

# From Steel to Synthetic: Unlocking the Potential of PVA and Carbon Fibers in Ultra-High Performance Concrete

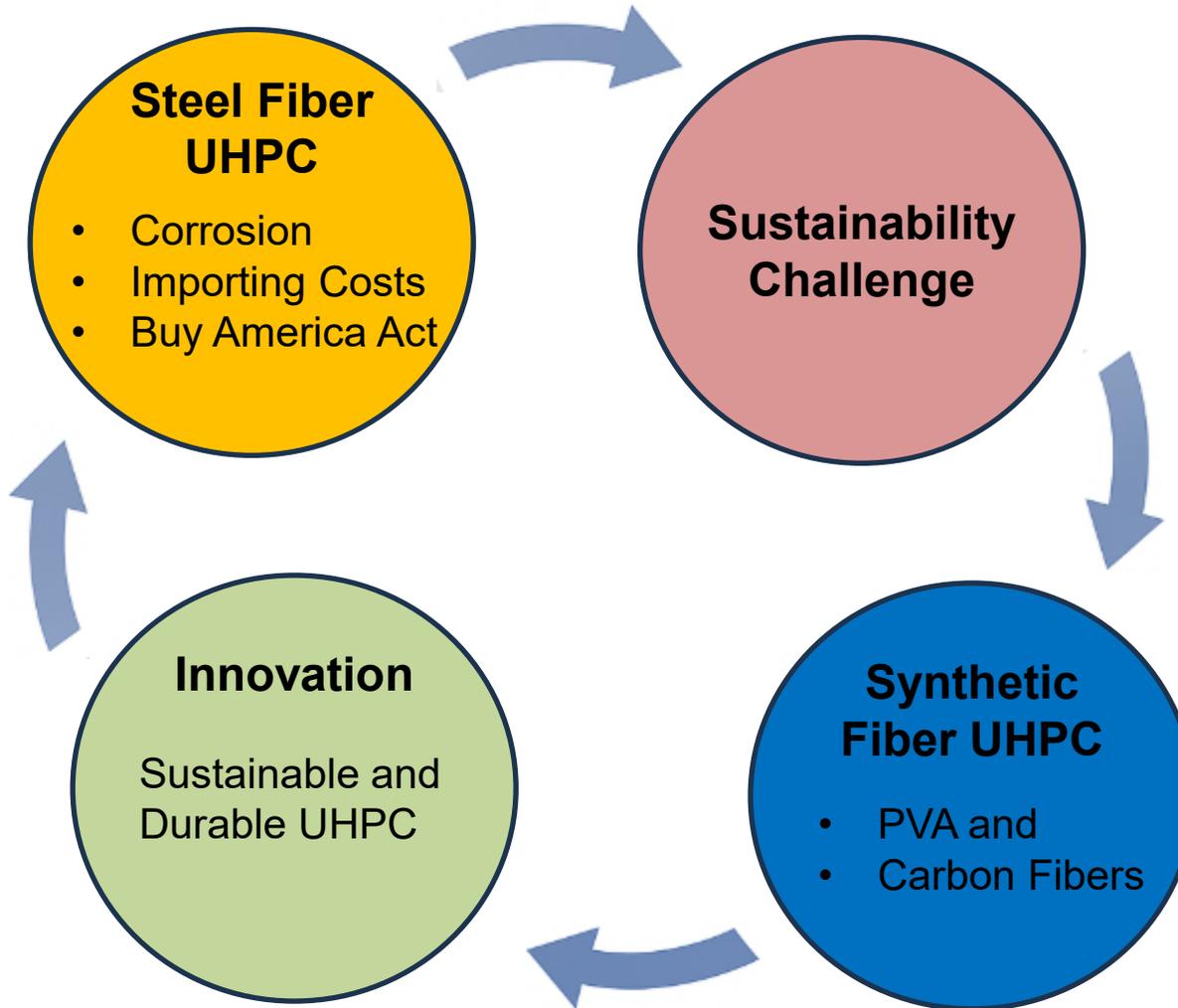
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# Introduction



# Research Objectives

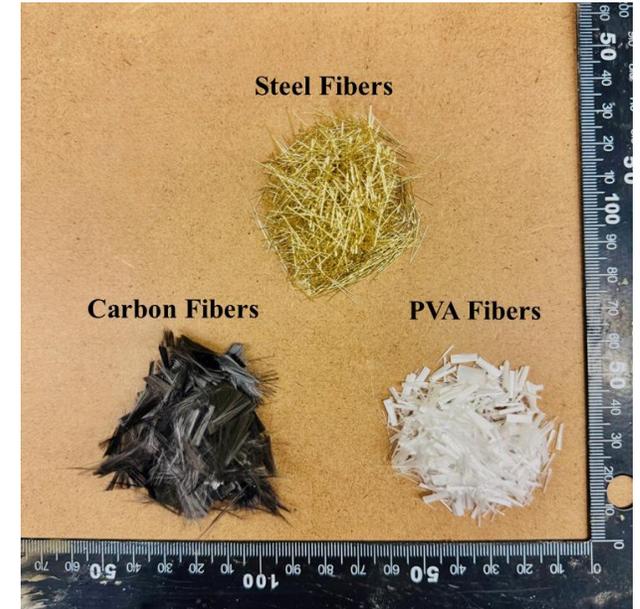
Develop synthetic fiber–reinforced UHPC mixtures using polyvinyl alcohol (PVA) and carbon fibers (CF) as sustainable alternatives to steel fibers and evaluate effects on workability, mechanical strength, shrinkage, and durability properties.

## Research Focus

- Investigate fiber replacement levels (0%, 33%, 50%, 75%).
- Maintain total fiber volume at 1.5%.
- Identify optimum synthetic fiber combination balancing strength, ductility, and workability.

## Hypothesis

Partial replacement of steel fibers with PVA and carbon fibers can maintain UHPC performance while improving sustainability.



