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Center for Research & Education in Advanced Transportation Engineering Systems (CREATES)

Developing Ultra High Performance Concrete (UHPC) from New Jersey Aggregates

Harshdutta Pandya
Alexander Semler
Kyle Selle
Gilson R. Lomboy

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Outline

- UHPC Overview
- Materials
- Mixture Design
- Results
- Application

Ultra-High Performance Concrete

Cementitious composite material composed of an optimized gradation of granular constituents, a water-to-cementitious materials ratio less than 0.25, and a high percentage of discontinuous internal fiber reinforcement.

Properties

Strength

- Compressive: 17.4 to 35 ksi
- Flexural: 2.2 to 3.6 ksi
- Modulus of Elasticity: 6500 to 7300 ksi
- Postcracking tensile: > 0.72 ksi

Fresh property

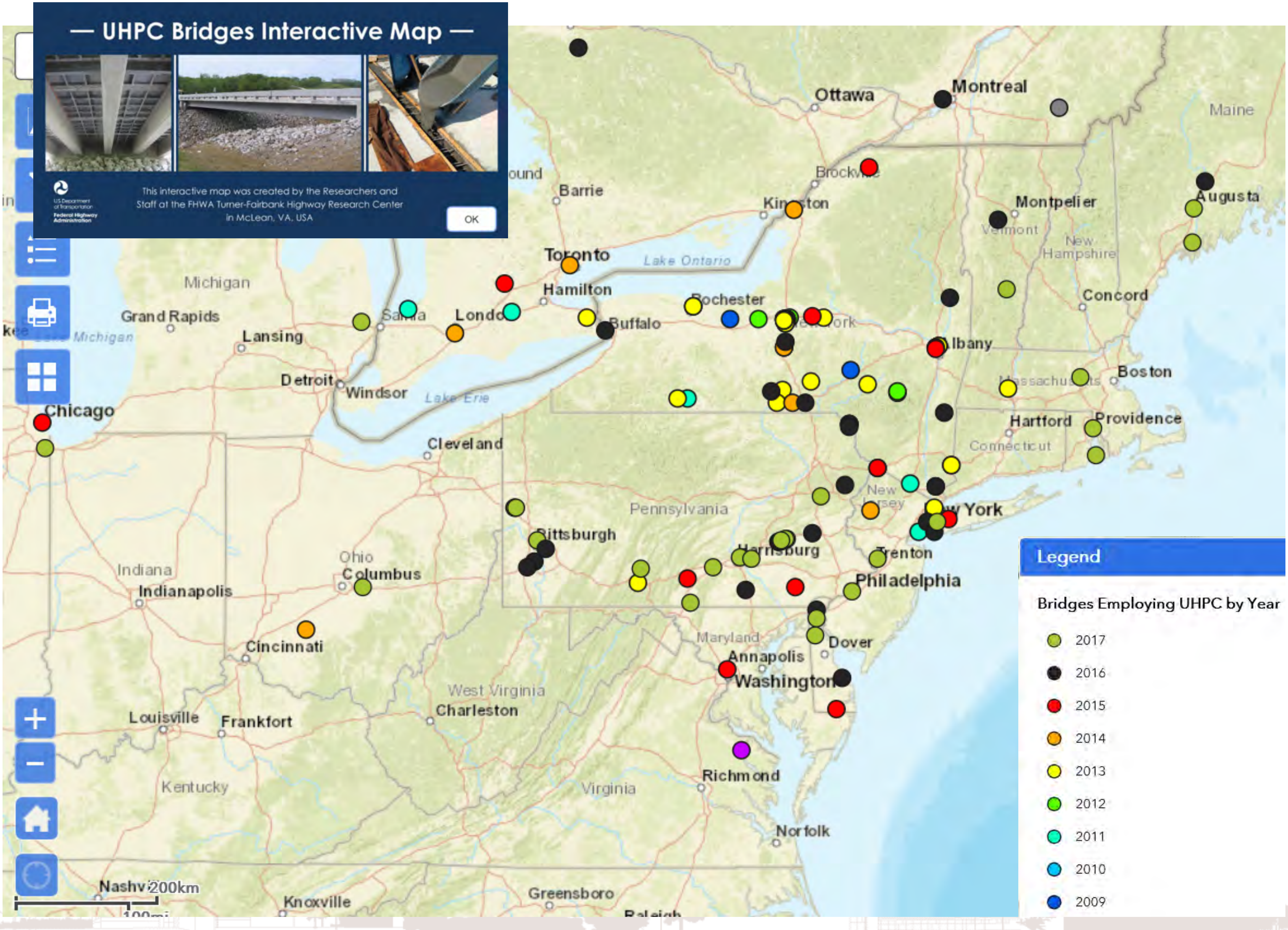
- Flow: 8-10 in

Properties

Durability

- Freeze/thaw (after 300 cycles): 100%
- Salt-scaling (loss of residue): < 0.013 lb/ft^3
- Abrasion (relative volume loss index): 1.7
- Chloride Ion permeability: < 10 C
- Carbonation depth: < 0.02 in.

Discontinuous pore structure that reduces liquid ingress, significantly enhancing durability compared to conventional and high-performance concretes.


— UHPC Bridges Interactive Map —
This interactive map was created by the Researchers and Staff at the FHWA Turner-Fairbank Highway Research Center in McLean, VA, USA
OK
Legend
Bridges Employing UHPC by Year
2017
2016
2015
2014
2013
2012
2011
2010
2009
Ottawa
Montreal
Maine
Barrie
Montpelier
Augusta
Toronto
Lake Ontario
Hamilton
Michigan
Rochester
Concord
Grand Rapids
Buffalo
Lansing
Albany
Boston
Detroit
Windsor
Lake Erie
Chicago
Hartford
Providence
Connecticut
Cleveland
Pennsylvania
Pittsburgh
Trenton
Philadelphia
Ohio
Indiana
Columbus
Indianapolis
Cincinnati
Maryland
Dover
Annapolis
Washington
West Virginia
Charleston
Louisville
Frankfort
Richmond
Kentucky
Virginia
Norfolk
200km
Knoxville
Greensboro

SR 46 Bridge

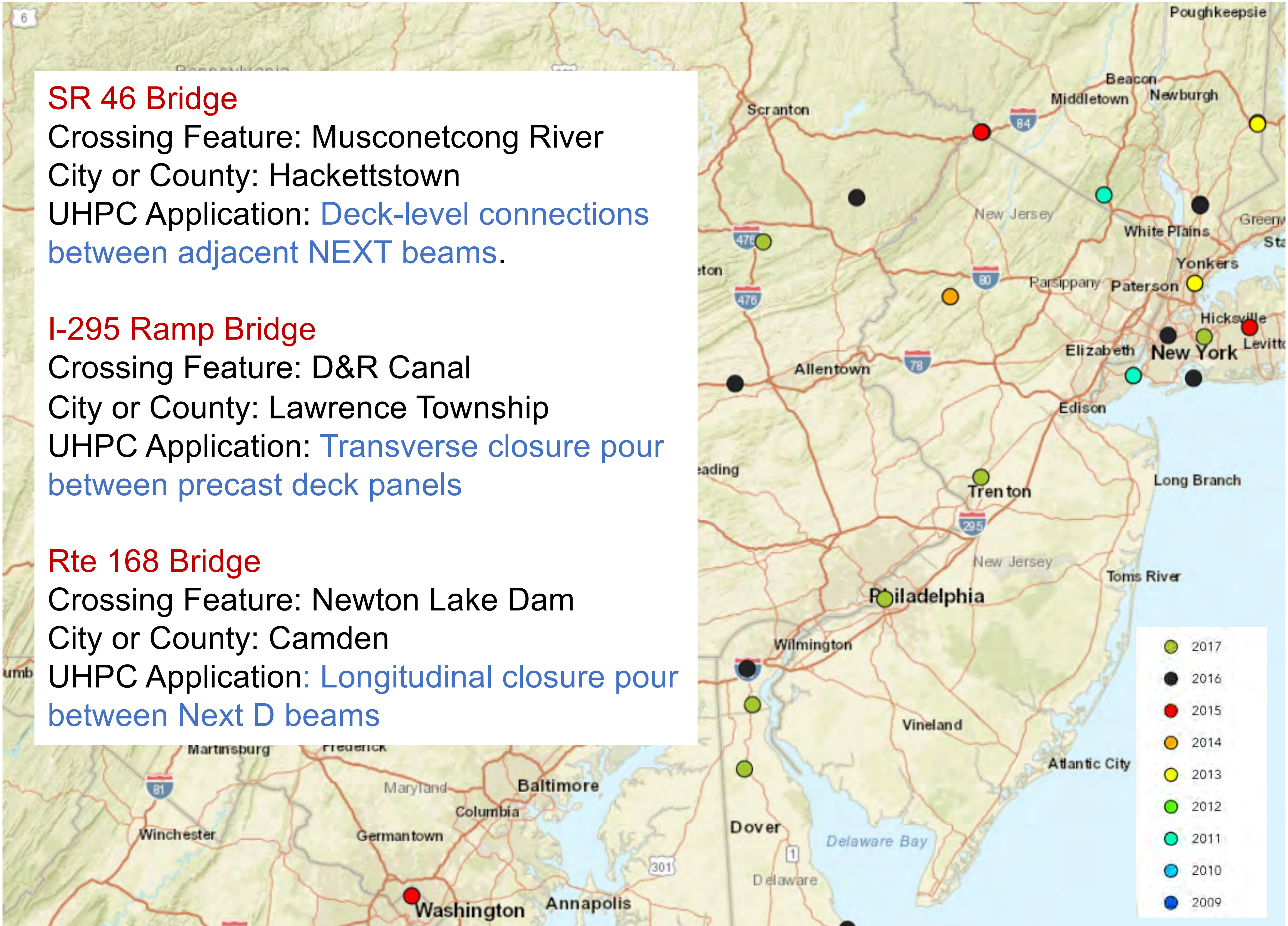
Crossing Feature: Musconetcong River
City or County: Hackettstown
UHPC Application: Deck-level connections between adjacent NEXT beams.

I-295 Ramp Bridge

Crossing Feature: D&R Canal
City or County: Lawrence Township
UHPC Application: Transverse closure pour between precast deck panels

Rte 168 Bridge

Crossing Feature: Newton Lake Dam
City or County: Camden
UHPC Application: Longitudinal closure pour between Next D beams



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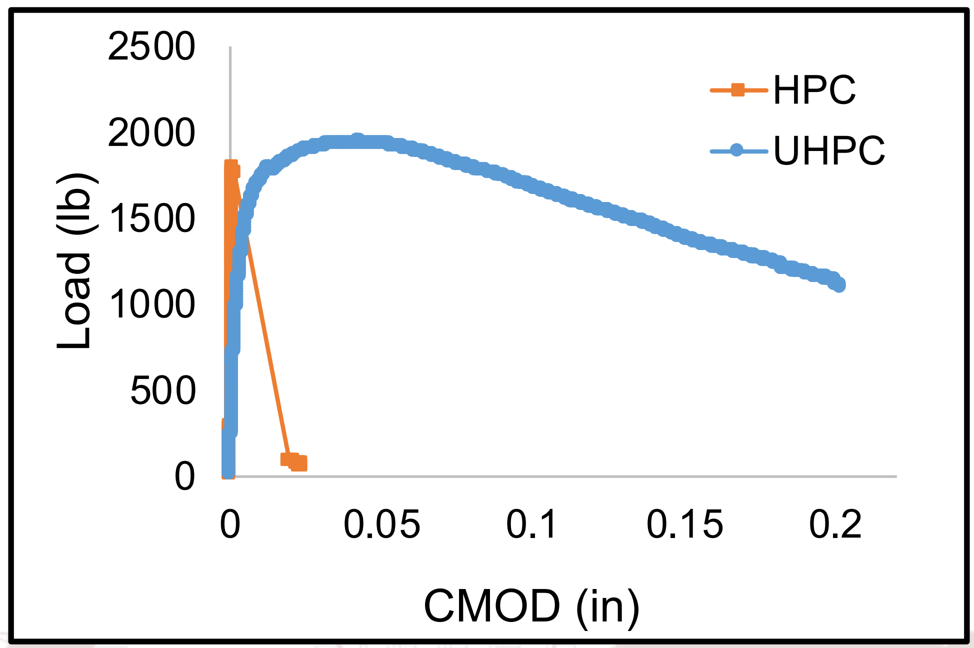
Overlays and Repairs

Overlay and Repairs

- UHPC mixture
- Fracture properties of HPC-UHPC composites
- Accelerated corrosion
- Repair testing
- Numerical modelling



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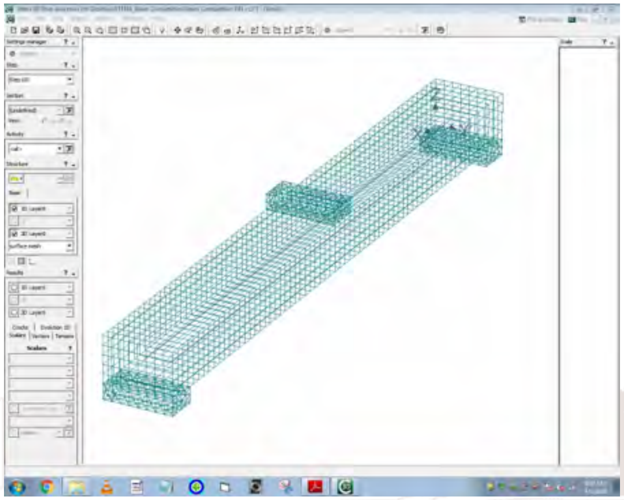
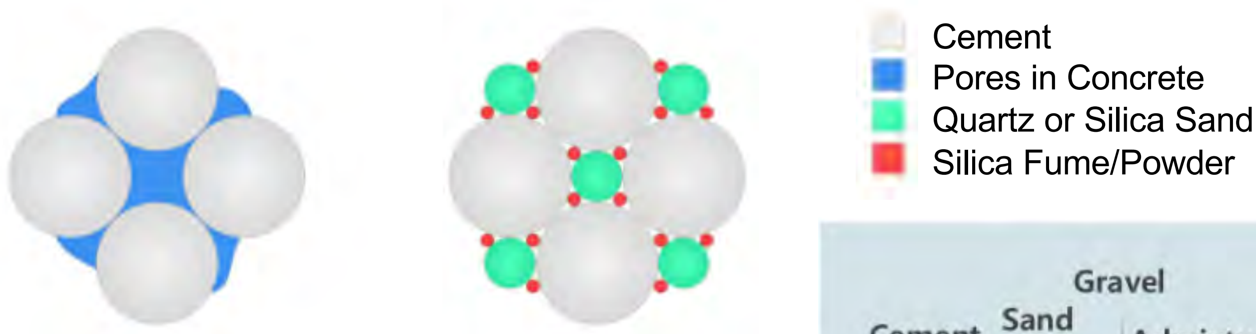


Composition

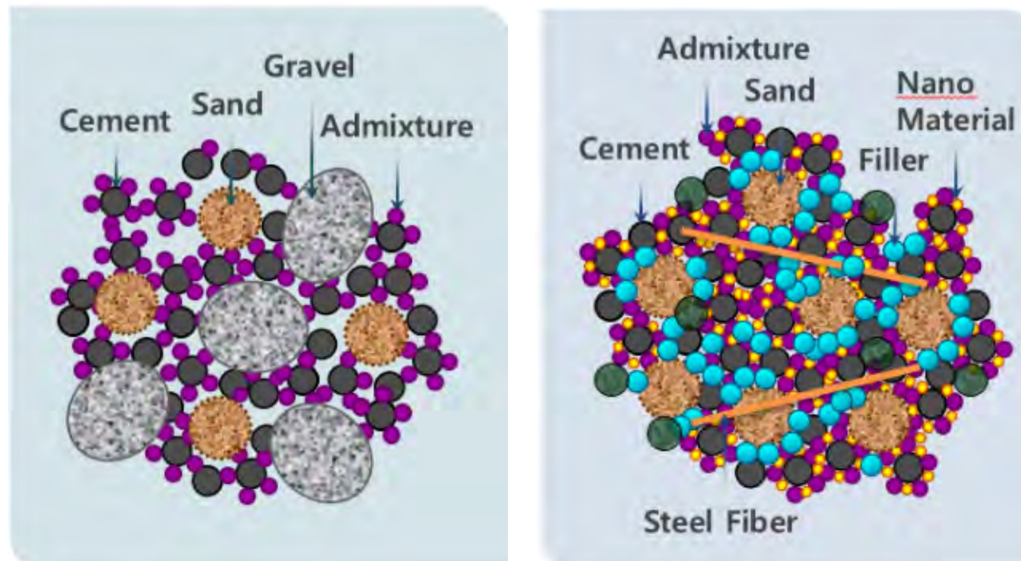
Constituent	Particle Size	Conventional Concrete (pcy)	UHPC (pcy)
Coarse Aggregate	25 – 9.5 mm	1,739	-
Sand	4.75 – 0.15 mm	1,429	1,720
Ground Quartz	60 μm	-	355
Cement	60 – 2 μm	600	1,200
Silica Fume	0.10 μm	-	390
Water	-	300	220
Superplasticizer	-	-	50
Steel Fibers	15 x 0.20 mm	-	265

Material Characteristics UHPC



Conventional concrete   UHPC

- Mineral additives (pozzolans) further react, converting CH into more CSH
- Very dense packing and fiber content control shrinkage.
- Fiber reinforcement greatly enhances crack propagation resistance.
- Low porosity – very resistant to freeze/thaw action and chemical attacks (chloride penetration, carbonation).



