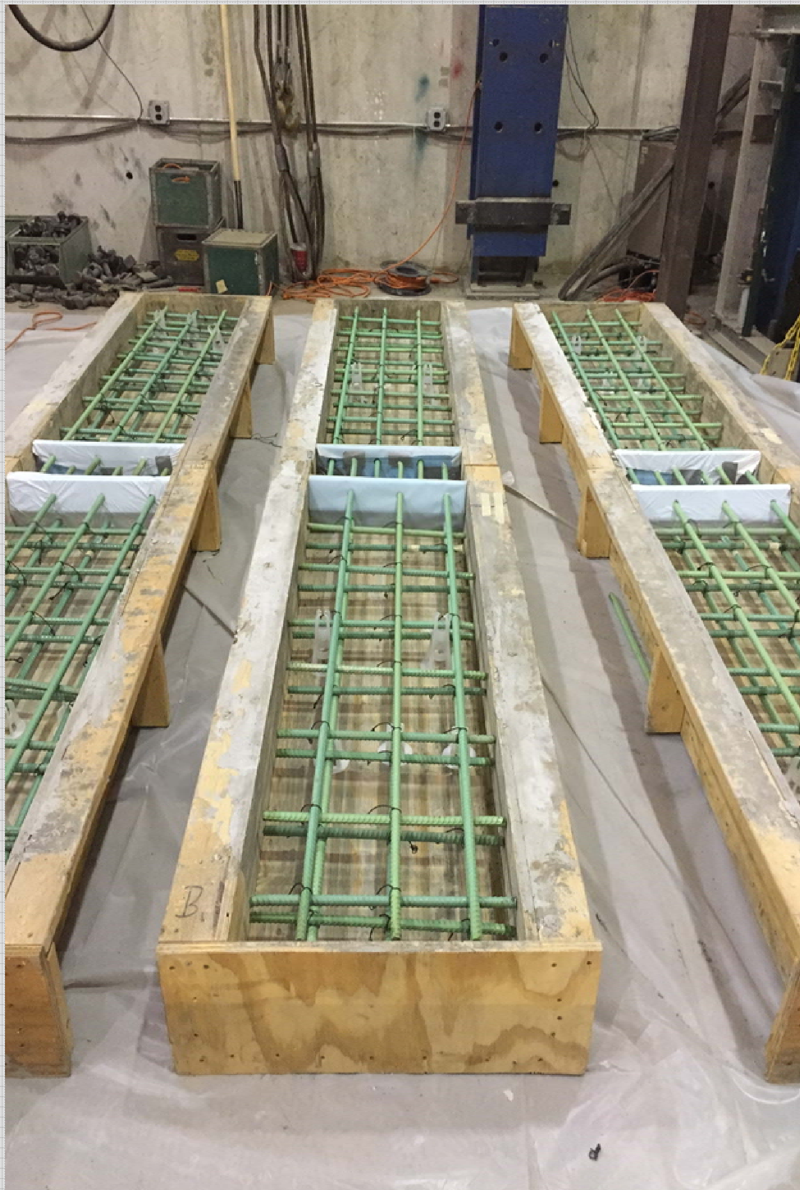
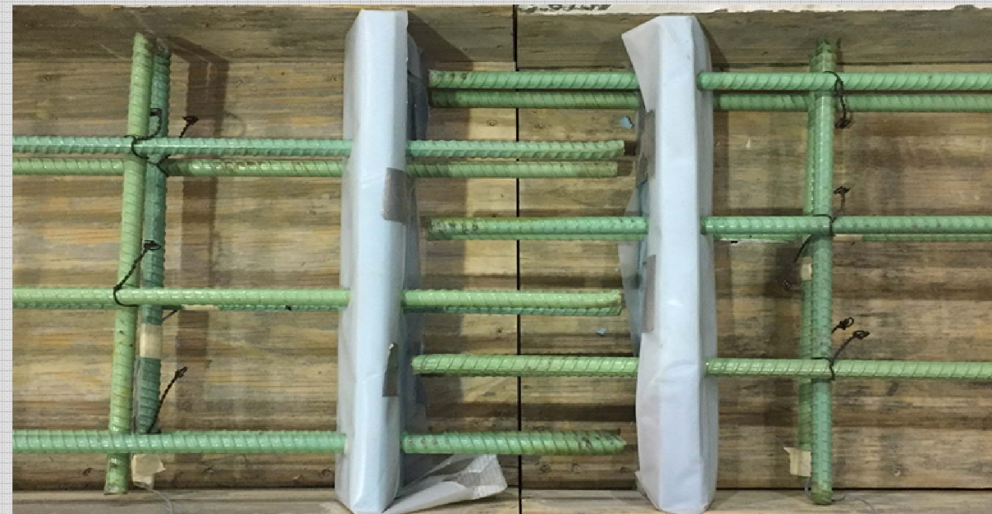
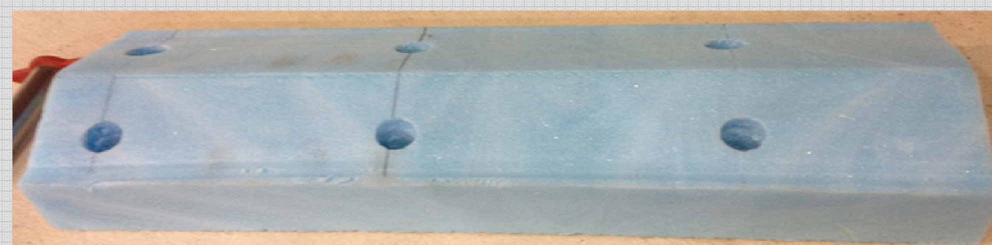
Europe
FHWA
Current Study
$1.1\sqrt{f'c}$
$\tau_{bond}/\sqrt{f'c}$ (MPa)
$\tau_{bond}/\sqrt{f'c}$ (ksi)
0
1
2
3
4
5
6
0.0
0.5
1.0
1.5
2.0
0
5
10
Embedment Length (d_b)

