DEVELOPMENT OF NON-PROPRIETARY ULTRA HIGH PERFORMANCE CONCRETE

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Sponsored by the Montana Department of Transportation

Introduction

Objectives

- Develop and characterize non-proprietary UHPC mixes with materials readily available in Montana
- Mix designs anticipated to be significantly less expensive than commercially available options
- MDT interested in using UHPC as field-cast jointing material for precast components – reduced bond length and subsequent joint spacing

https://www.fhwa.dot.gov/publications/research/infrastructure/structures/11022/

Introduction

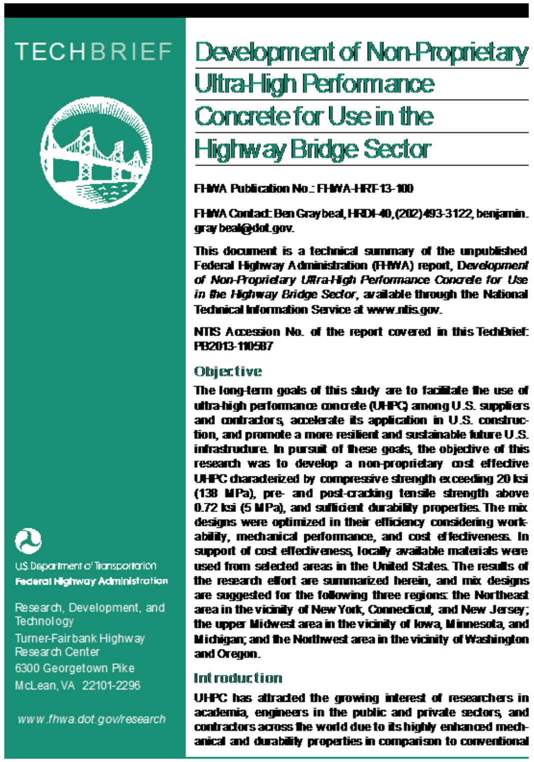
Scope

- Task 1 – Literature Review
- Task 2 – Response Surface Methodology to develop suitable UHPC mixes
- Task 3 – Characterize long-term mechanical and durability performance of selected UHPC mixes
- Task 4 - Reporting

Literature Review

Literature Review

- Extensive Research Documenting the Enhanced Performance of UHPC
  - Mechanical Properties
  - Durability
  - Structural Performance
- Non-Proprietary UHPC Research
  - Large-scale investigation completed by FHWA in 2013
  - Several state DOTs looking into this as well
    - Michigan
    - Nebraska
- Field Cast Joints
  - FHWA
  - Michigan



TECHBRIEF

Development of Non-Proprietary Ultra-High Performance Concrete for Use in the Highway Bridge Sector

FHWA Publication No.: FHWA-HRT-13-100

FHWA Contact: Ben Graybeal, HRDI-40, (202) 493-3122, benjamin.graybeal@dot.gov.

This document is a technical summary of the unpublished Federal Highway Administration (FHWA) report, *Development of Non-Proprietary Ultra-High Performance Concrete for Use in the Highway Bridge Sector*, available through the National Technical Information Service at www.ntis.gov.

NTIS Accession No. of the report covered in this TechBrief: PB2013-110587

Objective

The long-term goals of this study are to facilitate the use of ultra-high performance concrete (UHPC) among U.S. suppliers and contractors, accelerate its application in U.S. construction, and promote a more resilient and sustainable future U.S. infrastructure. In pursuit of these goals, the objective of this research was to develop a non-proprietary cost effective UHPC characterized by compressive strength exceeding 20 ksi (138 MPa), pre- and post-cracking tensile strength above 0.72 ksi (5 MPa), and sufficient durability properties. The mix designs were optimized in their efficiency considering workability, mechanical performance, and cost effectiveness. In support of cost effectiveness, locally available materials were used from selected areas in the United States. The results of the research effort are summarized herein, and mix designs are suggested for the following three regions: the Northeast area in the vicinity of New York, Connecticut, and New Jersey; the upper Midwest area in the vicinity of Iowa, Minnesota, and Michigan; and the Northwest area in the vicinity of Washington and Oregon.

Introduction

UHPC has attracted the growing interest of researchers in academia, engineers in the public and private sectors, and contractors across the world due to its highly enhanced mechanical and durability properties in comparison to conventional

U.S. Department of Transportation
Federal Highway Administration

Research, Development, and Technology
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101-2296

www.fhwa.dot.gov/research

Materials

Materials

Portland Cement

- Type I/II Portland cement was used as the cementitious material
  - Sourced from the CRH Trident Plant

https://www.thermofisher.com/blog/wp-content/uploads/2014/07/156638544.jpg

Materials

Fly Ash

- Fly ash chosen as secondary supplemental cementitious material
  - Low cost relative to other supplemental materials
  - Can react pozzolonically with hydration byproducts
  - Spherical shape helps with workability
  - Class F fly ash from Coal Creek Station

http://www.brighthubengineering.com/concrete-technology/42969-what-is-fly-ash-concrete/

Materials

Silica Fume

- MasterLife SF 100 from BASF was utilized for this experiment
  - BASF materials are readily available throughout Montana

http://www.di-corp.com/public/uploads/product_files/Silica_Densified_(3)/1433380417-1280w_Silica_Densified_(3).JPG

Materials

Aggregates

- High quality aggregates required for UHPC
  - Masonry Sand from Quikcrete Plant in Billings
  - Good Gradation
  - Readily Available

Materials

High Range Water Reducer

- Fluid Premia 150 from CHYRSO, Inc. was chosen based on flow performance and reduction of entrapped air

CHRYSO®Fluid Premia 150

High range water reducing Super plasticizing admixture

CHRYSO®Fluid Premia 150 is a new generation superplasticizer based on modified polycarboxylate.
CHRYSO®Fluid Premia 150 has evolved from CHRYSO®Fluid Premia 100 and gives more water reduction for the same dosage.
CHRYSO®Fluid Premia 150 has been designed for use in precast concretes. When used in concretes which contain many fine particles, exceptional fluidity can be obtained, which greatly helps the laying of concrete, even without using vibrating techniques.
CHRYSO®Fluid Premia 150 produces concrete with very high early and long term strengths. When used in a specially formulated concrete, **CHRYSO®Fluid Premia 150** can give hard concrete a first class finish.

