UNIVERSITY of WISCONSIN
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aci CONCRETE CONVENTION
March 24-28, 2024 | New Orleans, LA, USA
THE WORLD'S GATHERING PLACE FOR ADVANCING CONCRETE

MAGNETORHEOLOGICAL CEMENTITIOUS NANOCOMPOSITES TUNED FOR ACTIVE CONTROL AND DIGITAL CONSTRUCTION

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Concrete Sustainability & Resilience Center

University of Wisconsin-Milwaukee

Concrete Advancement Network – CAN

Concretology

Concrete NanoTECH Society – CNNS

March 26, 2024

Outline

Introduction

- Concrete in 1920s and 2020s
- What is next? 2D, 3D and 4D Printing
- Nano-modification and UHPC Materials

Research Concepts

- Rheological models
- Introduction to MRF

Experimental Program

- Concept Realization
- Research findings

Conclusions

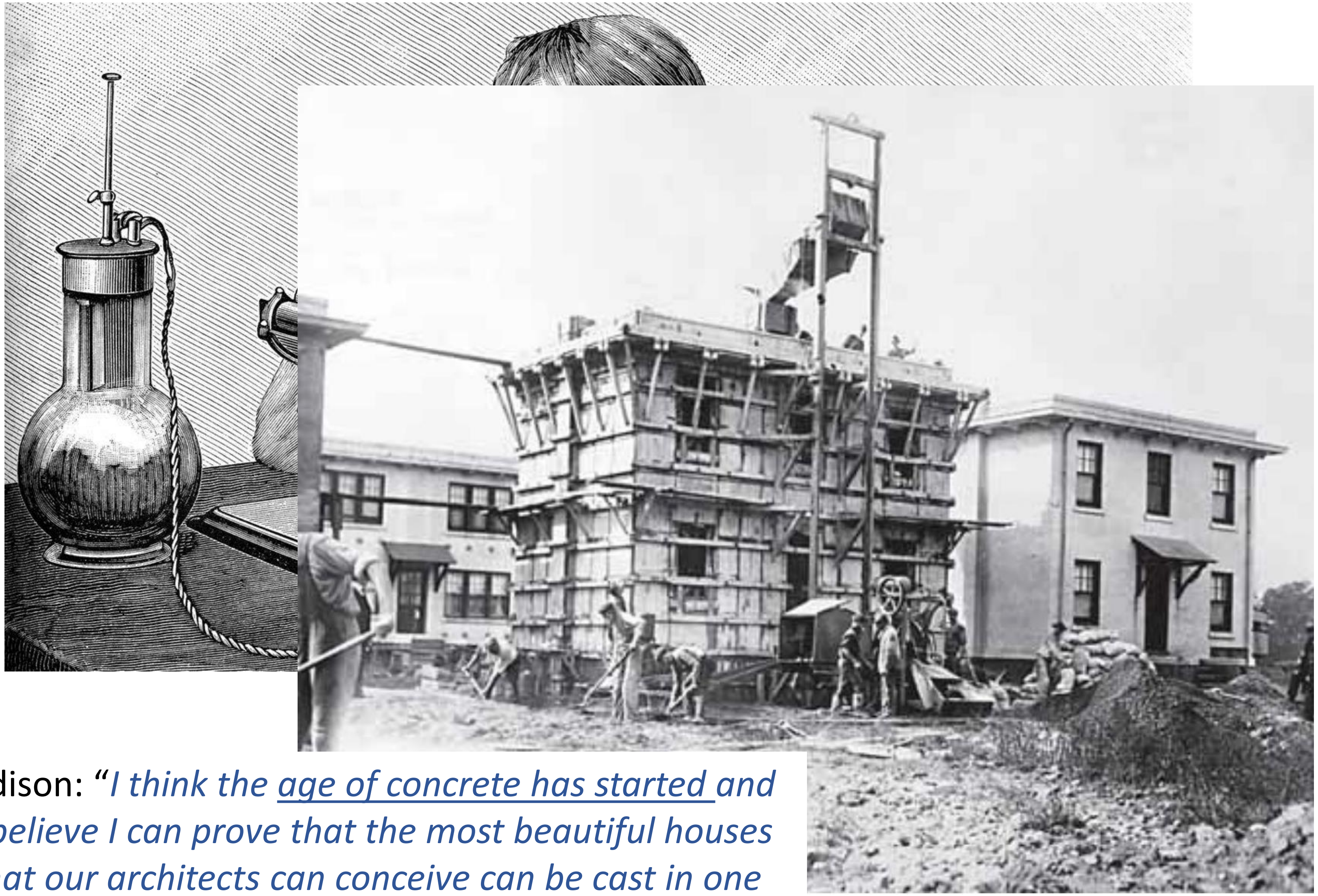
Possible Applications

PCA: Concrete in 1920s

Edison contributed to the first experimental concrete pavement in New Jersey.

Edison invented a foamed concrete using aluminum powder that reacted with the alkalies from cement to form hydrogen gas, creating fine bubbles and foam.

Edison developed a “free-flowing” concrete for use in building residential all-concrete homes that he designed and built using metal molds that could be assembled and disassembled.



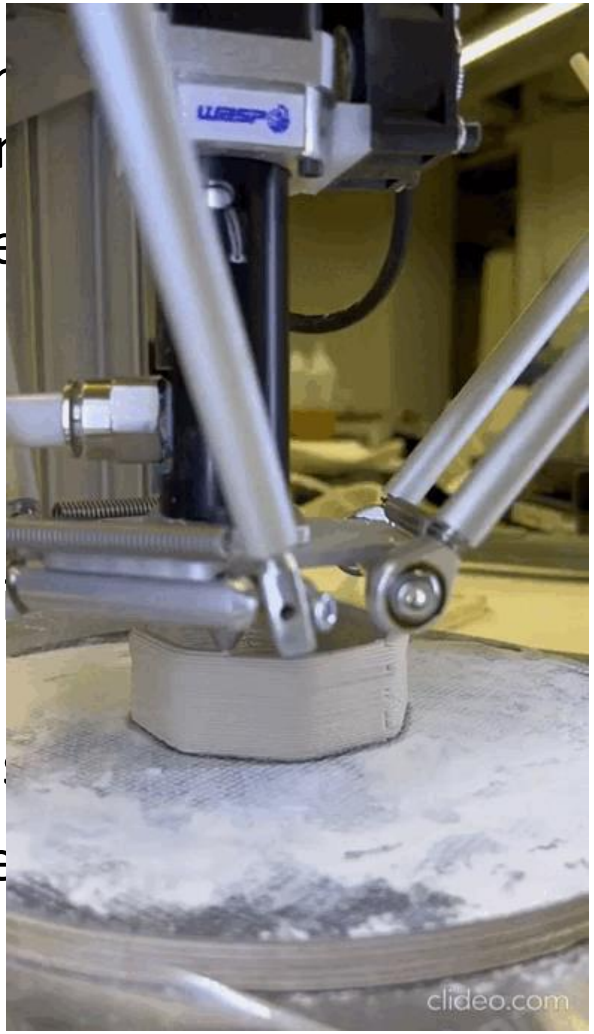
Edison: “*I think the age of concrete has started and I believe I can prove that the most beautiful houses that our architects can conceive can be cast in one operation in iron forms for a cost which will be surprisingly low*.”

Concrete Age

… to be continued

What is next?
Digital construction/3D printing of concrete

- 3D Printing refers … ess i… dimensional obje… of …
- Creation of a 3D … ware
- Also Known as:
  - Rapid Prototy…
  - Additive man…
- Additive manufac… sol… digital model
- The creation of a … oces…
- In an additive pro… ssive… until the entire o…
- Next step – 4D pr…



Material challenges in concrete 3D printing

Ultimate control of fresh properties;

as printed materials must demonstrate

- adequate fluid properties to be pumped and deposited/printed (pumpability and printability) while also displaying

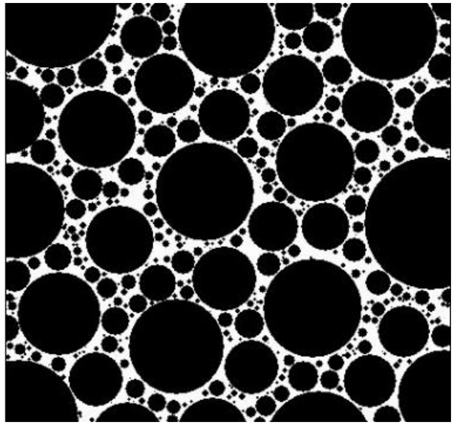
- Sufficient green strength and solid-like properties to ensure they can maintain their shape without formwork (buildability), withstand self-weight throughout the printing process, and achieve the desired structural performance.

Materials must be able to exhibit all these properties simultaneously to be viable in 3D-printed construction applications.

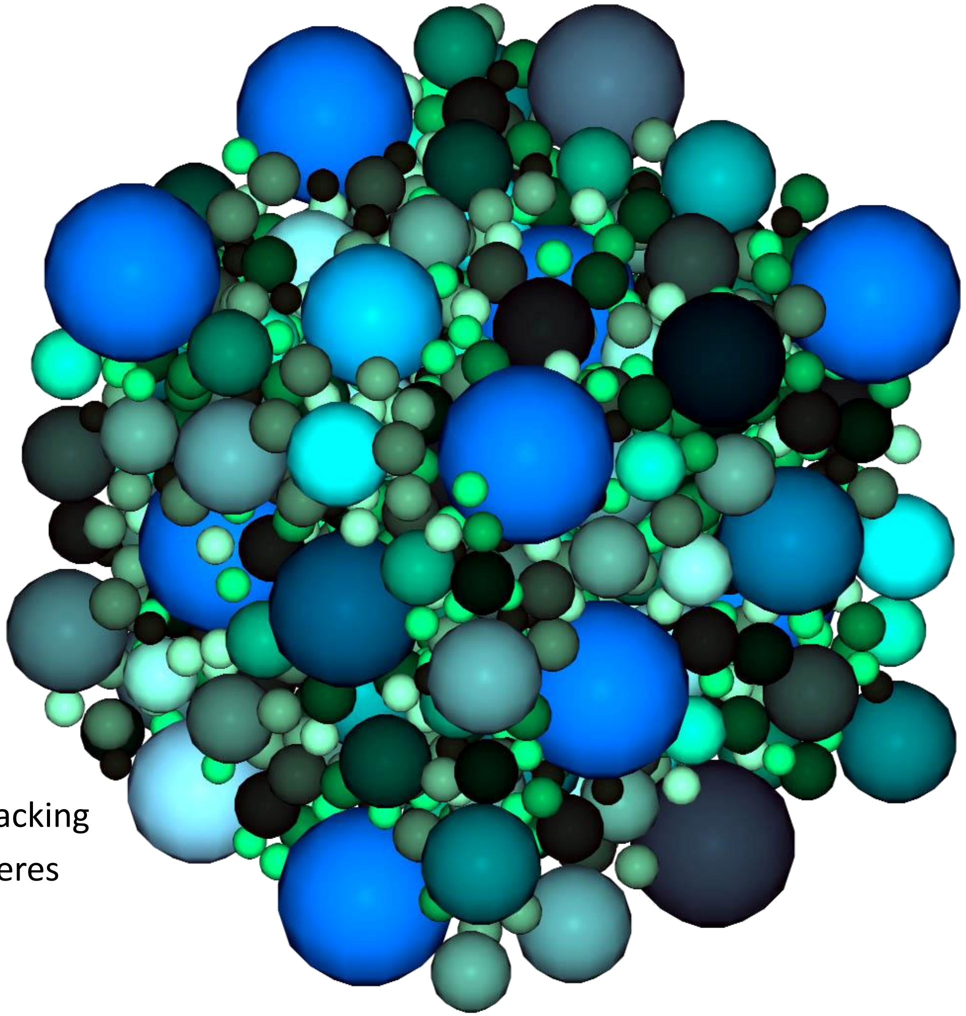
High-performance concrete can be challenging to print due to its rheological and stiffening properties. In general, additives and admixtures can improve the strength and control of rheological properties by improving either the process reactions – such as material setting and stiffening – or the material function.

Aggregate fineness, gradation, and grain size also influence material performance. The less sand or fine aggregate material has, the easier it is to extrude.

