Development and Characterization of Ultra-High Performance Concrete for Dry Cask Applications

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Outline

- Introduction
- Issues with dry cask storage
- Options for new materials selection
- Novel ultra-high performance concrete materials
- Materials development
- Microstructural characterization

Nuclear Reactor Core

Wet Pool Storage

Independent Spent Fuel Storage Installation (ISFSI)

Photographs by Brian Vangor, Senior Control Room Operator, Indian Point Energy Center

An Application

• 2,000 MT of spent nuclear fuel (SNF) produced per year

• Stockpile as of 2011: 65,000 MT of SNF primarily being stored on-site in spent-fuel pools and dry casks

• Findings of a National Research Council study: Safety and Security of Commercial Spent Nuclear Fuel Storage, 2006.

1. **“Less spent fuel is at risk in an accident or attack on a dry storage cask than on a spent fuel pool.”**
2. **“The potential consequences of an accident or terrorist attack on a dry cask storage facility are lower than for a spent fuel pool.”**
3. **“The recovery from an attack on a dry cask would be much easier than the recovery from an attack on a spent fuel pool.”**

Dry Cask Design Considerations/NRC Licensing Requirements

- Structural Resilience- SNF must be protected in Earthquakes, tornados, floods, tsunami, lightning, fire, and explosion loading.
- Radiation Attenuation- Minimize exposure to people working with spent nuclear fuel. 5rem at the fence line.
- Heat Removal Capability- sufficient for normal and accident conditions
- Criticality- Neutron absorber must last as long as cask.
- Activation- “Provisions must be made to…minimize the quantity of radioactive wastes and contaminated equipment” (10 CFR 72.130 Criteria for Decommissioning)

Current dry-cask storage system designs are licensed for 20 years, with a reasonable expectation for relicensing for an addition 20 years, but after that...

Literature of Materials for Shielding

- Work on optimizing concrete for shielding has been ongoing since at least the 1950s with heavy-weight aggregates and materials with boron a primary focus

TABLE 5—PROPERTIES OF VARIOUS CONCRETE MIXTURES FOR RADIATION SHIELDING*

Type of concrete	Percentage of concrete, by weight: Water†	Cement	Fine aggregate	Coarse aggregate	Iron	Unit weight: g per cu cm	lb per cu ft	Half-thickness, cm: Neutrons	γ-rays	Diffusion length, cm
Ordinary	8.4	17.7	27.6	46.3	—	2.35	146.7	10.7	13.3	5.6
Ordinary + 1.25 percent Pyrex	6.05	18.37	27.78	46.55	—	2.39	149.2	7.4	13.3	3.3
Magnetite aggregate	5.5	11	83.5		51.06	3.78	236.0	8.5	9.0	2.9
Limonite aggregate	10.5	21	68.5		35.36	2.63	164.2	4.8	9.0	2.5
Limonite + scrap iron	4.71	9.54	26.35	59.4	73.24	4.41	275.3	5.4	7.9	2.5
Limonite + scrap iron + 0.7 percent Pyrex	12.8	12.3	32.8	41.4	62.78	3.60	224.7	5.0	7.7	2.3

*Data from reference 8.
†Water added only; water present in limonite ore not counted.

From: Callan, Edwin J., Concrete for Radiation Shielding, Journal of the American Concrete Institute, Title No. 50-2, Sept., 1953

Optimum concrete for radiation shielding…

1. Minimized volume and weight for required level of attenuation
2. Relatively easy to construct with very high probability of homogeneity
3. Relatively long life expectancy
4. Low activation – easily recycled
5. Cost effective

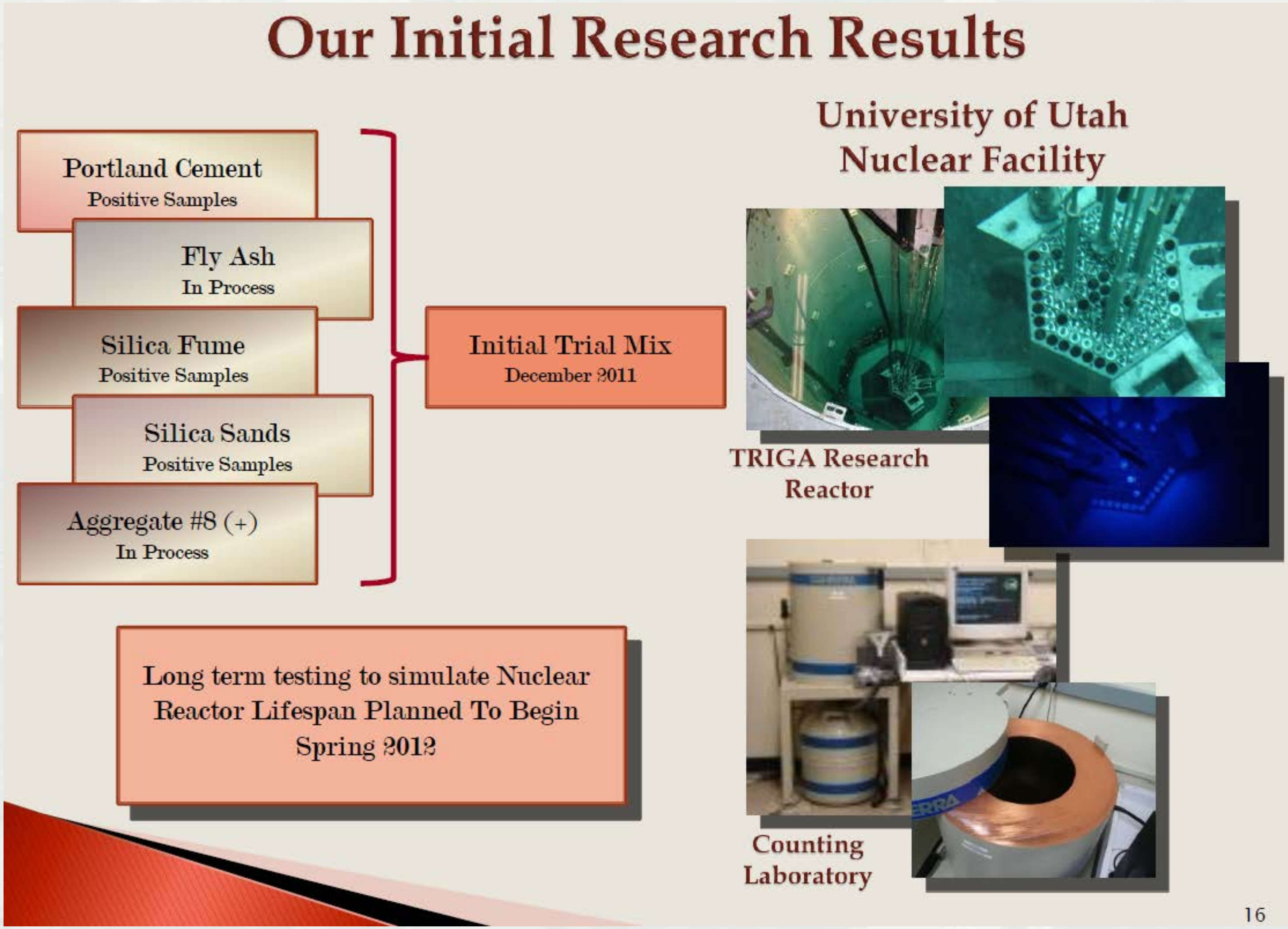
Optimum concrete for ballistic penetration resistance… very similar objectives