Indicative characteristics

- Nature: liquid
- Colour: White
- Freezing point: 0 °C
- Ash content: ≤ 0,5%
- Shelf life: 9 months

Specifications

- Specific gravity (20°C): 1,060 ± 0,010
- pH: 5,00 ± 1,00
- Solid content (halogen): 29,00% ± 1,40%
- Solid content (EN 480-8): 29,00% ± 1,40%
- Na_2O equivalent: ≤ 1,00%
- Cl^- ions content: ≤ 0,10%

Norms and regulations

- This product conforms to CE marking. The appropriate declaration can be found on our internet site.
- This product conforms to NF 085 certification, which technical specifications are those applied in the non harmonised part of NF EN 934-2.
- This product doesn't have any effect on the corrosion of steel in concrete (electrochemical test according to DIN V 18998:2002-11).

Domains of application

- All cement types
- Self consolidating concrete
- High early strength
- High Performance Concrete
- Prestressed concrete
- Precast

Precautions

Protect from frost.
Avoid prolonged exposure to high temperatures.
Store in plastic containers, PVC excluded.
Should the product freeze, it will recover its properties. After thawing, an efficient agitation is necessary until the product is entirely homogeneous again.

Method of use

Dosage: 0.25 to 2.00 kg for 100 kg of cement.

This product must be added to the mixing water or at the end of the mixing cycle.
Should the product be added to fresh concrete, into the mixing truck, it is necessary to mix at high speed, for 1 minute per m3 of concrete (with a total minimum of 6 minutes).

Construction sites references

Car park in Terminal 2E, Roissy Charles de Gaulle Airport, France: prestressed SCC caissons.

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CHRYSO S.A.S. - 19 Place de la Résistance - 92446 Issy les Moulineaux cedex - France - Tel : +33 (0)1 41 17 18 19 - Fax : +33 (0)1 41 17 18 80 www.chryso.com

15/07/2013

Materials

Steel Fibers

- Nycon-SF Type I “Needles”
- 0.2 mm diameter by 13mm in length

Materials

Estimated Costs (rough estimate)

Material	Manufacturer	Cost (per ton)
Fine Aggregate	QUIKRETE	$26
Portland Cement, Type I/II	CRH	$145
Silica Fume	BASF	$840
Fly Ash, Type F	Coal Creek	$135
HRWR (per gallon)	CHRYSO, Inc.	$14
Steel Fibers	Nycon	$1,600

Methods

Methods

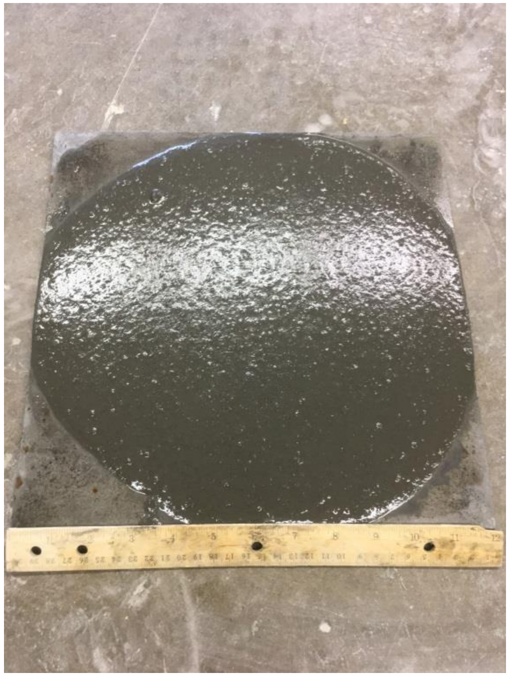
Mixing Procedure

- Modified mixing procedure required for UHPC
  - Aggregate and silica fume dry mixed for 5 minutes
  - Portland cement and fly ash added and mixed for an additional 5 minutes
  - Mix water and 1/3 HRWR added to mix
  - Remaining HRWR added within 1 minute
  - Mixing speed increased after turnover
  - Mixed until desired fluidity achieved, 5-10 additional minutes

Methods

Flow Testing

- Flow determined using ASTM C230 flow cone



Methods

Specimen Preparation

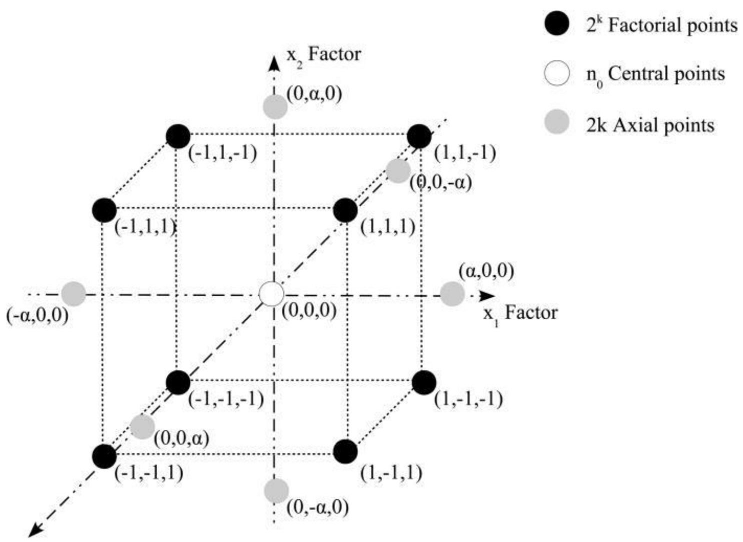
Methods

Experimental Design

Experimental Design

Response Surface Methodology

- Maximizes output while minimizing input
- RSM is used when the relationship between input variables and responses are not exactly known
- Especially useful when no mechanistic models are available



http://manufacturingscience.asmedigitalcollection.asme.org/article.aspx?articleid=1440072