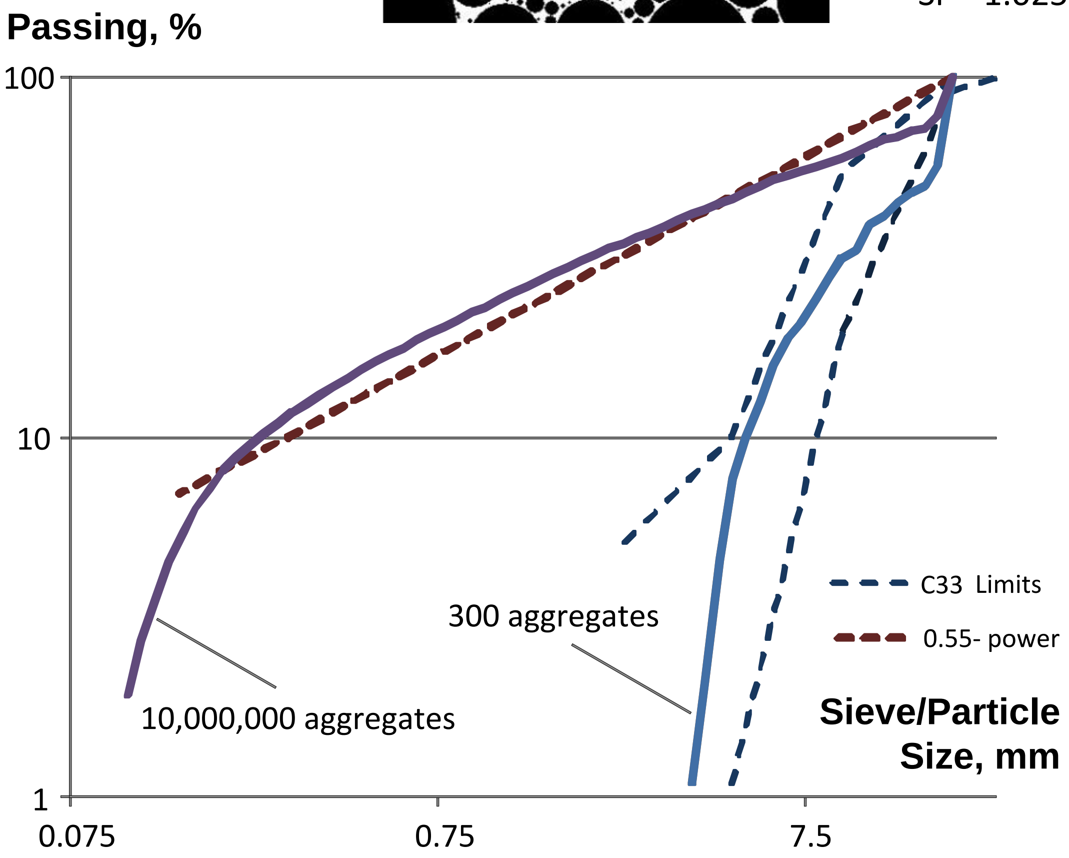
AGGREGATE'S OPTIMIZATION:
Virtual Aggregate Packing



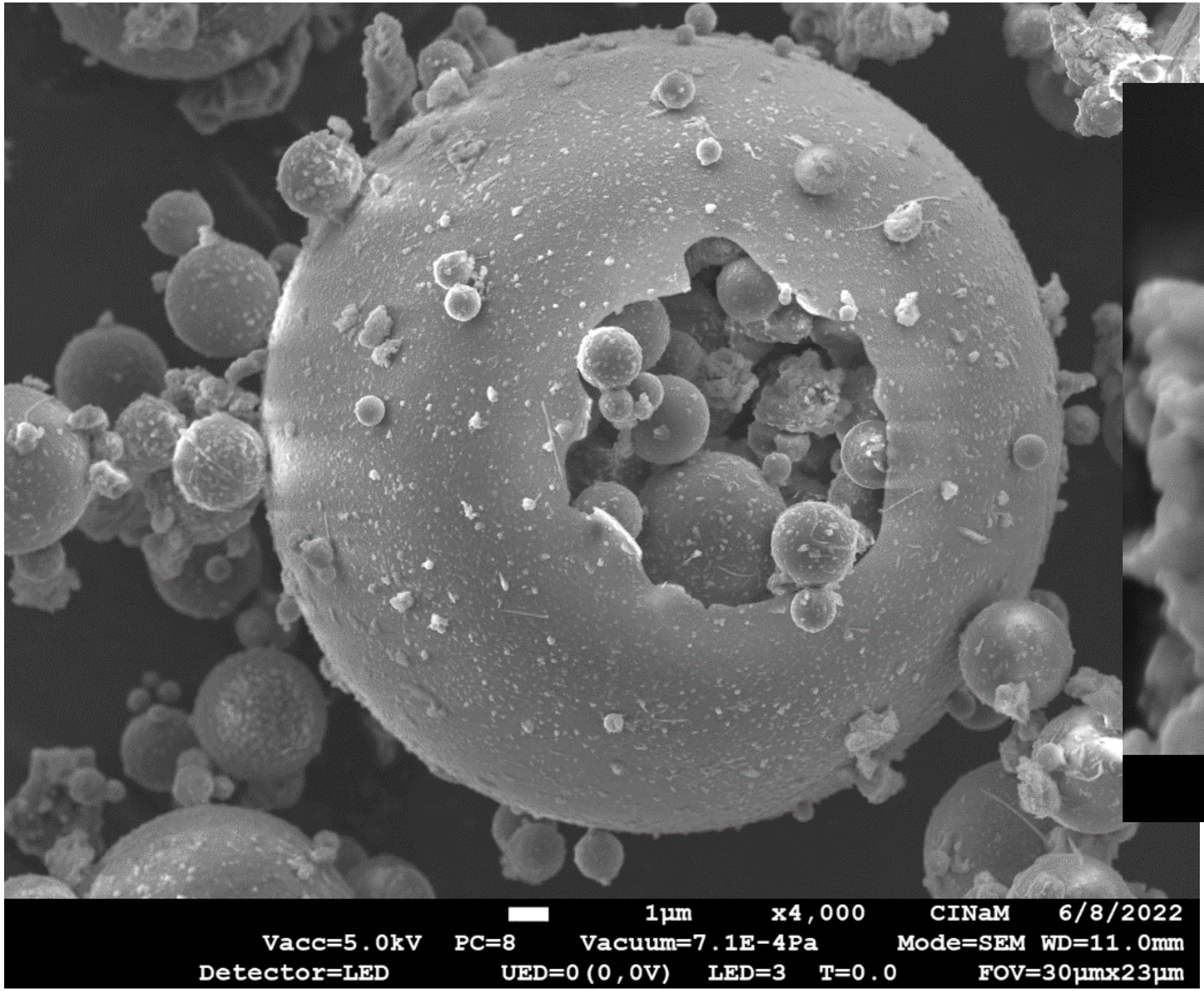
- 86% packing
- 500 disks
- N=10
- Kr=1.005
- Ks= 10
- Sr = 1.025