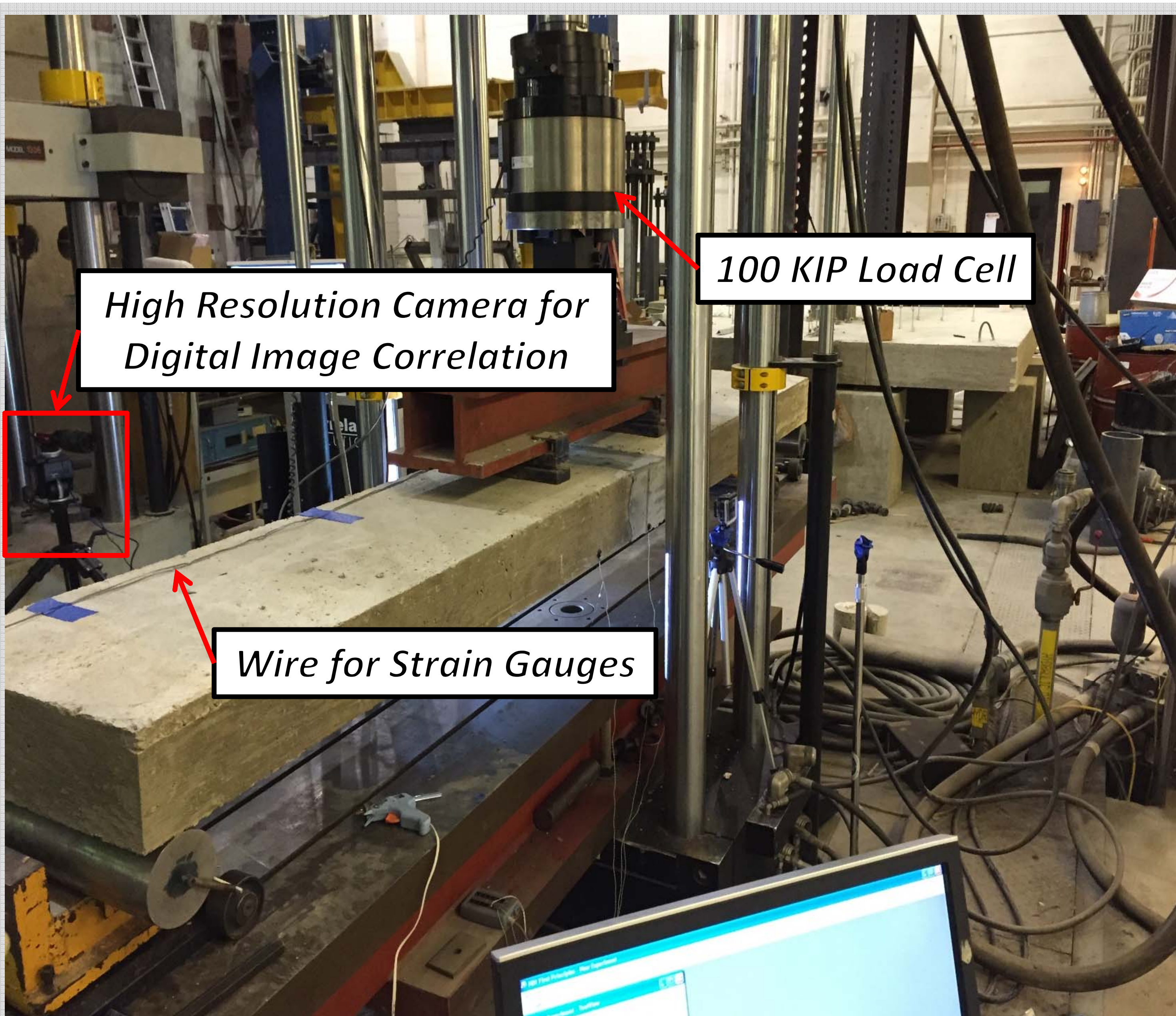
Strength of UHPC Lap Spliced Joints

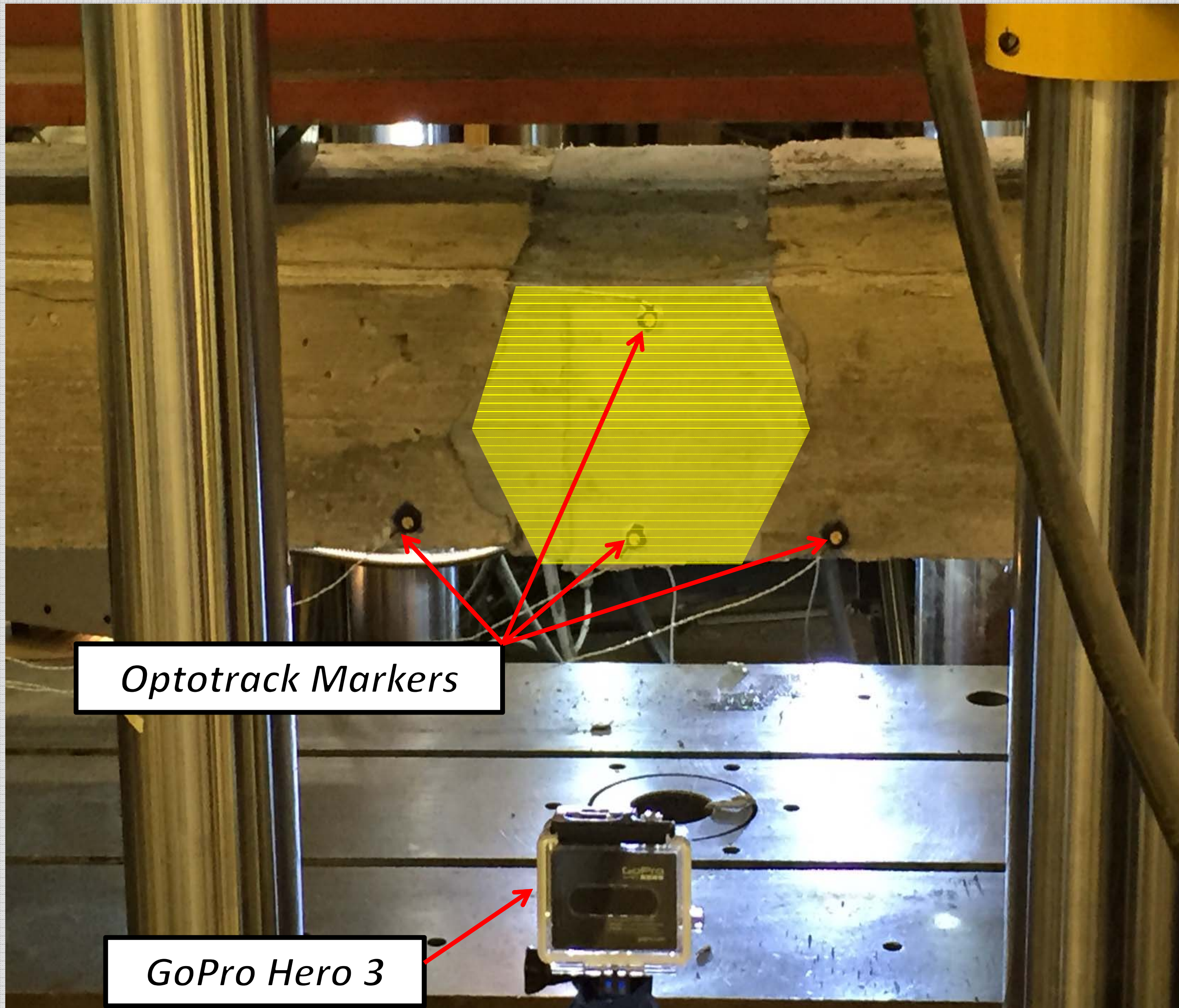
Alkaysi, M., S. El-Tawil. "Simplified Ultra-High Performance Concrete (UHPC) Joints for Accelerated Bridge Constructions," *ASCE Journal of Bridge Engineering,* In *Preparation*