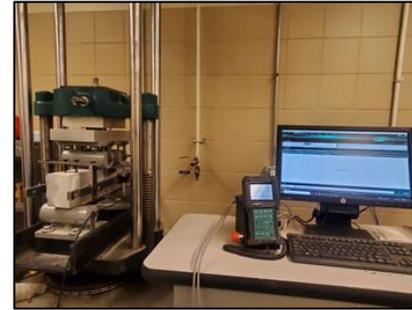
# Experimental Methods



Flow table test : ASTM C1437



Compressive Strength :  
ASTM C109



Flexural Testing :  
ASTM C1609



Split Tensile Strength  
: ASTM C496



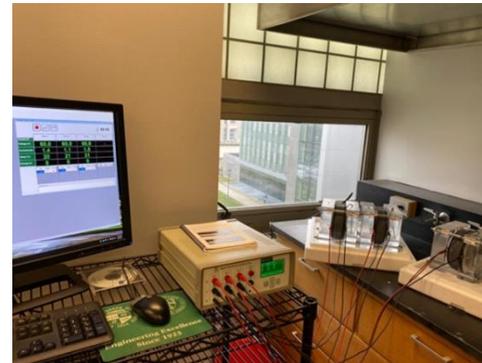
Modulus of Elasticity  
: ASTM C469



Drying shrinkage  
: ASTM C157



Sorptivity: ASTM C1585



RCPT : ASTM C1202

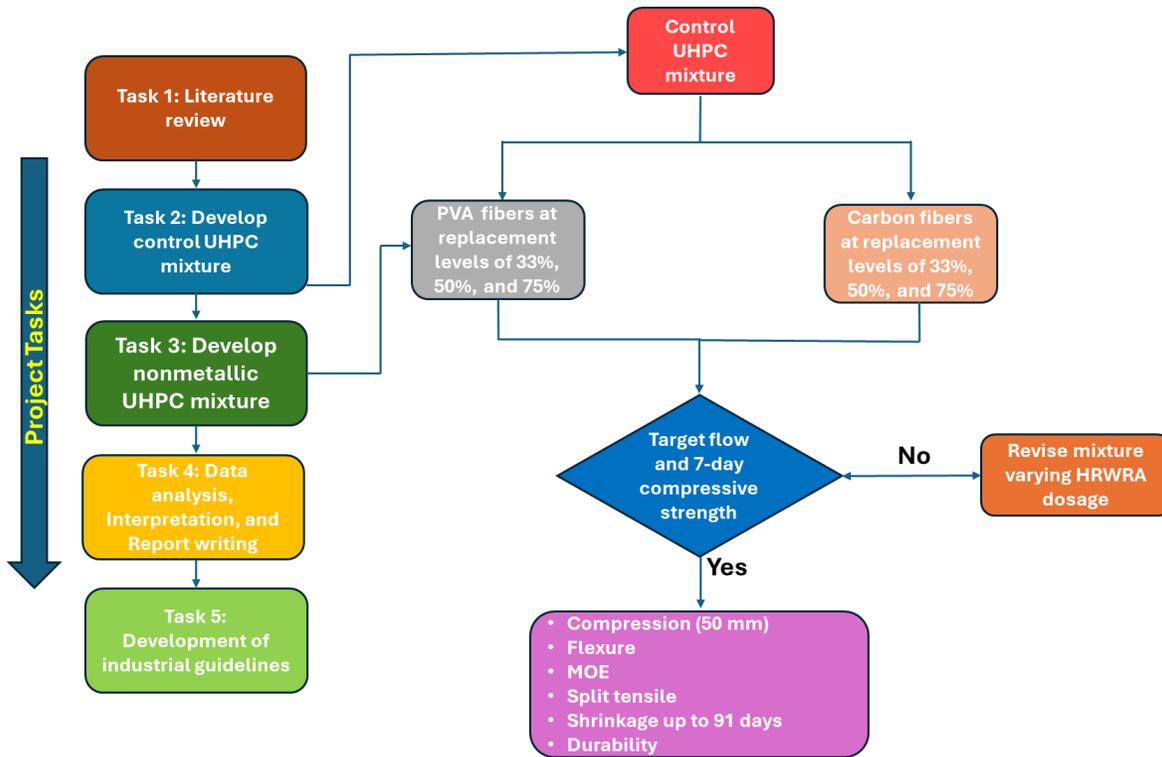


Surface Resistivity :  
AASHTO T 358

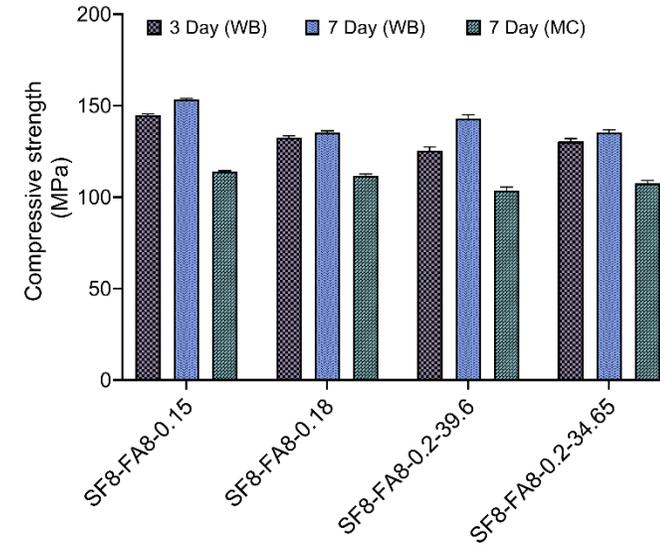
**Repeated at least twice for consistency, reliability, and comparability of the results.**

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# Research Approach



Total fiber volume: 1.50%

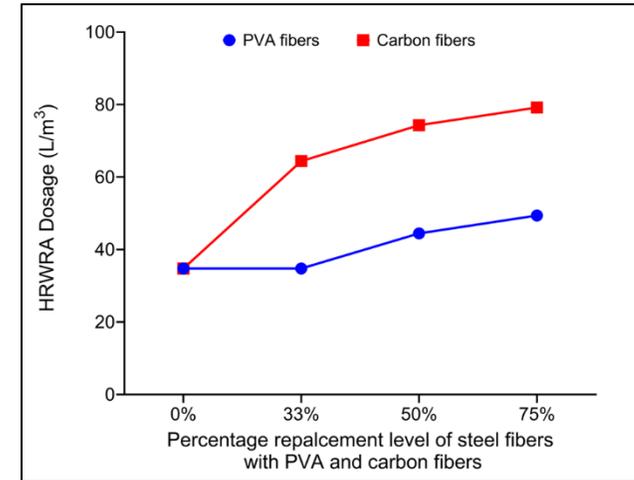


- Mixture **SF8-FA8-0.2-34.65g (Control UHPC)** exhibited desired workability ( 203 to 230 mm), seven day compressive strengths.
- This mixture is being used in the development of nonmetallic UHPC.

# Workability

## Mixture proportions for synthetic fiber reinforced UHPC mixtures developed in this study

Mixture Designation	PLC kg/m <sup>3</sup>	SF kg/m <sup>3</sup>	FA kg/m <sup>3</sup>	Sand kg/m <sup>3</sup>	Steel kg/m <sup>3</sup>	PVA kg/m <sup>3</sup>	Carbon kg/m <sup>3</sup>	Water kg/m <sup>3</sup>	HRWRA L/m <sup>3</sup>	w/cm	Flow mm
Control UHPC	890	89	89	939.7	118.7	0	0	213.6	34.65	0.2	254
PVA 33%	890	89	89	920.6	79.5	6.5	0	232.6	34.65	0.2	245
PVA50%	890	89	89	895.2	59.3	8.8	0	232.1	44.56	0.2	240
PVA75%	890	89	89	882.5	39.2	13.3	0	231.9	49.5	0.2	240
Carbon 33%	890	89	89	844.4	79.5	0	9	231	64.36	0.2	230
Carbon 50%	890	89	89	819	59.3	0	13.7	230.5	74.27	0.2	220
Carbon 75%	890	89	89	806.3	39.2	0	18.31	230.3	79.2	0.2	220