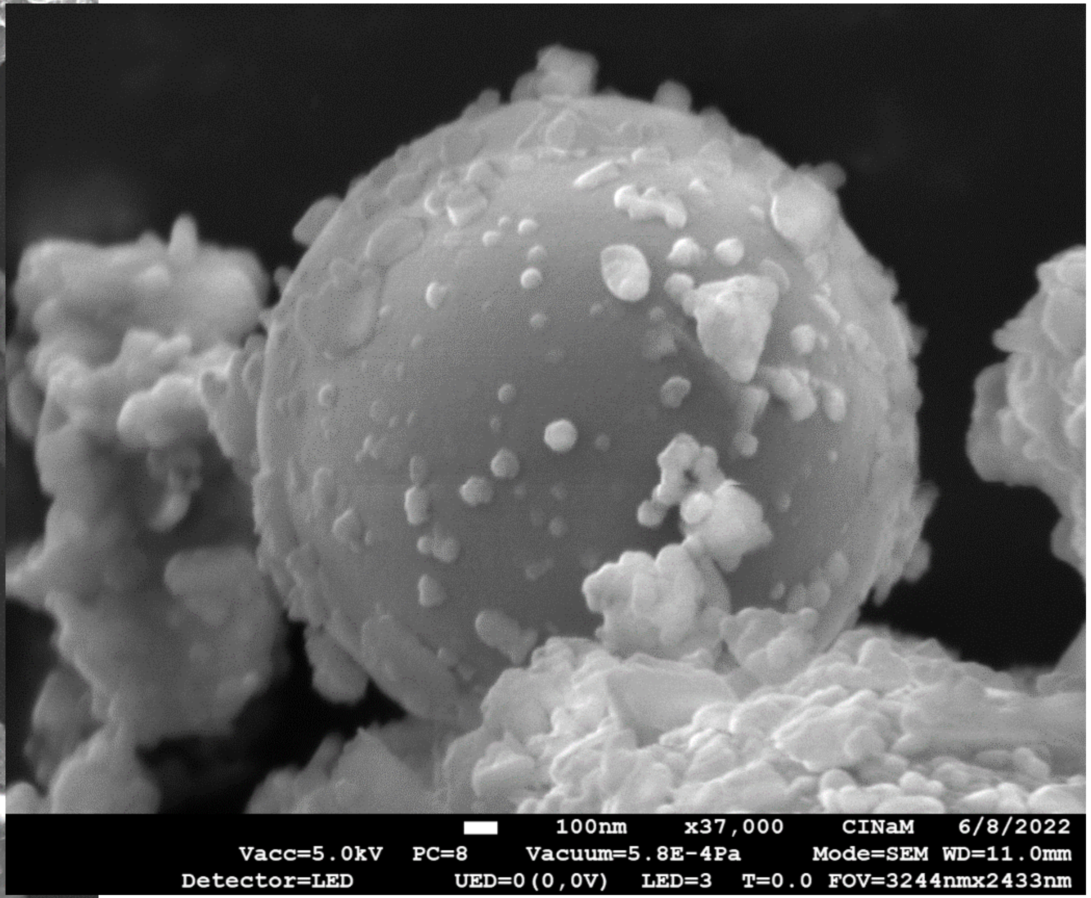


- 50.39% Packing
- 1000 Spheres
- N= 100k
- Kr= 1.001
- Ks= 1.5
- Sr= 1.001



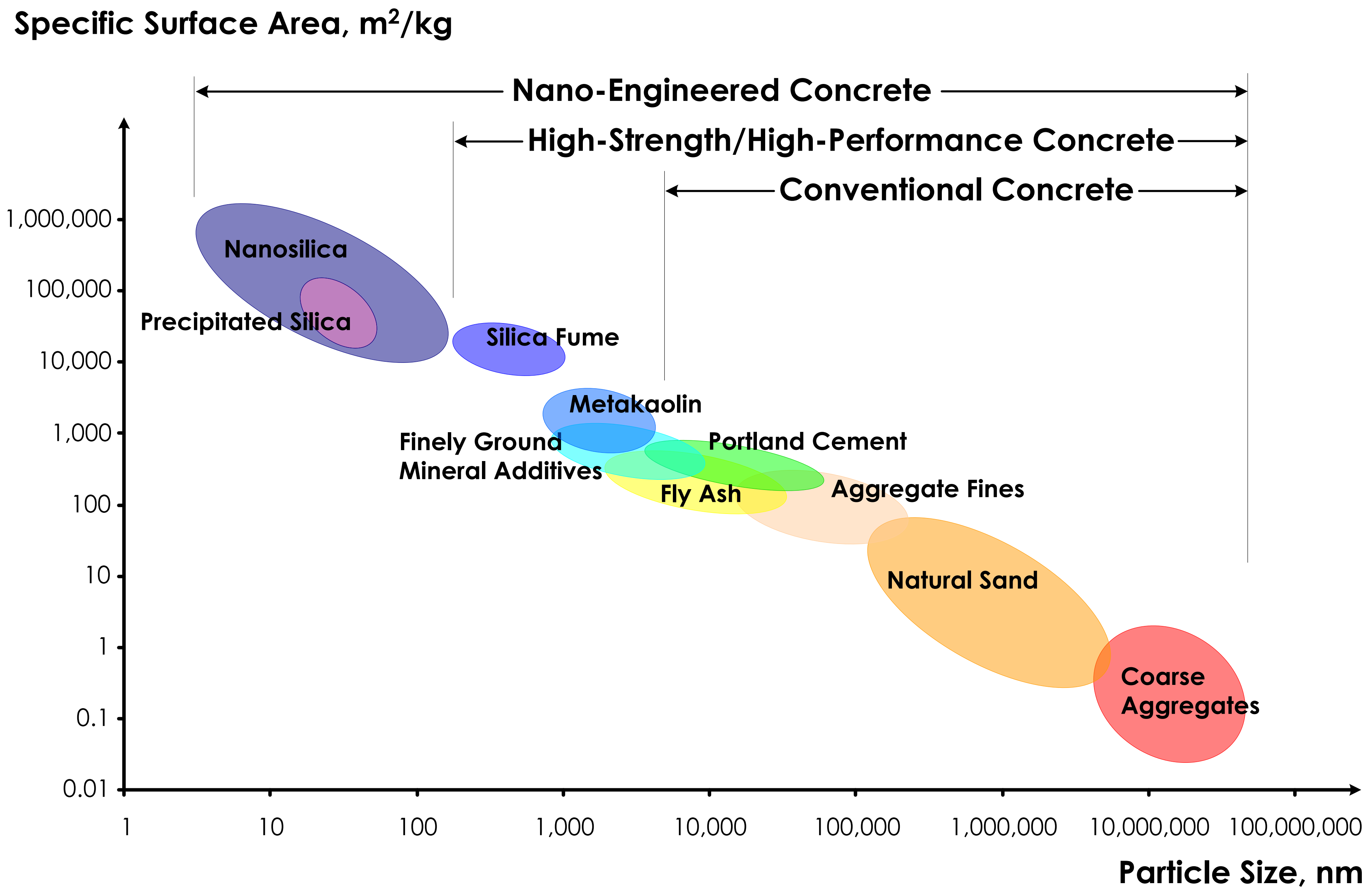
PARTICLE SIZE SCALE RELATED TO CONCRETE





courtesy of Olivier Grauby @ CNRS

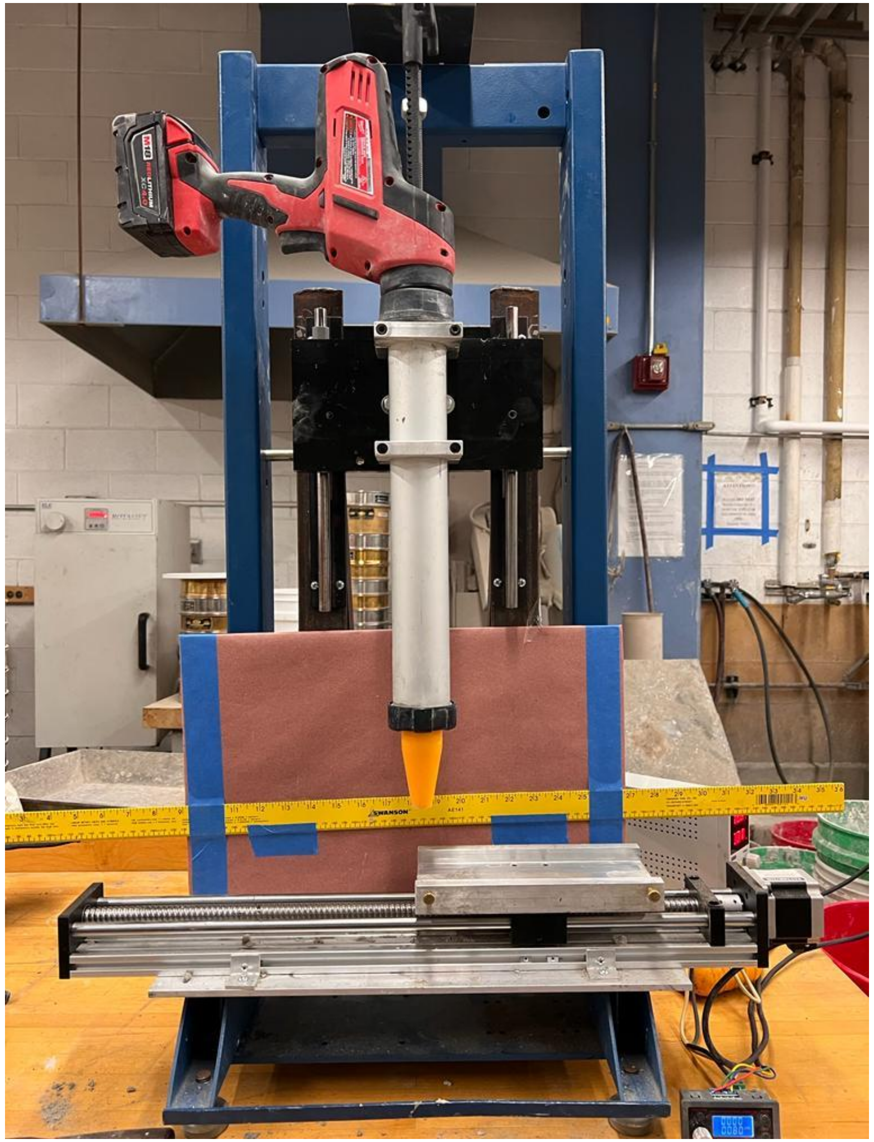
PARTICLE SIZE SCALE RELATED TO CONCRETE

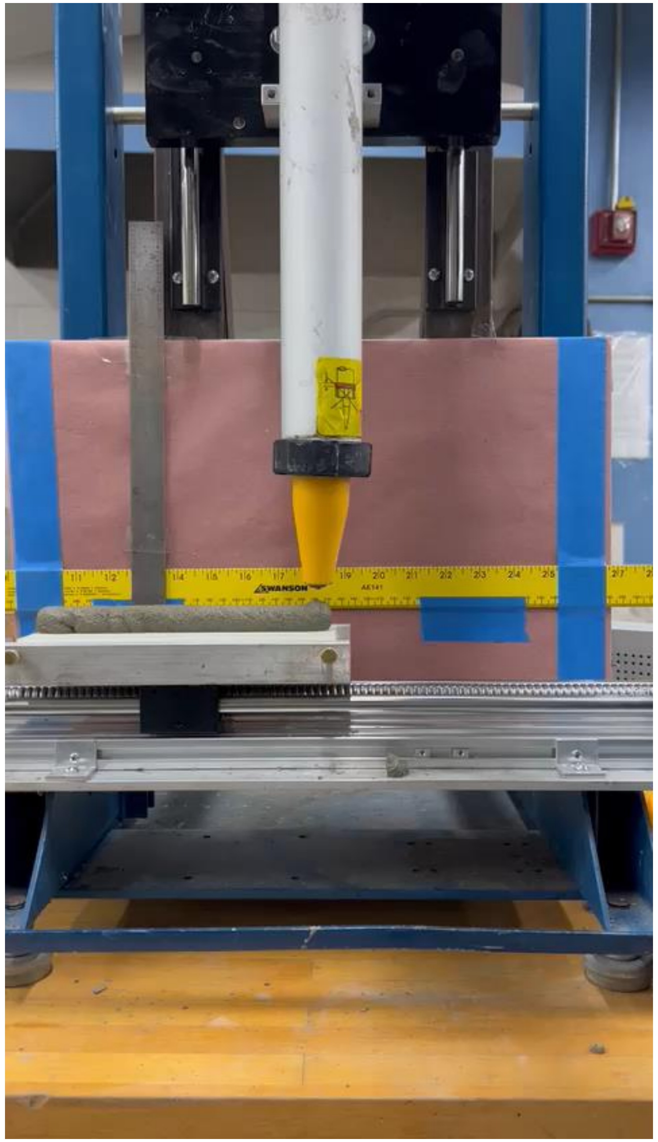


Sobolev K. and Ferrada-Gutiérrez M., How Nanotechnology Can Change the Concrete World: Part 2. American Ceramic Society Bulletin, No. 11, 2005, pp. 16-19.

2D printing

- The experiment focused on cement-based materials' printability using a custom 2D printer frame
- The experiment aimed to find the best printing parameters for different mixes and nozzle sizes
- Considering effect of S/C, and NS on printability
- Replacing the PC with SCM powders
- Use of nanoparticles as VMA

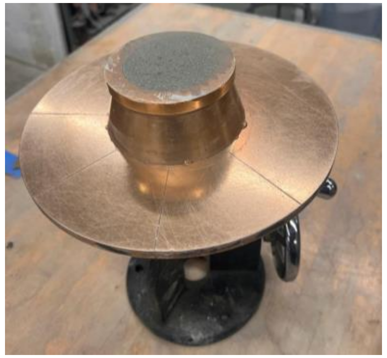


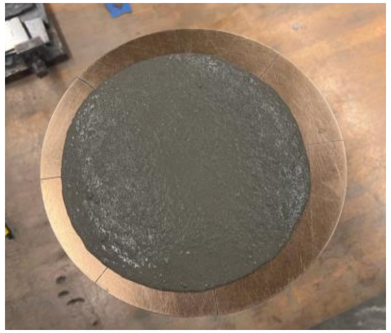


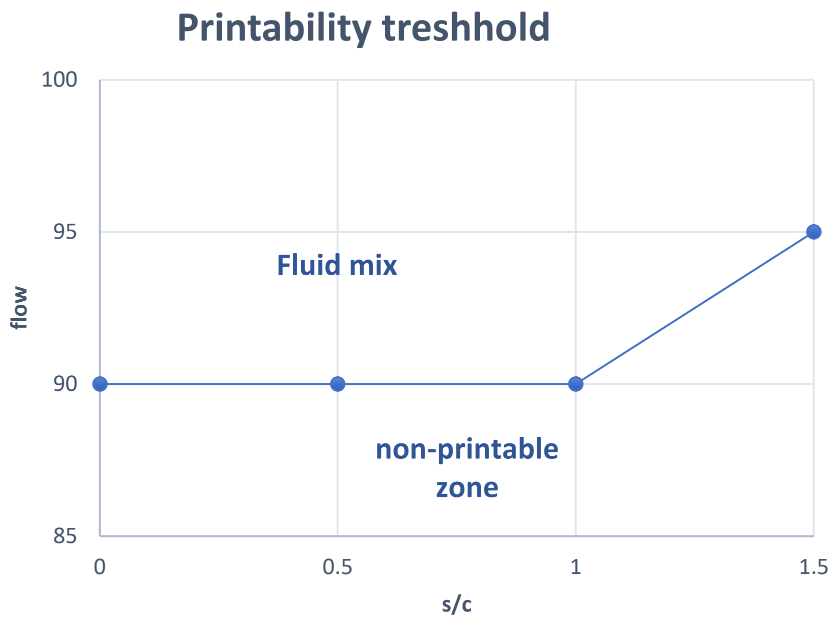
2D printing

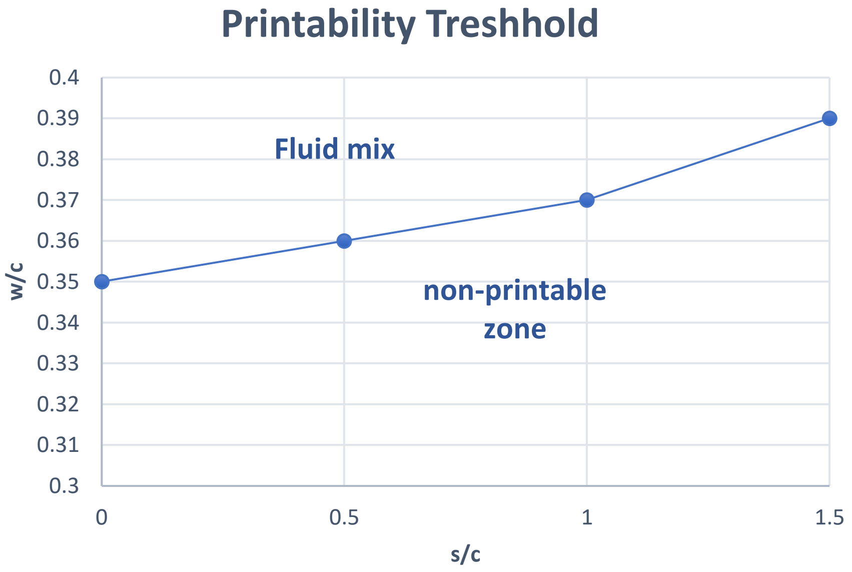
What is a printable mix, and what are the differences between a smooth flow, fluid mix, and poor workability