Conventional Concrete   UHPC

http://www.whitecubeholdings.com/what-is-uhpc/
Lee, et al., J. Engg Sci & Tech, 8(3)(2013)296-305

Availability

Proprietary versions

- Bagged, pre-blended fines
- Fibers in separate bag

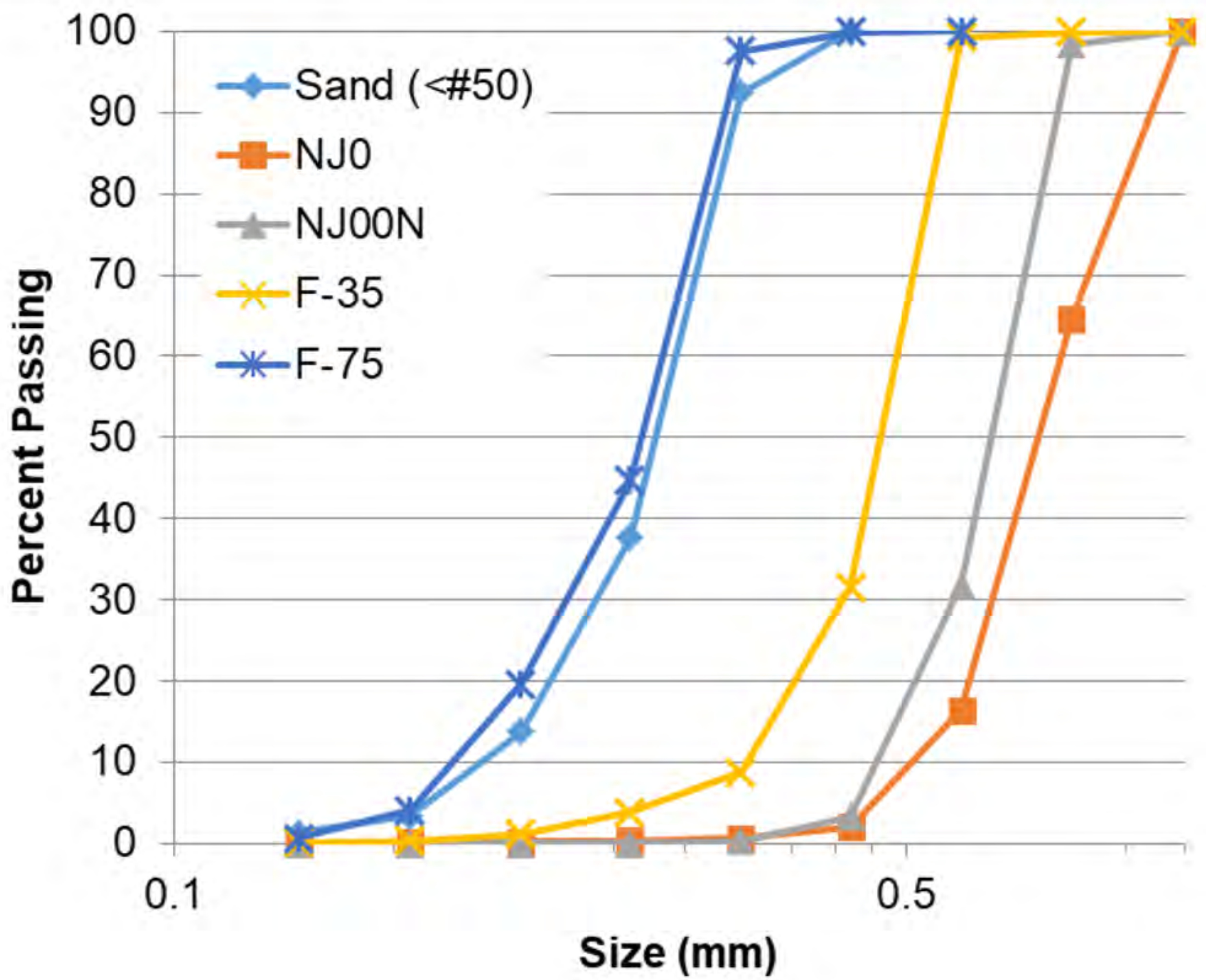
Non-proprietary versions

- Development of Non-Proprietary Ultra-High Performance Concrete for Use in the Highway Bridge Sector, FHWA-HRT-13-100, Kay Wille
- University mixtures
- El-Tawil, S., et al. "Development, Characterization and Applications of a Non Proprietary Ultra-High-Performance Concrete for Highway Bridges," Report No. RC-1637, 2016.

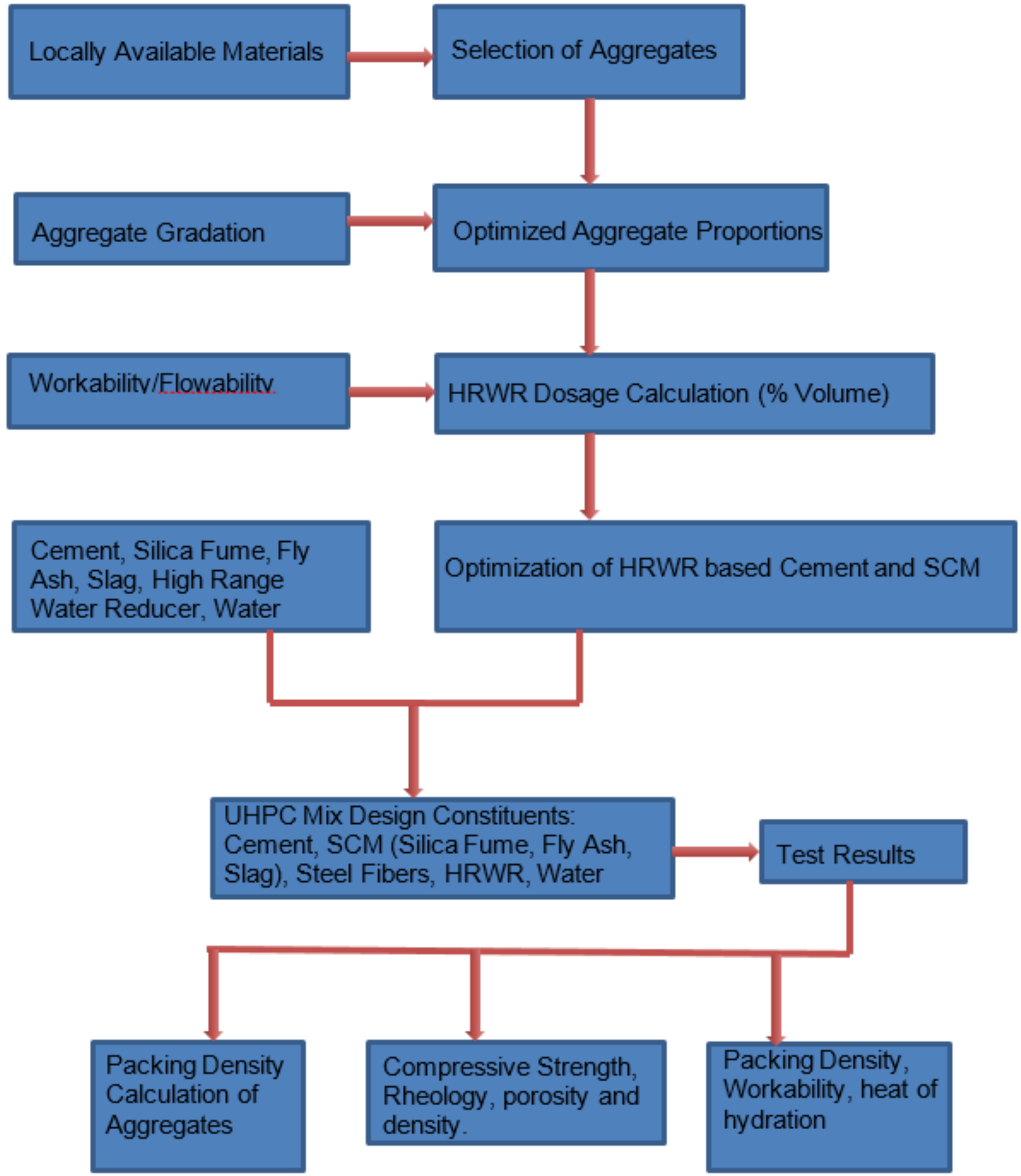
Materials used

Constituent	Type	Source	Size
Sand	Concrete Sand	Hammonton, NJ	0.23 mm
Ground Silica	NJ0 NJ00N F35 F75	Mauricetown, NJ Mauricetown, NJ Ottawa, IL Ottawa, IL	0.77 mm 0.50 mm 0.47 mm 0.22 mm
Cement	Type I	(PC1) (PC2)	449 m^2/kg 512 m^2/kg
Silica Fume	Densified Undensified	(SF-D) (SF-UD)	
GGBFS	Grade 100	(GGBFS-1) (GGBFS-2)	454 m^2/kg 542 m^2/kg
Fly Ash	Class C	(FA)	564
Superplasticizer	Polycarboxylate	(HRWR-1) (HRWR-2)	
Steel Fibers	Copper coated steel		12.5mm x 0.20mm

Aggregates


Sand (<#50)
NJ0
NJ00N
F-35
F-75
Percent Passing
100
90
80
70
60
50
40
30
20
10
0
0.1
0.5
Size (mm)

Mix Design Flow Diagram



Mixtures

Mass, pcy\Mix No	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
PC1	1285	1281	1261	1263	1259	1266	1270	1238	1219	1202				647	647	647	647			
PC2											647	647	647					647	647	647
SF-D	321	320	315	315	315	316	318	309	305	300							325			
SF-UD											325	325	325	325	325	325		325	325	325
Fly Ash	321	615	605	315	605	886	1168	594	585	577										
GGBFS-1																647				
GGBFS-2											647	647	647	647	647		647	647	647	647
Water	142	139	136	165	162	160	157	187	209	229	284	284	284	284	284	284	284	284	284	284
Sand	355	355	348	350	348	351	351	342	337	332										393
NJ0												1572		1572	1572	1572	1572	982		
NJ00N	1398	1128	1109	1373	1107	827	553	1089	1072	1057			1572						982	
F35											1572									1572
F75											393	393	393	393	393	393	393	982	982	
Fiber	227	228	252	251	251	252	252	252	251	251	259	259	259	259	259	259	259	259	259	259
HRWR-1	175	173	197	171	171	172	172	168	165	163					39					
HRWR-2											39	39	39	39		39	39	39	39	39