Relevant current concrete technologies…

1. Self-Consolidating Concrete (SCC)
2. Fiber-Reinforced Concrete (FRC)
3. Ultra-High-Performance Concrete (UHPC)
4. High-Strength-High-Ductility Concrete (HSHDC)*

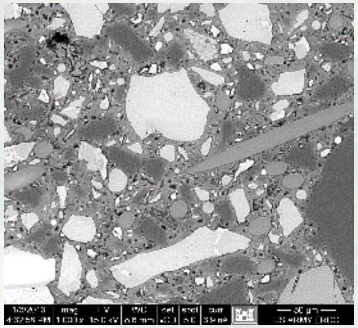
*From: Ravi Ranade, Victor C. Li, Michael D. Stults, William F. Heard and Todd S. Rushing, "Composite Properties of High-Strength, High-Ductility Concrete," <u>ACI Materials Journal</u>, 110-M37, July-August, 2013

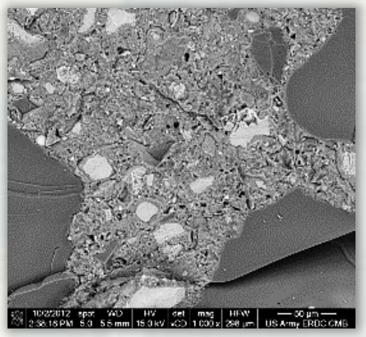
More recent work…

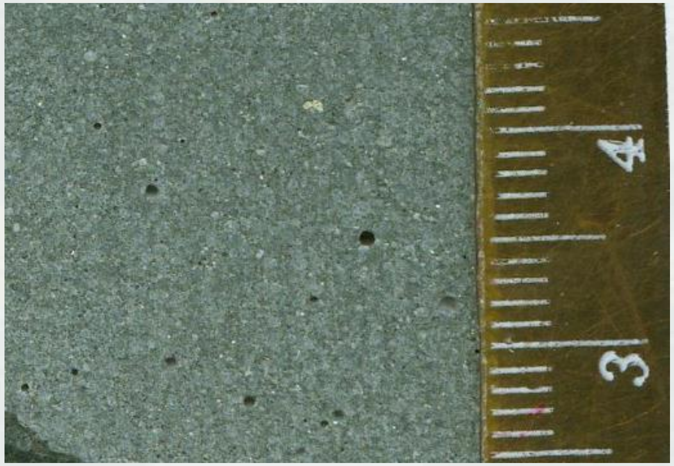


From: Rapich et al, Radiation Resistant Concrete, ACI Fall Convention, 2011

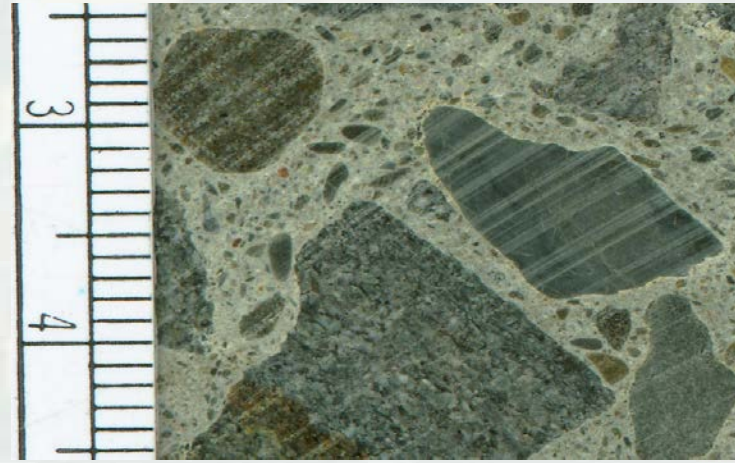
UHPC vs. NSC







Cross Section of UHPC



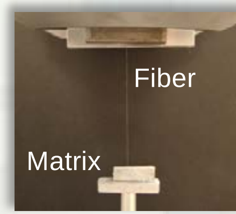
Cross Section of NSC

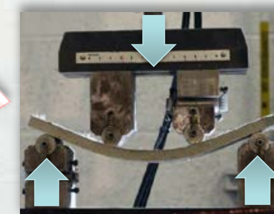
	Concrete Properties		
	UHPC	High Strength	Normal Strength
Compressive Strength	> 150 MPa (21.7 ksi)	>41.4 Mpa (>6 ksi)	<41.4 MPa (<6 ksi)
Density	2500 kg/m^3 (156 lb/ft^3)	Slightly higher than NSC	2300 kg/m^3 (144 lb/ft^3)