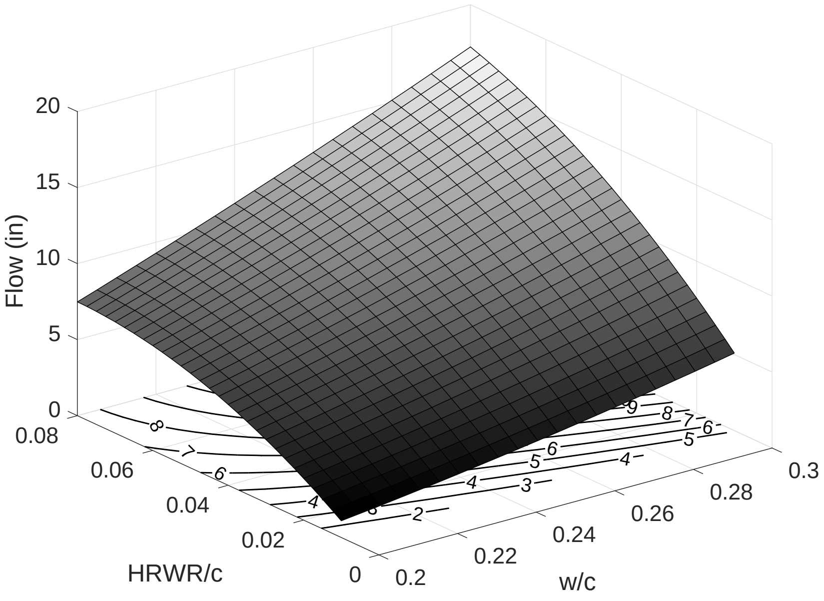
Experimental Design

Mix ID	Independent Variables				Measured Responses			
	w/c Ratio	Sand/c Ratio	SF/FA Ratio	HRWR/c Ratio	Flow (inches)	28-Day f'c (ksi)	Cost/yd^3	Unit Wt. (lb/ft^3)
27 C	0.250	1.25	1.00	0.0450	8.50	18.05	$367.34	140.7
25 C	0.250	1.25	1.00	0.0450	7.00	17.19	$367.34	142.7
12	0.275	1.50	1.15	0.0275	4.00	11.29	$314.88	139.9
14	0.275	1.00	1.15	0.0625	12.25	17.52	$429.97	138.5
16	0.275	1.50	1.15	0.0625	10.25	14.48	$379.60	140.5
4	0.225	1.50	1.15	0.0275	4.00	1.67	$326.42	n/a
23	0.250	1.25	0.70	0.0450	7.00	14.96	$346.64	141.5
17	0.200	1.25	1.00	0.0450	4.00	11.67	$382.05	n/a
6	0.225	1.00	1.15	0.0625	7.25	17.36	$448.16	140.9
15	0.275	1.50	0.85	0.0625	8.75	16.91	$363.44	143.0
1	0.225	1.00	0.85	0.0275	4.00	6.61	$351.01	n/a
26 C	0.250	1.25	1.00	0.0450	7.50	17.03	$367.34	142.5
20	0.250	1.25	1.00	0.0800	9.50	16.28	$437.40	141.0
19	0.250	1.25	1.00	0.0100	4.00	0.41	$296.26	n/a
11	0.275	1.50	0.85	0.0275	4.00	3.36	$298.69	n/a
24	0.250	1.25	1.30	0.0450	7.75	17.03	$382.69	141.7
5	0.225	1.00	0.85	0.0625	11.00	17.57	$428.59	142.2
8	0.225	1.50	1.15	0.0625	5.00	16.82	$393.41	144.0
2	0.225	1.00	1.15	0.0275	4.00	5.57	$370.62	133.6
22	0.250	1.75	1.00	0.0450	5.25	14.26	$327.32	142.4
21	0.250	0.75	1.00	0.0450	12.50	18.89	$421.28	138.7
13	0.275	1.00	0.85	0.0625	11.50	17.40	$411.21	139.6
3	0.225	1.50	0.85	0.0275	4.00	2.66	$309.62	n/a
7	0.225	1.50	0.85	0.0625	9.25	18.49	$376.64	144.9
9	0.275	1.50	0.85	0.0275	4.00	8.37	$298.69	137.8
10	0.275	1.00	1.15	0.0275	5.75	16.32	$355.46	139.7
18	0.300	1.25	1.00	0.0450	13.00	18.16	$353.73	139.3
Min.	0.200	0.75	0.70	0.0100	4.00	0.41	$296.26	133.6
Max.	0.300	1.75	1.30	0.0800	13.00	18.89	$448.16	144.9
Average	0.250	1.27	1.00	0.0450	7.22	13.20	$366.88	140.7
CV	-	-	-	-	0.43	0.45	0.12	0.02

Experimental Design

Initial Experimental Design

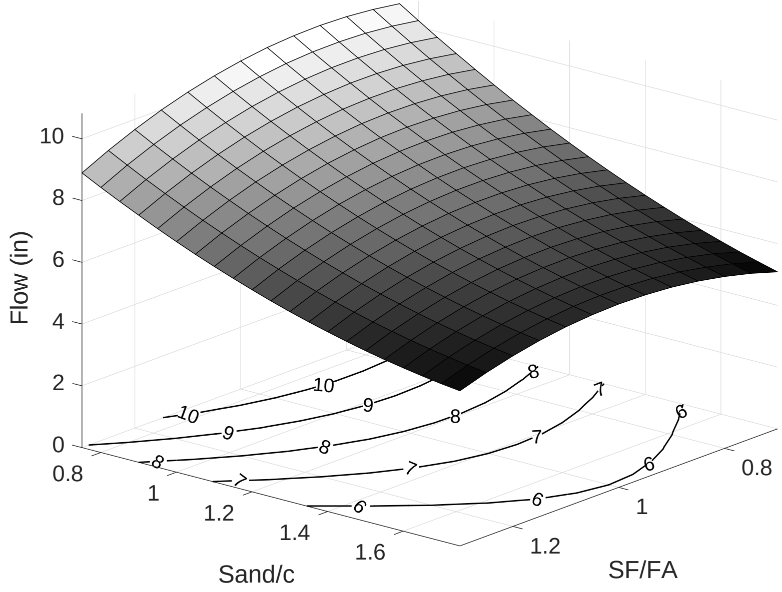
- Response Surfaces
  - Flow vs. HRWR/c and w/c