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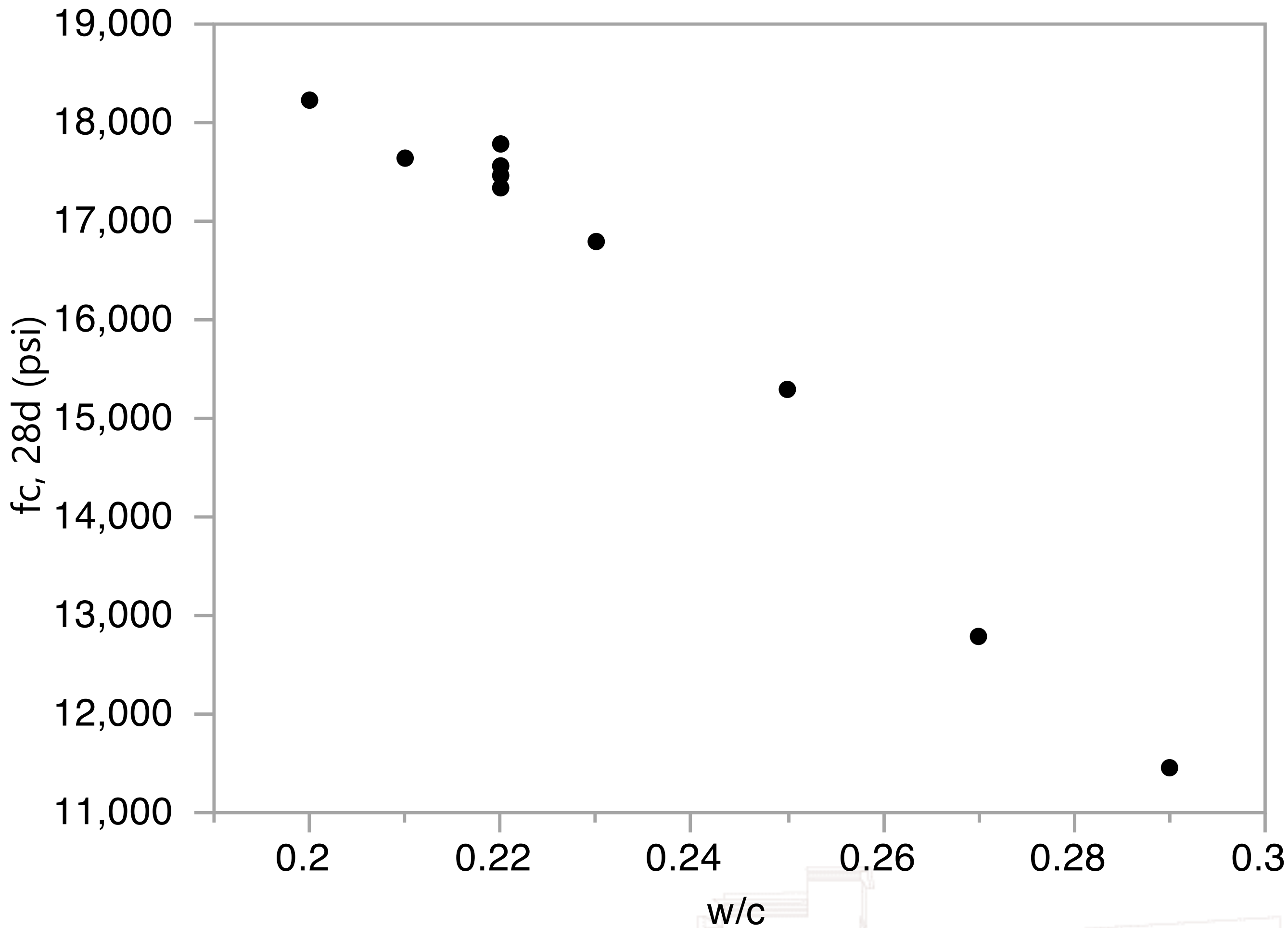
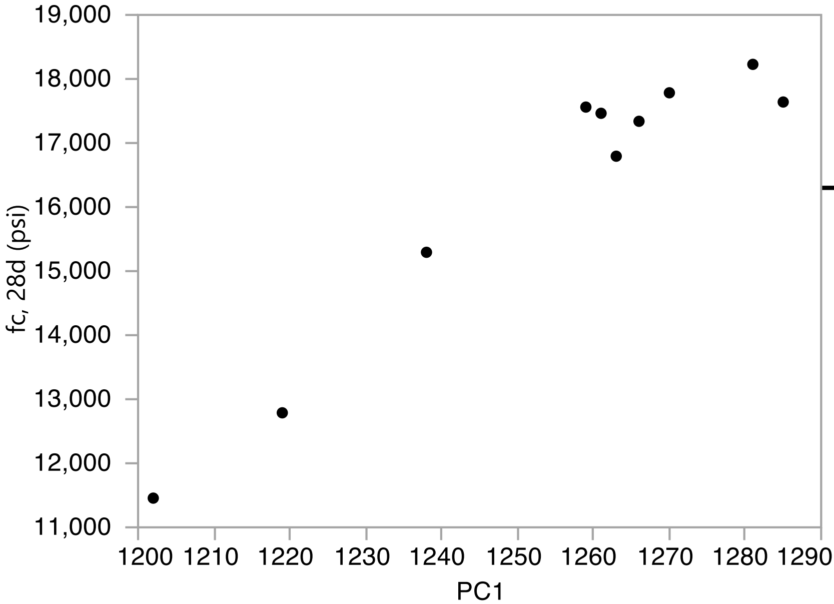
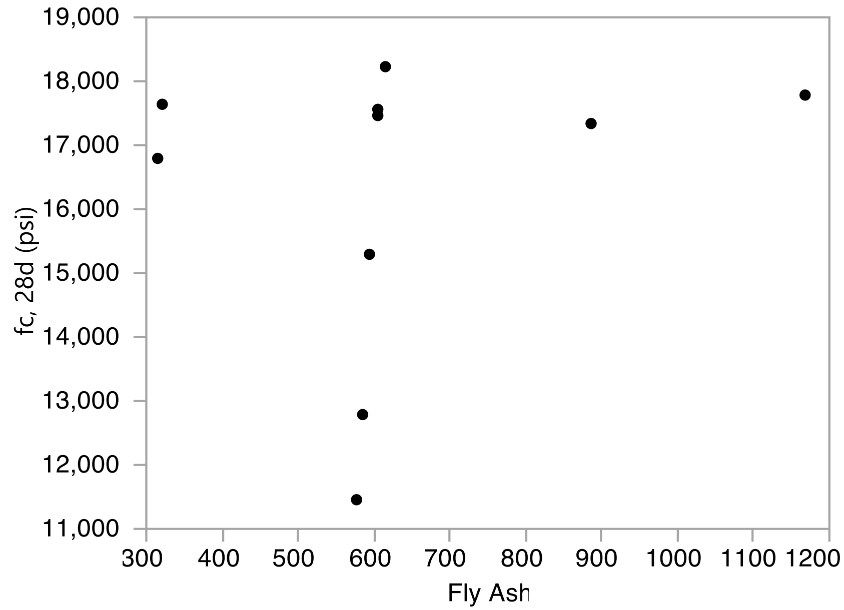
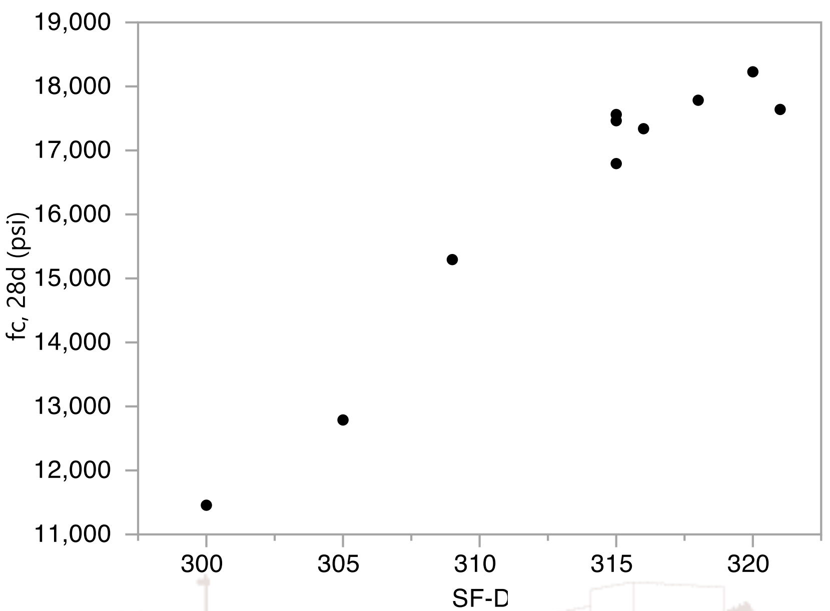
w/c



