Revolutionizing Ultra-High Performance Concrete: Unleashing Metakaolin and Diatomaceous Earth as Sustainable Fly Ash Alternatives

Meghana Yeluri (Doctoral Candidate)

Yashovardhan Sharma (Doctoral Candidate)

Dr. Srinivas Allena (Assistant Professor)

Cleveland State University

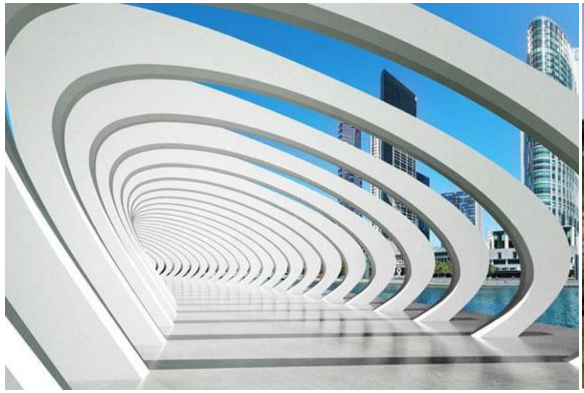
Cleveland, OH

Introduction

- **UHPC Definition (ASTM C1856):** The concrete must have a flow between **8 to 10 inches**, and the nominal maximum size of aggregate should be less than ¼ inch. Additionally, it should have a compressive strength of at least **17,000 psi**.
- Superior flexural performance
- Enhanced tensile ductility
- Dense microstructure
  - Enhanced durability and resistance to various forms of degradations
- Design versatility
  - Reduced number of structural elements
  - Thinner X-sections

Applications of UHPC



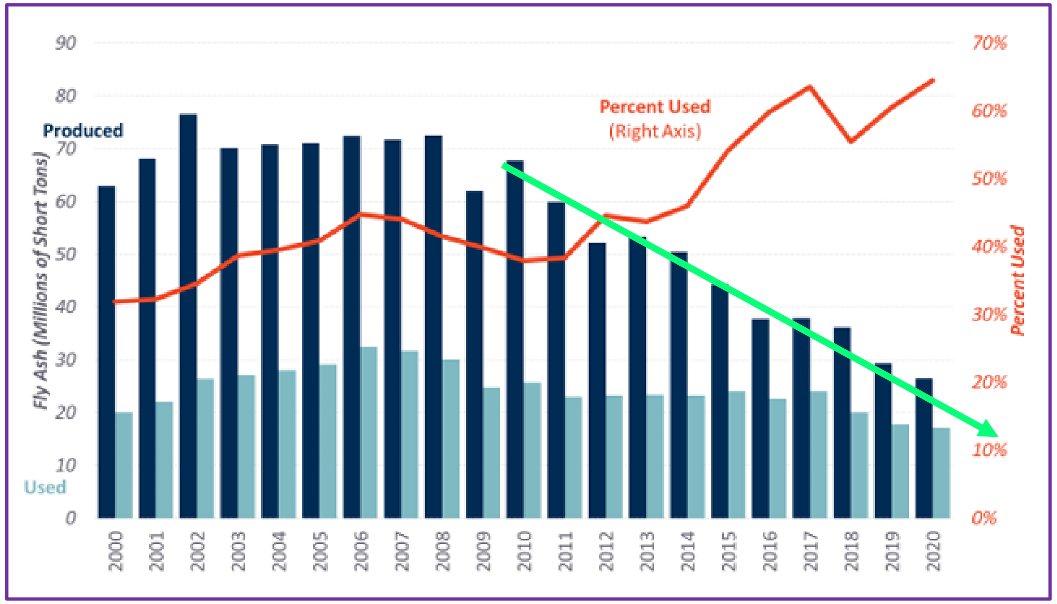



American Mars Hill Bridge,
Wapello county, Iowa

- Connection of bridge elements
- Closure pore spaces
- Overlays and repairs
- Grout for bridge shear keys
- Architectural elements-Intricate shapes
- Nuclear applications - Grout for nuclear waste disposal

Research Significance

- Silica fume is the primary supplementary cementitious material (SCM) in UHPC.
- Expensive silica fume is often substituted with inexpensive class F fly ash.
- Unfortunately, the future availability of fly ash is uncertain as the energy industry moves toward renewable energy.
- Fly ash shortages create an urgent need to find cost-effective and environmentally-friendly alternatives for fly ash.



Report from American Coal Ash Association

Enhance the sustainability of non-proprietary UHPC by investigating the alternative SCMs: Metakaolin and Diatomaceous earth.