Effect of S/C on printability



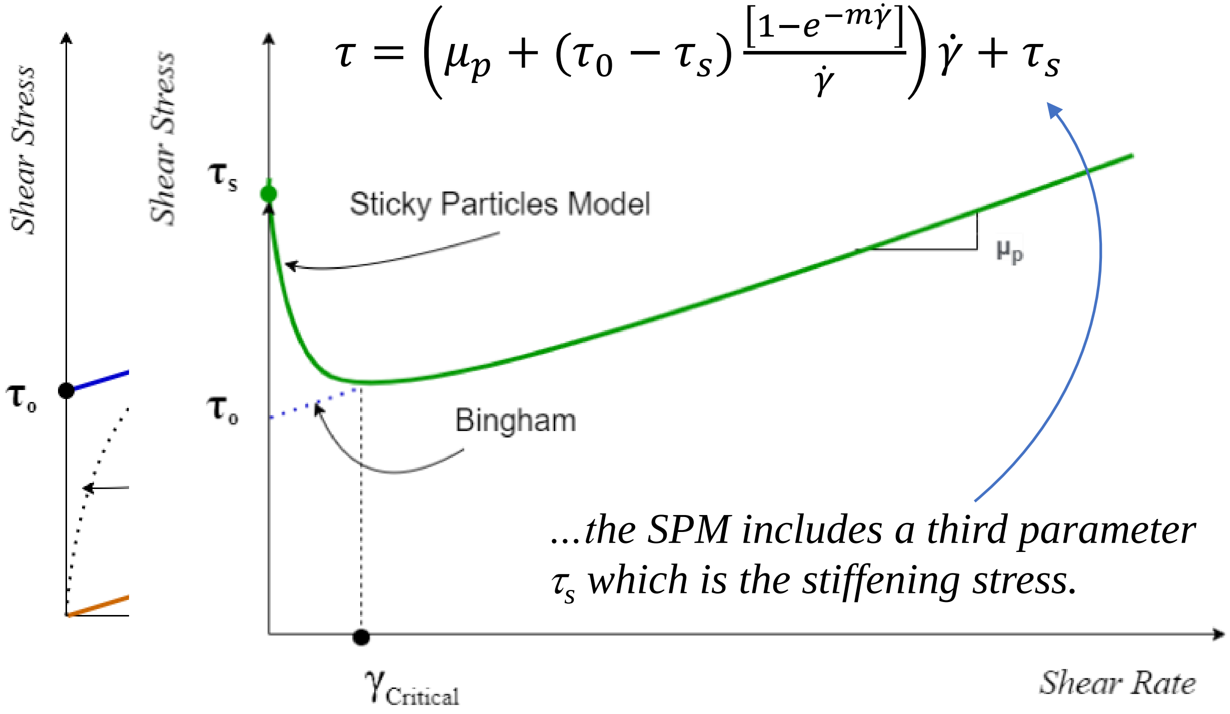




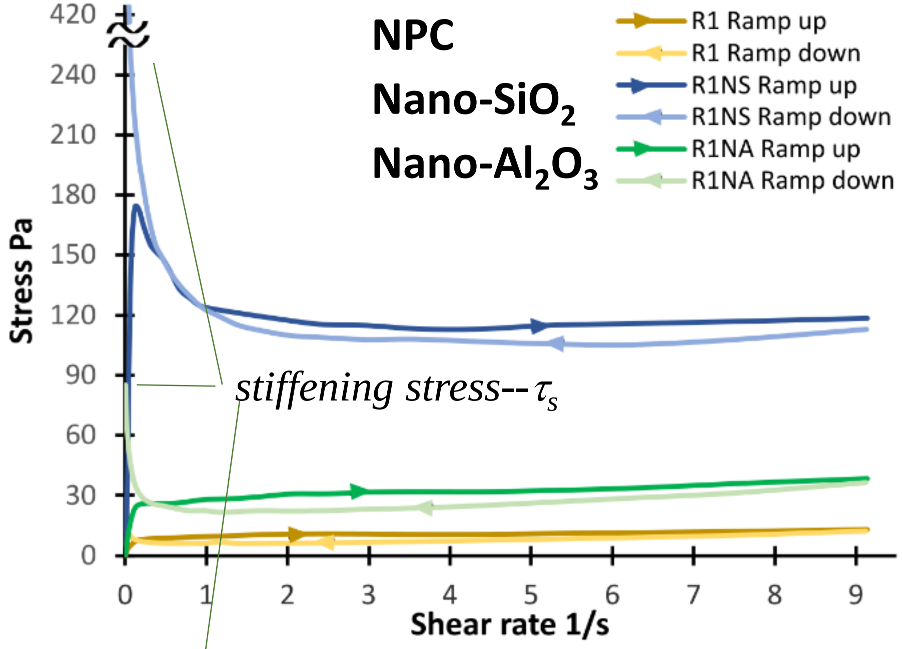


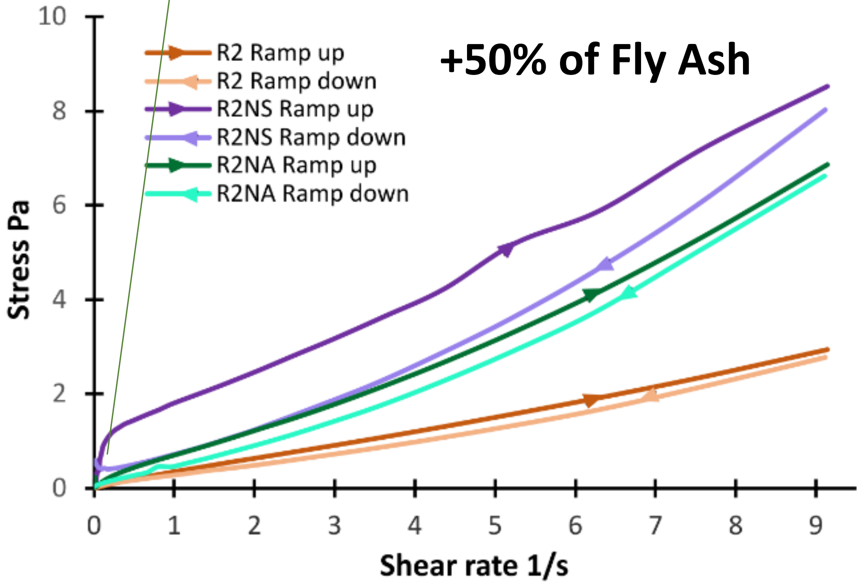
Control of rheological response: SCC and 3D printing

$$\tau = \left(\mu_p + (\tau_0 - \tau_s)\frac{[1-e^{-m\dot{\gamma}}]}{\dot{\gamma}}\right)\dot{\gamma} + \tau_s$$



...the SPM includes a third parameter τ_s which is the stiffening stress.





ACI MATERIALS JOURNAL TECHNICAL PAPER

Title No. 118-M103

Rheological Response of Magnetorheological Cementitious Inks Tuned for Active Control in Digital Construction

by Aparna S. Deshmukh, Reed T. Heintzkill, Rosalba A. Huerta, and Konstantin Sobolev

Experimental Program

Mixture ID	Mixture constituents	Composition, %					
		Portland ce[illegible]	[illegible]	[illegible]lica	Nano-alumina	Magnetite	HRWRA
R_1	PC+SP	100	[illegible]	[illegible]	[illegible]	—	0.15
R_2	PC+FA+SP	50	[illegible]	[illegible]	[illegible]	—	0.15
R_1NS	PC+SP+NS	100	[illegible]	[illegible]	[illegible]	—	0.15
R_1NA	PC+SP+NA	100	[illegible]	[illegible]	[illegible]	—	0.05
R_2NS	PC+FA+SP+NS	50	50	0.25	—	—	0.15
R_2NA	PC+FA+SP+NA	50	50		0.25	—	0.05
R_1M	PC+SP+M	95	[illegible]	[illegible]	[illegible]	5	0.15
R_2M	PC+FA+SP+MP	50	[illegible]	[illegible]	[illegible]	5	0.15
R_1NSM	PC+SP+NS+MP	95	[illegible]	[illegible]	[illegible]	5	0.15
R_1NAM	PC+SP+NA+MP	95	[illegible]	[illegible]	[illegible]	5	0.05
R_2NSM	PC+FA+SP+NS+MP	50	[illegible]	[illegible]	[illegible]	5	0.15
R_2NAM	PC+FA+SP+NA+MP	50	[illegible]	[illegible]	[illegible]	5	0.05

Portland Cement

+Nano-silica
+Nano-alumina fibers

+Magnetite Powder

Portland Cement +
Class F fly ash

+Nano-silica
+Nano-alumina fibers

+Magnetite Powder

Note: PC is portland cement; FA is fly ash; HRWRA is high-range water-reducing admixture; NS is nanosilica; NA is nanoalumina, MP is magnetite powder (also M is used for Mixture ID); R1 is compositions based on superplasticized portland cement pastes; R2 is compositions based on superplasticized cement-fly ash systems,

water-cementitious materials ratio (w/cm) of 0.3

Magnetorheological Cementitious Ink (MRCI)

- MRCI is the proposed cementitious ink which constitutes special **magnetic components or advanced (nano) materials** into the cementitious material that show a desired response to an **external magnetic field**, changing the behavior of the material from more **liquid like to more solid like;**
- In addition to iron particles present in cement and fly ash, magnetic powders based on iron oxide can be added to cement paste and activated when the external magnetic field is applied;
- The rheological properties of cement paste can be altered as desired by changing the quantity of magnetic particles and strength of applied magnetic field;
- Due to application of static magnetic fields during hardening, denser C-S-H morphology and reduced porosity can be created;
- Significant influence should be observed in the hydration process due to magnetic field potentially enhancing the mechanical performance.

Experimental program

0 - 2 Minutes — **End of Mixing**
- Sample placed into cylindrical container
- Container placed inside electromagnet
- Start recirculating chiller attached to electromagnet

1 Minute — **Soak Time**
- Connect and set the power supply to 5 amperes
- Measure the sample temperature and magnetic flux density to match 0.1 T
- Record electromagnet flux density, voltage, and temperature

2 Minute — **Preconditioning/Preshear**
- The rheometer starts performing preshear on the sample to break down any irregular agglomerations at shear rate of 100 1/s

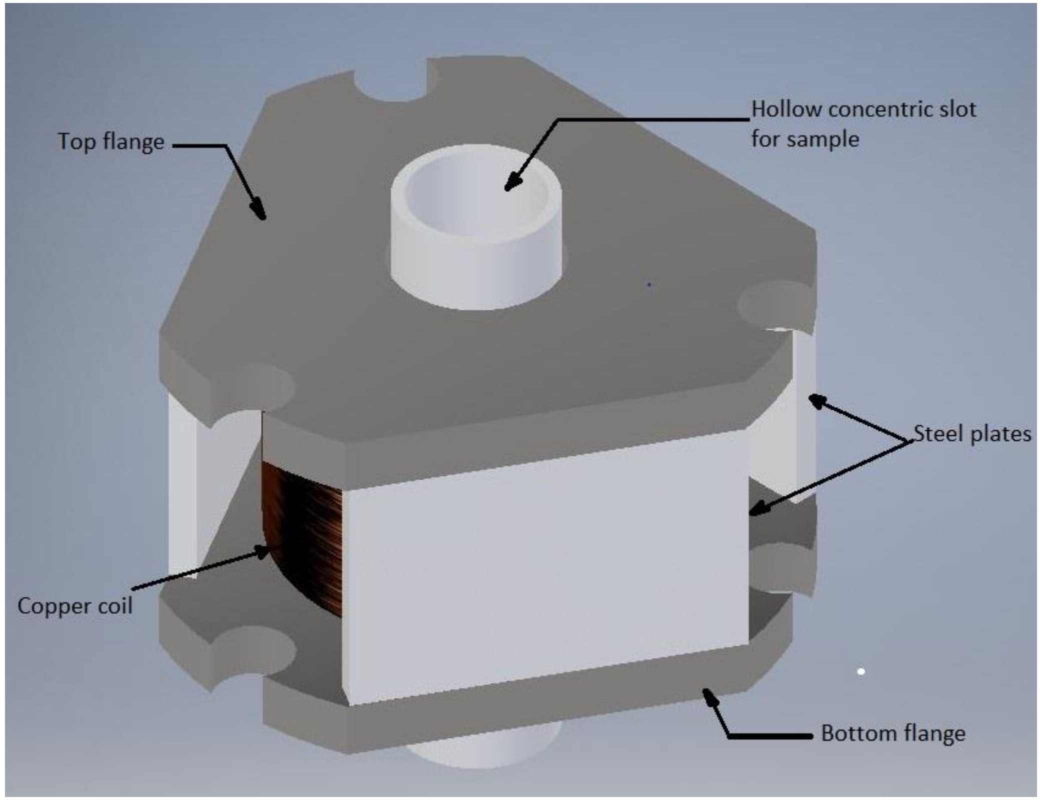
30 Second — **Rest**
- Allows for sample to settle and stop moving before ramp sequence