Experimental Design

Initial Experimental Design

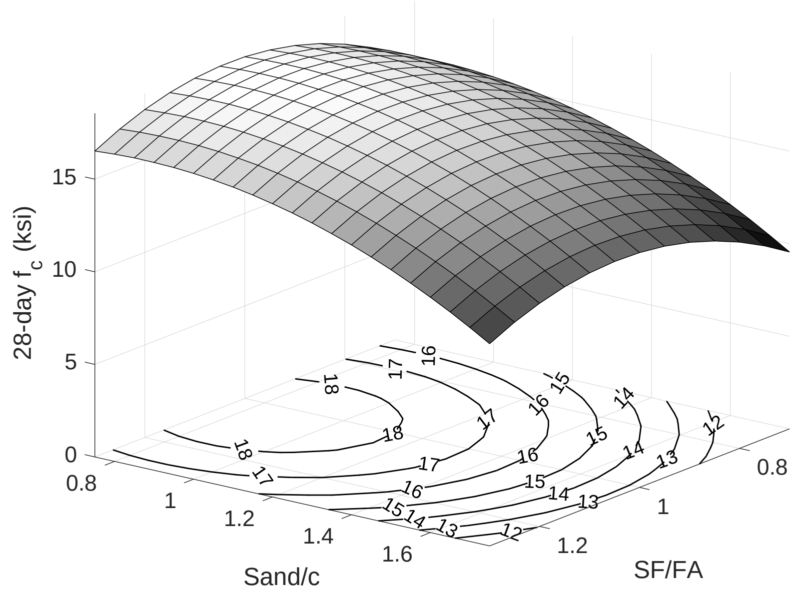
- Response Surfaces
  - Flow vs. sand/c and SF/FA



Experimental Design

Initial Experimental Design

- Response Surfaces
  - 28-day compressive strength vs. sand/c and SF/FA



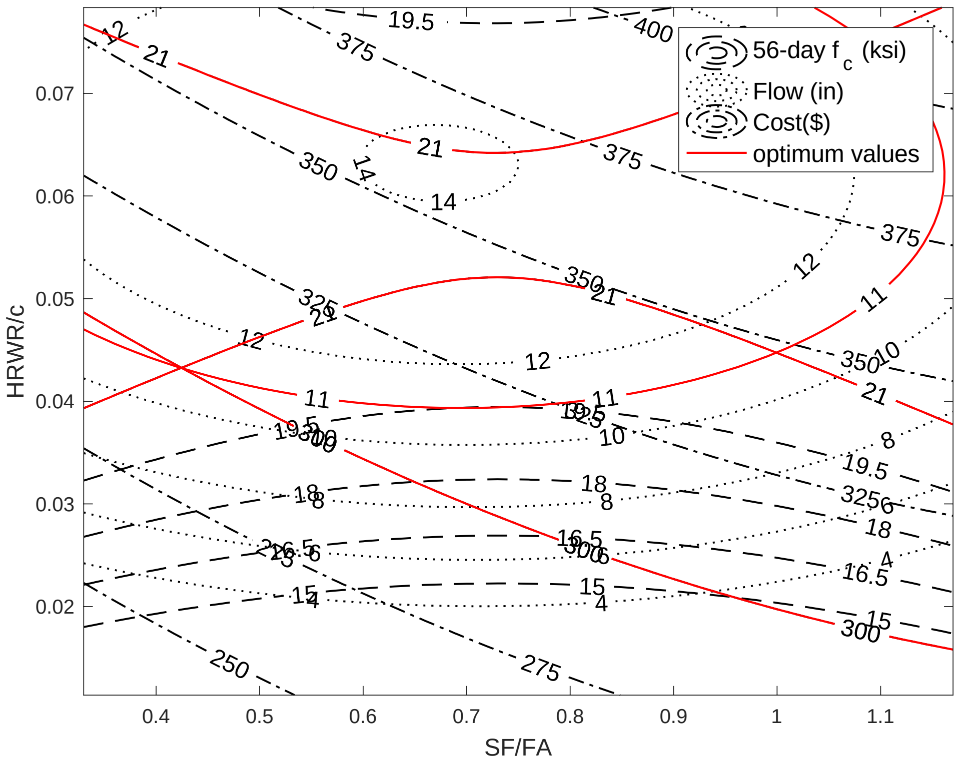
Mix Optimization

Mix Optimization

Mix Optimization

- Targeted Responses
  - Flow of 10 inches
  - Compressive Strength of 20 – 21 ksi
  - Cost of $300-350
- Independent Variables
  - w/c ratio
  - HRWR/c ratio
  - SF/FA ratio

Mix Optimization



Mix Optimization

Mix Optimization

Variable/Response	3M1		3M2		3M3		3M4	
w/c Ratio SF/FA Ratio HRWR/c Ratio	0.236 0.38 0.042		0.237 0.31 0.046		0.274 0.43 0.043		0.216 0.68 0.049	
	Predicted (95% CI)	**Measured**	**Predicted (95% CI)**	**Measured**	**Predicted (95% CI)**	**Measured**	**Predicted (95% CI)**	**Measured**
Flow (inches)	11.00 (8.9 to 13.1)	12.00	11.00 (8.2 to 13.8)	11.25	11.00 (7.0 to 15.0)	12.50	11.0 (9.2 to 12.9)	10.50
7-day *f'c* (ksi)	14.4 (11.6 to 17.3)	13.0	14.6 (10.9 to 18.3)	14.1	16.3 (11.0 to 21.6)	14.4	15.2 (12.7 to 17.6)	11.2
28-day *f'c* (ksi)	18.7 (15.5 to 22.0)	16.2	19.4 (15.1 to 23.7)	18.2	20.7 (14.6 to 26.9)	18.2	19.1 (16.2 to 22.0)	15.1
56-day *f'c* (ksi)	20.0 (17.3 to 22.7)	16.9	21.0 (17.5 to 24.5)	18.2	21.0 (15.9 to 26.0)	20.4	20.0 (17.6 to 22.3)	18.6