Experimental Protocol

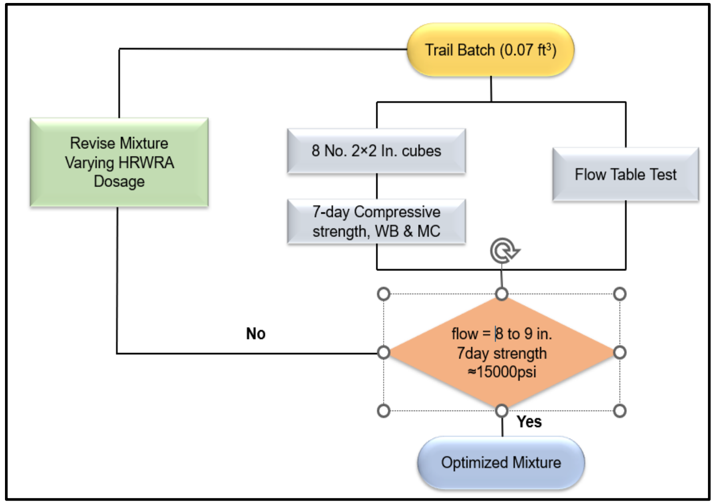
Materials:

- ASTM #4 local sand
- ASTM Type 1L cement (PLC)
- Class F fly ash (FA), Silica fume (SF), Metakaolin (MK) , and Diatomaceous earth (DE)
- Polycarboxylate based HRWRA
- 0.5 inch Steel fibers (aspect ratio = 65)

Curing Regimens:

Moist curing	MC	After demolding, the specimens were placed in a moist room with ~100% RH and temperature 23.5°C (74°F) until the day of testing
Warm bath curing	WB	After demolding, specimens were cured in a water bath at 90˚C (194˚F) until the time of testing.

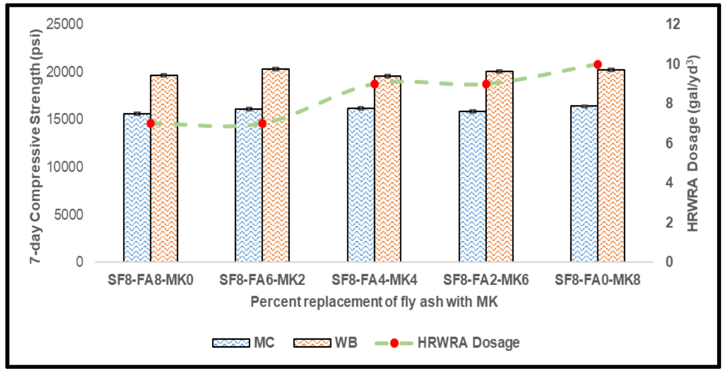
Final Mixture Proportions



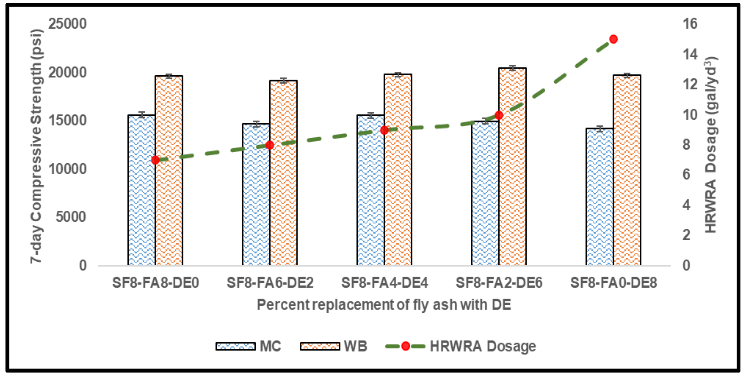
Control UHPC

Mixture		PLC lb/yd^3	SF lb/yd^3	FA lb/yd^3	MK lb/yd^3	DE lb/yd^3	Sand lb/yd^3	Steel fibe lb/yd^3	HRWRA gal/yd^3	Water lb/yd^3	w/cm	Flow inches
Control UHPC	SF8-FA8	1500	150	150	0	0	1584	200	7	360	0.2	10
MK Modified UHPC	SF8-FA6-MK2	1500	150	112.5	37.5	0	1602	200	7	353	0.2	9
	SF8-FA4-MK4	1500	150	75	75	0	1577	200	9	345	0.2	9
	SF8-FA2-MK6	1500	150	37.5	112.5	0	1596	200	9	338	0.2	9
	SF8-FA0-MK8	1500	150	0	150	0	1592	200	10	330	0.2	9
DE Modified UHPC	SF8-FA6-DE2	1500	150	112.5	0	37.5	1575	200	8	353	0.2	8.5
	SF8-FA4-DE4	1500	150	75	0	75	1566	200	9	345	0.2	8.5
	SF8-FA2-DE6	1500	150	37.5	0	112.5	1558	200	10	338	0.2	8.5
	SF8-FA0-DE8	1500	150	0	0	150	1461	200	15	330	0.2	8.5