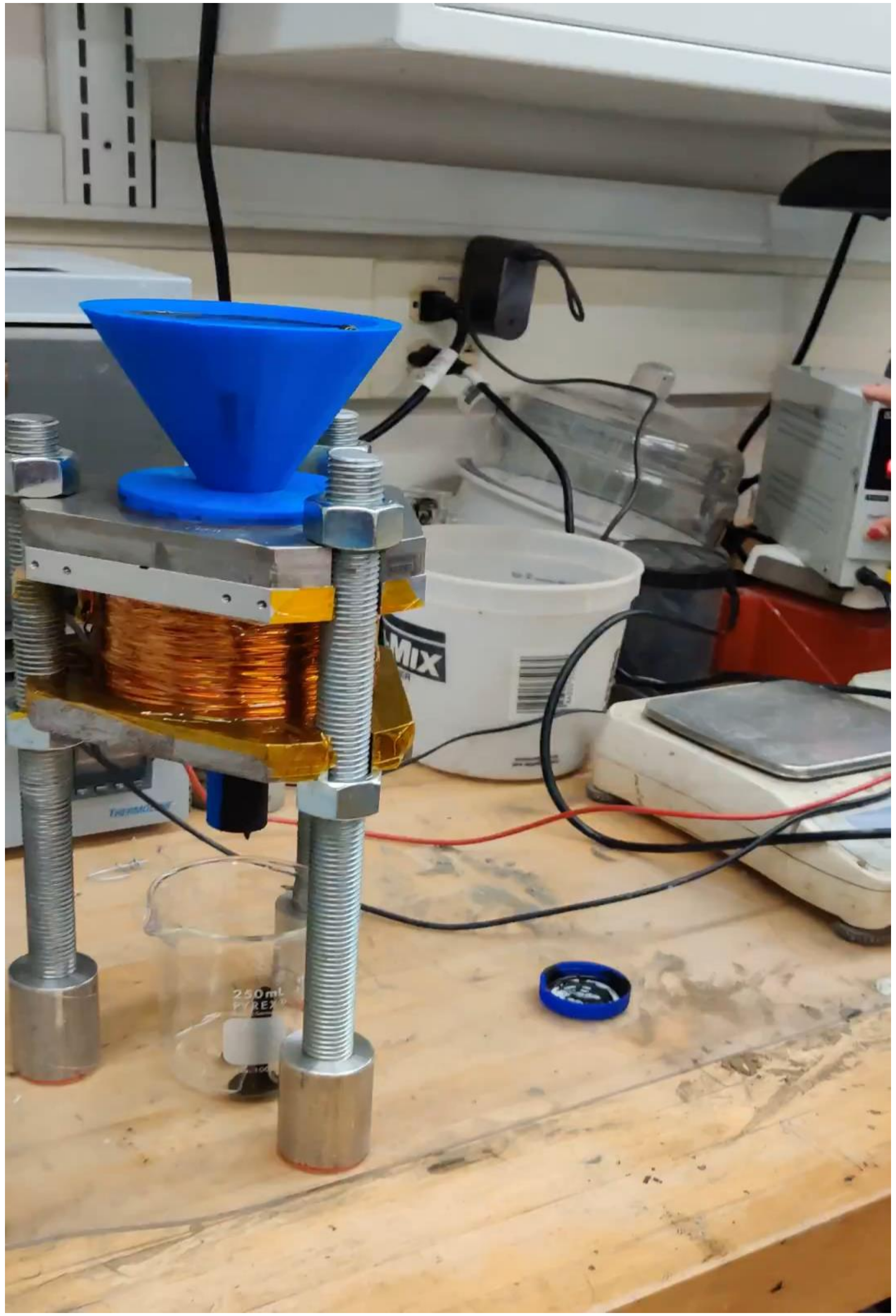
4 Minutes — **Ramp Up & Ramp Down (1)**
- Shear rate ramps up from 0.01 1/s to 10 1/s (2 minutes)
- Shear rate ramps down from 10 1/s to 0.01 1/s (2 minutes)

4 Minutes — **Ramp Up & Ramp Down (2)**
- Shear rate ramps up from 0.01 1/s to 10 1/s (2 minutes)
- Shear rate ramps down from 10 1/s to 0.01 1/s (2 minutes)

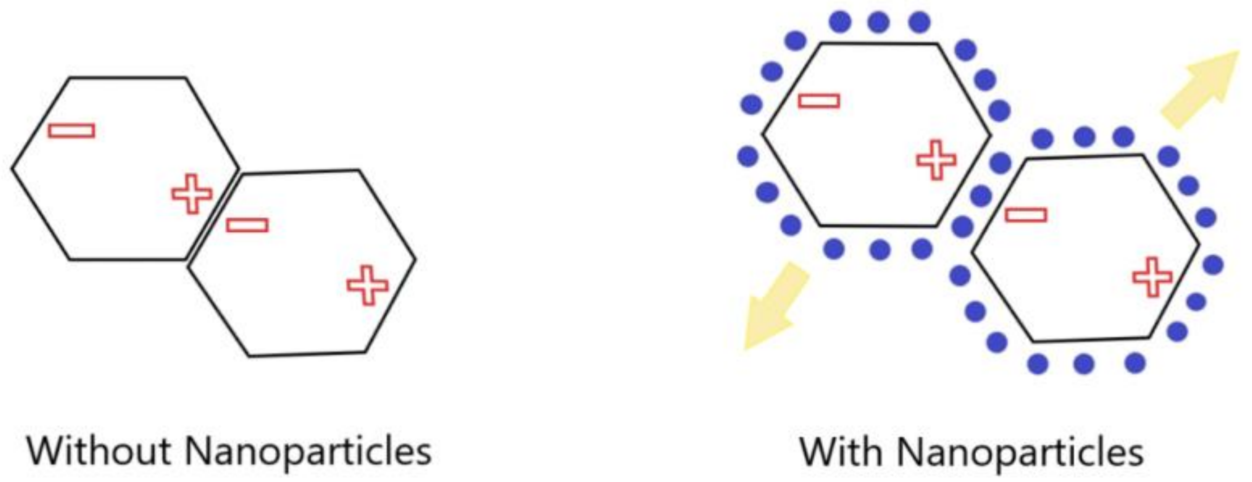
4 Minutes — **Ramp Up & Ramp Down (3)**
- Shear rate ramps up from 0.01 1/s to 10 1/s (2 minutes)
- Shear rate ramps down from 10 1/s to 0.01 1/s (2 minutes)
- Measure sample temperature and magnetic flux density
- Record electromagnet flux density, voltage, and temperature