Scaled-Up Trial Mixes, Mix Selection

- Scaled-up Mixes
  - All trial batches 0.2 cu. ft
  - Increased to 1.5 cu. ft
    - initially with fixed-fane rotation-drum concrete mixer
    - horizontal fixed-drum rotation-fin mortar mixer
  - Varied properties
    - flows and strengths off
  - Center-point performed best

Scaled-Up Trial Mixes, Mix Selection

- Variability between mixes and specimens
  - Specimen preparation
    - film forming on surface – moisture loss
      - continuously agitate and cover with plastic wrap
    - cut top end off hardened cylinder before grinding
      - entrapped air
  - Inclusion of steel fibers
    - increased ductility
    - reduced variability between specimens
  - Left in molds for 48 hours rather than 24

Mechanical and Durability Properties

Selected Mix

Mix Parameters

w/c Ratio	Sand/c Ratio	SF/FA Ratio	HRWR/c Ratio
0.240	1.40	0.75	0.045

Mix Proportions

Mix Weights		
Item	Fraction of Volume	Mix Weight (lbs)
Water	0.16	2.011
HRWR	0.03	0.4332
Retarder/Stabilizer	0.00	0.0000
Portland Cement	0.24	9.63
Silica Fume	0.08	2.06
Fly Ash	0.11	2.75
Fine Aggregate	0.36	11.53
Steel Fibers	0.02	1.95

Rough Cost Estimate

Cubic Yard Calculations			
	Mix Wt. (lbs)	Cost/ton	Cost/ cu. Yd
Water	271.5	$	$
HRWR (gallons)	6.74	$ 14.00	$ 94.37
Portland Cement	1299.5	$ 145.00	$ 94.21
Silica Fume	278.5	$ 840.00	$ 116.95
Fly Ash	371.3	$ 135.00	$ 25.06
Fine Aggregate	1556.4	$ 26.00	$ 20.23
Steel Fibers	262.8	$ 1,600.00	$ 210.26
		Total	$ 561.09

Testing Protocol

Mechanical Properties

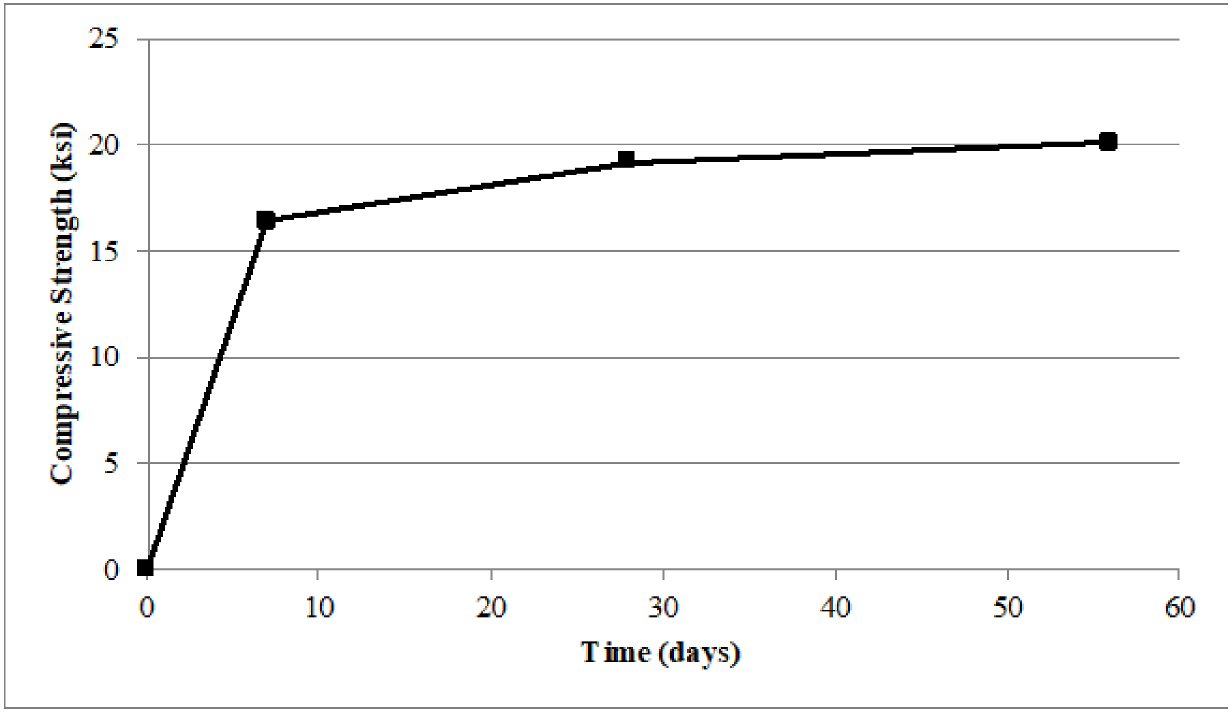
Material Property	ASTM Test Method
Compressive Strength	C39
Elastic Modulus	C469
Modulus of Rupture	C78
Splitting Tensile Strength	C496
Shrinkage	C512

Durability Properties

Durability Property	ASTM Test Method
Abrasion	C944
Absorption	C642
Alkali Silica Reactivity	C1567
Chloride Permeability	C1202
Freeze-Thaw	C666
Scaling	C672