Optimization – MK and DE Modified UHPC



Optimization of MK content



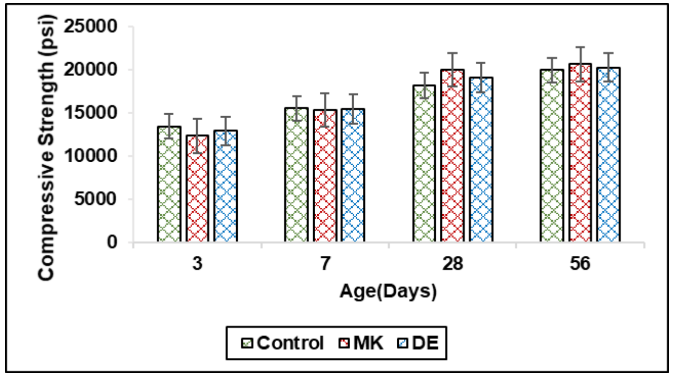
Optimization of DE content

MK and DE replaced 100% of the FA, as these mixtures exhibited compressive strengths greater than 17,000 psi.

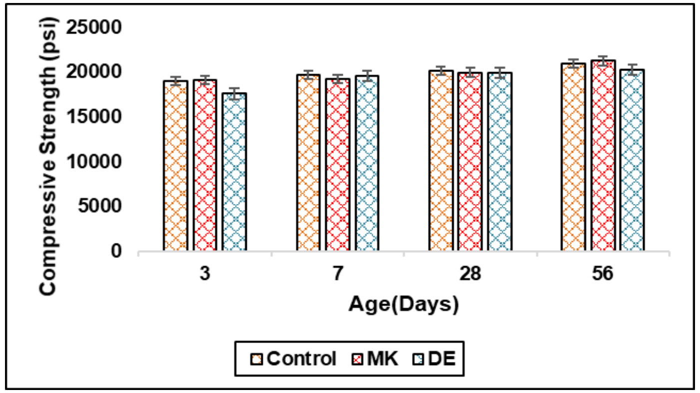
- ✓ As the dosage of MK increased, there was an increase in HRWRA dosage.
- ✓ The SF8-FA0-MK8 mixture (100% FA replacement) showed the highest strength, with 6.8% and 2.2% increases in MC and WB cured specimens, respectively, compared to the control specimens.

- ✓ As the dosage of DE increased, there was an increase in HRWRA dosage.
- ✓ Maximum strength was observed in mixtures with 75% replacement of fly ash with DE in WB curing.
- ✓ 100% replacement resulted in 10% decrease in MC and 5% decrease in WB when compared to control.

Compressive Strengths of UHPC Mixtures



Compressive strengths of MC cured UHPC

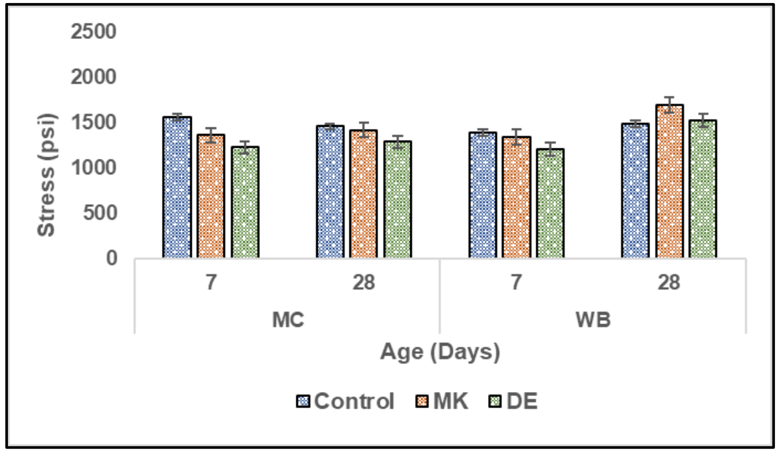


Compressive strengths of WB cured UHPC

- ✓ Compressive strength is increasing with age, whereas rate of hydration is decreasing.
- ✓ Strength gain in fly ash based UHPC (control) was faster compared to UHPC mixtures with MK and DE.
- ✓ The control mixture gained 68% of its 56-day strength within three days, whereas MK and DE-based mixtures achieved approximately 60% of their 56-day strength in the same time frame.