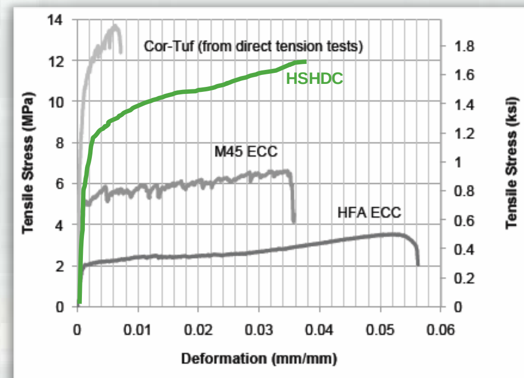
Ultra-High Performance Concretes (UHPC)

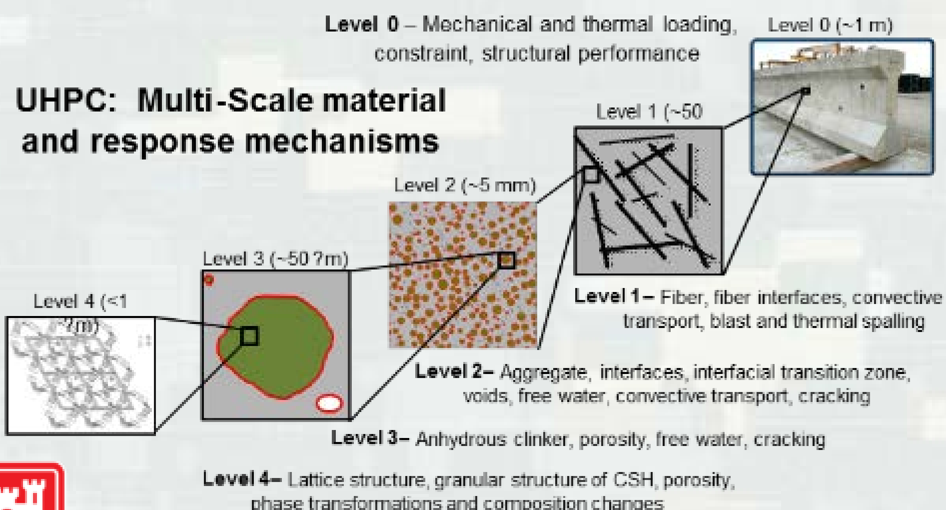
Decades of R&D on development, characterization, testing, modeling, and fielding of UHPCs:

- The Corps' Cor-Tuf UHPC formulation
- Strengths in excess of 200MPa / 30ksi
- High toughness and durability
- High-strength, high-ductility formulations



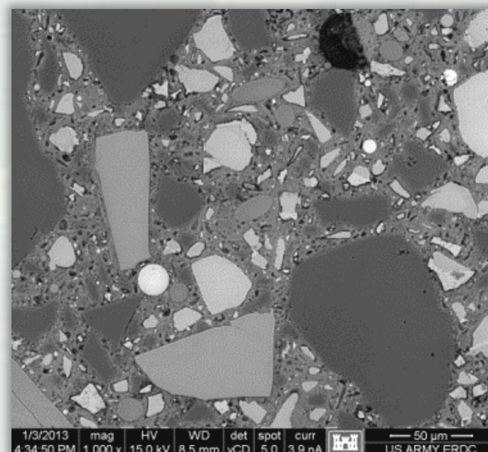






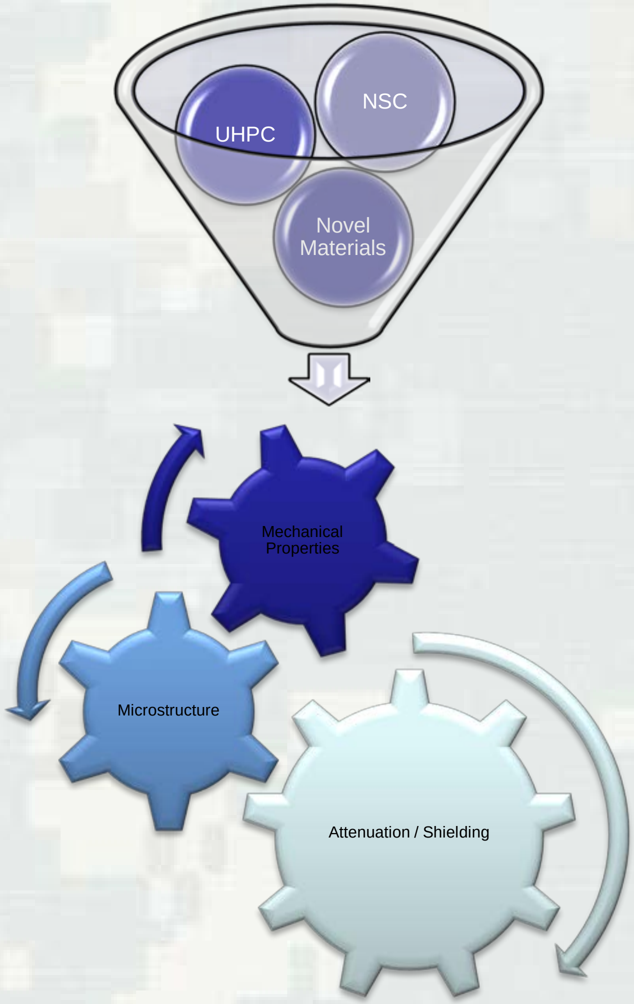
History WES/ERDC UHPC Research
Very-High-Strength Concrete - VHSC

- “Local” materials used
- Not RPC, incorporating ASTM C 33 concrete sand
- Developed by Donald M. Walley and Billy Neeley
- Early/Mid 1990’s
- **Mixture #247!**
- 200 MPa (29,000 psi) with steam curing at 190° F
- **Revolving-drum mixer truck used to produce!**
- **Lead to Cor-Tuf ® UHPC**