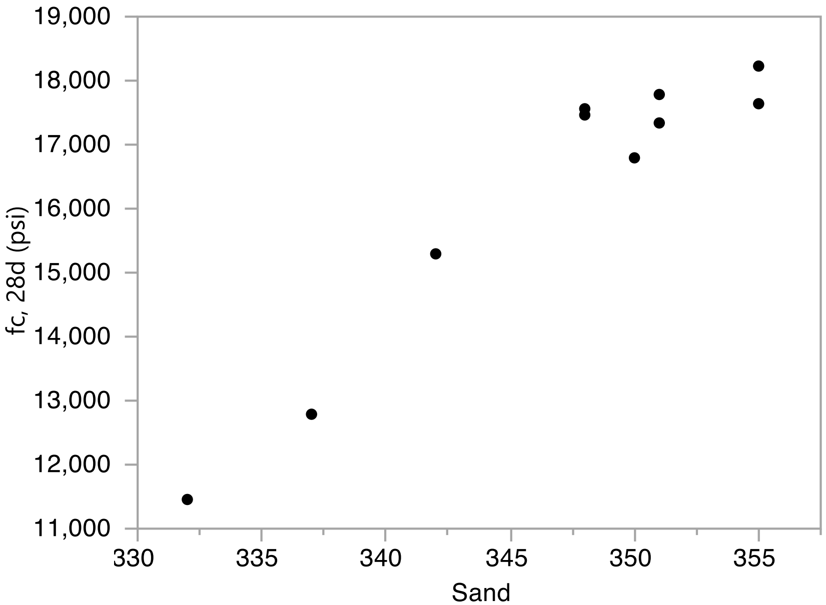
Effects of binder

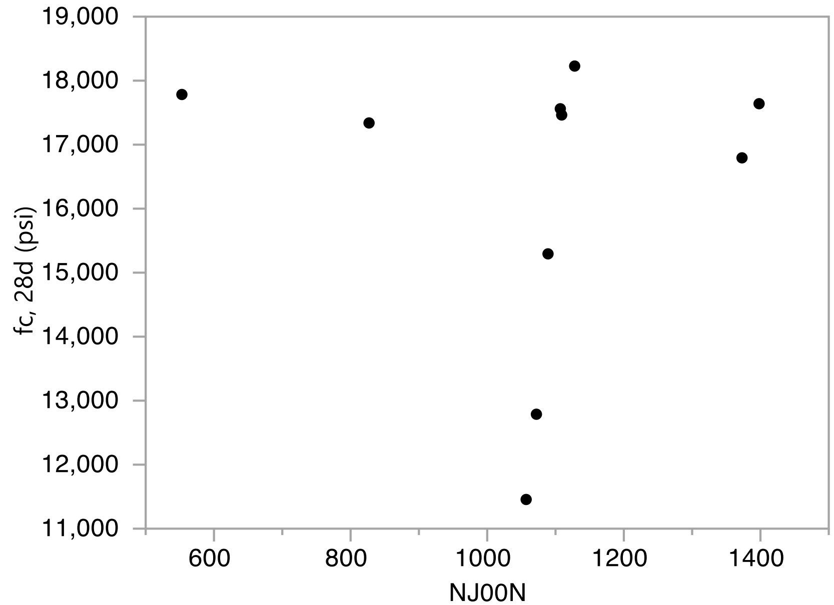




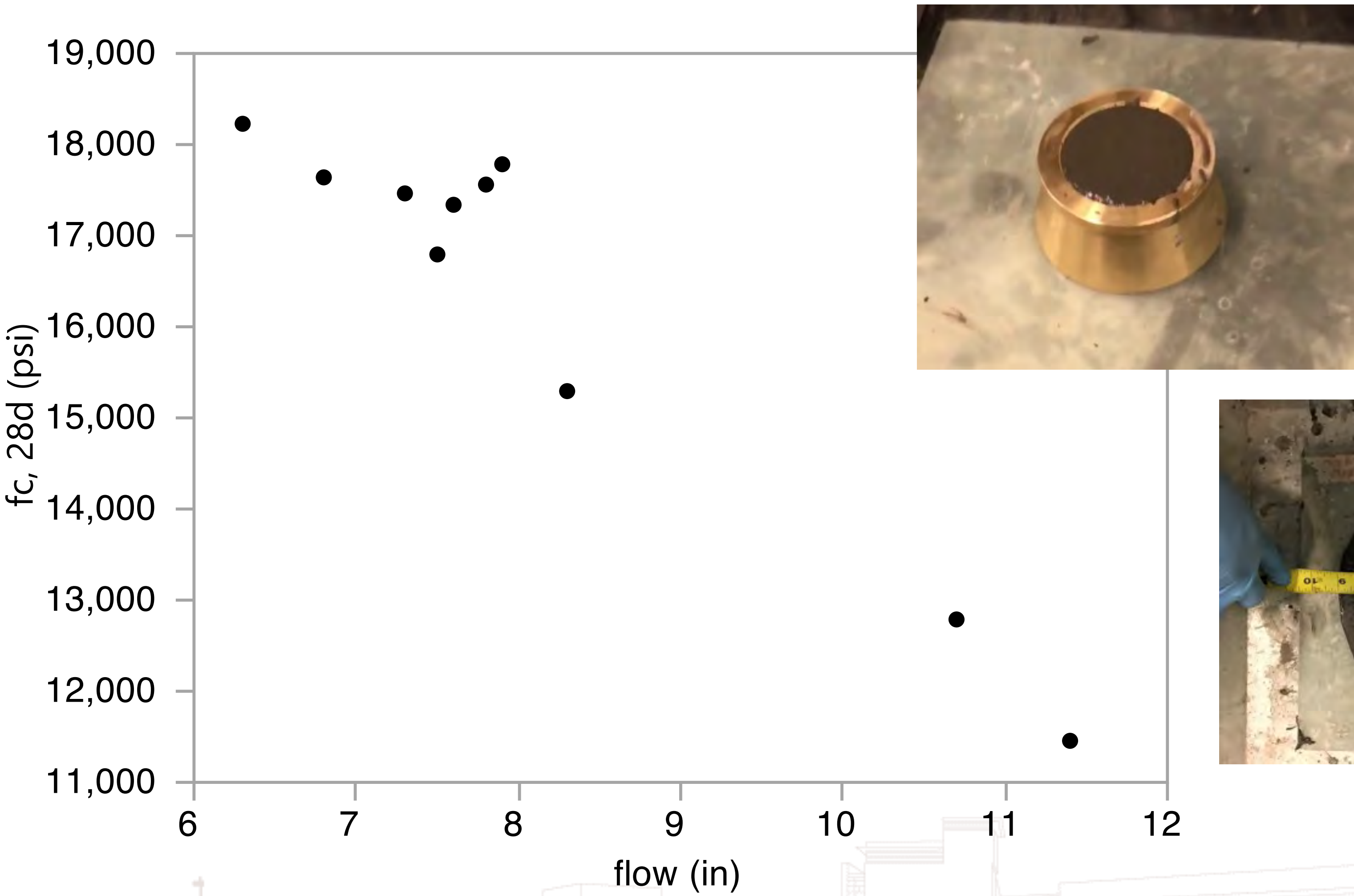


Effect of aggregates





Flow and strength



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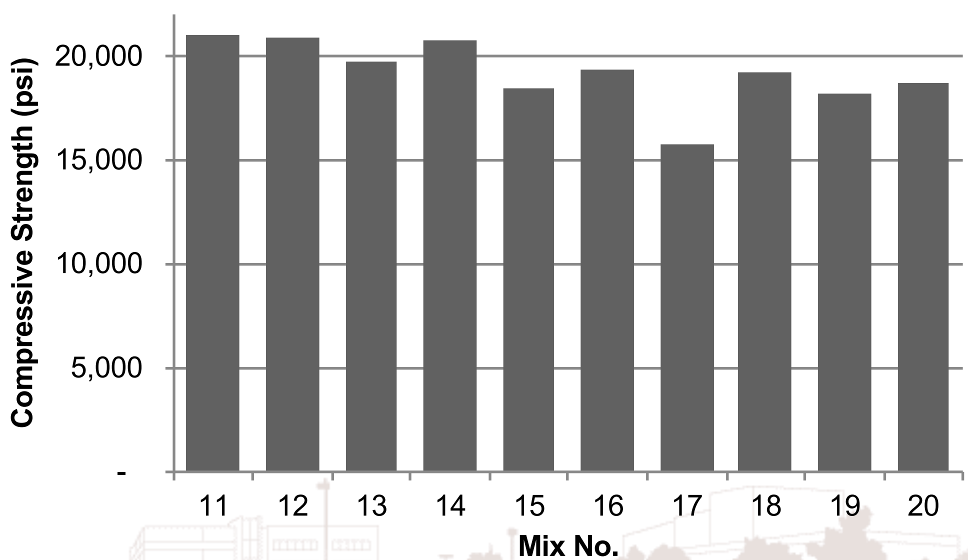
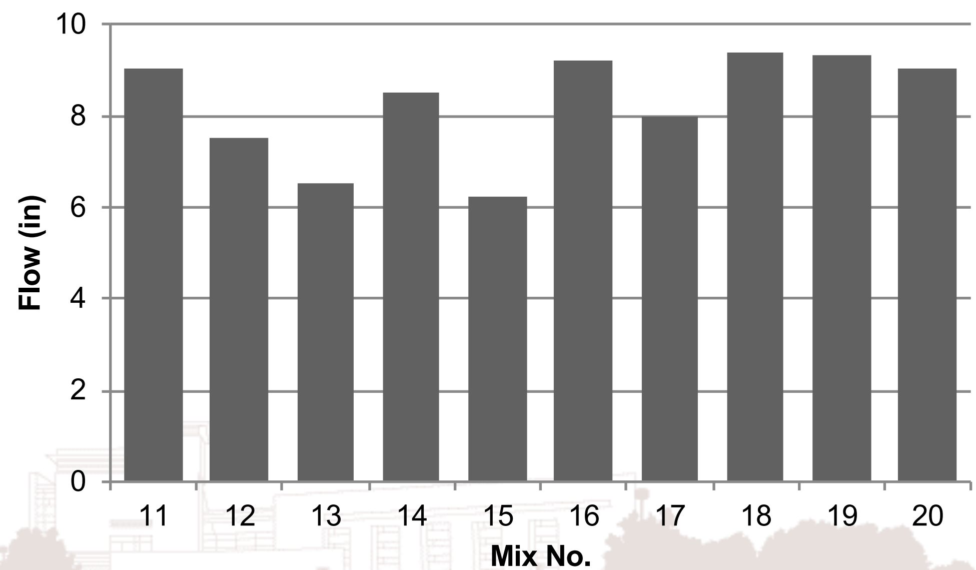
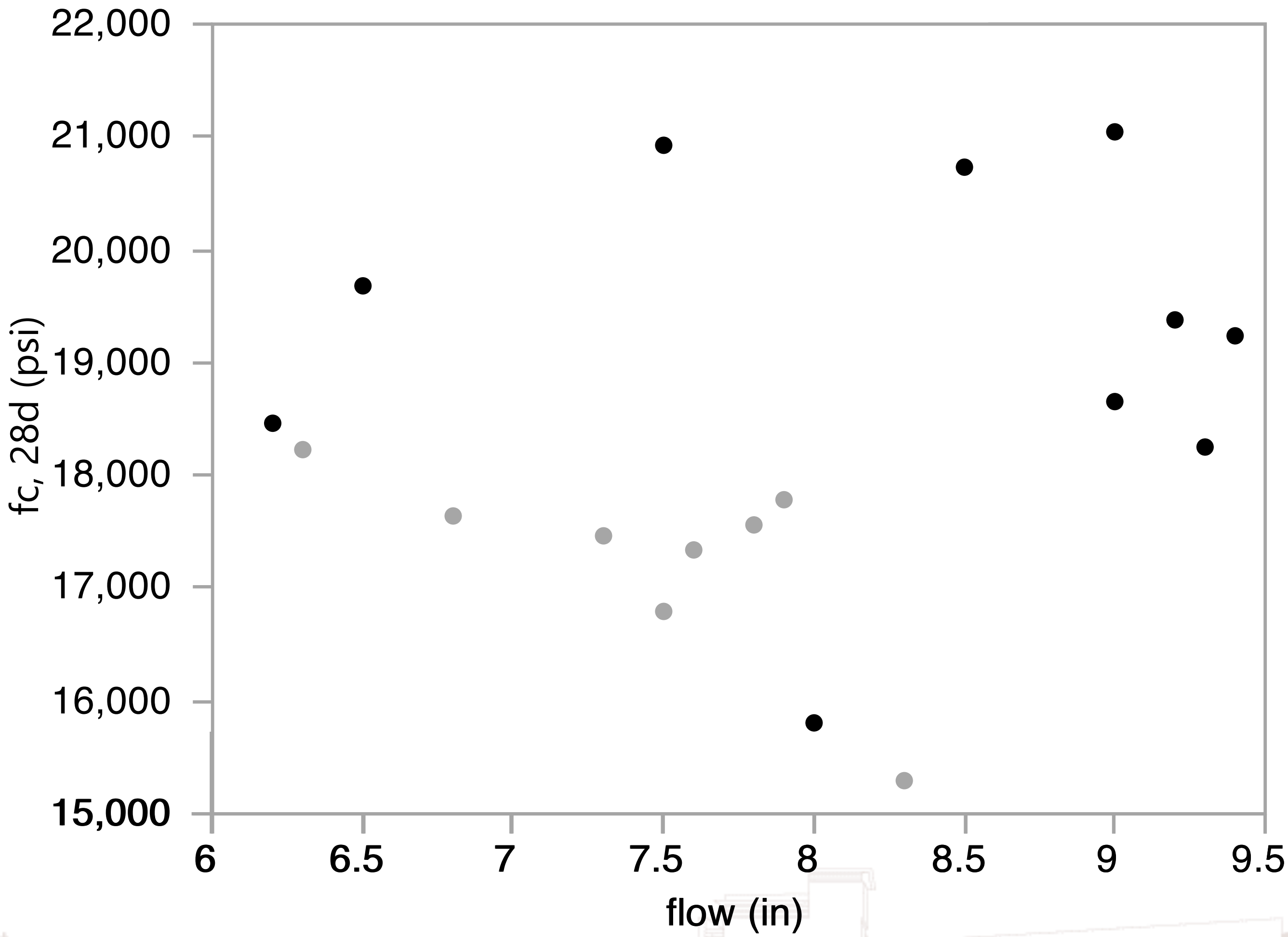
Change in material

Mix/pcy	PC1	PC2	SF-D	SF-UD	GGBFS-1	GGBFS-2	Sand	NJ0	NJ00N	F35	F75	HRWR-1	HRWR-2
Mix 11		647		325		647				1572	393		39
Mix 12		647		325		647		1572			393		39
Mix 13		647		325		647			1572		393		39
Mix 14	647			325		647		1572			393		39
Mix 15	647			325		647		1572			393	39	
Mix 16	647			325	647			1572			393		39
Mix 17	647		325			647		1572			393		39
Mix 18		647		325		647		982			982		39
Mix 19		647		325		647			982		982		39
Mix 20		647		325		647	393			1572			39





Flow versus strength



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Change F35 to NJ0 and NJ00N

Mix/pcy	PC1	PC2	SF-D	SF-UD	GGBFS-1	GGBFS-2	Sand	NJ0	NJ00N	F35	F75	HRWR-1	HRWR-2
Mix 11		647		325		647				1572	393		39
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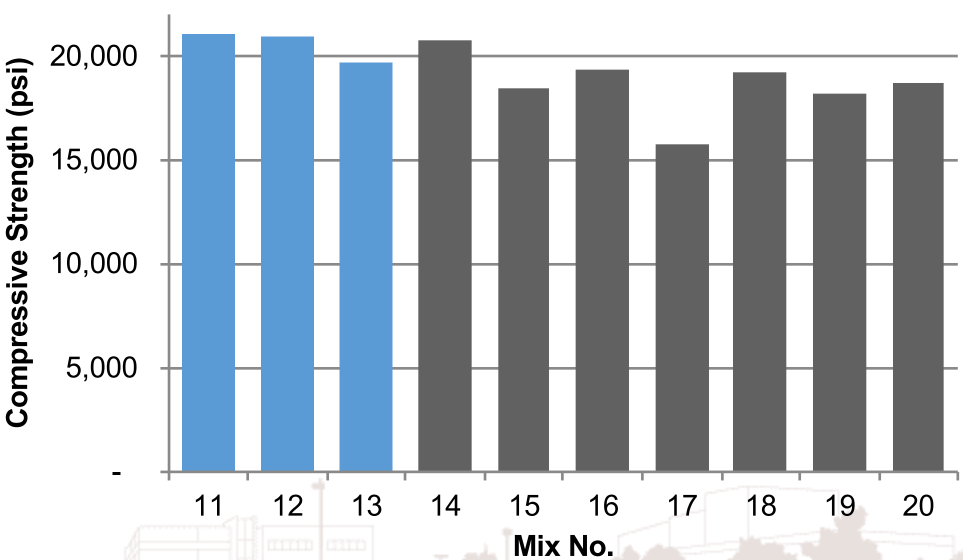
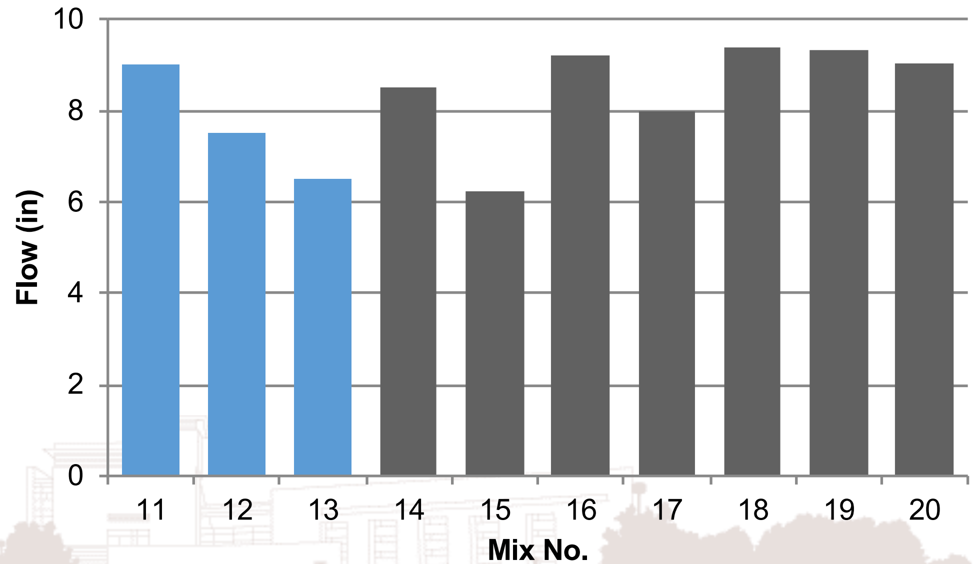
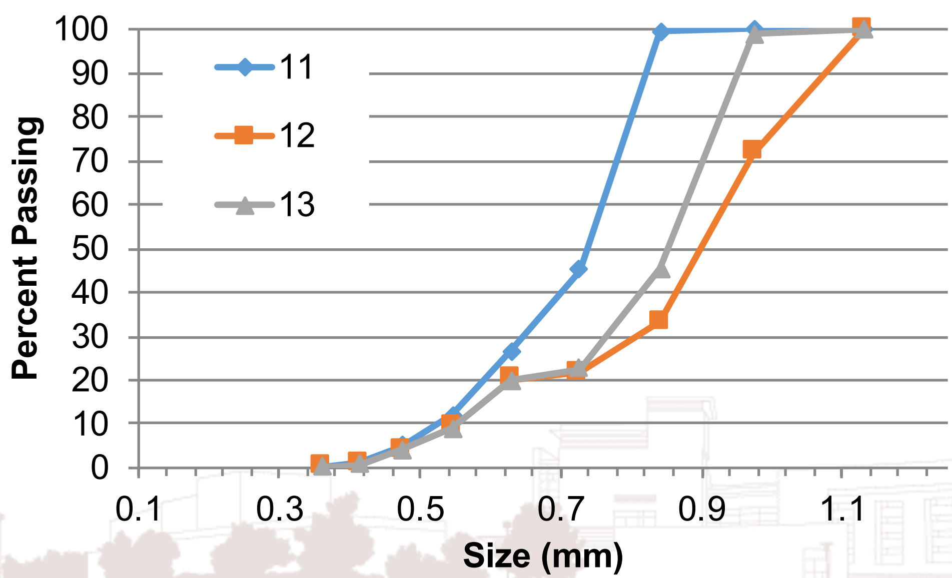
Mix 14	647			325		647		1572			393		39
Mix 15	647			325		647		1572			393	39	
Mix 16	647			325	647			1572			393		39
Mix 17	647		325			647		1572			393		39
Mix 18		647		325		647		982			982		39
Mix 19		647		325		647			982		982		39
Mix 20		647		325		647	393			1572			39





Change F35 to NJ0 and NJ00N

Mix/pcy	PC1	PC2	SF-D	SF-UD	GGBFS-1	GGBFS-2	Sand	NJ0	NJ00N	F35	F75	HRWR-1	HRWR-2
Mix 11		647		325		647				1572	393		39
Mix 12		647		325		647		1572			393		39
Mix 13		647		325		647			1572		393		39
Mix 14	647			325		647		1572			393		39
Mix 15	647			325		647		1572			393	39	
Mix 16	647			325	647			1572			393		39
Mix 17	647		325			647		1572			393		39
Mix 18		647		325		647		982			982		39
Mix 19		647		325		647			982		982		39
Mix 20		647		325		647	393			1572			39



Different PC

Mix/pcy	PC1	PC2	SF-D	SF-UD	GGBFS-1	GGBFS-2	Sand	NJ0	NJ00N	F35	F75	HRWR-1	HRWR-2
Mix 11		647		325		647				1572	393		39
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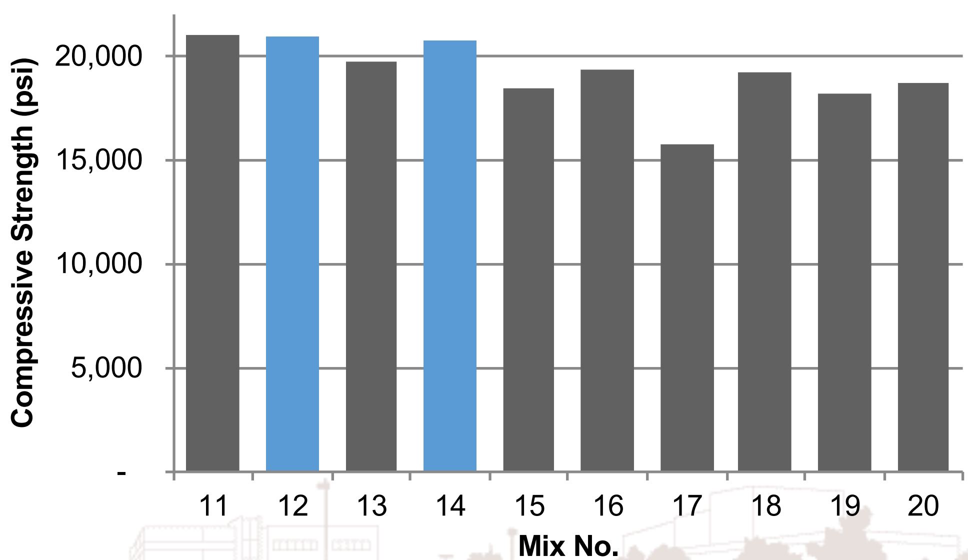
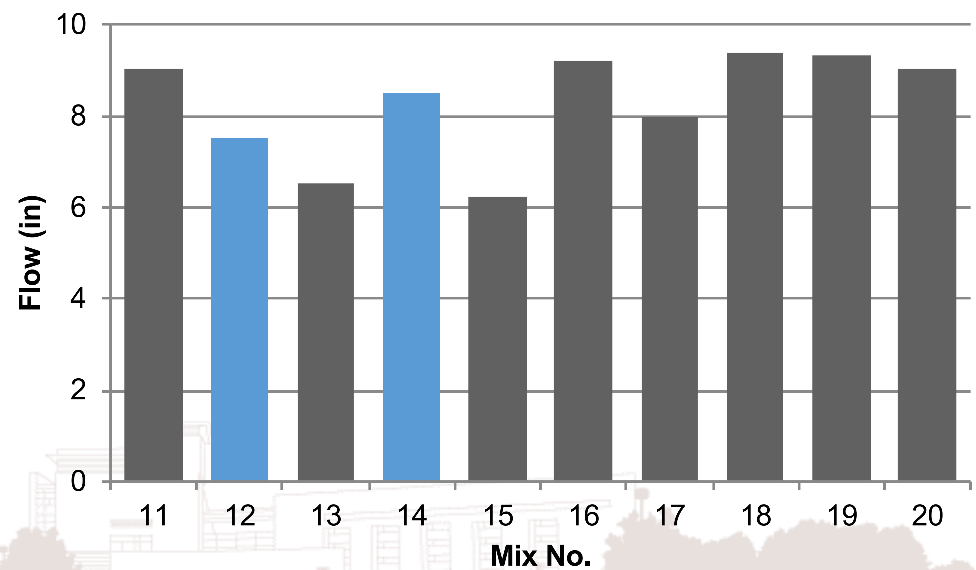
Mix 15	647			325		647		1572			393	39	
Mix 16	647			325	647			1572			393		39
Mix 17	647		325			647		1572			393		39
Mix 18		647		325		647		982			982		39
Mix 19		647		325		647			982		982		39
Mix 20		647		325		647	393			1572			39