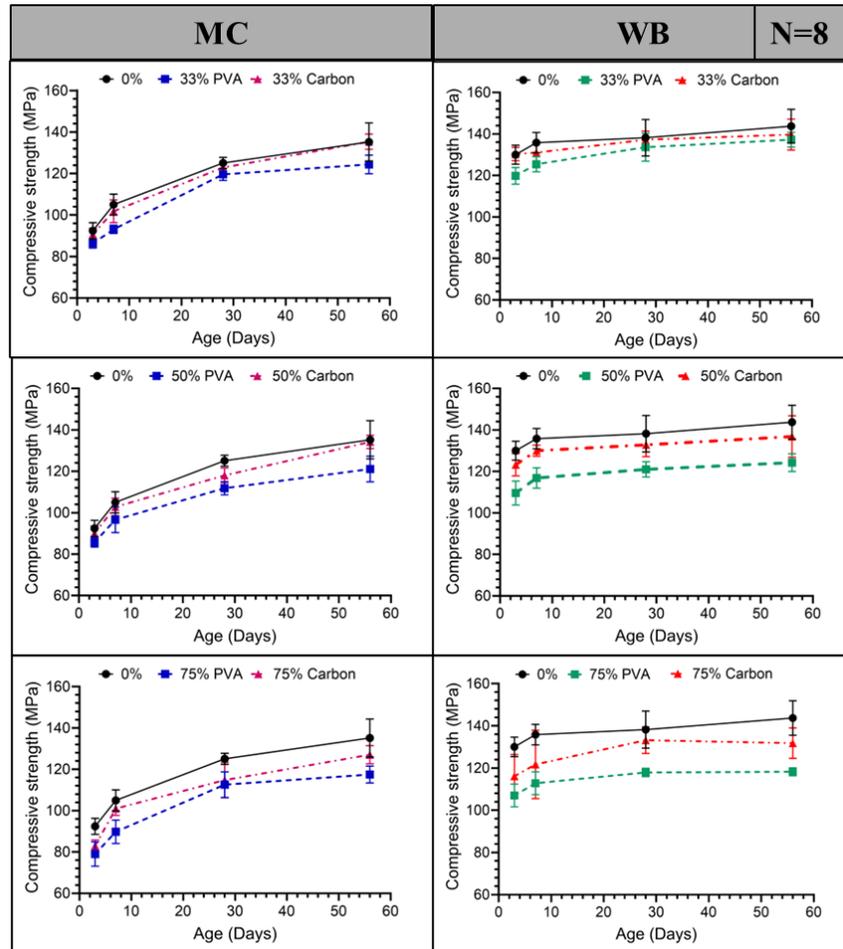


- PVA 33% refers to a mixture in which 33% (0.5%) of the total fiber volume is PVA fibers, with the remaining 67% (1.0%) as steel fibers.
- HRWRA dosage adjusted to achieve target flow of 203–230 mm.
- Workability decreased with higher synthetic fiber content.
- PVA fibers required up to 49.5 l/m<sup>3</sup> HRWRA at 75% replacement (vs 34.65 l/m<sup>3</sup> for control), because of hydrophilic nature of PVA fibers.
- Carbon fibers showed greater impact, needing 64–79 l/m<sup>3</sup> at 33–75% replacement. Though hydrophobic in nature, reduction attributed to fiber agglomeration, higher surface area, and water absorption.



# Compressive Strength of 50 mm cubes

Steel fiber > Carbon fiber > PVA fiber  
regardless of replacement level or testing age



## PVA Fiber Mixtures

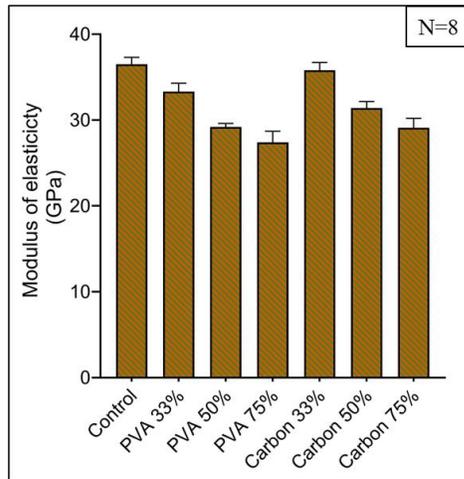
- 33% replacement showed the smallest reduction
- All mixtures achieved  $\geq 120$  MPa by 28 days in WB, except at 75% replacement under both curing regimens (even at 56 days).
- Lower elastic modulus of polymeric fibers vs. steel  $\rightarrow$  less effective in bridging microcracks under compression.
- High aspect ratio of PVA  $\rightarrow$  poor dispersion, fiber clustering, and premature debonding at the matrix interface resulting in non-uniform load transfer.

## Carbon Fiber Mixtures

- Negligible loss in compressive strength ( $< 5\%$  for 33% and 50% replacement levels and  $< 10\%$  for 75% replacement levels in both the curing regimens.
- Due to poor wetting and agglomeration.
- All mixtures still achieved UHPC'S target strength by 56 days in MC.



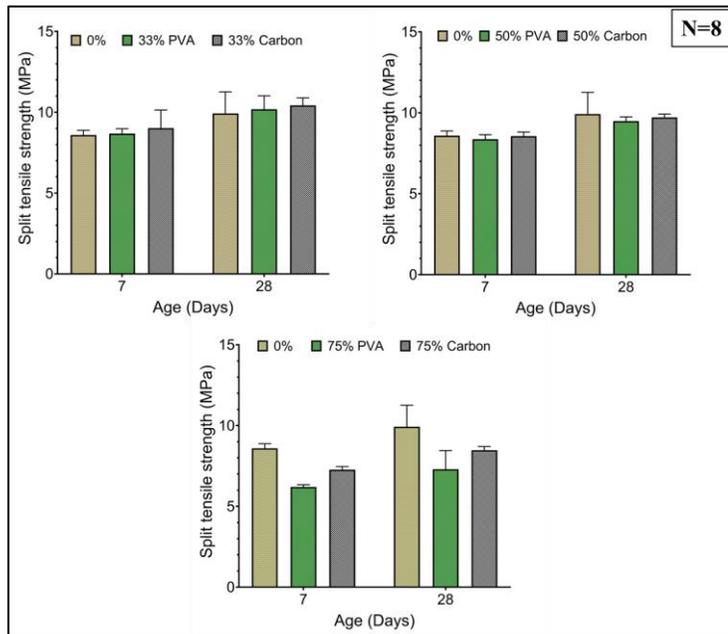
# Modulus of Elasticity and Split Tensile Strength



**Modulus of Elasticity:** Control > Carbon > PVA

Slight decline with increasing steel fiber replacement  
33% replacement maintained ~95% of control stiffness.

- **PVA mixtures** showed least stiffness reduction due to polymeric flexibility.
- **Carbon fibers** provided better stiffness retention owing to their higher modulus and strong confinement effect.