- ✓ 90% of 56-day compressive strength was attained in three days.
- ✓ After 28 days, there was a marginal strength gain (<10%).
- ✓ At 56 days, the MK mixture showed a 3.5% increase, while the DE mixture exhibited a 1.7% decrease when compared to the control mixtures.
- ✓ Specimens cured under both WB and MC regimens exhibited similar strengths at 56 days (less than 5% difference).

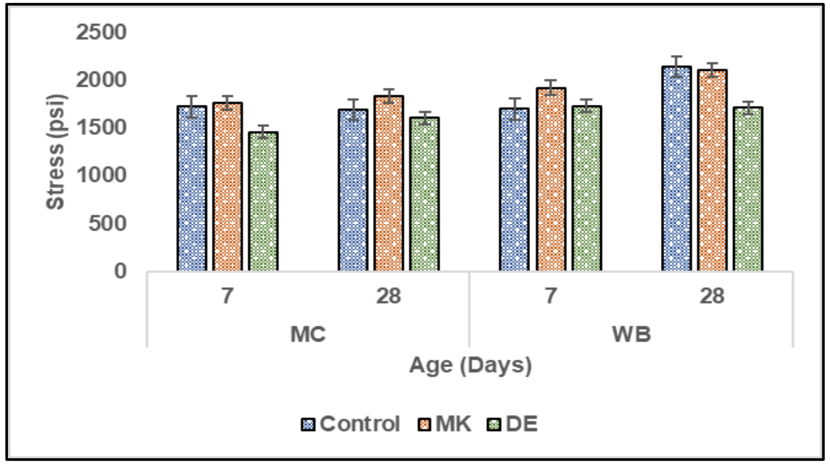
Flexural Strength of UHPC Mixtures



First Peak Strength (MOR)

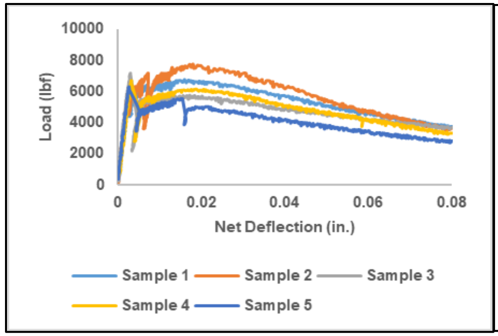
- Control mixture performed better than MK and DE modified UHPC.
- At seven days, MC cured specimens exhibited greater flexural strengths than WB cured specimens while at 28 days, WB cured specimens performed better.
- At 28 days, the flexural strength in MK and DE modified WB cured UHPC showed a 26% increase compared to the strength at seven days.

The seven day flexural strength of MK and DE modified UHPC, when WB cured, exhibited a decrease of 1.1% and 1.2%, respectively, compared to MC cured specimens.

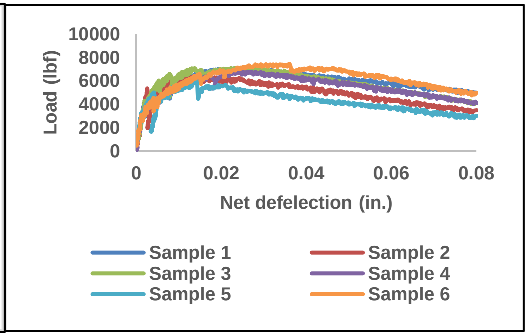


Peak Strength

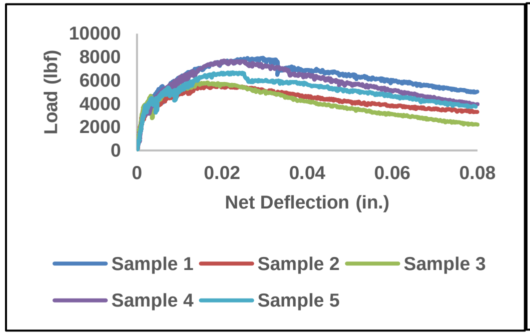
Load Deflection Curves



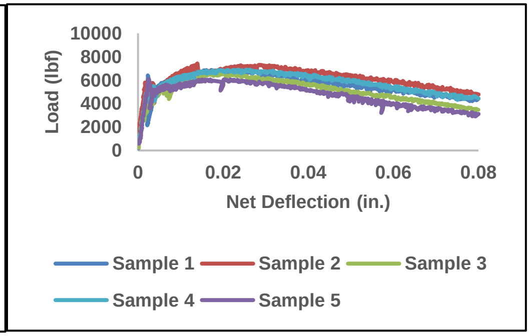
(a)



(b)