Different HRWR

Mix/pcy	PC1	PC2	SF-D	SF-UD	GGBFS-1	GGBFS-2	Sand	NJ0	NJ00N	F35	F75	HRWR-1	HRWR-2
Mix 11		647		325		647				1572	393		39
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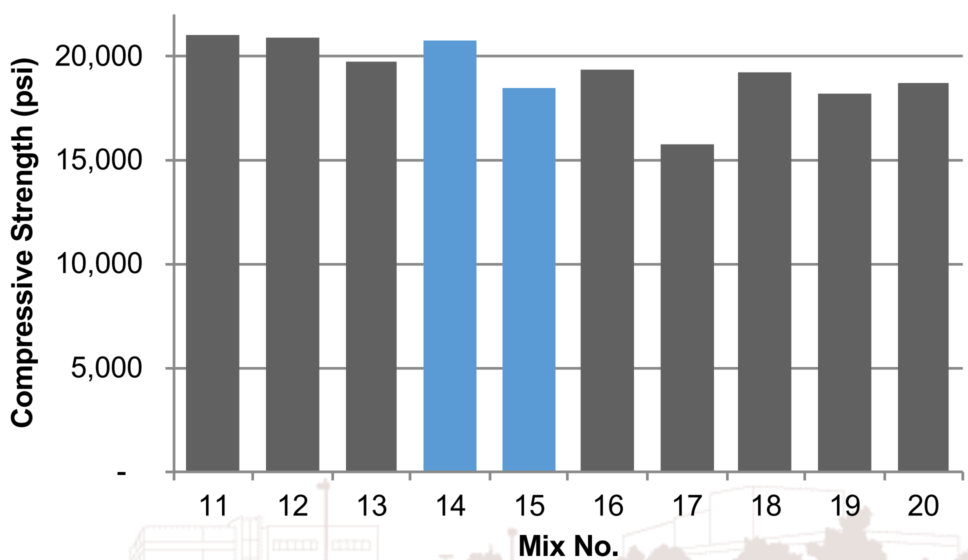
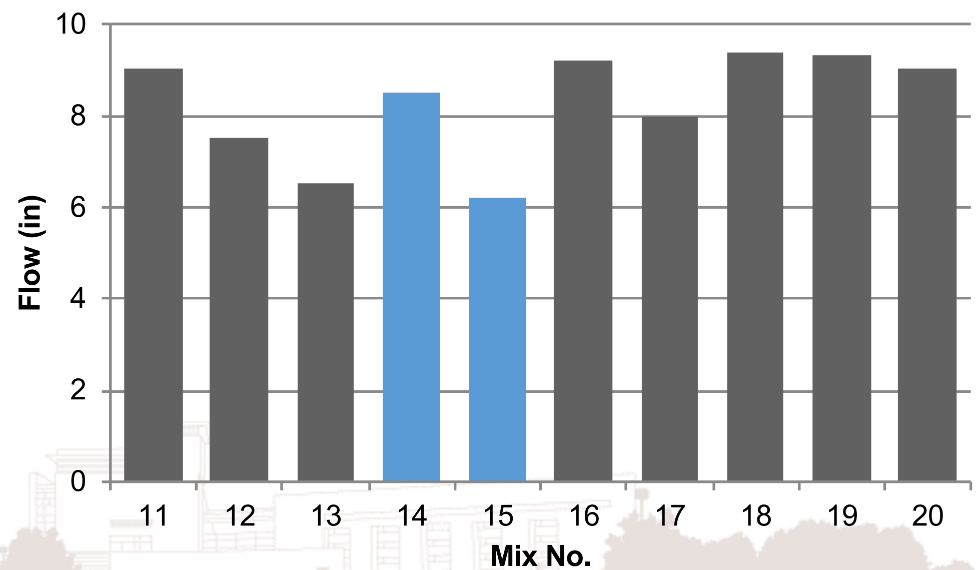
Mix 16	647			325	647			1572			393		39
Mix 17	647		325			647		1572			393		39
Mix 18		647		325		647		982			982		39
Mix 19		647		325		647			982		982		39
Mix 20		647		325		647	393			1572			39





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Different GGBFS

Mix/pcy	PC1	PC2	SF-D	SF-UD	GGBFS-1	GGBFS-2	Sand	NJ0	NJ00N	F35	F75	HRWR-1	HRWR-2
Mix 11		647		325		647				1572	393		39
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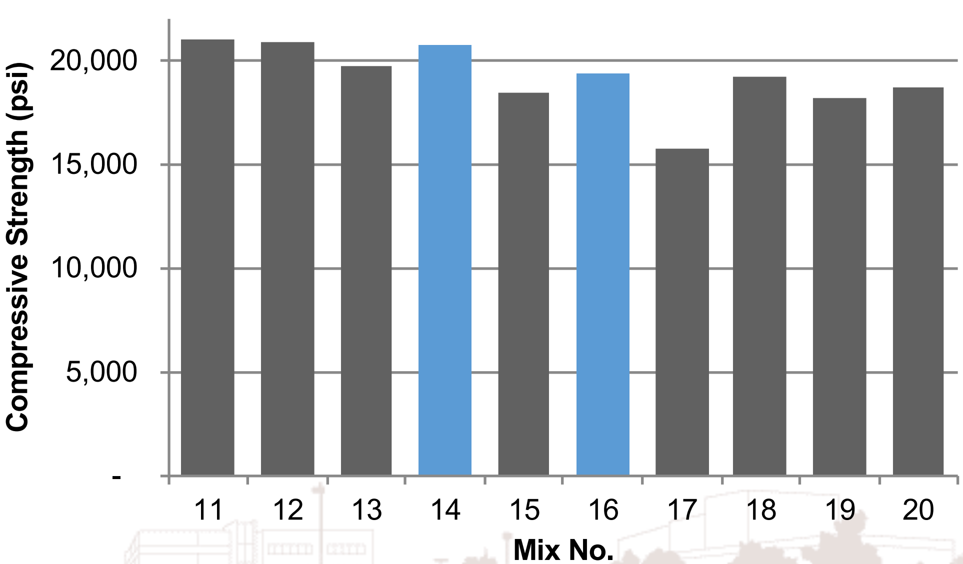
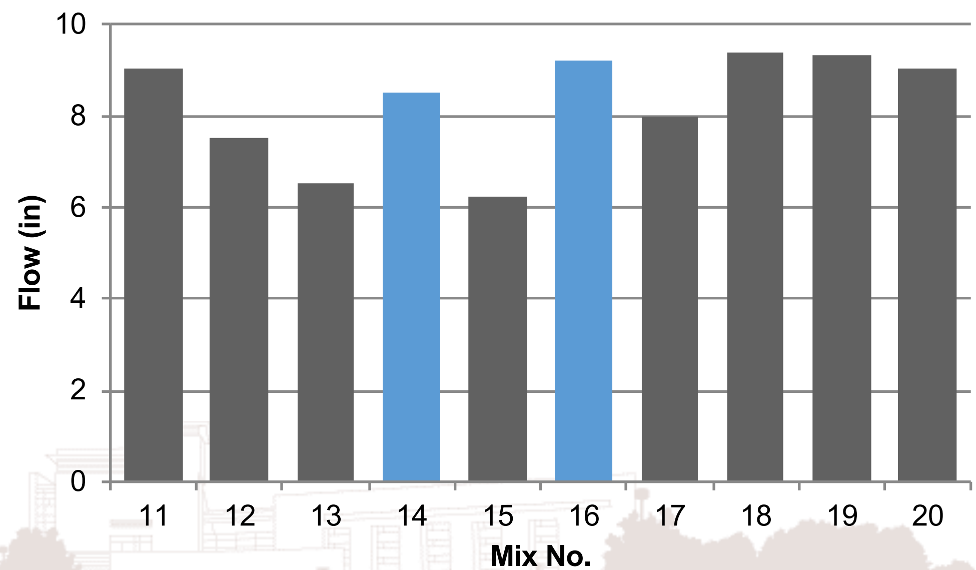
Mix 15	647			325		647		1572			393	39	
Mix 16	647			325	647			1572			393		39
Mix 17	647		325			647		1572			393		39
Mix 18		647		325		647		982			982		39
Mix 19		647		325		647			982		982		39
Mix 20		647		325		647	393			1572			39





Different SF

Mix/pcy	PC1	PC2	SF-D	SF-UD	GGBFS-1	GGBFS-2	Sand	NJ0	NJ00N	F35	F75	HRWR-1	HRWR-2
Mix 11		647		325		647				1572	393		39
Mix 12		647		325		647		1572			393		39
Mix 13		647		325		647			1572		393		39
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Mix 15	647			325		647		1572			393	39	
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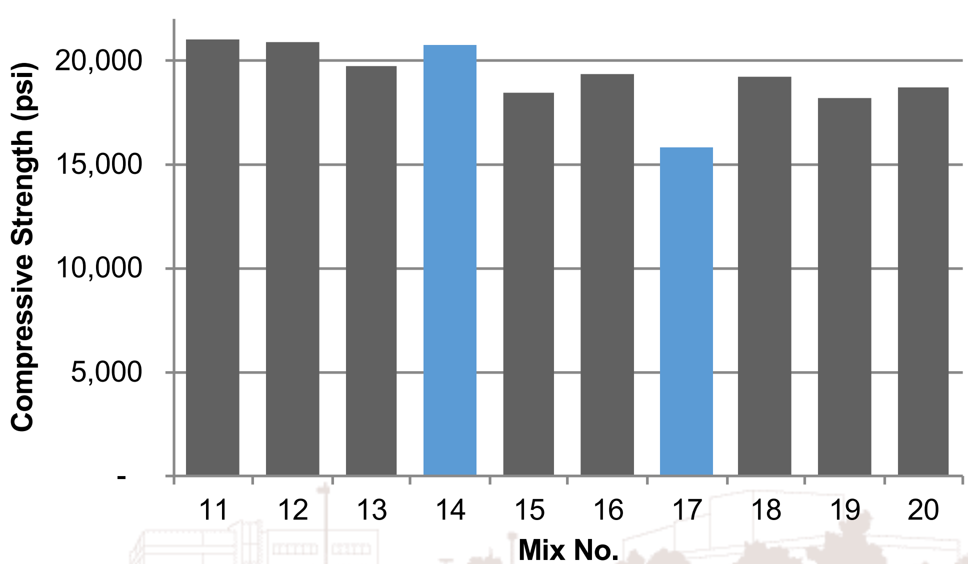
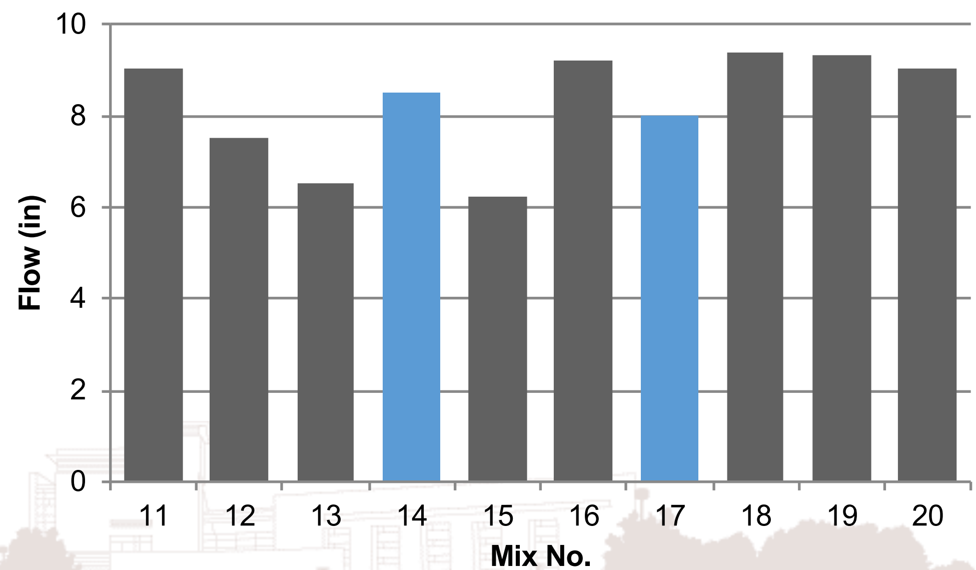
Mix 17	647		325			647		1572			393		39
Mix 18		647		325		647		982			982		39
Mix 19		647		325		647			982		982		39
Mix 20		647		325		647	393			1572			39





Change aggregate ratio

Mix/pcy	PC1	PC2	SF-D	SF-UD	GGBFS-1	GGBFS-2	Sand	NJ0	NJ00N	F35	F75	HRWR-1	HRWR-2
Mix 11		647		325		647				1572	393		39
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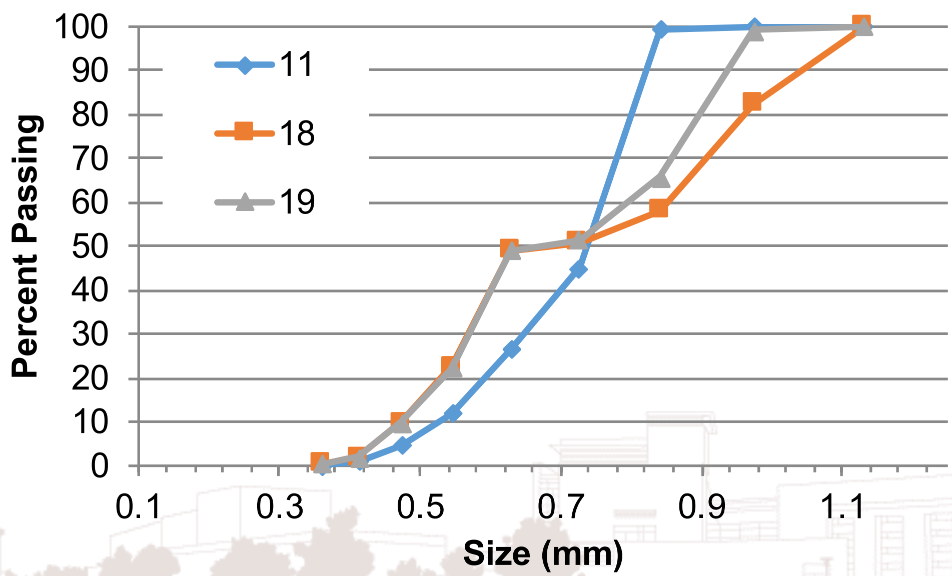