Unconfined Compressive Strength

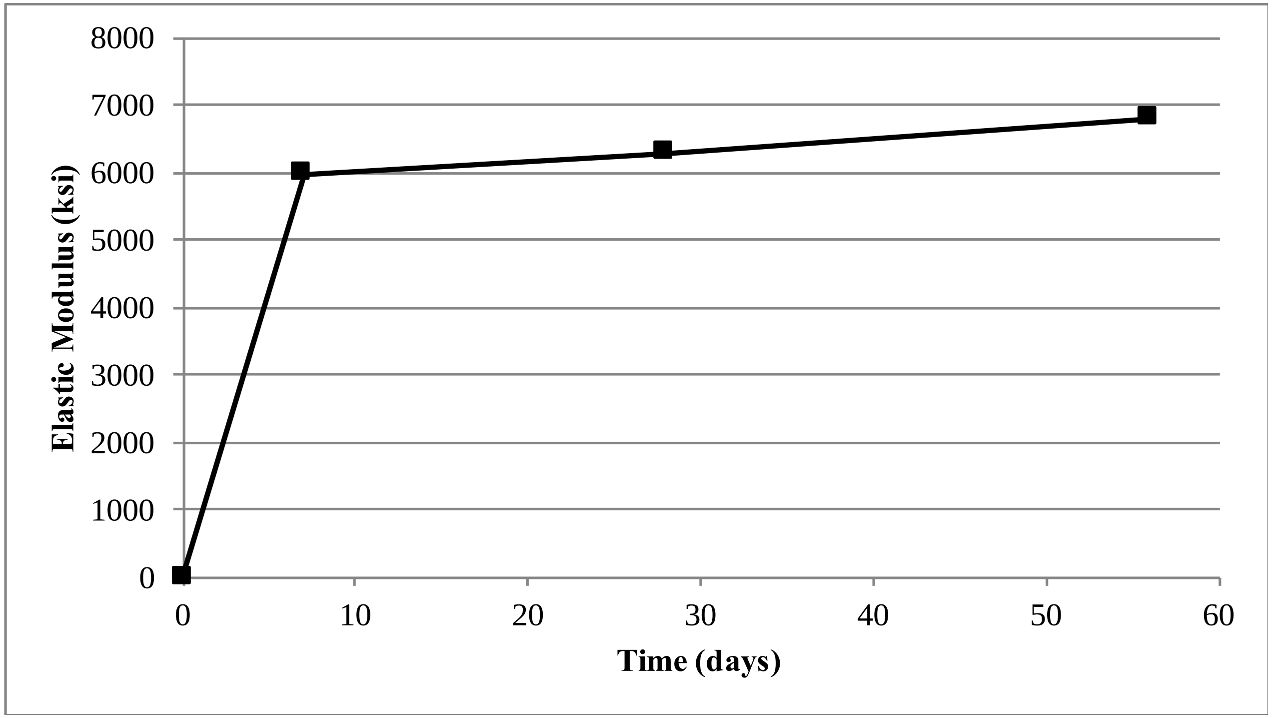
Age (days)	$f'c$ (ksi)
7	16.4
28	19.2
56	20.1



Elastic Modulus

Predictive ACI Equation: $E_c = {w_c}^{1.5} 33\sqrt{f'_c}$

Age (days)	f'c (ksi)	E_{Meas} (ksi)	E_{Pred} (ksi)	$\frac{E_{Meas}}{E_{Pred}}$
7	16.4	5977	7993	0.75
28	19.2	6289	8643	0.73
56	20.1	6787	8847	0.77



Flexural Tensile Strength

Predictive ACI Equation: $f_r = 7.5\sqrt{f'_c}$

28-day Results:

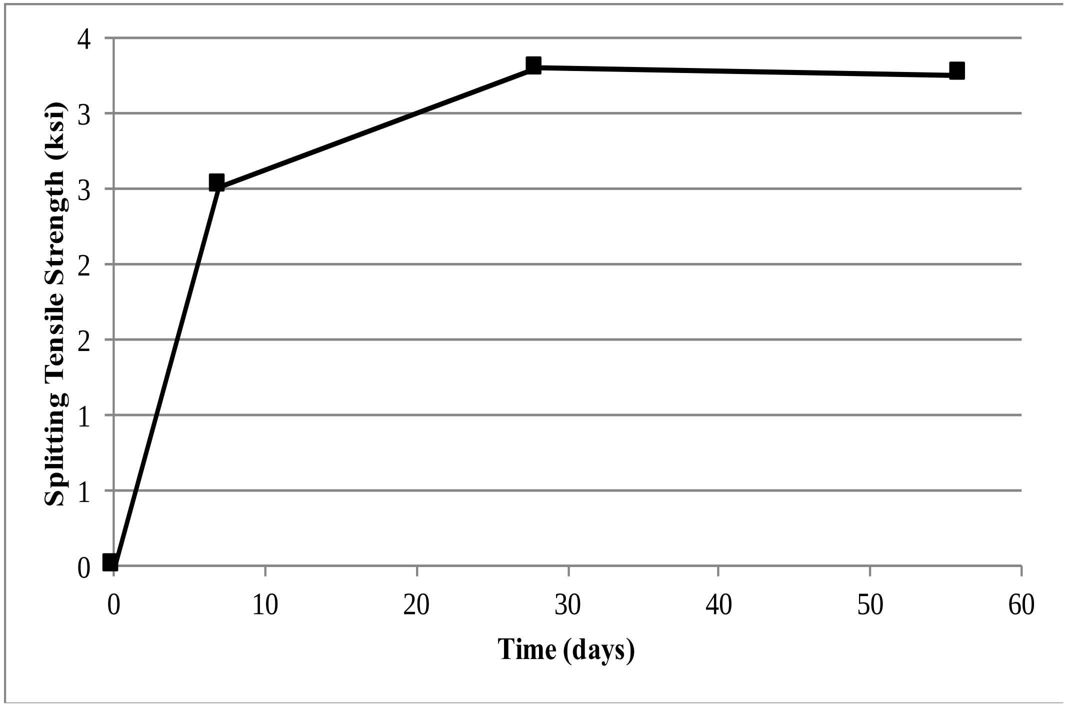
Stress at Initial Crack (ksi)	Stress at Ultimate (ksi)	Predicted (ksi)	Meas/Predicted Initial	Meas/Predicted Ultimate
1.98	3.39	1.05	1.89	3.23