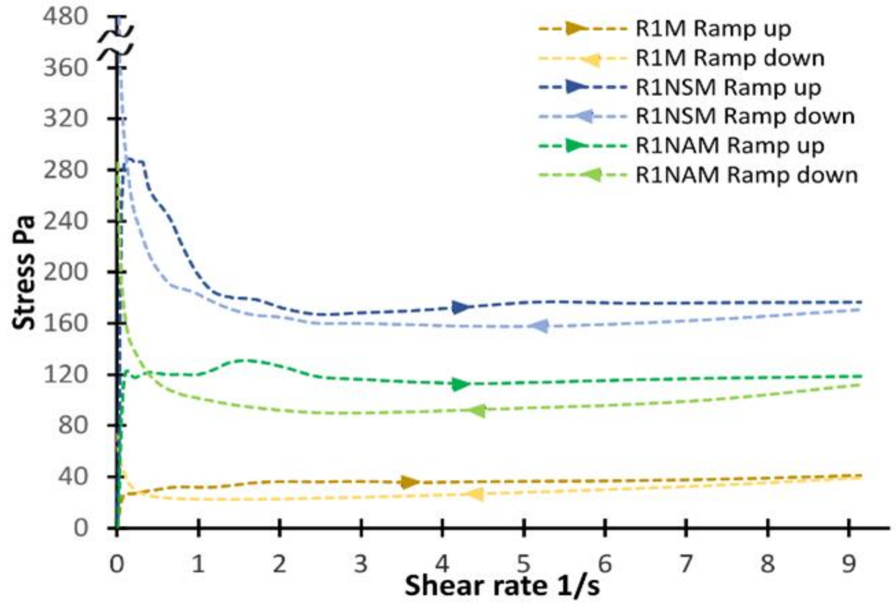
Realization of the concept

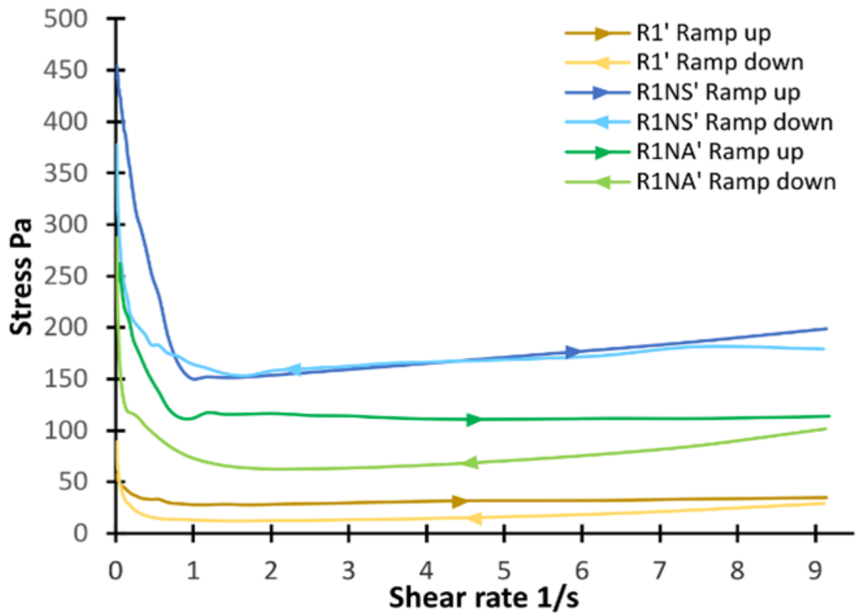


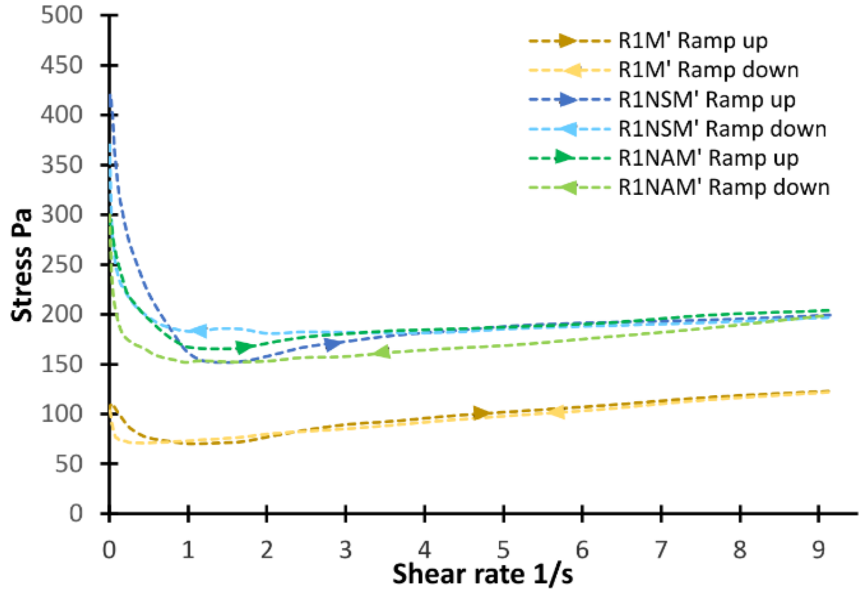


Effect of magnetic field: R_1 system

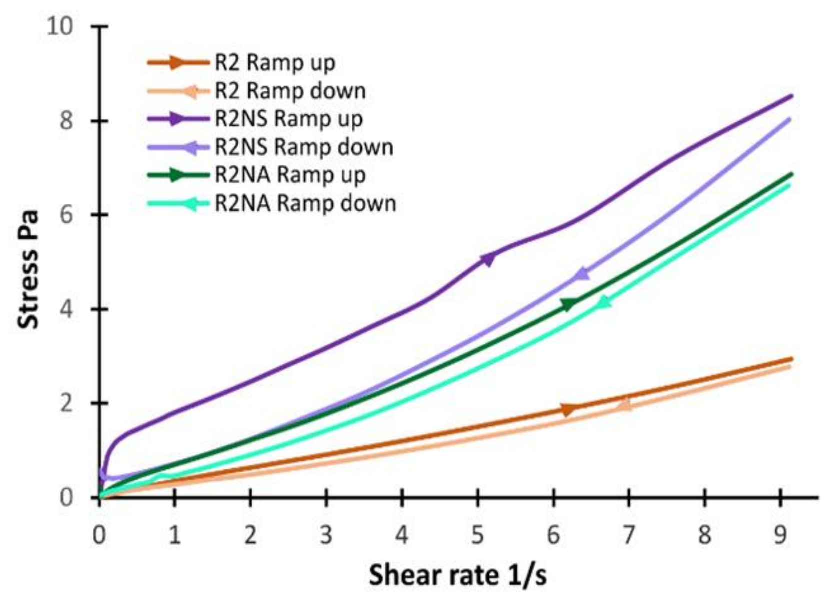


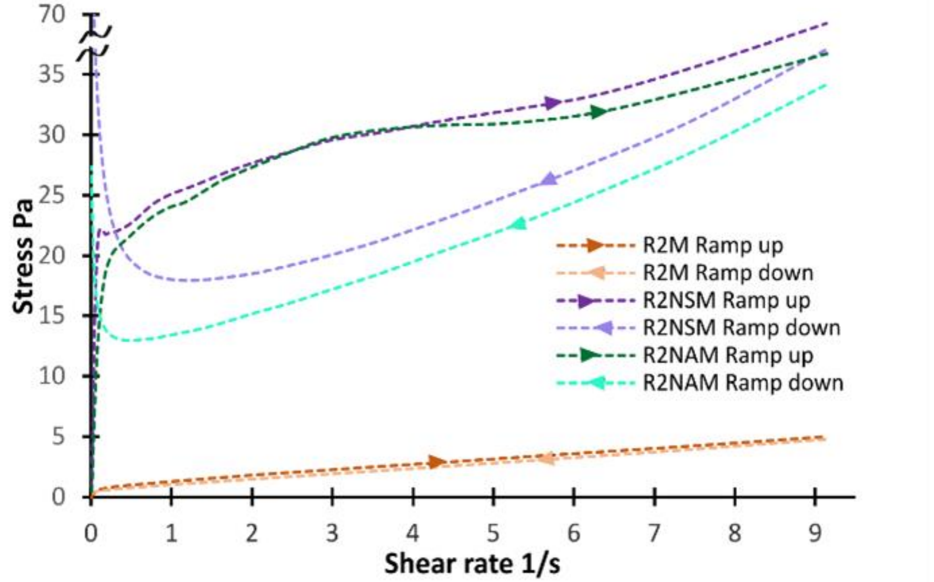


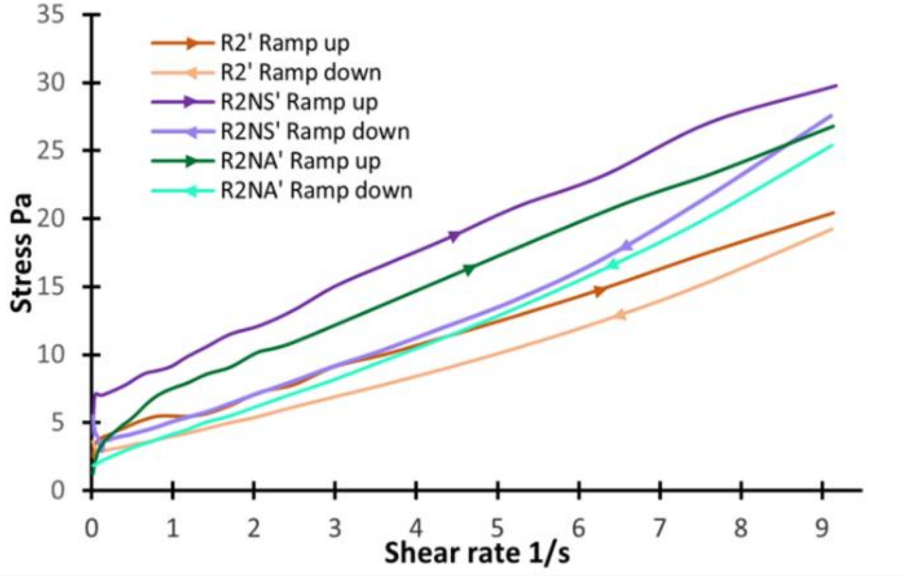


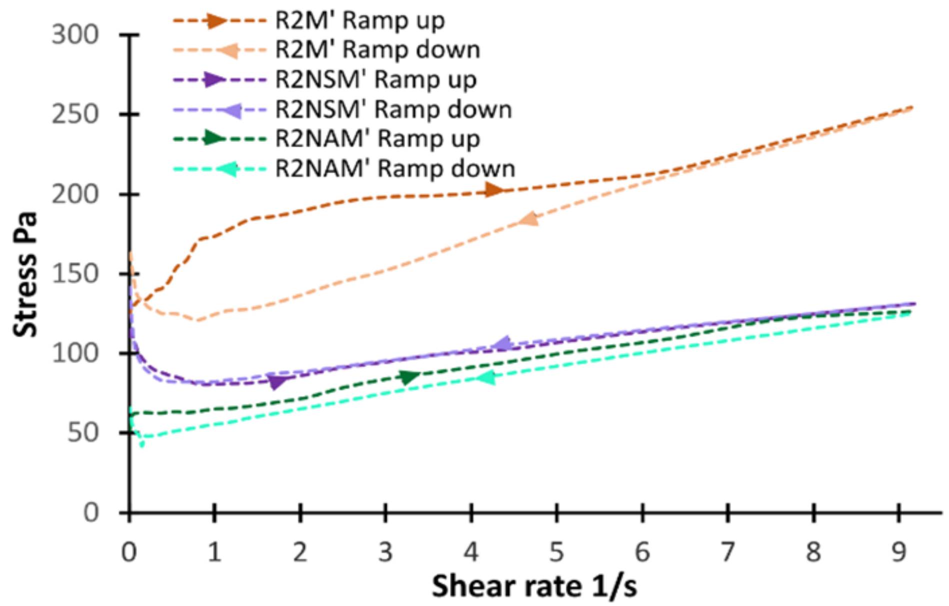


Effect of magnetic field: R_2 system

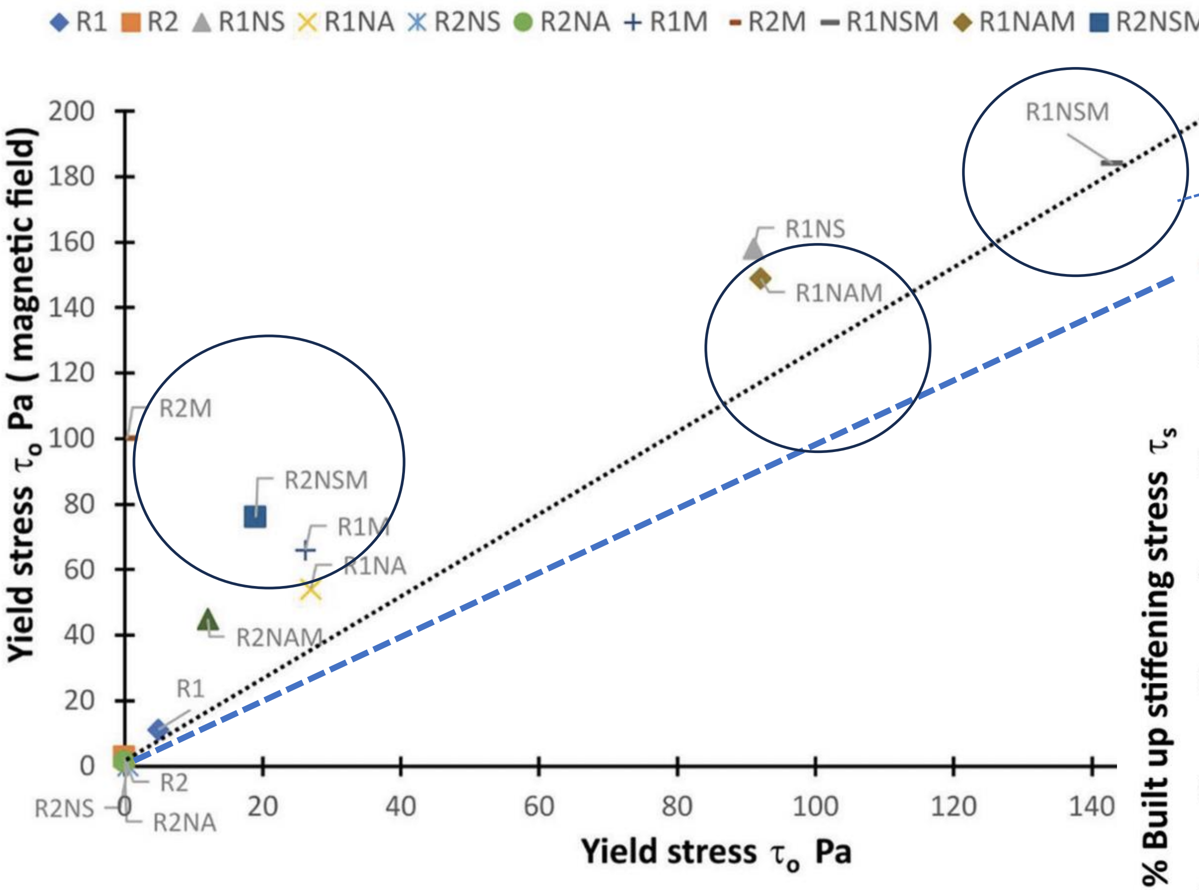


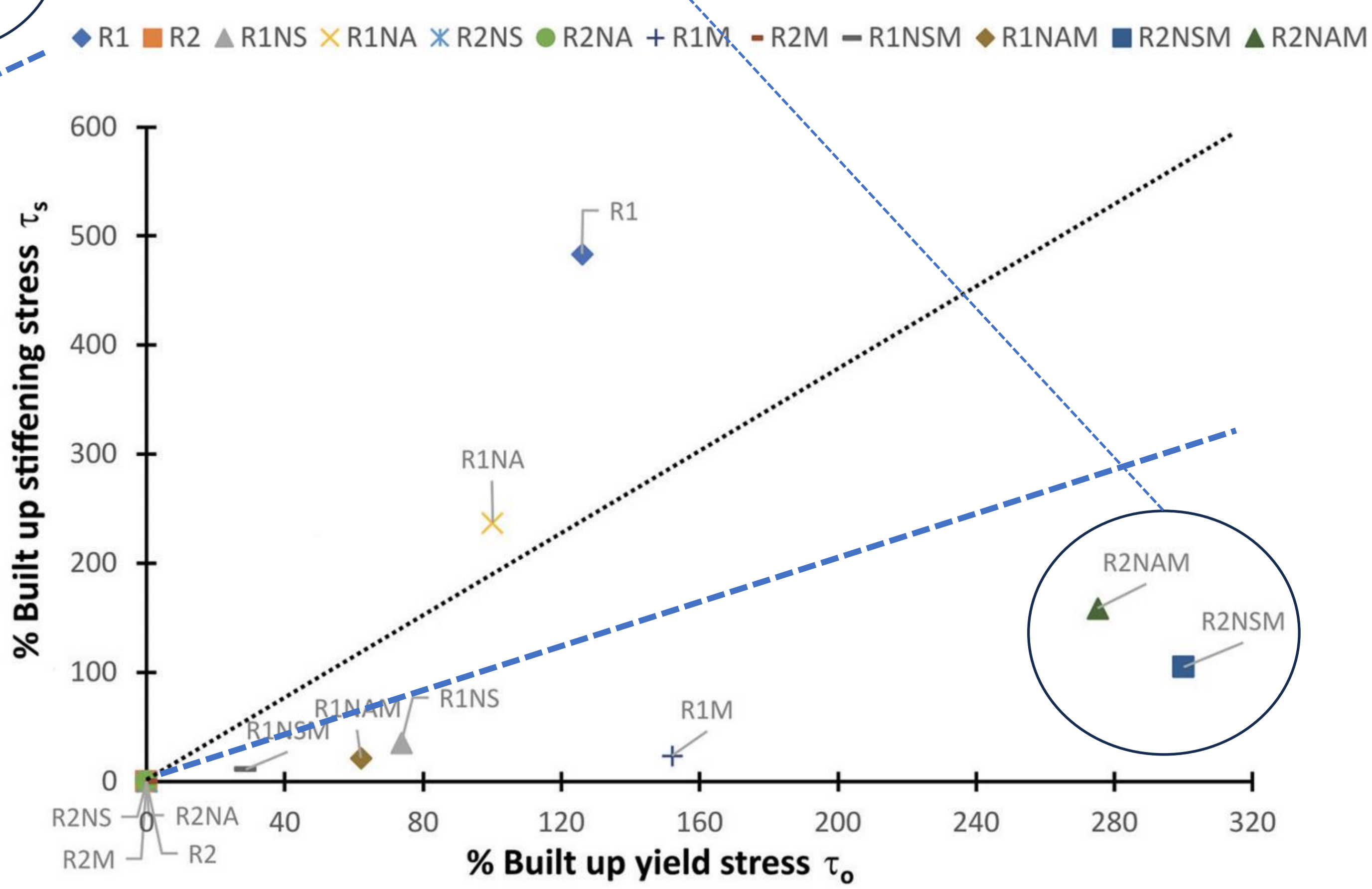