## Splitting Tensile Strength

**Control UHPC mixture:** 9.9 MPa

**PVA fiber mixtures:**

33% replacement → 2.6% ↑

50–75% replacement → further reduction of 4.4% and 30.5%

**Carbon fiber mixtures:**

33% replacement → 4.8% ↑

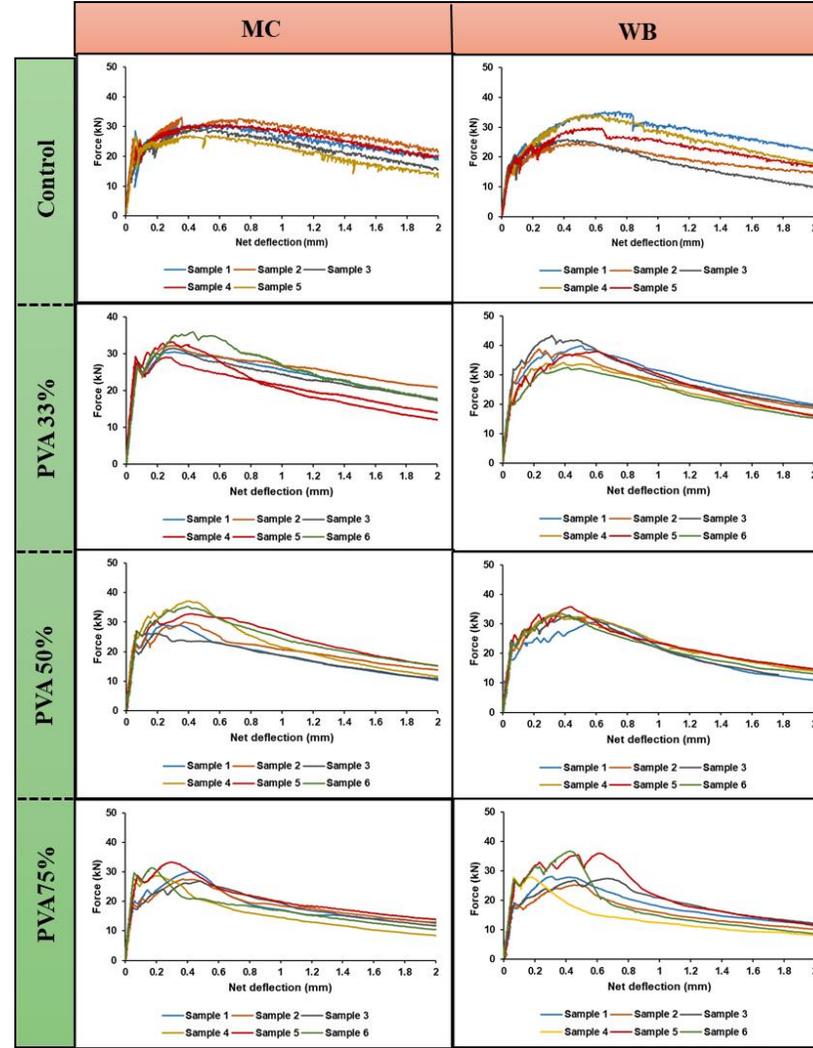
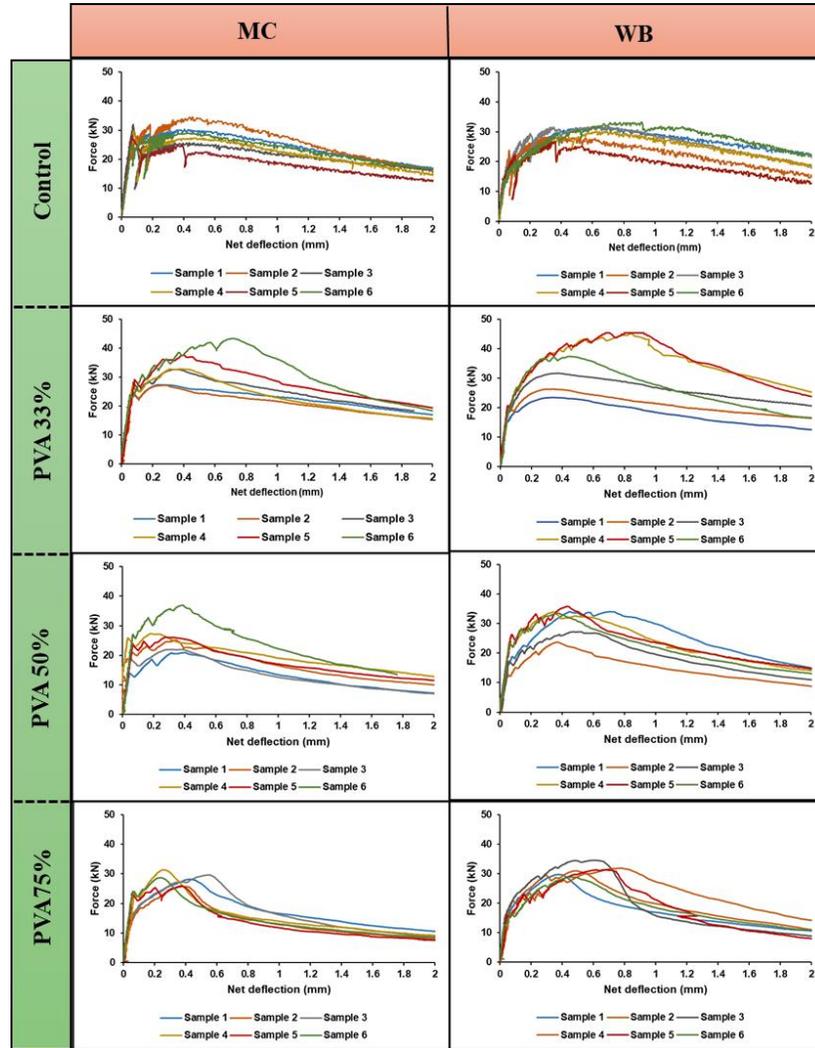
50% replacement → 2.1% ↓