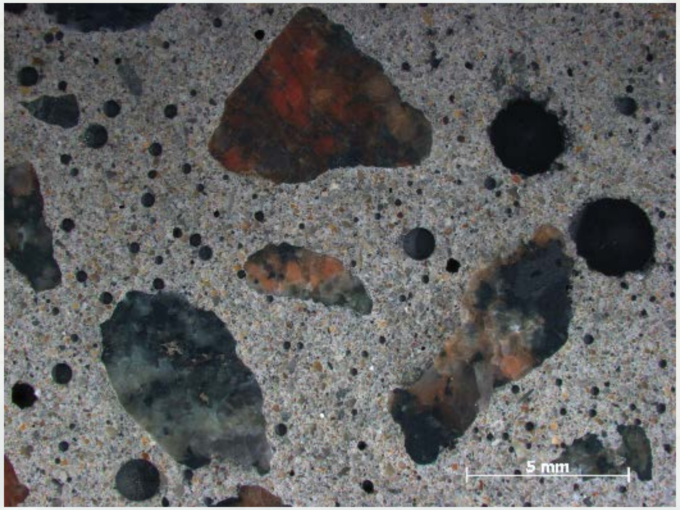


New Materials Development and Testing

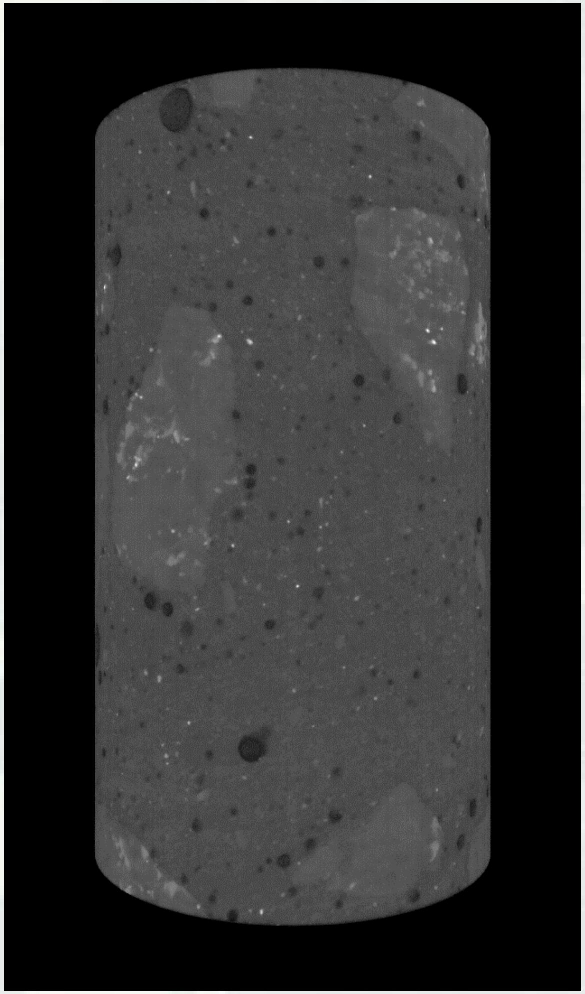
- Adapt existing Cor-Tuf UHPC formulation
- Increase density using steel "sand"
  - Material obtained from powder metal supplier
- Replace silica sand with steel "sand"
- Include steel fibers with steel "sand"
- NSC control material

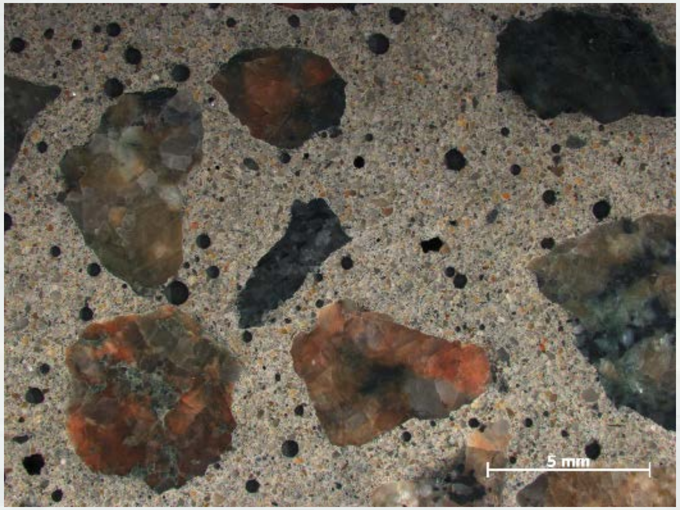


Microstructural Characterization of NSC

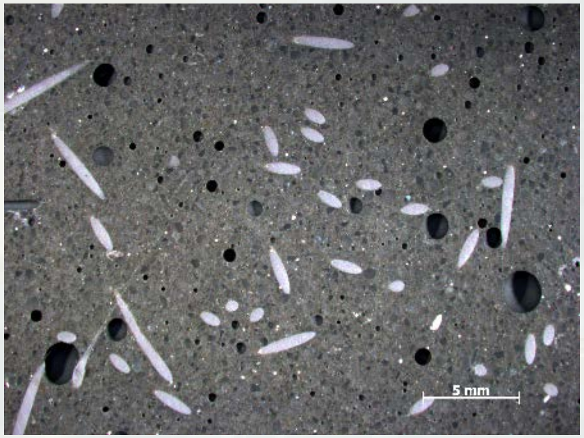


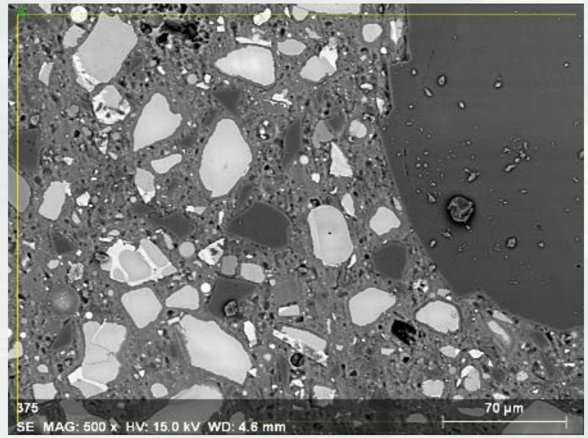
Typical microstructure, coarse, fine agg, paste, and porosity