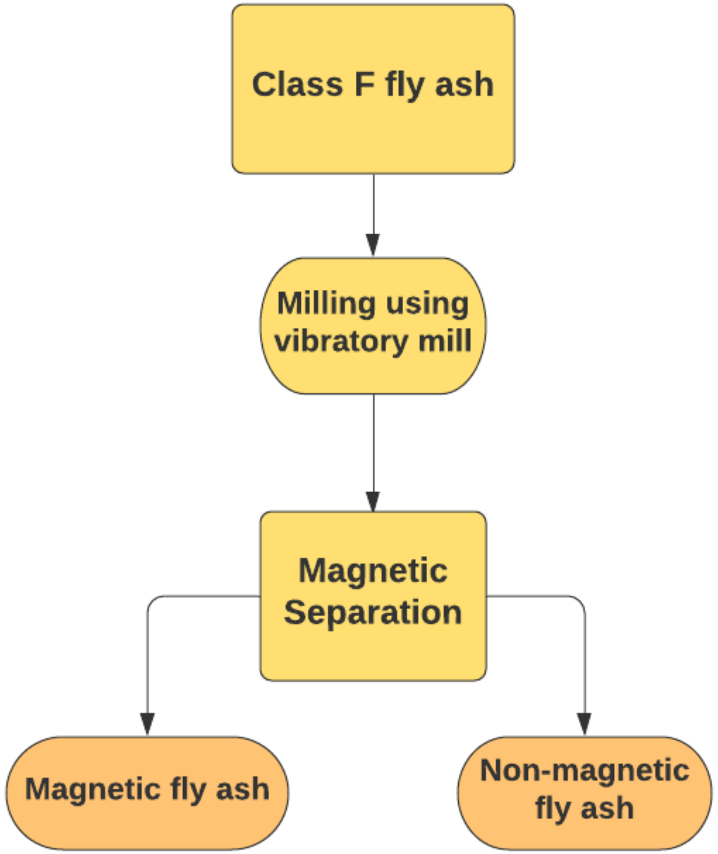
Yield/stiffening stress with application of magnetic field





Fly ash for MRCI?

Sustainable ferromagnetic product



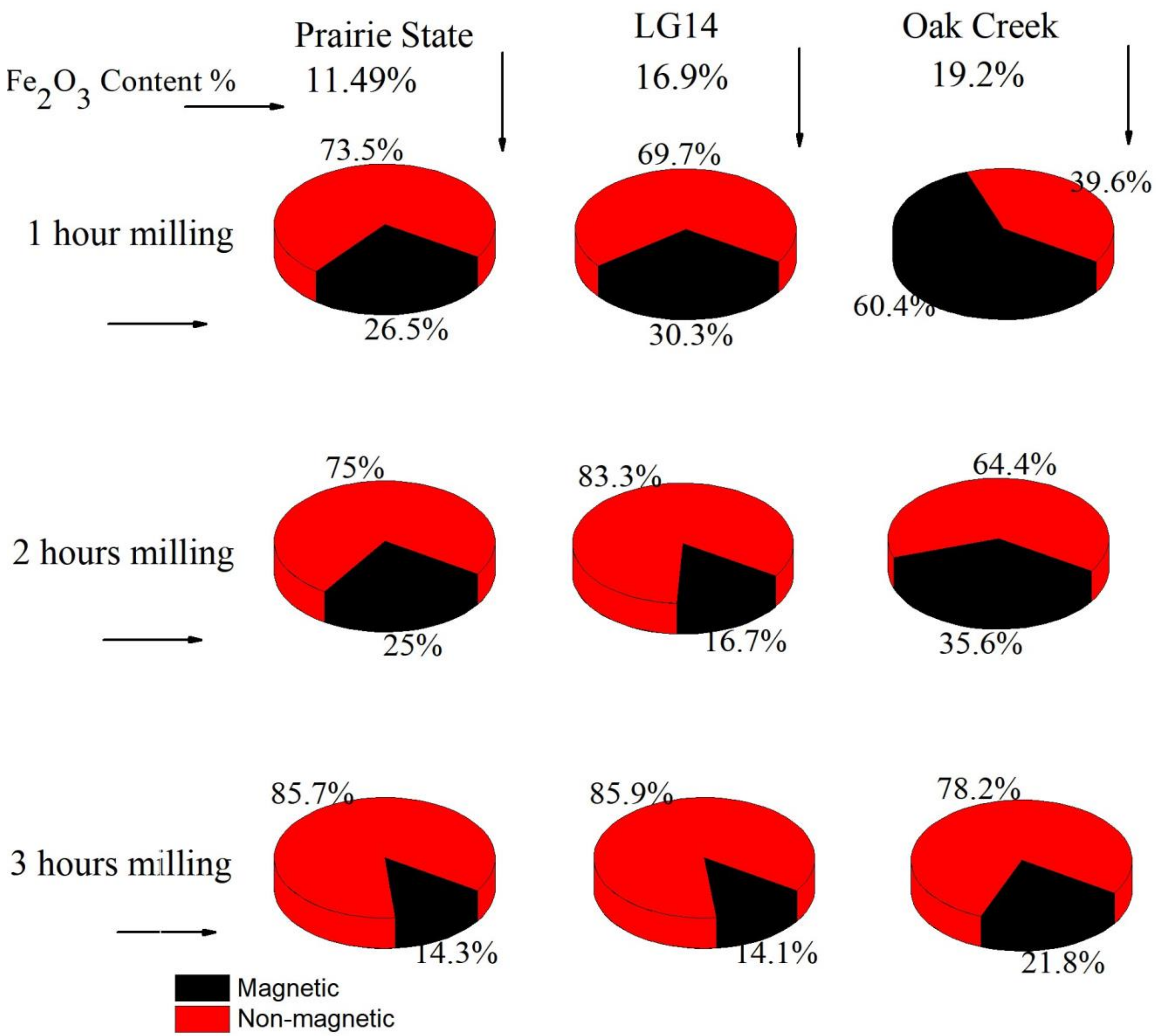
fly ash beneficiation process

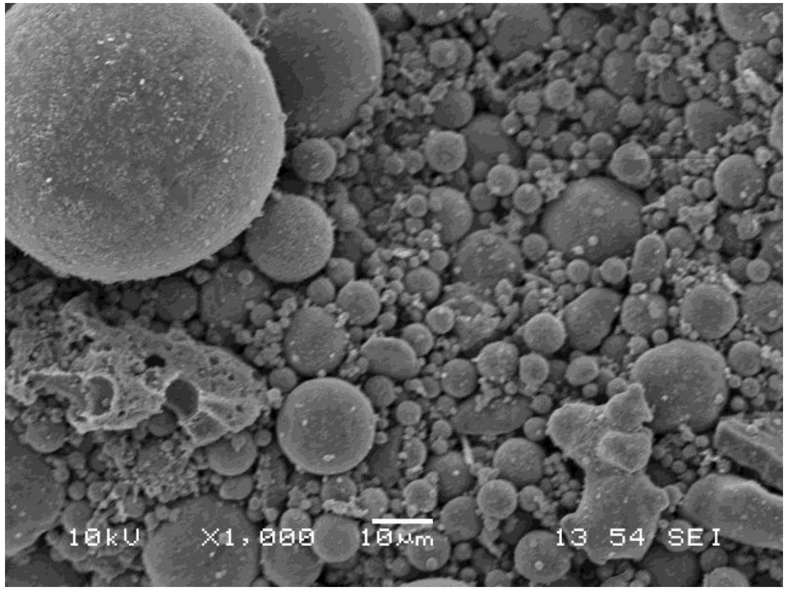
Fly ash Beneficiation

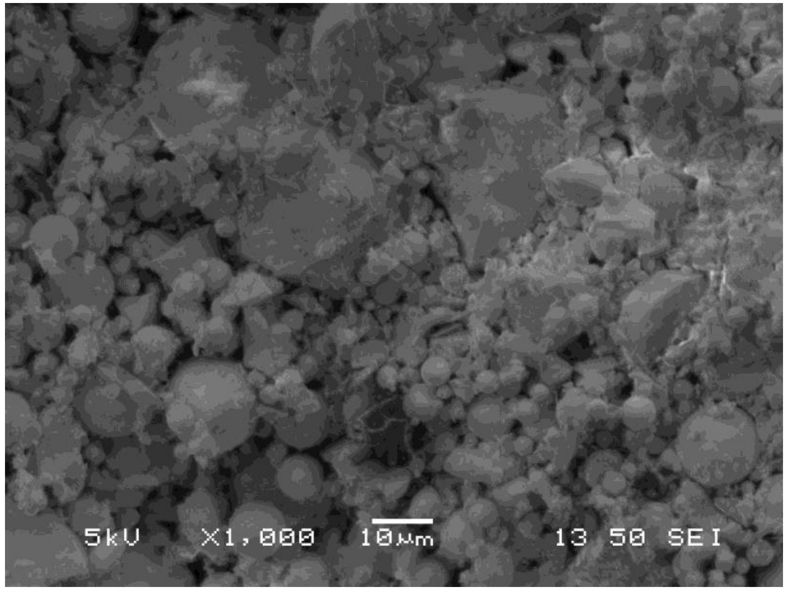
<u>Types of Fly ash Beneficiated</u>:

- Class F Oak Creek fly ash
- Class F LG14 fly ash
- Class F Prairie State fly ash