75% replacement → 16% ↓

# P-Δ Behavior of PVA Fiber Reinforced UHPC

Seven Days

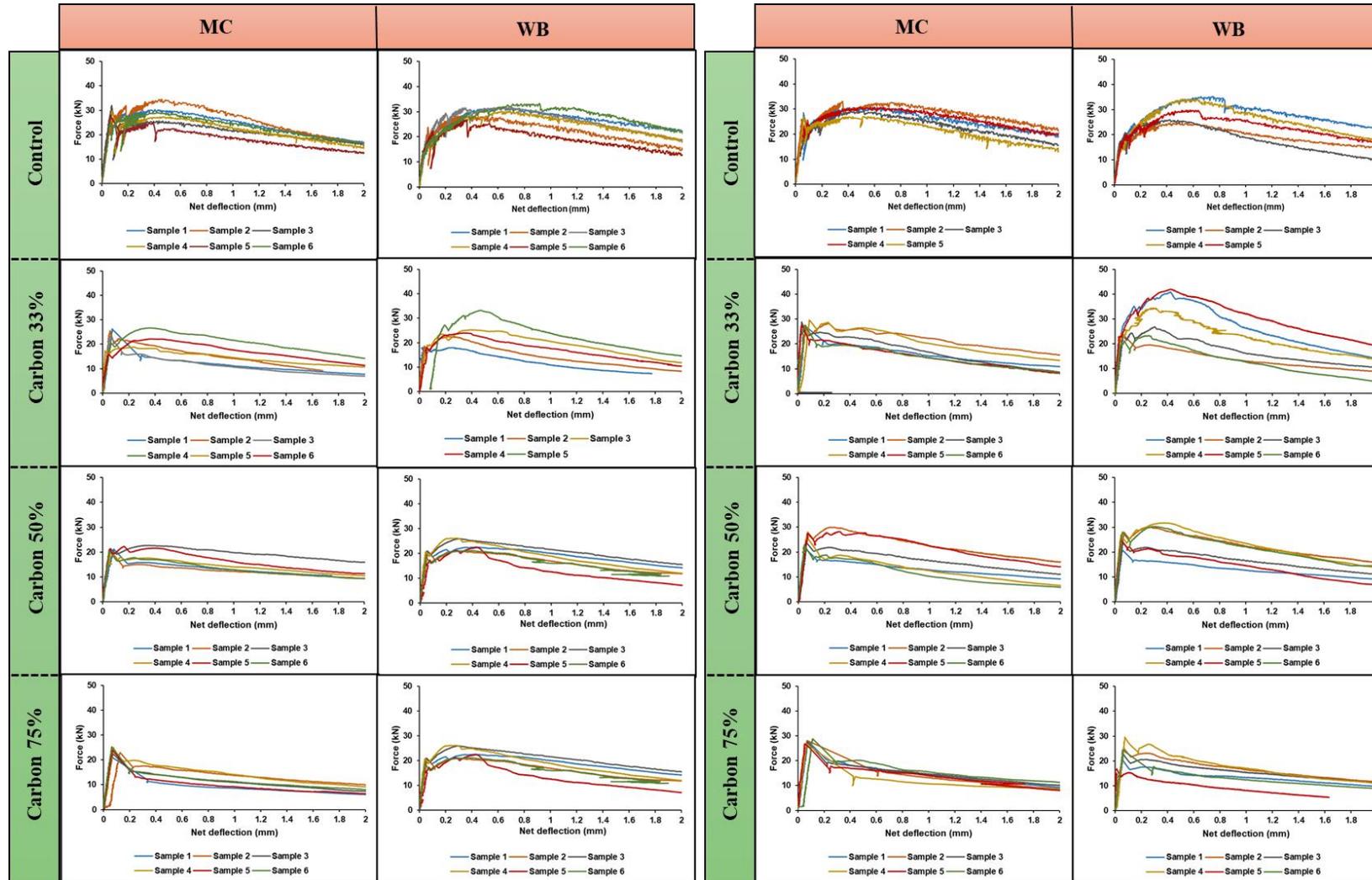
28 Days



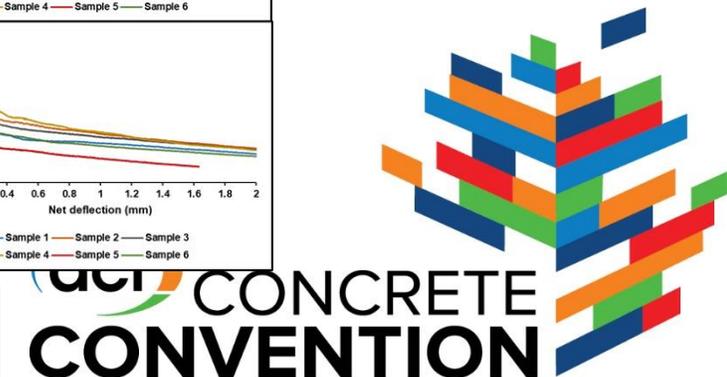
# P-Δ Behavior of Carbon Fiber Reinforced UHPC

Seven Days

28 Days

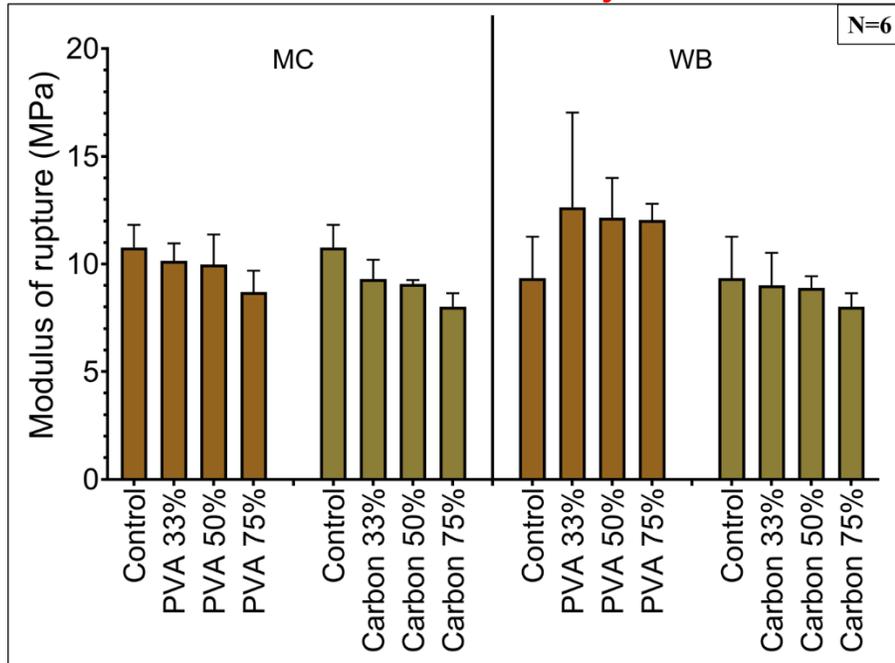


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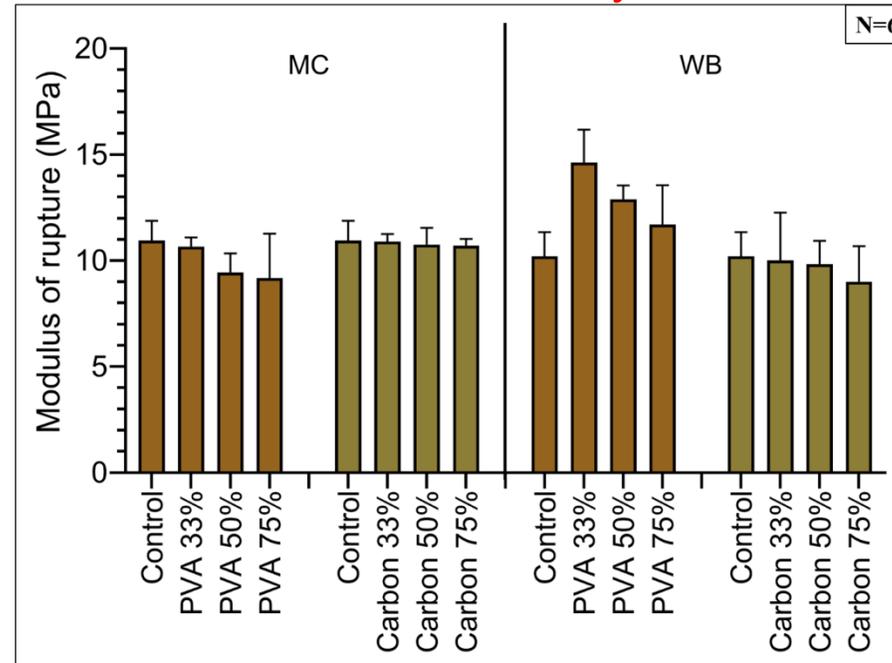