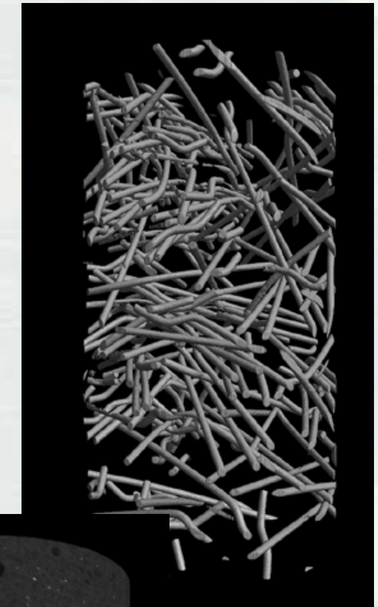


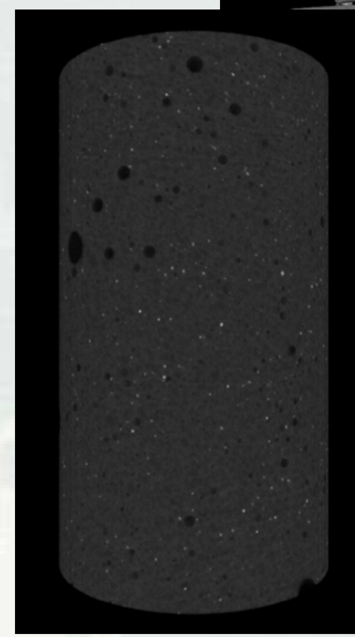


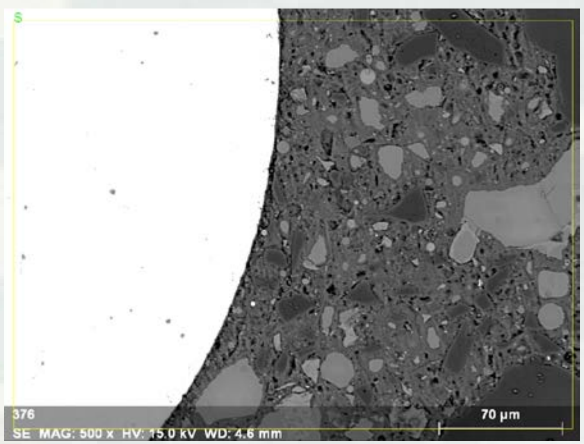
Microstructural Characterization of Cor-Tuf UHPC





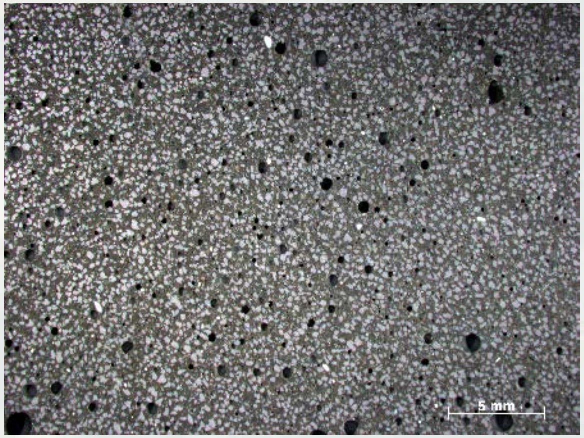




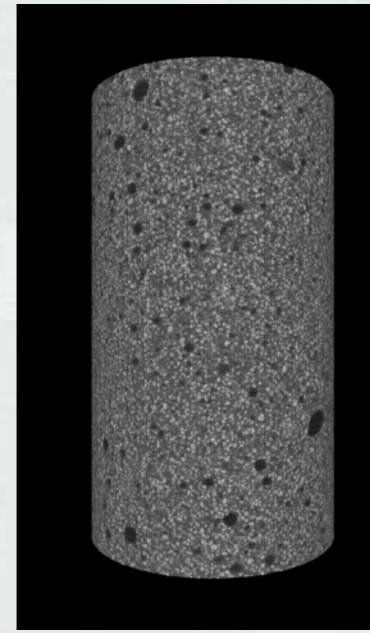


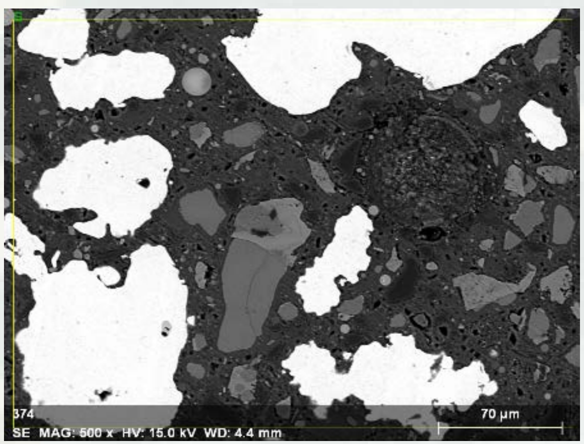
Typical UHPC microstructure, fine aggregate, silica flour, paste, fibers

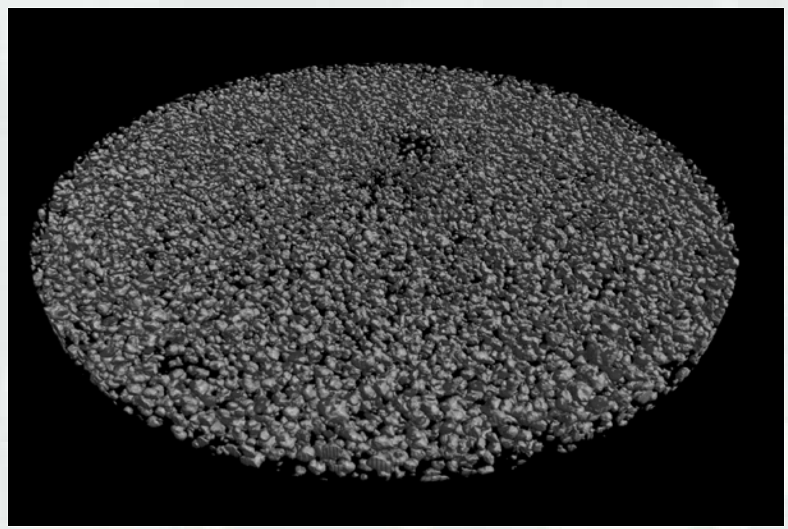
Microstructural Characterization of Cor-Tuf UHPC with Steel "Sand"