Reinforcement Schematic

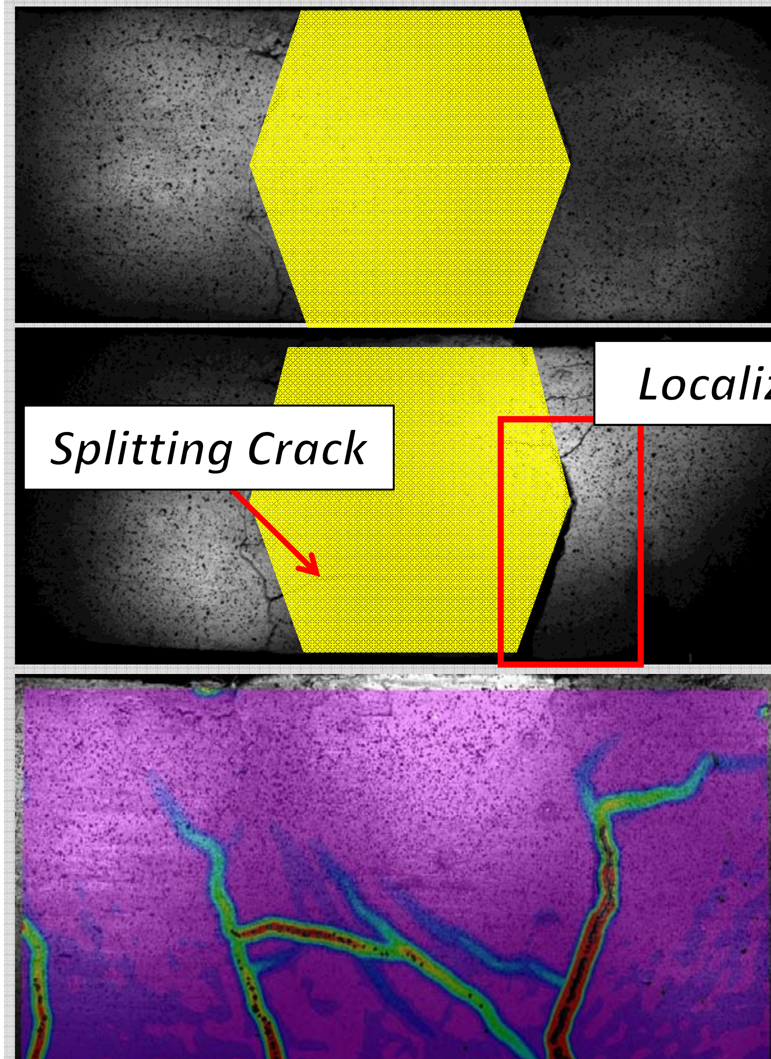


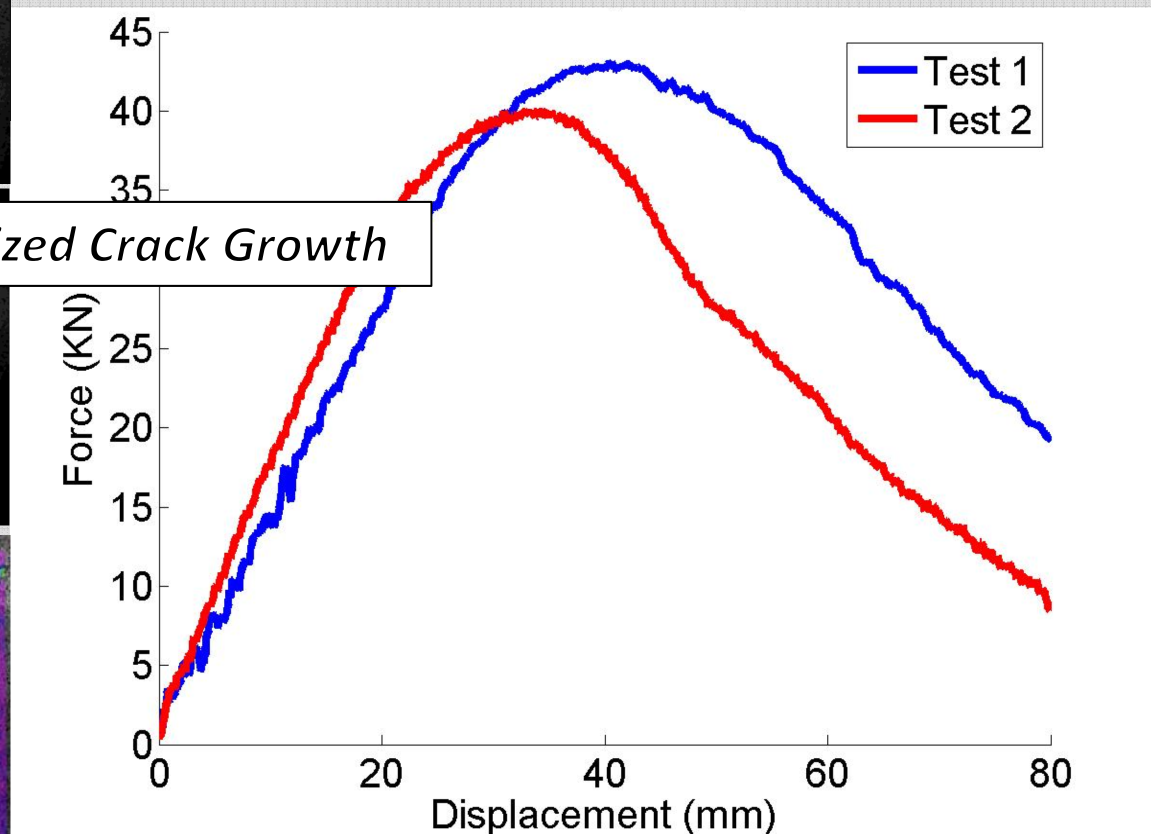


100 KIP Load Cell
High Resolution Camera for Digital Image Correlation
Wire for Strain Gauges


Optotrack Markers
GoPro Hero 3

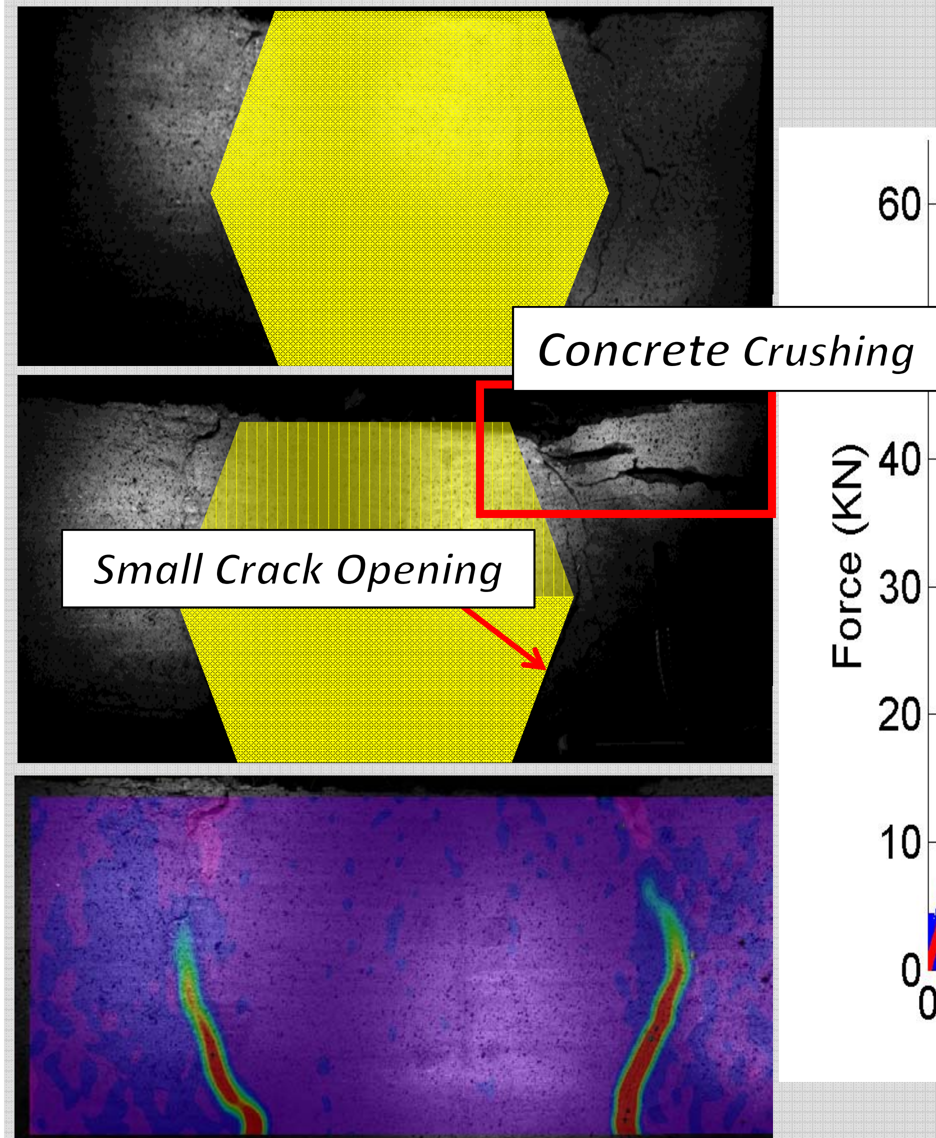
Results: Flexure Beams

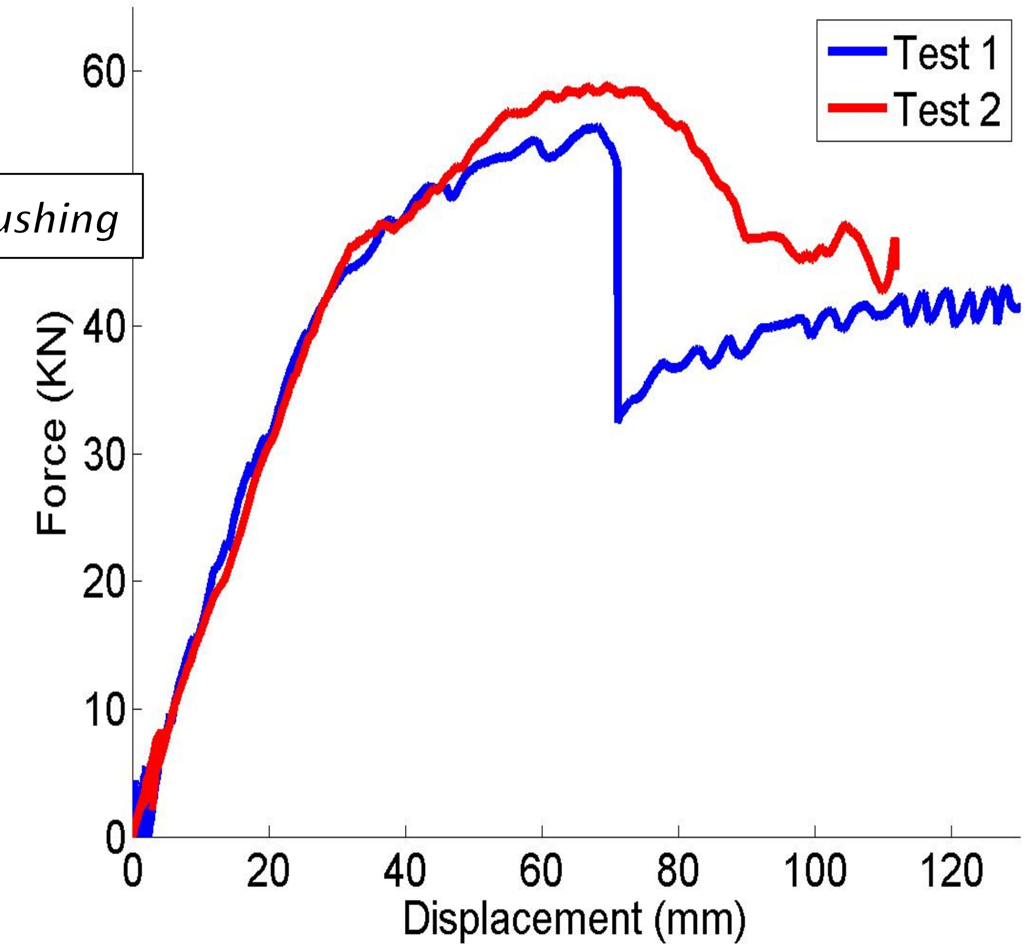


100 mm Joint, 2% Fibers by Vol.



150 mm Joint, 2% Fibers by Vol.





An Amazing Material!

- Very high strength in compression
  - f_c' = 28 ksi
- High performance tensile behavior
  - Potential for minimal cracking under service loading.
- Incredibly durable
  - Extreme resistance to freeze thaw and chloride penetration
  - Discontinuous pore structure
- Uses off-the-shelf materials
  - Employs GGBS, a byproduct of steel making
- Requires no special post-placement treatment

A Really Good Deal!

- Expensive components stripped out without affecting performance
- Total UHPC material cost $660/yd^3$
  - Fibers at 1.5% enable use in structural applications.
  - US steel fibers are $2/lb:
  - Roughly 5x the cost of regular concrete
- Imported steel fibers as low as $0.30/lb
  - Total UHPC cost reduces to $325 per cubic yard
  - Roughly 2.5x the cost of regular concrete.
  - A really good deal in the long term!!