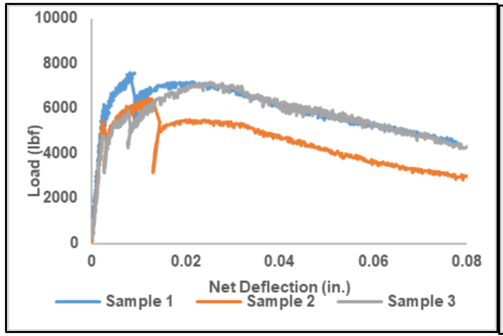


(c)

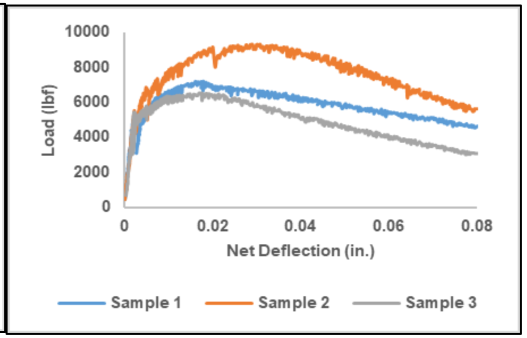


(d)

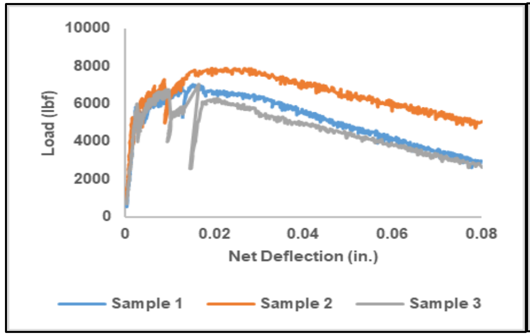
Load-deflection curves for specimens of control UHPC mixtures cured under (a) MC, 7days (b) WB,7days (c) MC, 28 days (d) WB, 28days



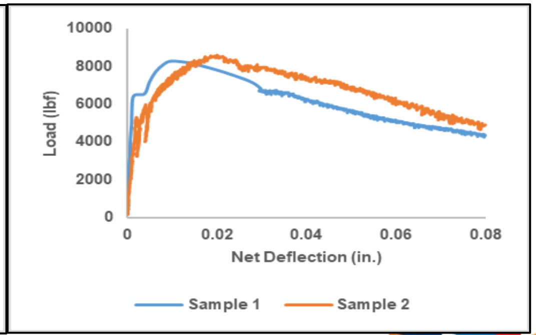
(a)



(b)



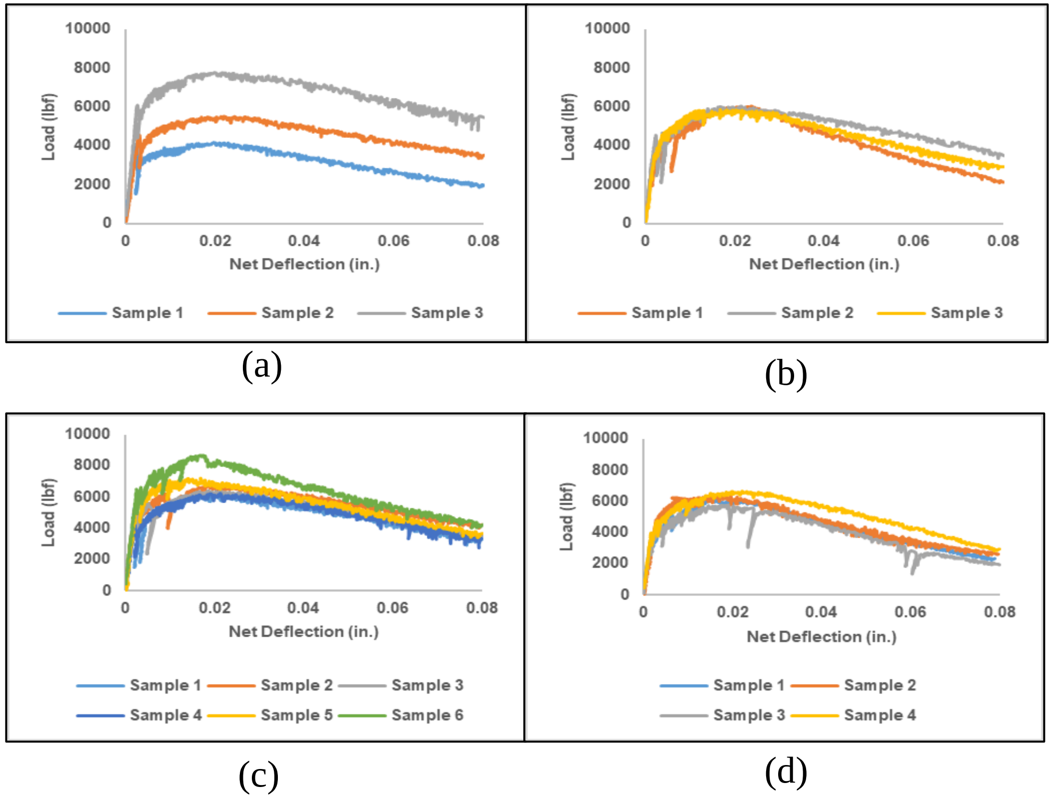
(c)