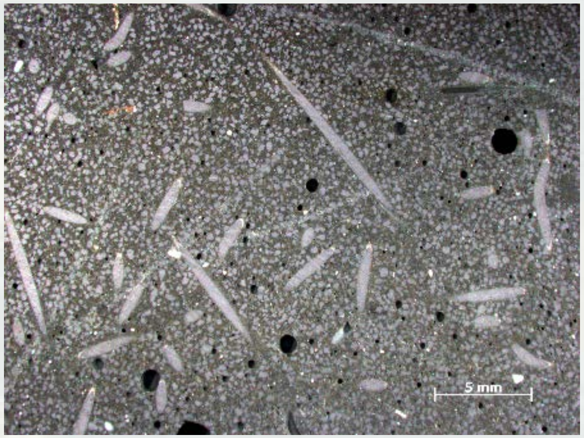
Typical UHPC microstructure without fibers but including steel "sand" particles

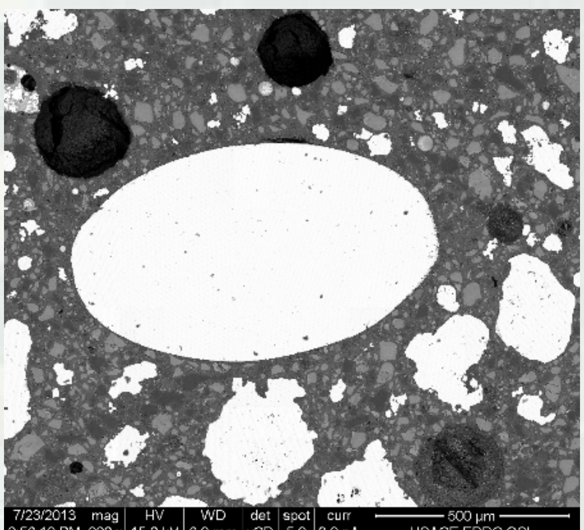




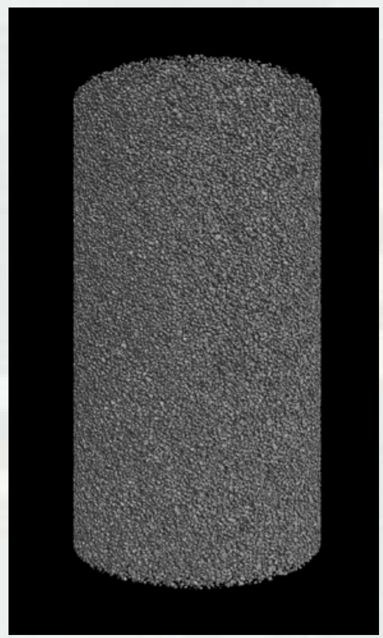


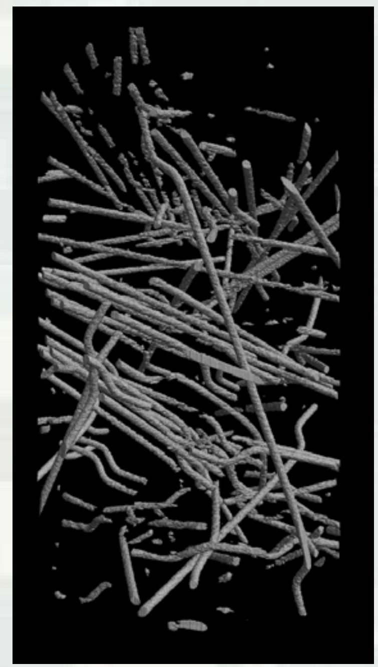
Microstructural Characterization of Cor-Tuf UHPC with Steel “Sand” and Fibers

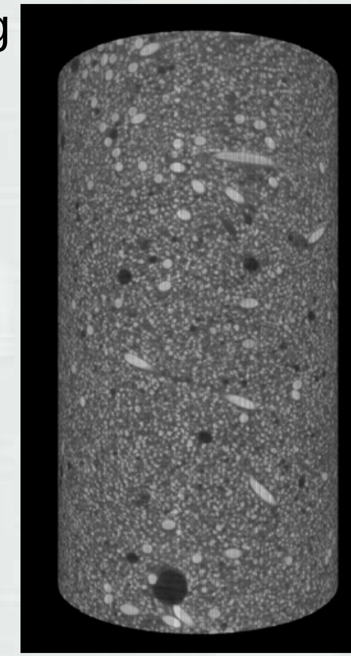




Typical UHPC microstructure including steel fibers and steel “sand”