Splitting Tensile Strength

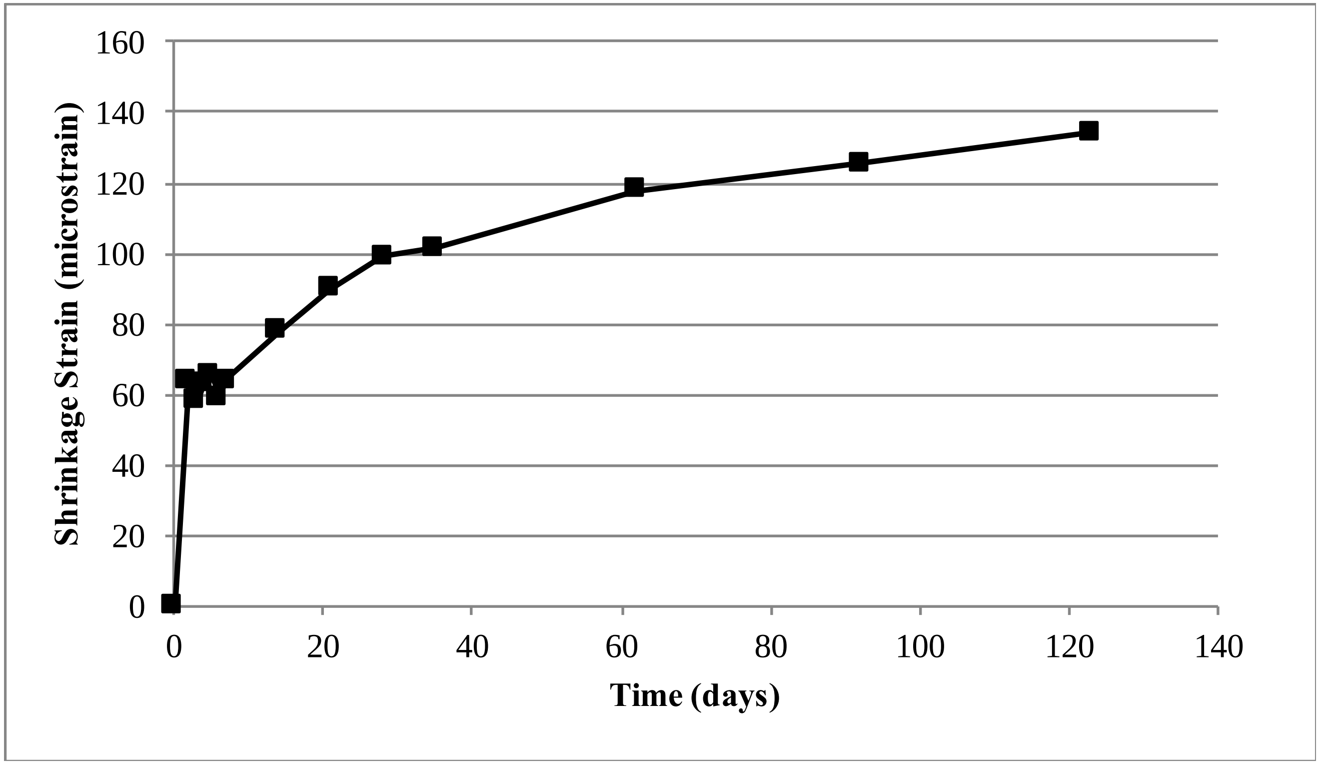
Predictive ACI Equation:

$$f_{ct} = 6.7\sqrt{f'_c}$$

Age (days)	Stress at Ultimate (ksi)	Predicted at Initial Crack (ksi)	Meas/Predicted
7	2.52	0.96	2.62
28	3.30	1.04	3.18
56	3.25	1.06	3.06



Shrinkage



Shrinkage Strain (microstrain)
0
20
40
60
80
100
120
140
160
0
20
40
60
80
100
120
140
Time (days)

Abrasion

https://www.fhwa.dot.gov/publications/research/infrastructure/structures/06103/chapt3c.cfm

Specimen #	Mass Loss	
	22 Pound (g)	44 Pound (g)
1	11.3	23.4
2	10.9	31.5

- Measured wear depth less than 1 mm
- Wear depth less than 2 mm - Grade 2 high performance structural concrete