Material balance after milling







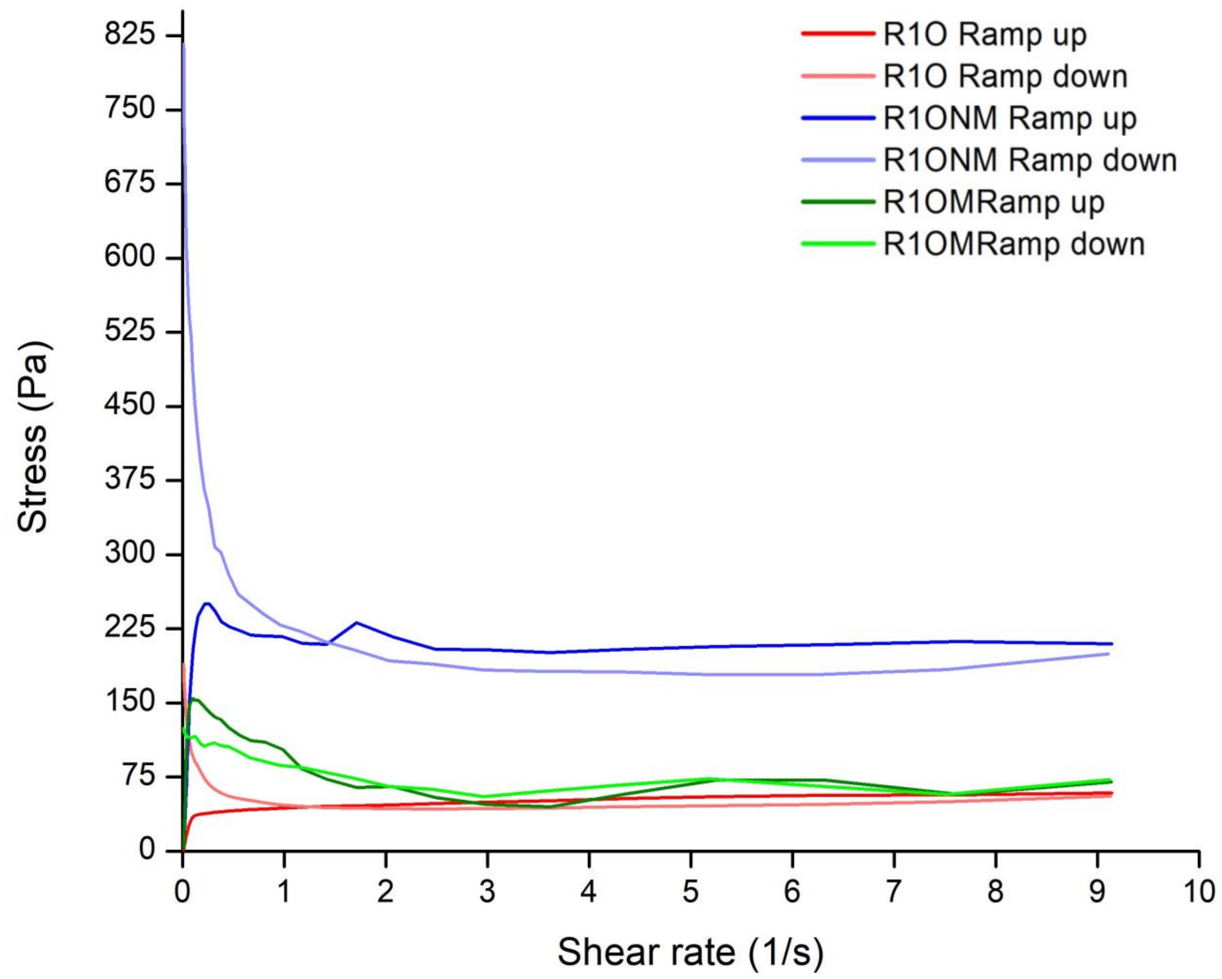
The use of activated fly ash for MRCI

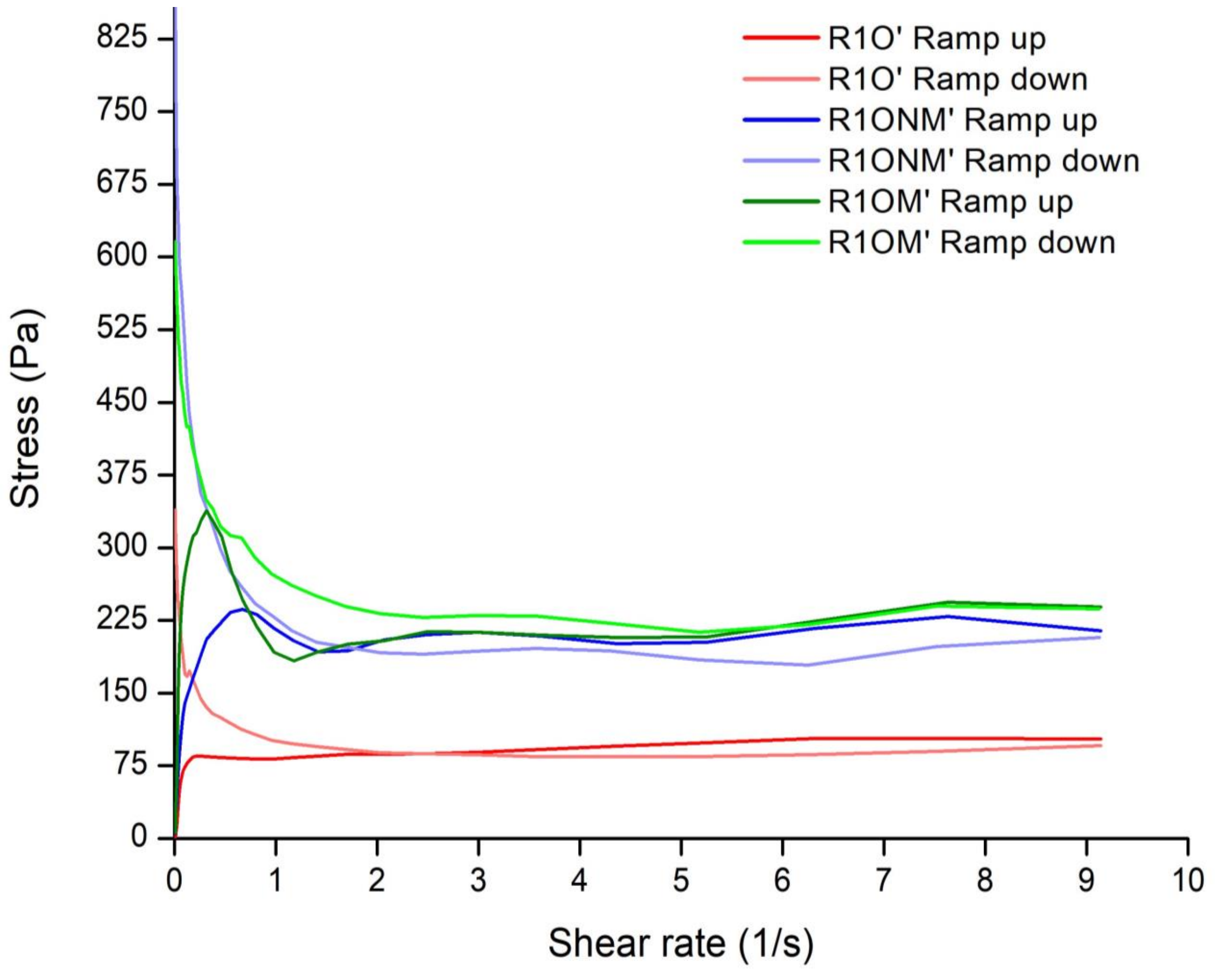
Portland Cement

+ Oak Creek Class F fly ash (reference)
+ Beneficiated OC (Magnet)
+Beneficiated OC (Non-magnet)

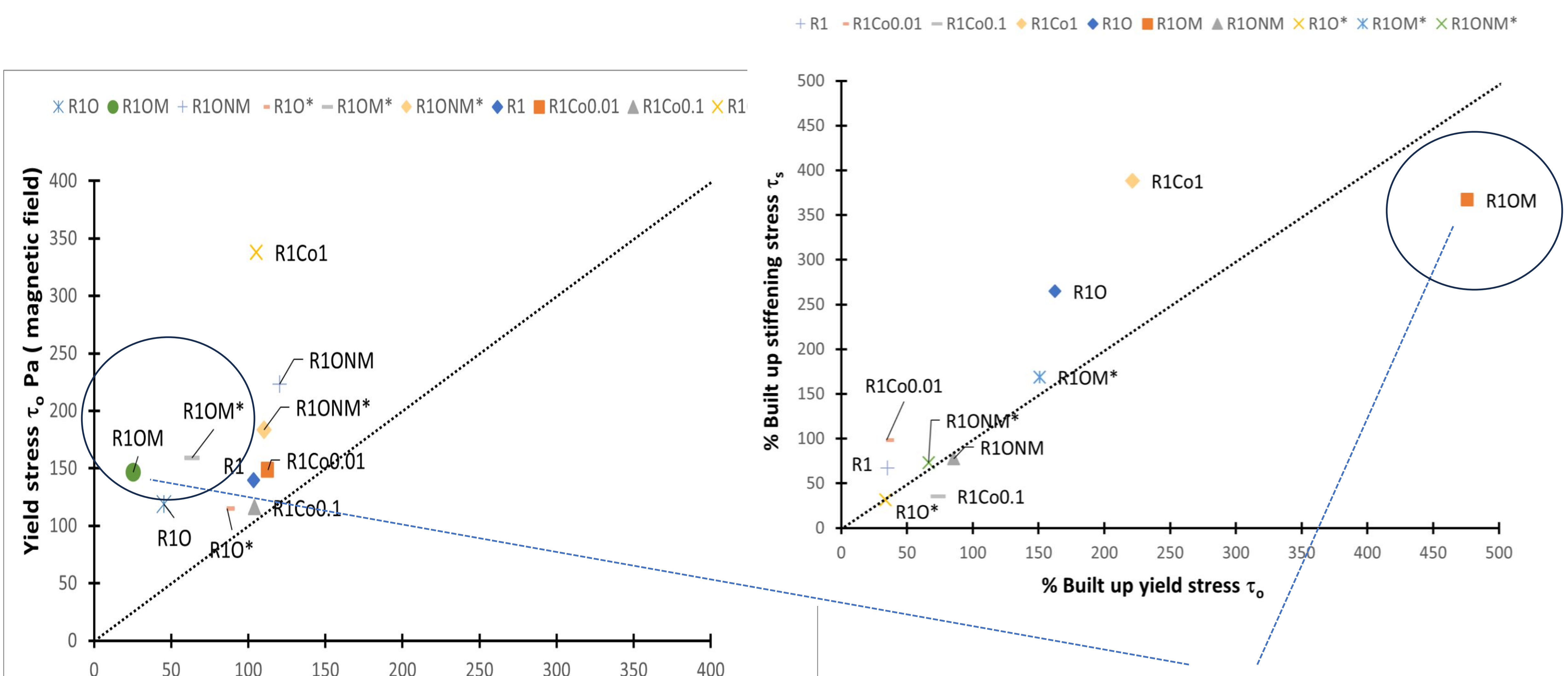
Mix Id	Mix Constituents	Ink Composition (%)				
		Portland Cement	Fly ash	Milled fly ash		Super Plasticizer
				Magnetic	Non-magnetic	
R_1O	PC+FA+SP	90	10	-	-	0.15
R_1OM	PC+OM+SP	90	-	10		0.15
R_1ONM	PC+ONM+SP	90	-	-	10	0.15
R_1O*	PC+FA	90	10	-	-	-
R_1OM*	PC+OM	90	-	10	-	-
R_1ONM*	PC+ONM	90	-	-	10	-

Rheological response of inks with beneficiated fly ash





Yield stress & Stiffening: the effect of the magnetic field



<u>Magnetic ash</u>

Conclusions

- The addition of fly ash to superplasticized portland cement ink intended for 3D printing applications increases the plastic viscosity and reduces yield stress to zero, making the system to follow the Newtonian response - this property makes the system workable and suitable for pumping operations; however, near-zero yield property was found to be not desirable for 3D printing;

- The use of nano-particles in reference systems based on portland cement and portland cement-fly ash inks produces an effect of a significant increase in yield stress and also results in a stiffening phenomenon at near-zero shearing rates as described by the Sticky Particle Model;

- Therefore, the addition of nano-silica or nano-alumina to the ink systems can be a very effective performance-enhancing solution for the development of a next generation of inks for 3DPC;

Conclusions

- The research results demonstrate that even a relatively small magnetic field of 0.1 T is capable of altering the rheological response of MRCI compositions based on a combination of portland cement, fly ash, nano-particles, and magnetite powder;

- The Sticky Particles Model, based on the “inverted” Papanastasiou equation describes the ideal ink material suitable for the design of smart MRCI intended for 3D printing applications, which incorporates the stiffening parameter;

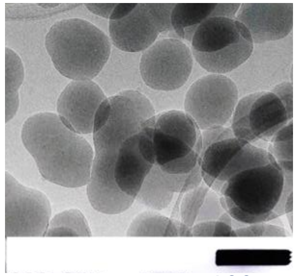
- Beneficiation of fly ash to harvest magnetic components was proven to be feasible. The portland cement systems with fly ash – especially, beneficiated fly ash - have demonstrated considerable increase in yield and stiffening when magnetic field was applied.

SMALL STEPS TO IMPACT CONCRETE WORLD

- **RILEM TC197 2002-08**
- Nanocem 2005
- ACI 236D 2005-15
- NICOM 1 2003
- NICOM 2 2005
- NICOM 3 2009
- Rusnano RT 2010
- TRB-1 2010
- NICOM 4 2012
- **ACI 241 2014**
- **CNNS 2014**
- NICOM 5 2015
- ACI 241 Report 2017
- ICNNC 2017
- **NICOM 6 2018**
- **NICOM 7 2022**
- **NICOM 8 2024**

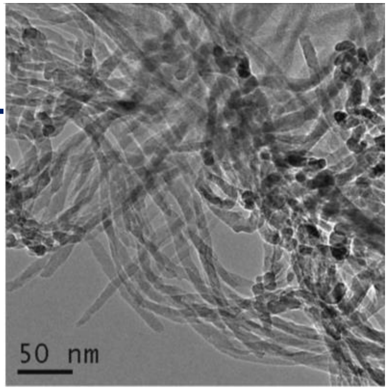
ACKNOWLEDGMENTS

- PCA
- EPRI
- HOLCIM
- Zignego Ready Mix
- BASF
- Grace Construction Products
- Handy Chemicals
- Kuraray
- WE Energies
- NSF
- UWM RGI & UWM Foundation



Nouryon

ANF Technology



- Aparna Deshmukh
- Rosalba A Huerta
- Ismael Flores-Vivian
- Marina Kozhukova
- Filip Zemajtis
- Reed T Heintzkill
- Milad Manjili
- Reza Moini
- Scott Muzenski

THANK YOU!!!

Questions?   E-mail: sobolev@uwm.edu