# Flexural Properties – First Peak Strength

Seven Days



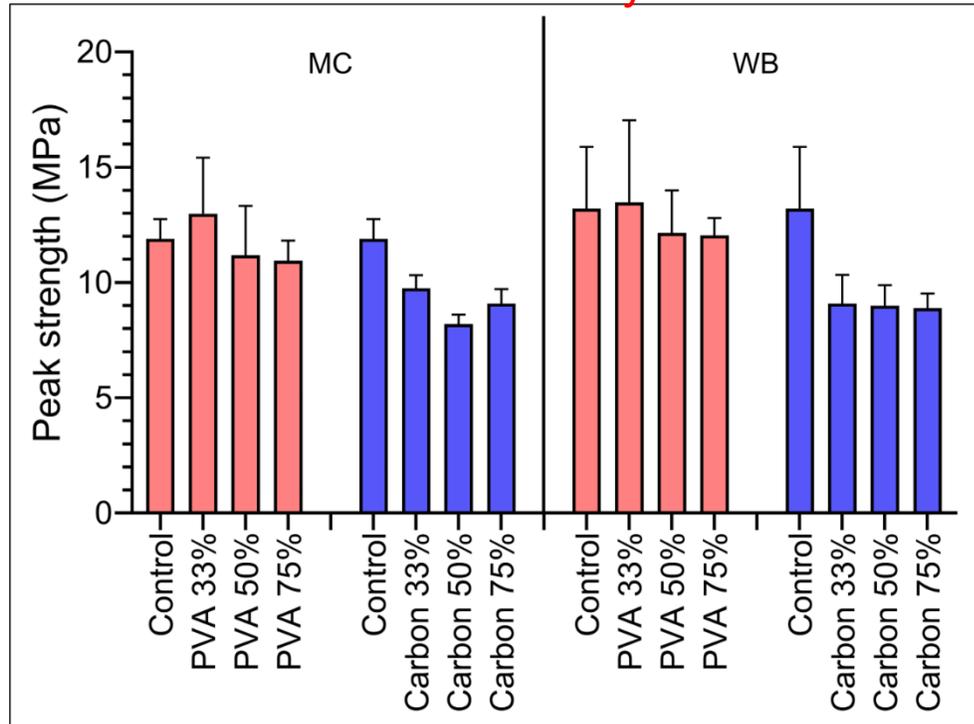
28 Days



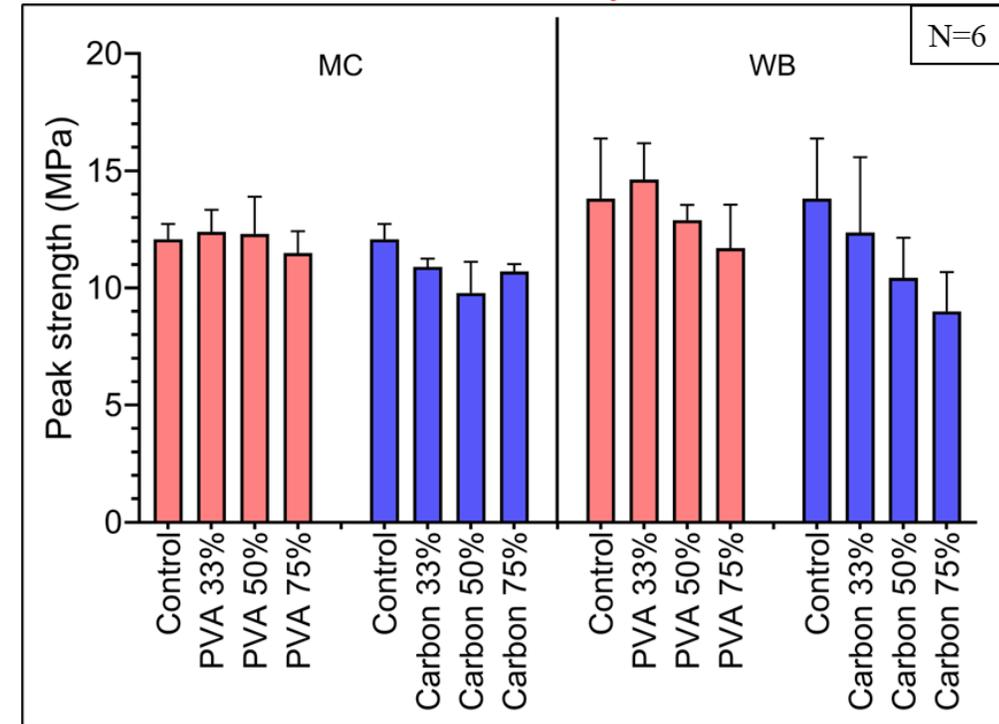
- MC (28 d): PVA < Control (-2.5, -13.7, and -16.1% as replacement ↑)  
Carbon ≈ Control (≤ ~2% lower)
- WB (28 d): PVA > Control (+14.6 to +43.3%)  
Carbon < Control (-1.8 to -11.8%)

# Flexural Properties – Peak Strength

Seven Days



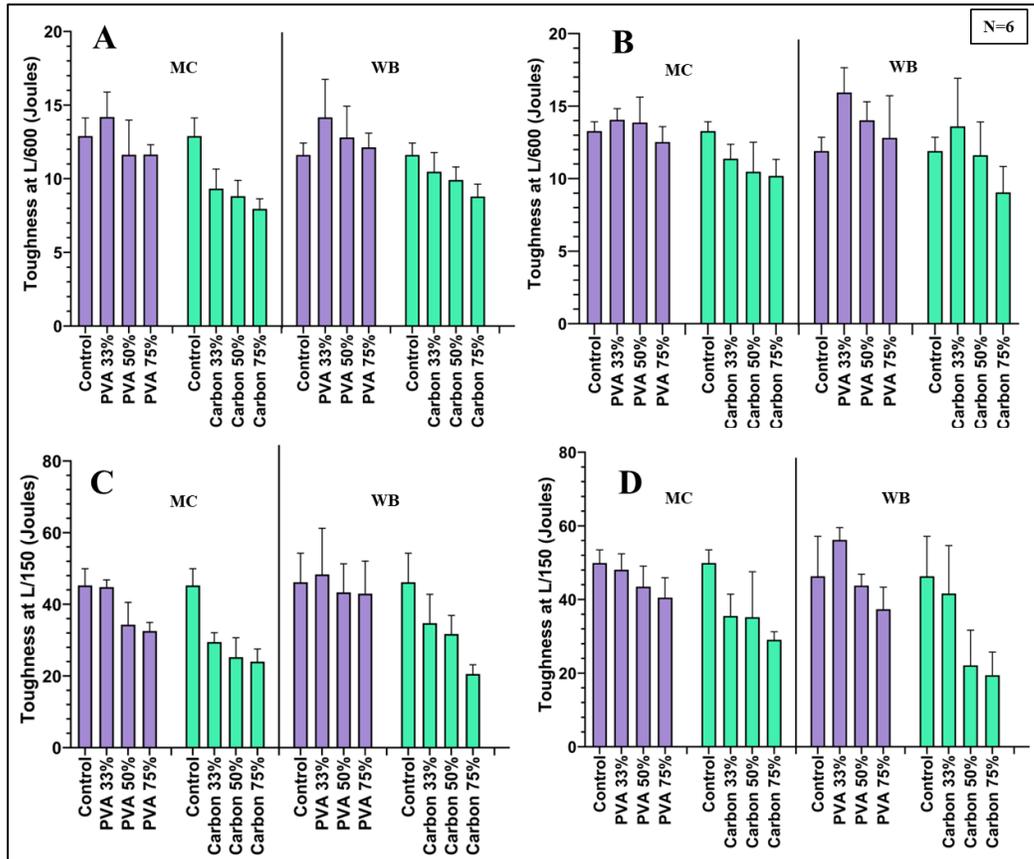
28 Days



The observed trends for peak flexural strength closely mirrored those for MOR.