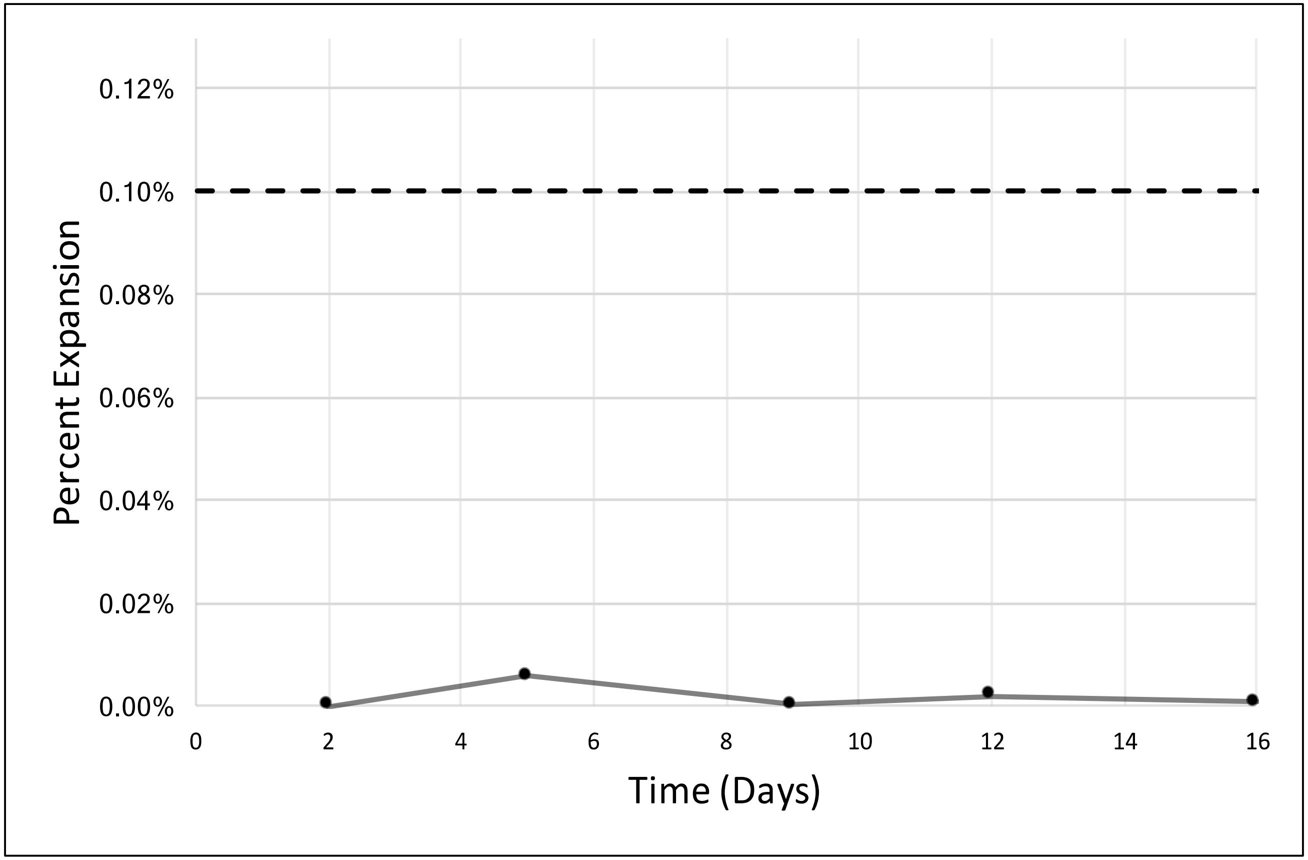
Absorption

http://www.ctre.iastate.edu/pubs/en_route/07summer/cptech-lab.htm

Specimen	Void Volume
1	1.36%
2	1.30%

- void volume < 12% will typically result in a durable concrete

Alkali Silica Reactivity



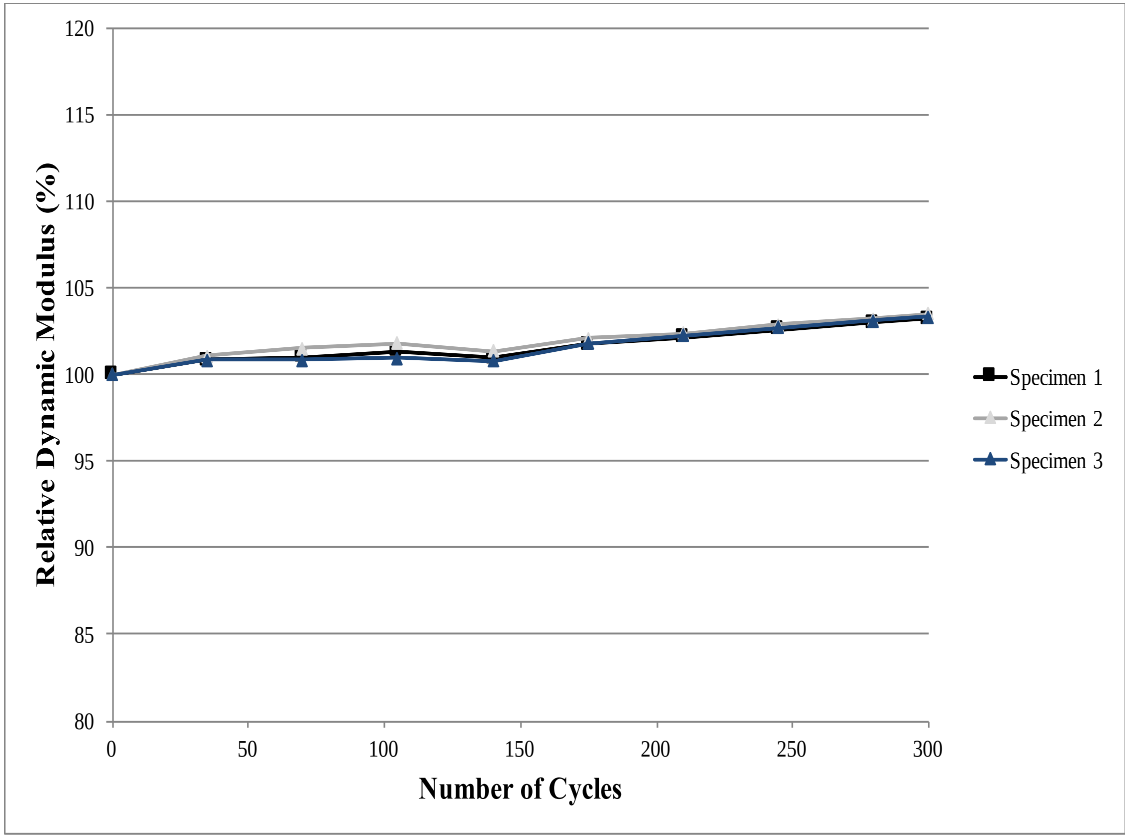
Chloride Permeability

Mix	Age at Test (days)	Avg. Adj. Charge Passed (coulombs)	Chloride Ion Penetrability
Specimen 1	56	75	Negligible
Specimen 2	56	56	Negligible

- Low Chloride Perm Range: 1000-2000 coulombs

Freeze-Thaw Resistance

Specimen #	# of Cycles	Mass Change (%)	Durability Factor
1	300	-0.089	103.2
2	300	-0.096	103.5
3	300	-0.066	103.4



Scaling

0 Cycles

50 Cycles

Conclusions

- Suitable materials for UHPC readily available in Montana
  - Type I/II portland cement from CRH in Trident, MT
  - fine masonry sand from Billings Quikrete
  - class F fly ash from the Coal Creek Station, ND
  - silica fume sourced through BASF
  - a high range water reducer (HRWR) sourced from CHRYSO
  - steel fibers from Nycon

- Response Surface Methodology Efficient/Effective Tool
  - characterizing the effect of the various constituents
  - optimization

Conclusions

- UHPC Sensitive to Various Parameters
  - batch size and mixer type
    - need fixed-drum rotating-fin mixer
  - specimen preparation technique
    - continuously agitate and cover to prevent moisture loss
    - cut ends off prior to grinding – over cast and grind top off in field
- Excellent Mechanical and Durability Properties
- Non-proprietary Economical UHPC Feasible in Montana

Recommendations

- Future Research to Investigate
  - Scaled-up mixes
    - batch sizes and equipment that would be used in the field (e.g., high-shear pan mixer)
    - various mixing conditions (e.g., temperatures and aggregate moisture conditions)
    - sensitivity to material variations
  - Confirm performance in proposed application
    - reduced development lengths
    - static and cyclic pull-out tests
  - Field demonstration project
    - potentially at Transcend in Lewistown

Thank you!