Change aggregate ratio

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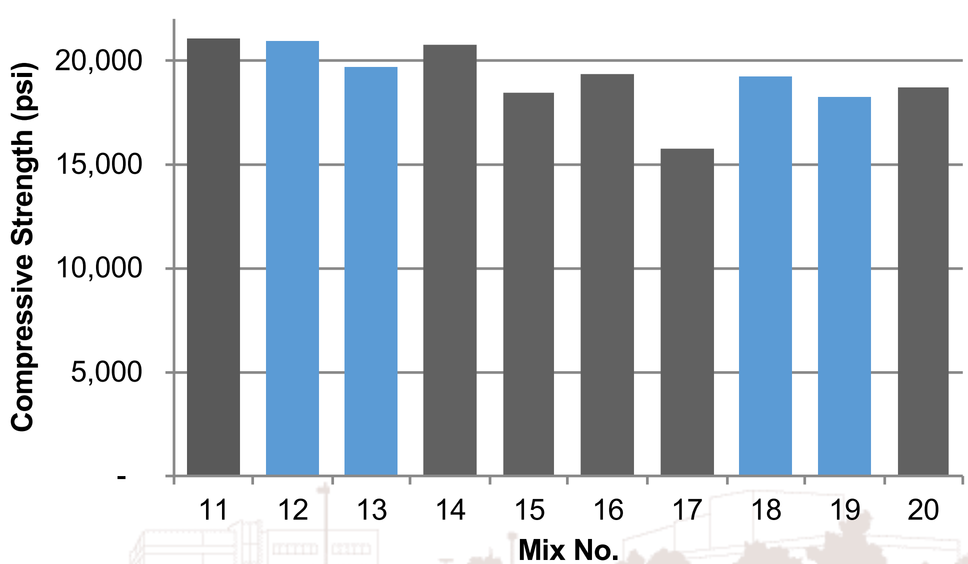
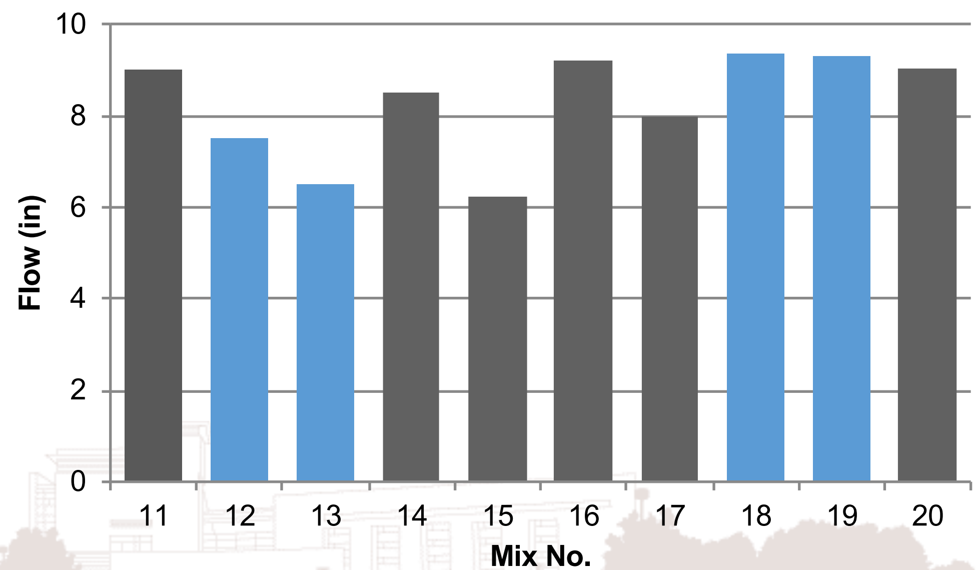
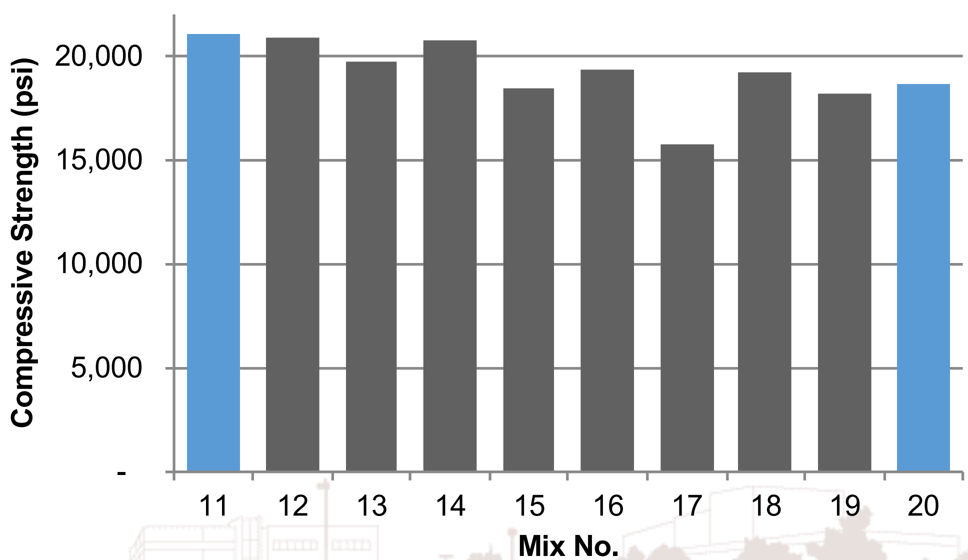
Mix 19		647		325		647			982		982		39
Mix 20		647		325		647	393			1572			39

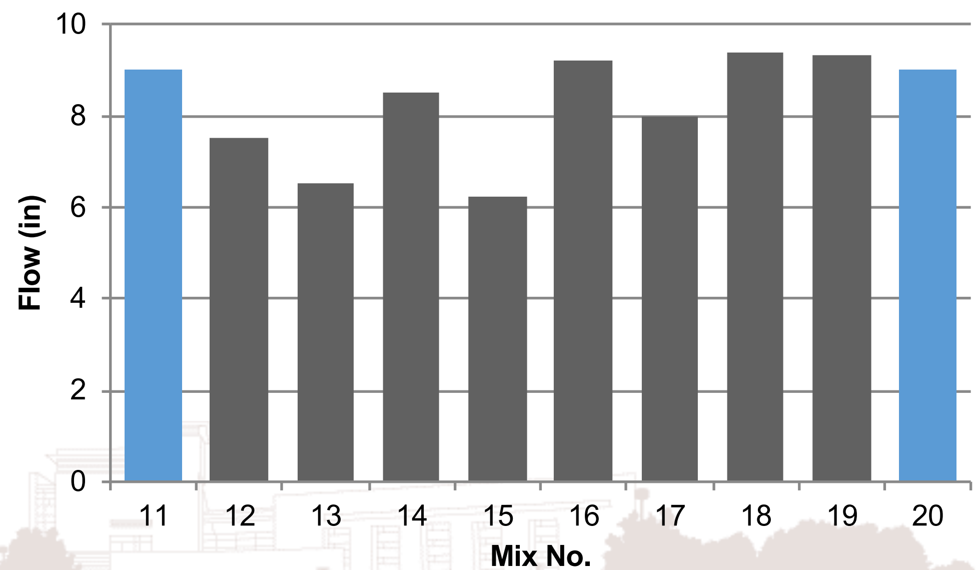




Different fines

Mix/pcy	PC1	PC2	SF-D	SF-UD	GGBFS-1	GGBFS-2	Sand	NJ0	NJ00N	F35	F75	HRWR-1	HRWR-2
Mix 11		647		325		647				1572	393		39
Mix 12		647		325		647		1572			393		39
Mix 13		647		325		647			1572		393		39
Mix 14	647			325		647		1572			393		39
Mix 15	647			325		647		1572			393	39	
Mix 16	647			325	647			1572			393		39
Mix 17	647		325			647		1572			393		39
Mix 18		647		325		647		982			982		39
Mix 19		647		325		647			982		982		39
Mix 20		647		325		647	393			1572			39





Conclusions

- Using coarser silica can reduce strength but improve flow
- Very fine concrete sand will provide good flow but reduced strength
- Finer PC and GGBFS will provide higher strength but lower flows
- FA tends to act as aggregates
- Use SF-UD provides better strength and flow

THANK YOU!

Proprietary UHPC

- Commercial or batch plant production
- Delivery time-batch plant to casting location
- Workability of fresh concrete during mixing and casting
- Higher Cost (20 times conventional concrete)
- Environmental concerns
- High Cement Content
- Massive Energy Consumption

Non-Proprietary UHPC

- Laboratory or trial batch production
- More economical (10-15 times conventional concrete)
- Higher durability and lower shrinkage
- Reduced shrinkage due to optimized proportions of supplementary cementitious material (SCM)
- Optimized proportions
- Optimum spread (flow)
- Optimized particle packing density
- Environmentally sustainable

Proprietary UHPC

- Lafarge
- Sika AG
- CeEntek
- Metalco
- TAKTL
- RAMPF Holding

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Comparison: Properties

Property	Conventional Concrete	UHPC
Compressive Strength	5000-7000 psi	22,000-30,000 psi
Flexural Strength	1000-1500 psi	6000 – 7000 psi
Modulus of Elasticity	4E+06-6E+06 psi	7E+06-9E+06 psi
Ductility	Less	More
Durability	Less	More
Bending/Flexural	Less	More
Tensile Strength	Less	More
Porosity	High	Low
Thermal Expansion/Contraction	Low	High
Resistance to abrasion, erosion and corrosion	High	Low

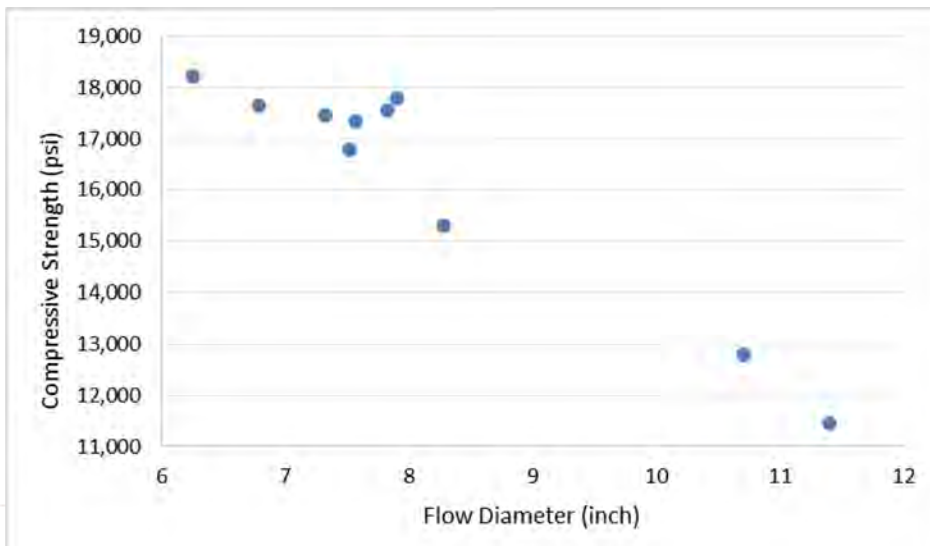
Design Potentials

- UHPC research- focusing on reduced amount of supplementary cementitious (e.g. slag, fly ash, and limestone) material which enhances strength by replacing them about 25-30%.
- Compressive strengths- more than 20,000 psi without further replacing cement. Efficient use of mineral admixtures, chemical admixtures and fibers.
- Aggregates with different (finer is better) gradation is being tested.
- Use of as Quartz sand, silica sand, sieved fine aggregate (≤ 50) at laboratory fine aggregate.

Results and Analysis

Component/Mix #	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6	Mix 7	Mix 8	Mix 9	Mix 10
Cement (kg)	1.201	1.195	1.065	1.069	1.064	1.069	1.071	1.046	1.031	1.016
Silica Fume (kg)	0.300	0.299	0.266	0.267	0.266	0.267	0.268	0.261	0.258	0.254
Fly Ash (kg)	0.300	0.574	0.511	0.267	0.511	0.748	0.985	0.502	0.495	0.488
Water (kg)	0.133	0.130	0.115	0.140	0.137	0.135	0.132	0.158	0.177	0.194
Sand (kg) (Sieved <50)	0.332	0.331	0.294	0.296	0.294	0.296	0.296	0.289	0.285	0.281
NJ00N Quartz (kg)	1.307	1.052	0.937	1.162	0.936	0.698	0.466	0.920	0.907	0.894
Fiber (g)	212.542	212.542	212.542	212.542	212.542	212.542	212.542	212.542	212.542	212.542
HRWR (ml)	151.043	149.493	154.465	134.358	133.760	134.388	134.605	131.477	129.555	127.689

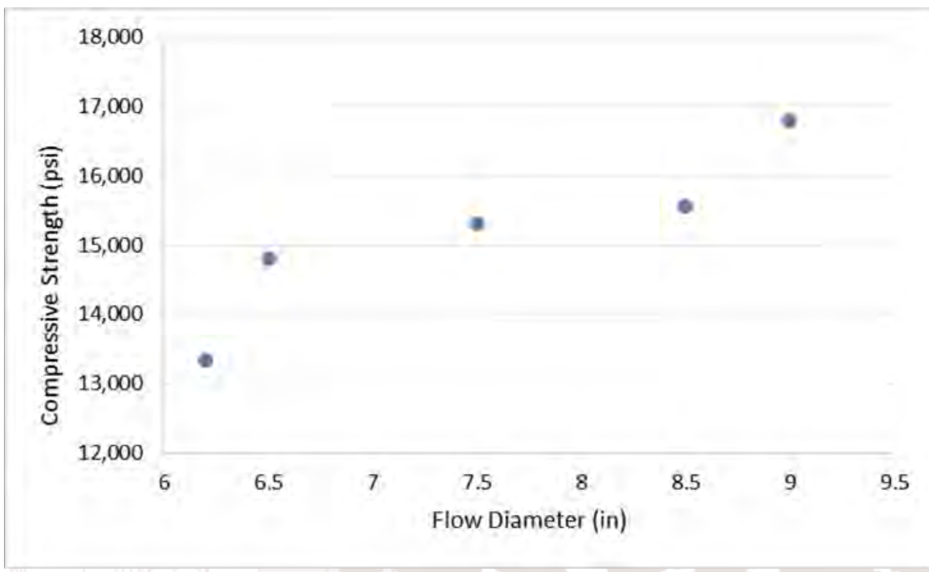
Mix #	W/C	fc' (psi)-28 days	Flow Diameter (in)
1	0.22	17,640	6.78
2	0.22	18,228	6.25
3	0.24	17,464	7.32
4	0.24	16,794	7.52
5	0.24	17,561	7.82
6	0.24	17,339	7.56
7	0.24	17,784	7.9
8	0.27	15,294	8.28
9	0.29	12,788	10.7
10	0.31	11,456	11.4



Results and Analysis

Component	Quantity (kg/m^3)
Type I OPC	390
Slag Cement	390
Silica Fume	196.2
HRWR	23.4
Sand A	237
Sand B	948
Steel Fibers	159
Water	171.6
W/C	0.22 for all ten mixes

Mix #	Change of Materials (Sand, HRWR and Cement)	fc' (psi)-28 days	Flow Diameter (in)
1	F75 and F35	21,045	9
2	F75 and NJ0	20,926	7.5
3	F75 and NJ00N	19,680	6.5
4	F75, NJ0, HRWR (1), Cement	20,732	8.5
5	F75, NJ0, HRWR (2), Cement	18,462	6.2
6	F75, NJ0, Cément, Slag	Due 27th Sep	9.2
7	F75, NJ0, Cément, Silica Fume	Due 27th Sep	8
8	F75-50%, NJ0-50%	Due 28th Sep	9.35
9	F75-50%, NJ00N-50%	Due 28th Sep	9.3
10	Sieved Sand (<#50)- 20%, F35-80%	Due 28th Sep	9



Flow Test

Fracture Properties

- Fracture mechanics - a failure theory for energy dissipation criteria by crack propagation
- Physical changes due to crack propagation depends on stress and energy dissipation
- Two kinds of structural failure
  - Plastic failure- shows the longer yielding region
  - Brittle failure- does not indicate such kind of yielding.
- Dissipated (fracture) energy- the area under the load-displacement plot,
  - i.e. the amount of energy the structure absorb during failure while applying loads.
- Fracture energy- use to determine ductility of the structure
- Fracture properties provide complete behaviour of fracture energy and crack width
- Standards: ASTM E 1820, ASTM E399, ASTM C1018, RILEM TC 162-TDF

Research Significance

- This represents the sensitivity analysis to observe behavioral changes in fracture properties of High Performance Concrete (HPC) and Ultra High Performance Concrete (UHPC).
- Total 4 beam specimens, with dimensions of 3 inch x 3 inch x 12 inch, were casted as independent parameters for the identification of the fracture properties.
- The variables were considered as use of steel fiber and notch length.
- The volume ratio of steel fiber in the concrete specimen is 6%.
- The notch length varied from 0 -1 inch (i.e. d/3).
- Three-point bending tests, load-CMOD and load-displacement curves were obtained.
- Fracture properties such as fracture energy, CTODc, KIC, ac and E values were calculated.