(d)

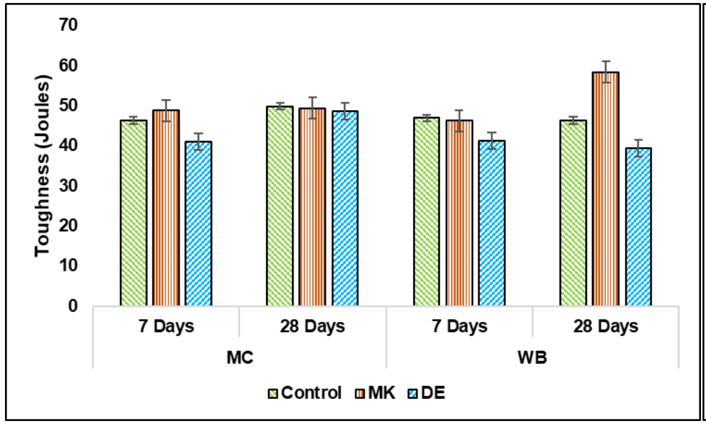
Load-deflection curves for specimens of MK modified UHPC mixtures cured under (a) MC, 7days (b) WB,7days (c) MC, 28 days (d) WB, 28days

Load Deflection Curves

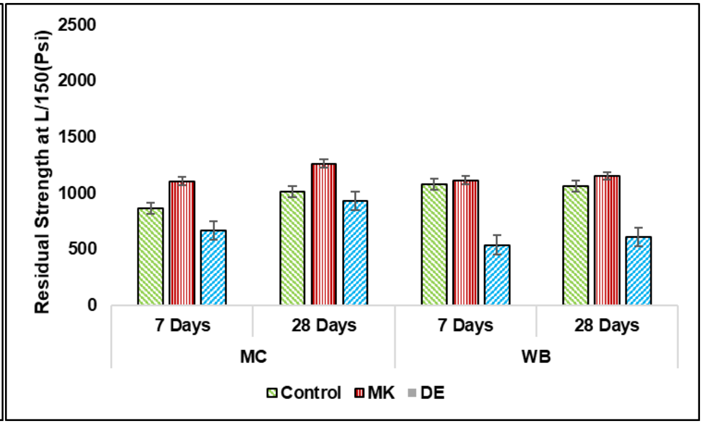


Load-deflection curves for specimens of DE modified UHPC mixtures cured under (a) MC, 7days (b) WB,7days (c) MC, 28 days (d) WB, 28days