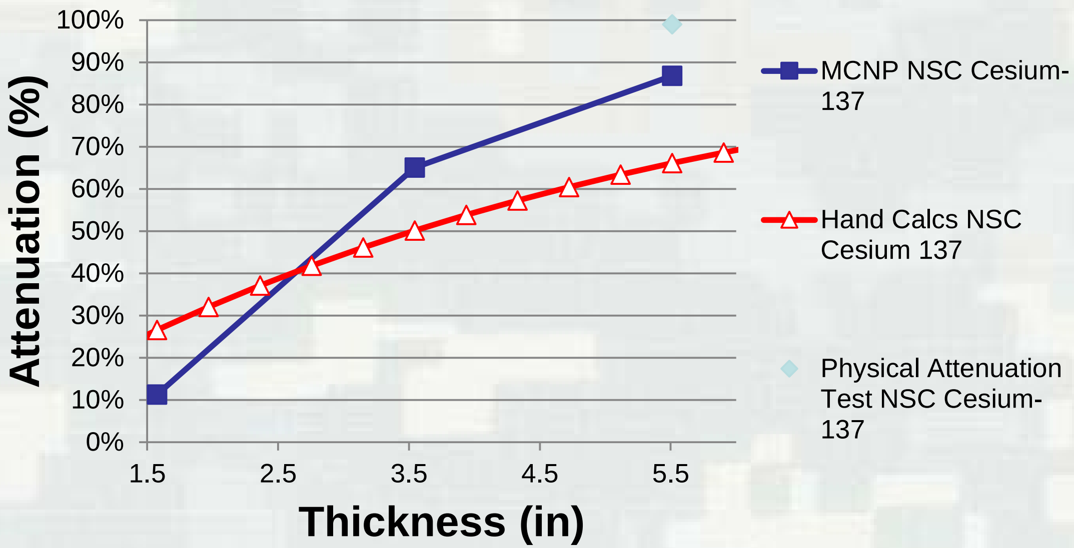


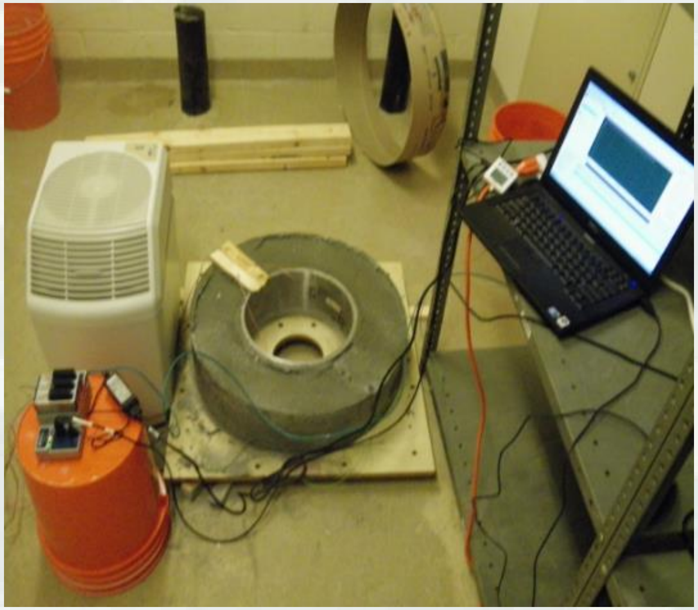


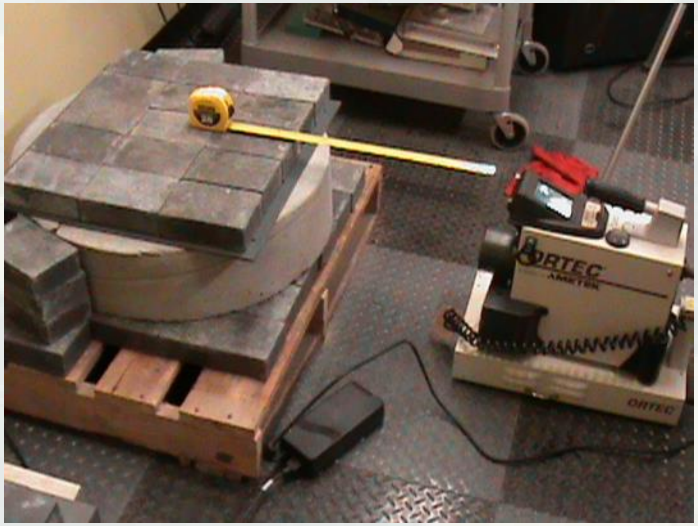
UHPC in Dry Storage of Spent Nuclear Fuel