Fracture Model

- Virtual Crack Model and RILEM Equations
  - Fracture energy, $G_F = \frac{W_0 + 2P_w\delta_0}{(b - a_0)t}$
  - Elastic Modulus $E = \frac{6Sa_0 v_1(\alpha)}{c_I d^2 b}$
  - Critical effective crack length, $E = \frac{6S a_c V_1(\alpha)}{C_u d^2 b}$

    $V_1(\alpha) = 0.76 - 2.28\alpha + 3.87\alpha^2 - 2.04\alpha^3 + \frac{0.66}{(1-\alpha)^2}$

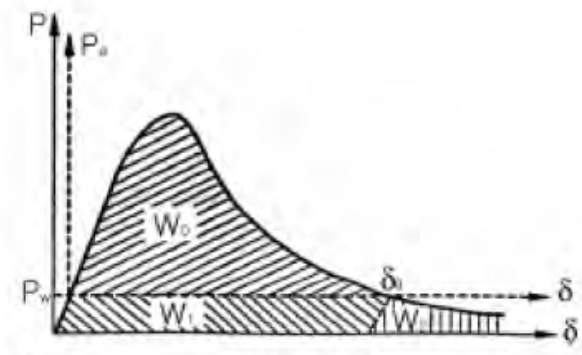
    $\alpha = (a_0 + HO)/(d + HO)$
  - Critical stress intensity factor,

    $K_{Ic}^s = 3(P_{max} + 0.5W)\frac{S(\pi a_c)^{1/2} F(\alpha)}{2d^2 b}$ $F(\alpha) = \frac{1.99 - \alpha(1-\alpha)(2.15 - 3.93\alpha + 2.7\alpha^2)}{\sqrt{\pi}^{1/2}(1+2\alpha)(1-\alpha)^{3/2}}$

    $\alpha = a_c/d$ $W = W_0 S/L$
  - Critical crack tip opening displacement,

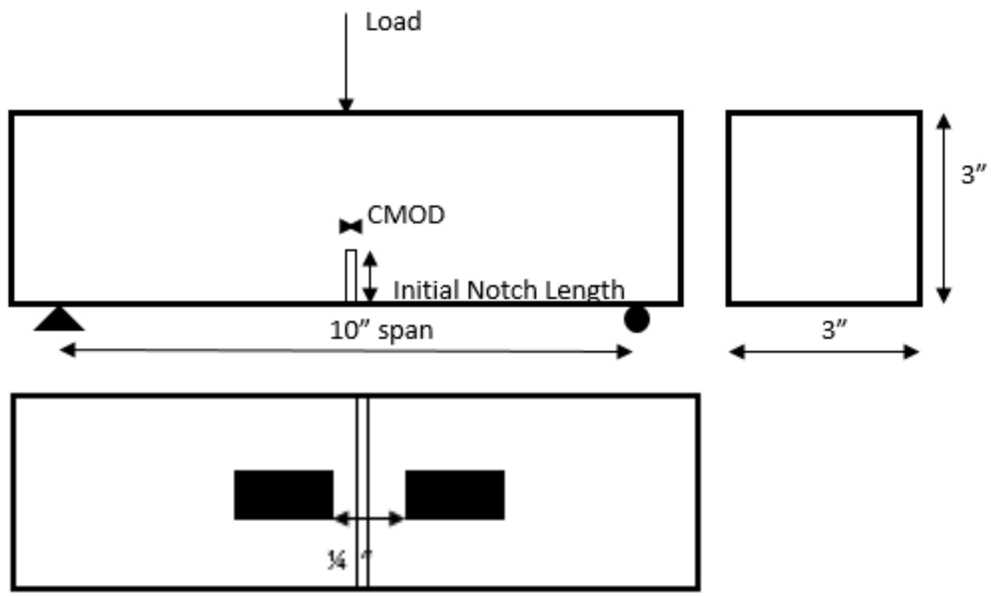
    $\mathrm{CTOD}_c = \frac{6P_{max} S a_c V_1(\alpha)}{Ed^2 b}[(1-\beta)^2 + (1.081 - 1.149\alpha)(\beta - \beta^2)]^{1/2}$

    $\alpha = a_c/d$ and $\beta = a_0/a$.



Experimental Set up

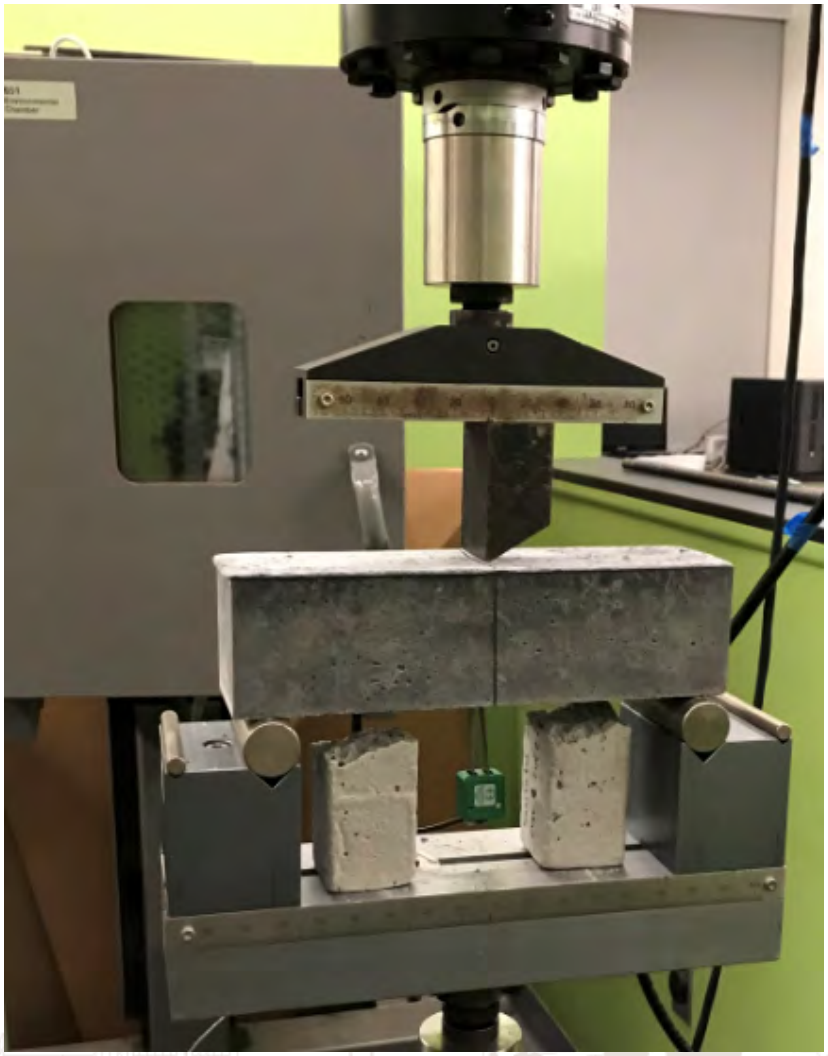
- 3- point bending fracture test and determination of fracture properties



Schematic Diagram

Experimental Set up

Fracture Testing



Experimental Set up of No Notch UHPC Beam

Experimental Set up of Notched UHPC Beam

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Fracture Testing

Failure Mechanism for Notched UHPC Beam

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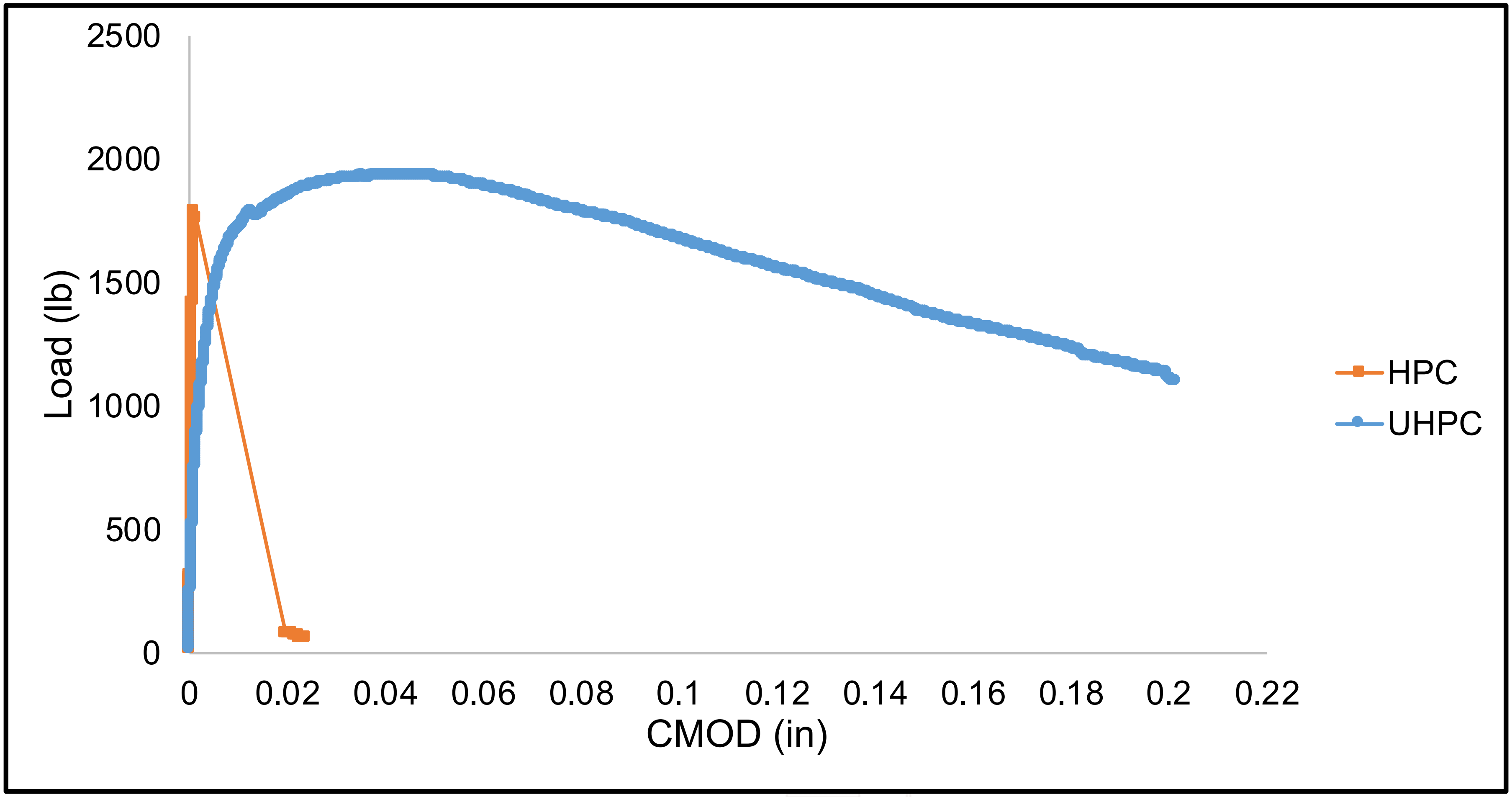
Fracture Results



Load-CMOD for HPC and UHPC

Fracture Analysis

HPC	UHPC
No Notch	
Pmax = 2945.92 lb	Pmax = 5445.58 lb
Axial Extension = 0.000491763 inch	Axial Extension = 0.05888 inch
Displacement = 0.053178 inch	Displacement = 0.1829 inch
Notch (1 inch)	
Pmax = 1672.34 lb	Pmax = 1994.28 lb
CMOD = 0.001111 in	CMOD = 0.04227 in
Displacement = 0.036506 inch	Displacement = 0.070231 inch
Fracture Properties	
GF = 105.42 lb/in	GF = 392.78 lb/in
E = 2.10 E+06 psi	E = 3.18 E+06 psi
ac = 1.0758 inch	ac = 1.486 inch
K_{IC} = 2496.701 lb/(in)^(3/2)	K_{IC} = 3084.083 lb/(in)^(3/2)
CTODc = 0.003486 inch	CTODc = 0.027427 inch

Fracture Summary

- Beams with no notch;
  - UHPC has a higher failure load (peak value) due to higher flexural strength; which also results in larger displacement before failure.
  - UHPC has an extended post cracking load carrying capacity due to the presence of steel fibers.
- Beams with 1 inch Notch;
  - As steel fiber controls the crack propagation due to the tensile stress and resists the tensile stress across the crack, for UHPC higher CMOD at peak load than CMOD for HPC (no steel fibers).
  - UHPC performs better in post cracking zone beyond peak load.
- UHPC fracture energy increased due to higher matrix strength and inclusion steel fiber.