# Flexural Properties – Toughness



Control: 45–50J , at all days in both the curing regimens

PVA33%: Nearly matched control (MC) and exceeded by > 20 % (WB, 28 days)

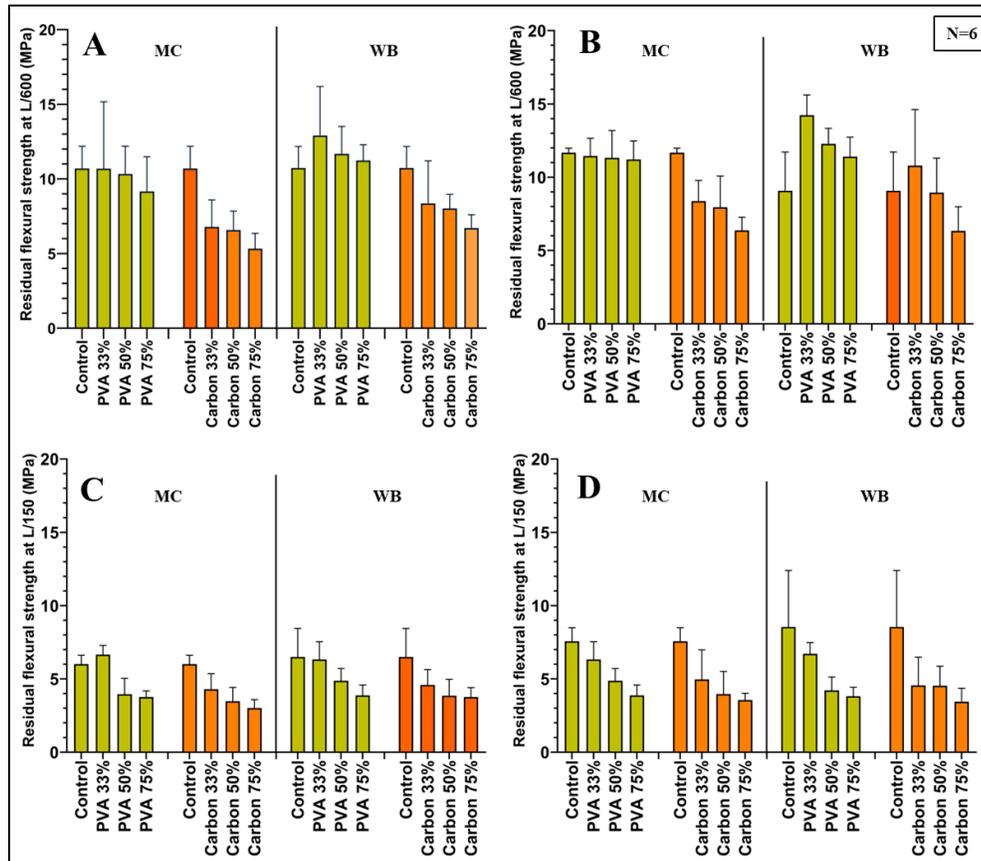
PVA50% & 75%: Retained acceptable toughness, especially under WB curing

Carbon-fiber mixtures: Significant reductions (30–50 %) due to weak bonding and low elongation

At L/600, 33 % PVA again > control by ~ 34 %; carbon mixtures remained below control

Average toughness of all UHPC mixtures cured under MC and WB curing regimens: (A) Deflection at L/600– seven days; (B) Deflection at L/600– 28 days; (C) Deflection at L/150 – seven days; and (D) Deflection at L/150 – 28 days

# Flexural Properties – Residual Flexural Strengths



Average residual strengths of UHPC mixtures cured under MC and WB curing regimens: (A) Deflection at L/600– seven days; (B) Deflection at L/600– 28 days; (C) Deflection at L/150 – seven days; and (D) Deflection at L/150– 28 days

## PVA Fiber Mixtures:

At 33 % replacement, exceeded control residual strength under WB curing at both L/600 and L/150, especially at 28 days.

Moderate replacement (33–50 %) enhanced post-crack strength and ductility.

Higher replacement (75 %) caused noticeable strength loss under both curing conditions.

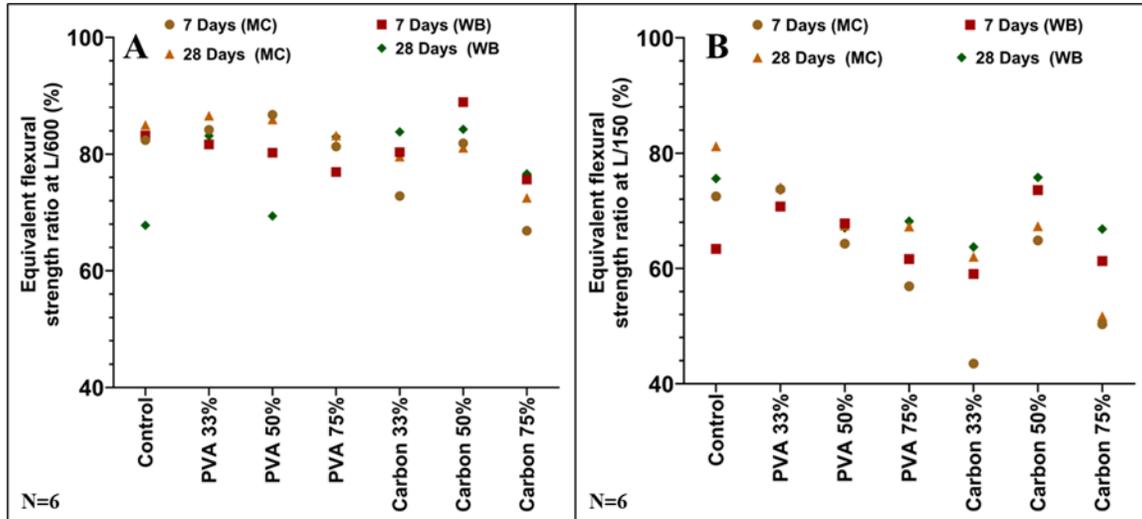
## Carbon Fiber Mixtures:

Consistently underperformed compared to the control and PVA mixtures at all deflection levels and ages.

Strength reductions reached 30–50 %, especially at higher replacement levels and larger deflections.

Limited crack-bridging and low elongation resulted in brittle behavior.

# Flexural Properties –Equivalent Flexural Strengths



Average equivalent flexural strengths of UHPC mixtures cured under MC and WB curing regimens at seven and 28 days: (A) Equivalent flexural strengths at L/600 (B) Equivalent flexural strengths at L/150

Control UHPC: 81.2% at 28 days

## PVA Fiber Mixtures:

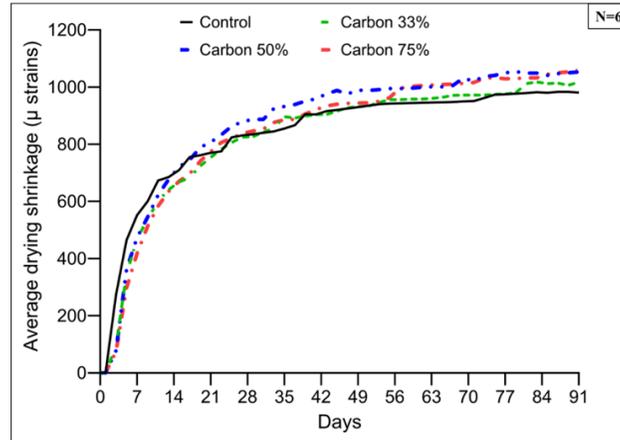
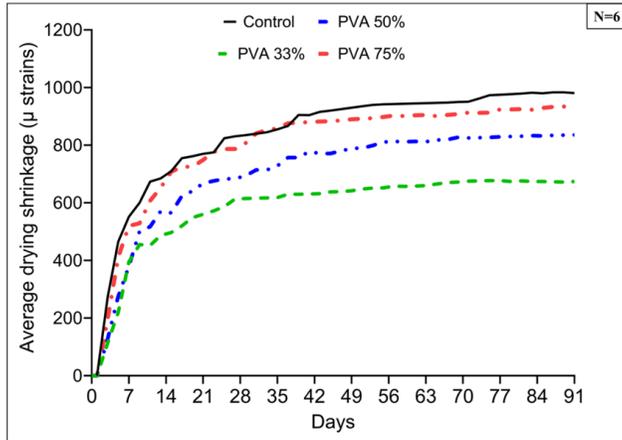
Under MC, the 33 % PVA mixture closely matched the control, while 50 % and 75 % replacements showed moderate reductions (down to 57–68 %).