Attenuation Modeling with
Monte Carlo N Particle (MCNP)
Transport Code

Attenuation vs. Concrete Thickness

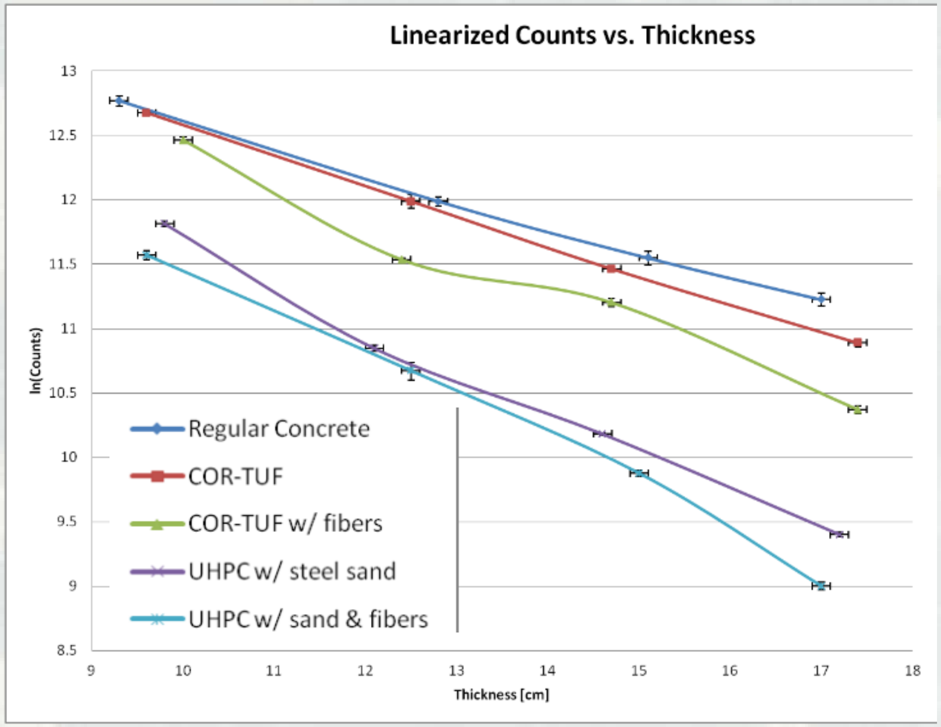


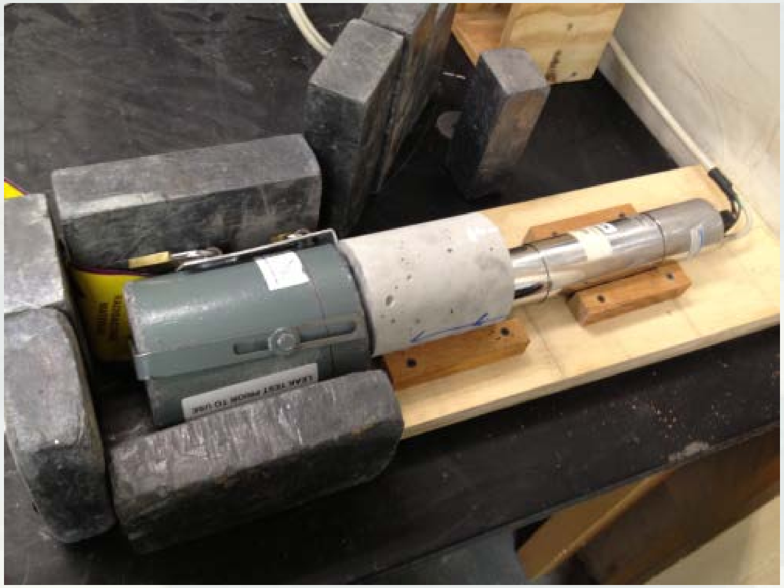


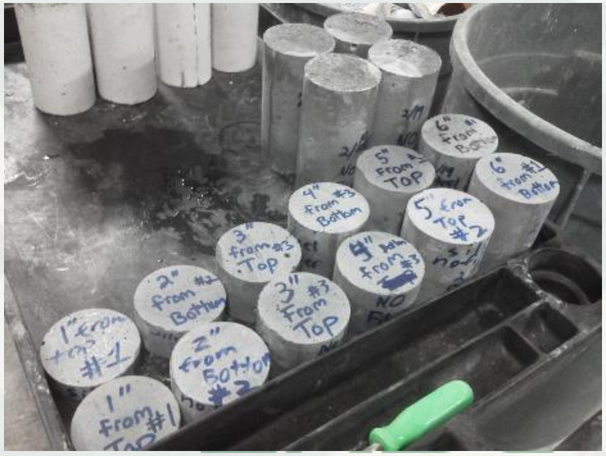


Chemical composition of UHPC
required as input for simulation.
Porosity distribution also characterized.

Material Optimization of the Dry Cask Storage System: Comparison of Attenuation Coefficients





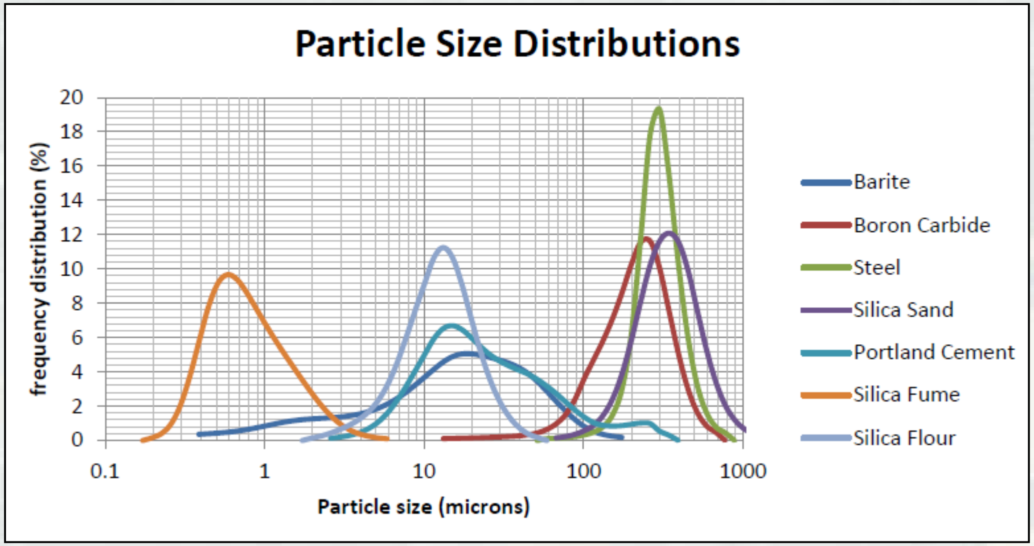


	Density [g/cm^3]	Compressive Strength [MPa]
Standard Concrete	2.21 ± 0.02	41.5 ± 0.7
COR-TUF	2.37 ± 0.02	200 ± 20
COR-TUF (steel fibers added)	2.60 ± 0.03	213 ± 2
UHPC (steel sand)	3.58 ± 0.05	231 ± 8
UHPC (steel sand & fibers)	3.84 ± 0.04	229 ± 2

A Study of Concrete Additives to Enhance Neutron Attenuation for Dry Cask Storage

Optimization of Ultra High Performance Concrete(UHPC) for Multi-Scale Penetration Resistance

UHPC Additive	Effective Macroscopic Cross Section [cm^{-1}]	Uncertainty
Glass Microspheres	0.05	0.01
Boron Carbide	0.062	0.009
Barite	0.079	0.008
Steel Sand	0.061	0.009
Silica Sand	0.055	0.005



	Unit Weight pcf	f`c ksi MPa
Silica	140	29 201
Glass Bubbles	110	14 96
Steel	210	37 254
Boron Carbide	135	27 186
Barite	155	32 219

Summary

- UHPCs are a unique class of materials with dense microstructure, low interconnected porosity, high strength, and high toughness

- Adapting UHPCs for shielding applications presents many unique properties, particularly with steel “sand”

- Improvements in attenuation of up to 50% observed in various testing along with improvements in mechanical properties (strength)

- Other dense particles can also be incorporated into UHPC to improve properties

Future Work

- Continue/expand the literature review.
- Resolve issues with the MCNP modeling.
- Utilize MCNP to guide optimization of mix design.

Thank you! Questions?

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