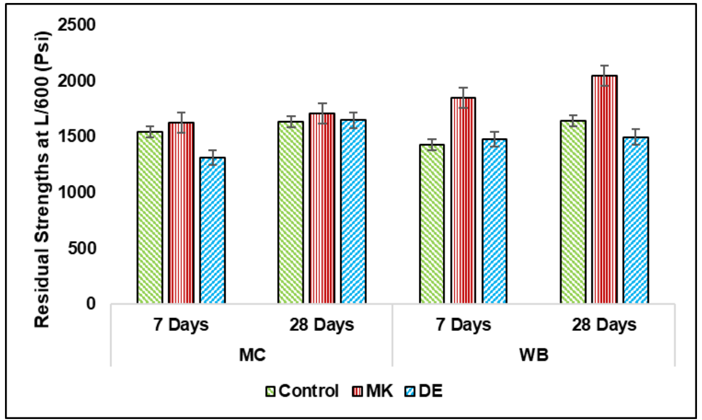
Toughness and Residual Strengths



Toughness



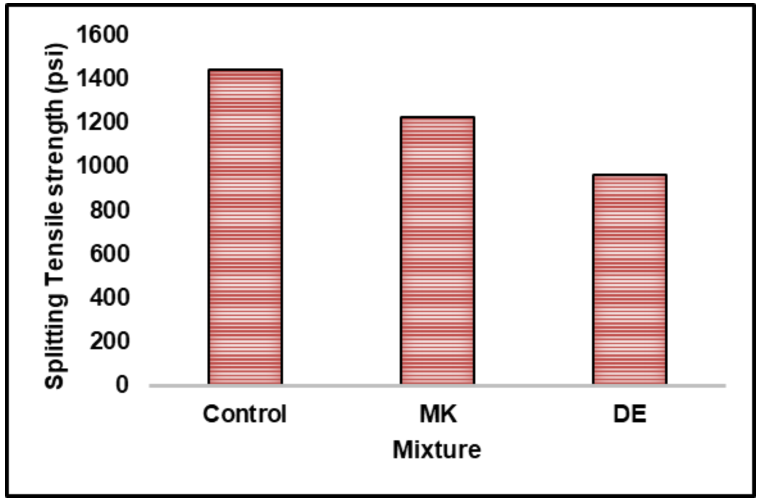
Residual Strengths at L/150



Residual Strengths at L/600

- MK modified UHPC cured under WB regimen exhibited greatest toughness value of 58.4 Joules at 28 days.
- f_{150}^{D} value of MK-modified UHPC was the greatest in both MC and WB curing regimens at seven and 28 days with DE being the least.
- Similar trend was observed for f_{600}^{D}, except in the cases of 28-day MC curing and 7-day WB curing regimens.
- At 28 days, MC-cured DE specimens had a residual strength nearly 1% greater than the control mixture, while WB-cured specimens at seven days exhibited a 3.5% increase compared to the control mixture.

Split Tensile Strength MC Cured UHPC

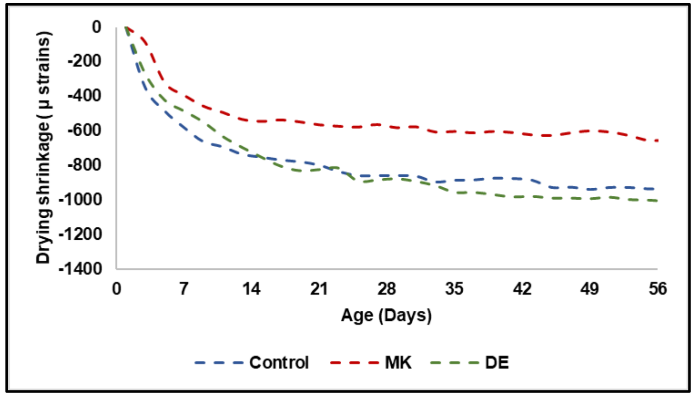


Splitting tensile strengths of UHPC mixtures

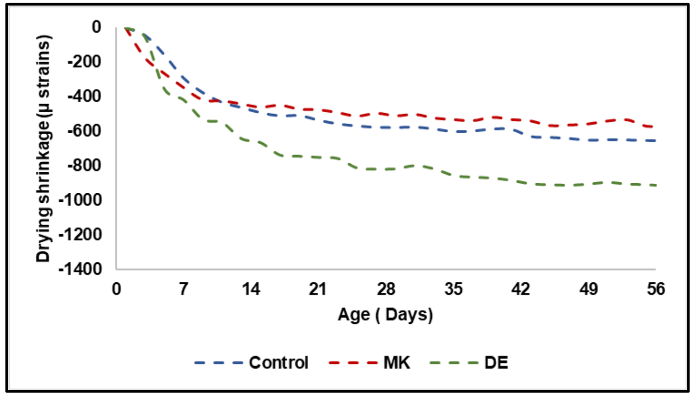
Split tensile strength testing

- The split tensile strength of MK and DE modified UHPC decreased by 15% and 33%, respectively, when compared to the control mixture.

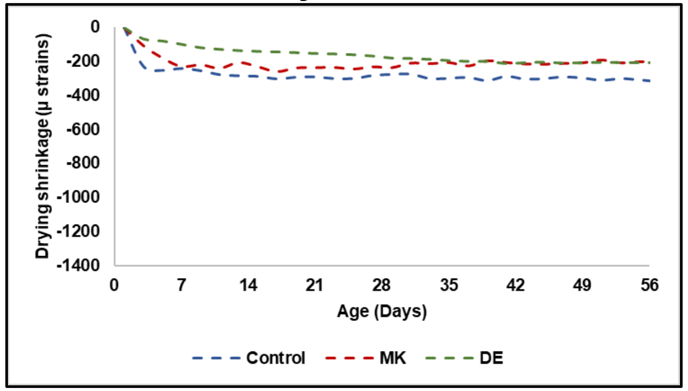
Effect of SCM Type on Drying Shrinkage of UHPC Cured Under Different Curing Conditions