Accelerated Corrosion (AC)

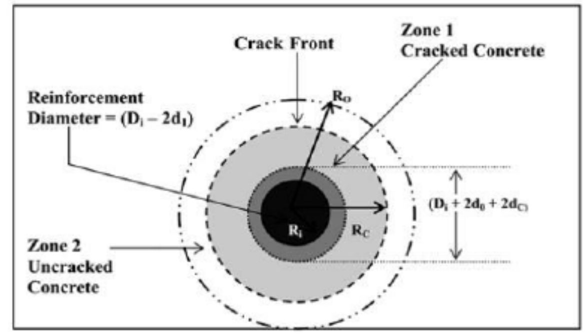
Reduction of Oxygen: $O_2(g) + 2H_2O(l) + 4e^-(aq) \longrightarrow 4OH^-(aq)$

Oxidation of Iron: $Fe(s) \longrightarrow Fe^{2+}(aq) + 2e^-(aq)$

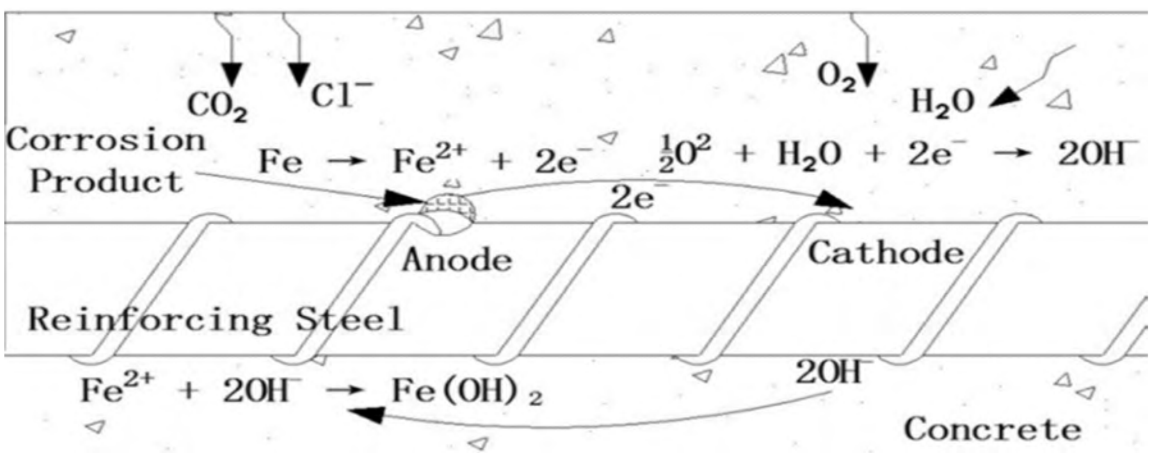
Iron Oxide: $4Fe^{2+}(aq) + O_2(g) \longrightarrow 4Fe^{3+}(aq) + 2O^{2-}(aq) \longrightarrow Fe_2O_3(s)$

In the presence of water following reactions are occurred

$Fe^{2+}(aq) + 2H_2O(l) \longrightarrow Fe(OH)_2(s) + 2H^+(aq)$; $Fe^{3+}(aq) + 3H_2O(l) \longrightarrow Fe(OH)_3(s) + 3H^+(aq)$



Cracking in steel bar



Typical corrosion process for steel rebar

Corroded RC structures

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AC Calculations

- Corrosion under natural process is very slow and takes longer time.
- To achieve desired corrosion levels in laboratory, accelerated corrosion process is
  - recommended, leads to favorable circumstances
- It is an electrochemical process, using chemicals and constant magnitude electric current
  - to embedded steel to simulate real life condition.
- Form a galvanic cell in the glass beaker with steel rebar (anode +), copper or stainless
  - steel plate (cathode -) and dissolved salt electrolyte

Size	Original Diameter		Original Area		Reduced Area		% Reduced Area	Reduced Diameter		% Reduced Diameter	% Mass Loss	Length		Wt (lb/ft)	# Rebar
	in	cm	in^2	cm^2	in^2	cm^2		in	cm			ft	in		
#5	0.625	1.5875	0.3068	1.9793	0.2761	1.7814	10	0.5929	1.5060	5.1317	10.0000	0.8333	20.0000	1.0430	2.0000
#6	0.75	1.905	0.4418	2.8502	0.3976	2.5652	10	0.7115	1.8072	5.1317	10.0000	0.8333	20.0000	1.5020	2.0000

Initial Mass (g)	Final Mass (g)	Degree of Corrosion	Icor (A)	*i* cor (μA/cm^2)	Equivalent Weight (EW)	Mass Loss Rate (g/m^2/day)	Mass Loss Rate (g/cm^2/day)	Mass Loss Rate (g/cm^2/hr)
788.4909	709.6418	10.0000	1	505222.4618	27.925	126326.0517	12.63260517	0.526358549
1135.4874	1021.9387	10.0000	1	350848.9318	27.925	87726.42479	8.772642479	0.36552677

Mass Loss (g/day)	Mass Loss (g/hr)	Days	Hrs
25.0040	1.041835208	3.1534535	75.68288
25.0040	1.041835208	4.541215	108.9892

AC-ASTM Standards

As per ASTM G102

- Corrosion current density i_{cor} = I_{cor}/A,
- Diameter of bar, $ø_1 = ø\sqrt{1-(\frac{p}{100})}$; $Ø_1$ = final dia, ø = initial dia, p = % wt. loss
- Corrosion Rate (CR) = K_1 (i_{cor}/ϱ) EW;
- Mass loss rate (MR) = K_2 i_{cor}EW
- Equivalent Weight, EW = W/n = 27.92,
- K_1 = 3.27E-03 mm g/µA cm yr ϱ = g/cm^3; K_2 = 8.954E-03 g cm^2/µA m^{2}d
- %Corrosion Level = (W_i – W_f/W_i)*100
- Corrosion current density, i_{app} = i_{corr} = (W_i – W_f)F/πDLWT

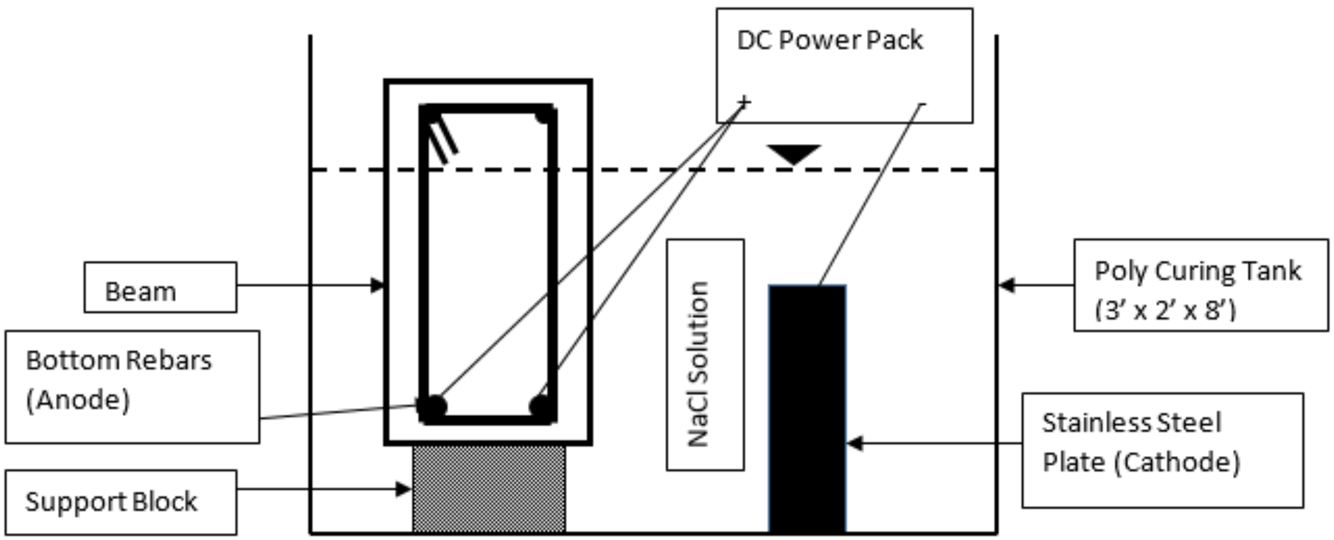
Where:

i_{cor} = corrosion current density, A/cm^2, I_{cor} = total anodic current A,
A = expose specimen area, cm^2, EW = the atomic weight of the element,
n = number of electrons required to oxidize an atom of the element in the corrosion process, i.e. the valence of the element.
W_i = Initial mass (g), W_f = final mass (g), F = Farady Constant, D = bar diameter, L = bar length
T = time in seconds W = Equivalent weight of steel

Note: EW value isn't depend on the unit system so may be consider dimensionless

Experimental Set Up

- Other small scale corrosion tests on RC beams (6” x 6” x 21”).
  - After 7 days of corrosion observe the cracking at tension and compression.
  - Break the beam and get the mass loss to determine reduction in bar diameter.

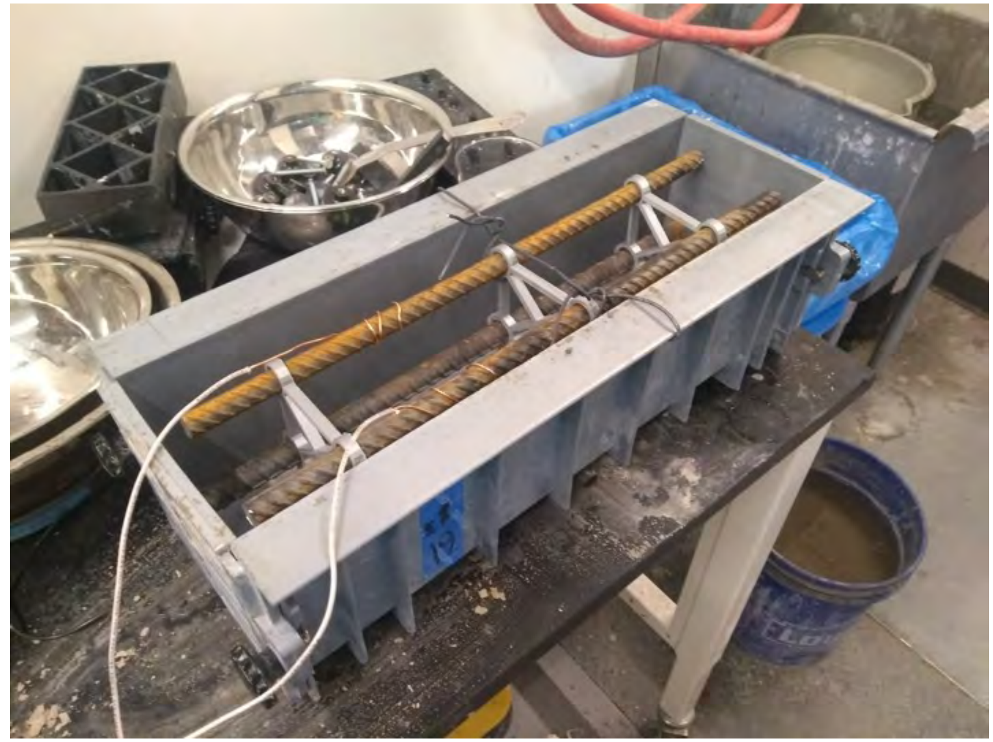


Accelerated Corrosion Set up for Beam

Concrete Crack Microscope

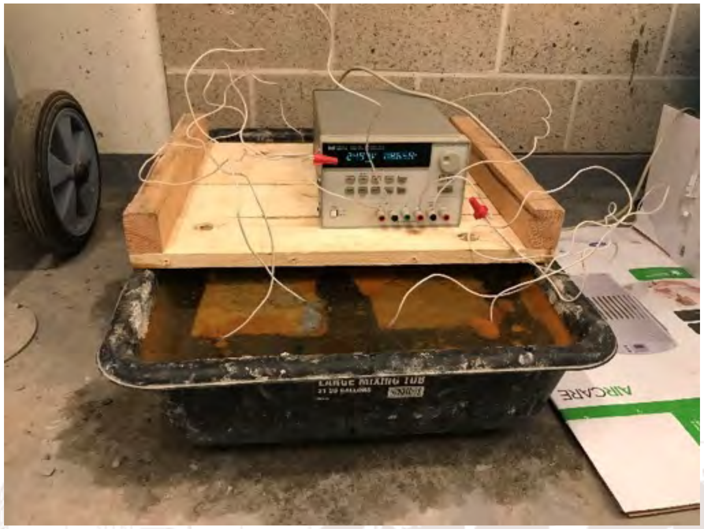
Casting of Beams

Beam for Bottom Corrosion

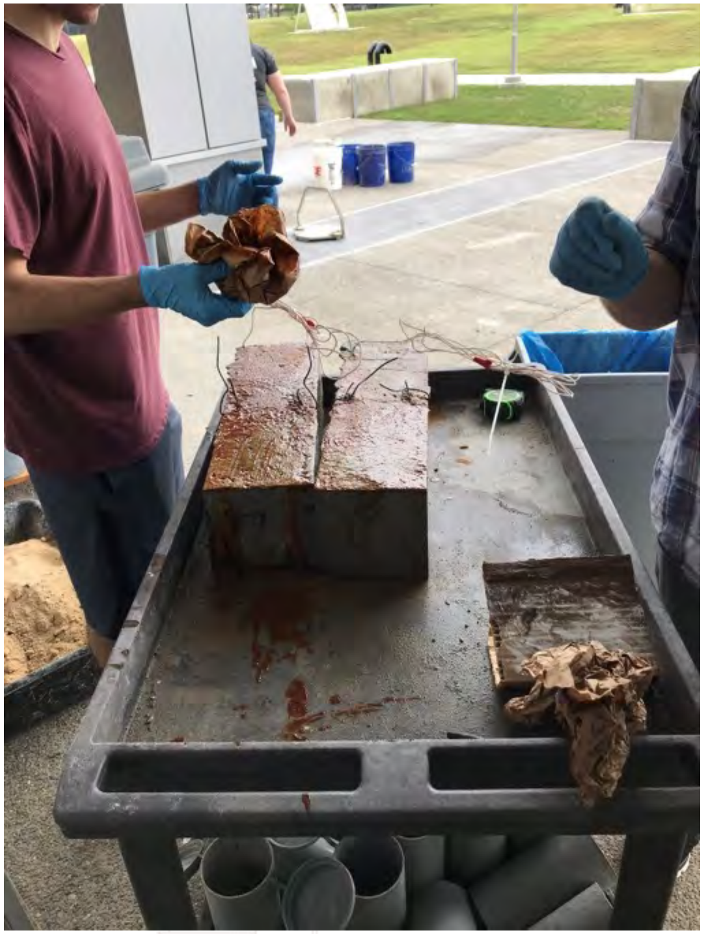


Beam for Top corrosion

Corrosion in Progress



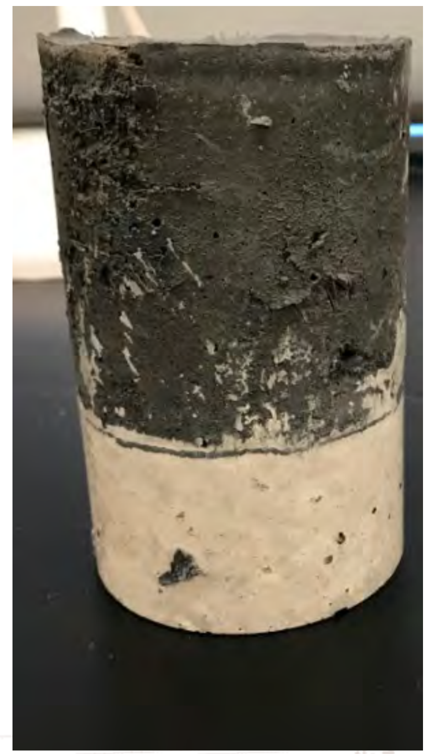
Corroded Beams



Repair and Retrofit

- The third point loading and flexure tests - bonding splitting occurs at the interface between UHPC and HPC substrate before the first flexural cracking.

6 in. x 6 in. x 21 in. composite beam
(4 inch of HPC and 2 inch of UHPC)



Composite cylinder (HPC and UHPC)