Air dry condition



MC-Dry condition

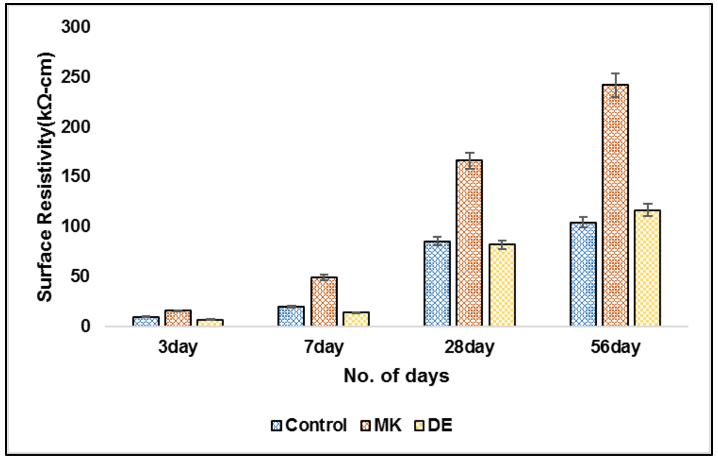


Moist condition

Mixture Designation	Drying shrinkage (μstrains)		
	Curing Condition		
	Air dry	MC-dry	Moist
Control	923	645	288
MK	655	561	210
DE	1001	928	215

- Air dry condition: MK shrank less by 29% and DE shrank more by 8.4%.
- Mc-dry condition: MK shrank less by 13% and DE shrank more by 44%.
- Moist condition: MK and DE shrank less by 27% and 25% respectively.

Surface Resistivity of UHPC Mixtures



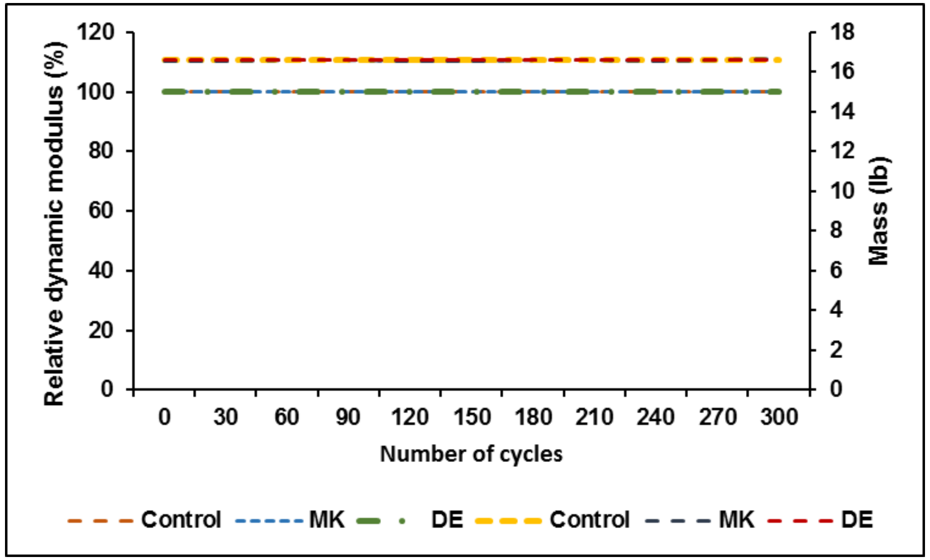
Surface resistivity of UHPC

Surface Resistivity	Chloride Ion Penetration
<12	High
12-21	Moderate
21-37	Low
37-254	Very Low
>254	Negligible

- Surface resistivity is increasing with age in all the UHPC mixtures.
- MK modified UHPC exhibited "very low" chloride ion penetration susceptibility in seven days.
- At 56 days, surface resistivity of DE modified UHPC was 12% greater than the control mixture.
- At the age of 56 days, all the mixtures fell under the category of "very low" chloride ion penetrability.

Surface resistivity measurement

Freeze –Thaw Durability of UHPC Mixtures



Relative Dynamic Modulus values of UHPC mixtures

Freeze-thaw testing

- No change in relative dynamic modulus was observed until 300 cycles.
- No change in mass was observed until 300 cycles was overserved.

Summary

- Metakaolin (MK) and diatomaceous earth (DE) were investigated as SCMs alternative to fly ash.
- Two different curing regimes: MC and WB were employed to investigate the effect of curing temperature on mechanical properties of UHPC.
- MK-modified UHPC exhibited greater compressive strength compared to DE and control mixtures, with DE-modified mixture being the least (~1% less than control).
- WB cured MK and DE modified mixtures exhibited greater flexural strengths at 28 days.
- All the mixtures shrank less than 1000 microstrains in any curing regimen.
- All the mixtures exhibited “very low” chloride ion penetrability.
- Excellent freeze-thaw durability was observed in all the mixtures.
- Both MK and DE are viable substitutes for fly ash, as MK- and DE-modified UHPC mixtures demonstrated desired flow values (8 to 10 inches) and comparable mechanical performance.

Questions?