Under WB, all PVA mixtures achieved comparable values, ranging from 67–74 %.

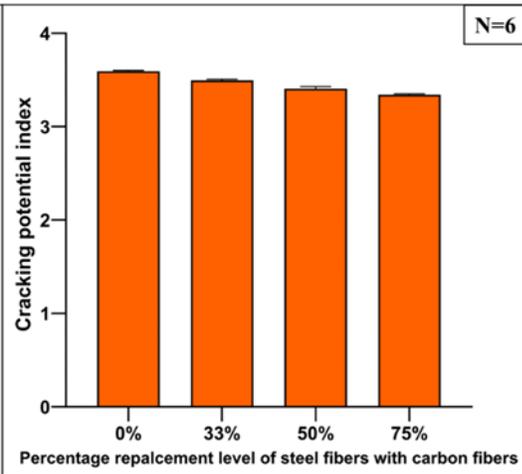
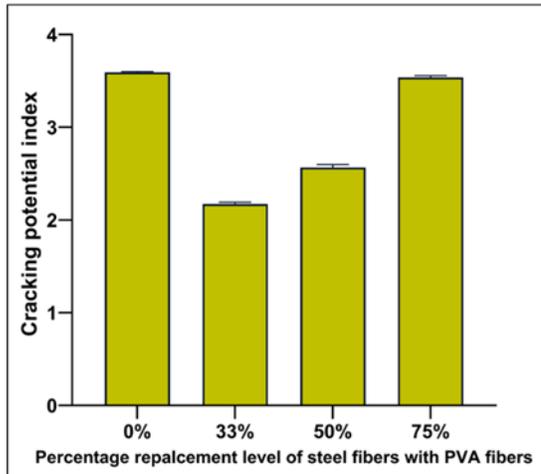
## Carbon Fiber Mixtures:

Under MC and WB, all carbon mixtures underperformed, reaching only 60–75 %.

# Drying Shrinkage



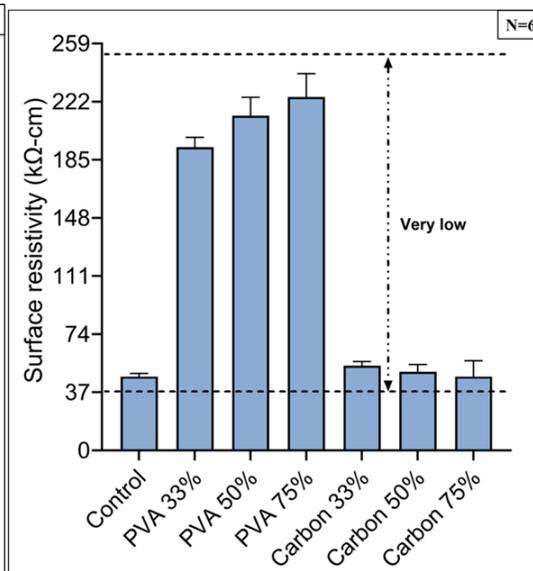
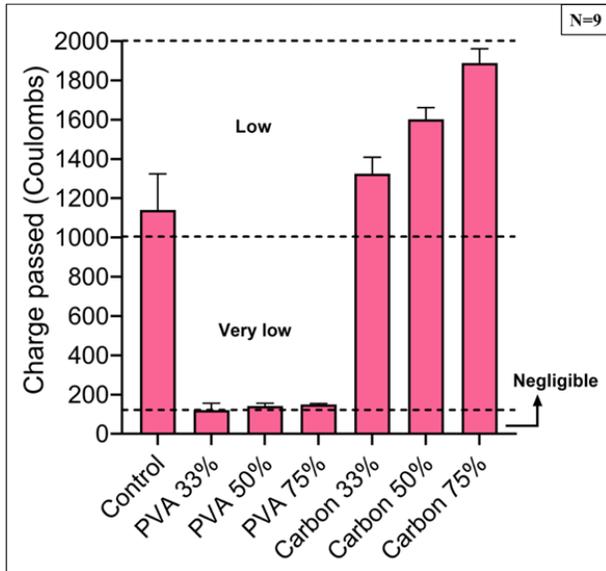
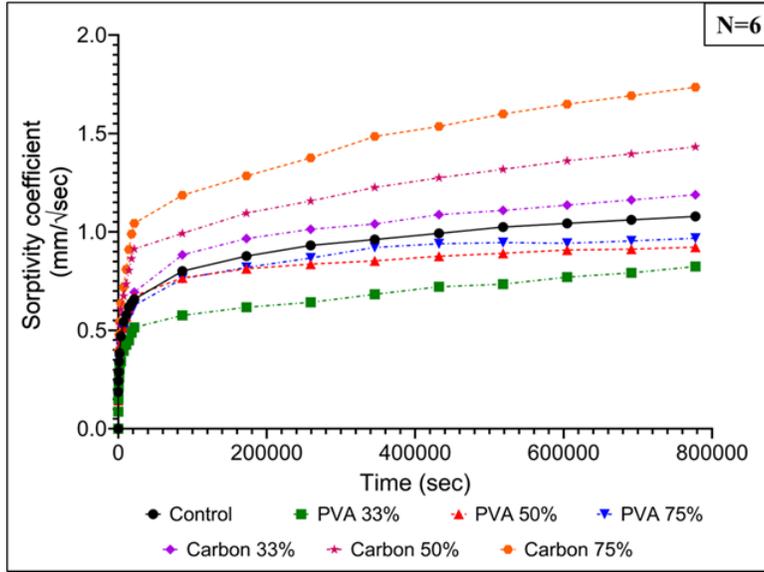
Mixture designation	Average drying shrinkage ( $\mu\epsilon$ )
Control	976
PVA 33%	664
PVA 50%	836
PVA 75%	941
Carbob 33%	1018
Carbon 50%	1053
Carbon 75%	1060



- 33% PVA mixture exhibited lowest shrinkage
  - optimal fiber dispersion and minimized agglomeration.
  - at higher dosages (50% and 75%), fiber clustering and interfacial voids may compromise matrix densification, reducing long-term shrinkage mitigation.
- Poor matrix densification around carbon fibers likely exacerbates capillary stress and drying deformation.



# RCPT, SRT, and Sorptivity



- PVA modified UHPC mixtures fall within the **very low penetrability** classification as per ASTM C1202 and AASHTO T358.
- Control and Carbon fiber reinforced UHPC mixtures fall under **low penetrability** category as per ASTM C1202.
- Intrinsic electrical conductivity of steel and carbon fibers, can create conductive pathways in the cementitious matrix and artificially elevate RCPT and SRT results.
- The lowest sorptivity coefficient of **0.82 mm/ $\sqrt{\text{sec}}$**  was achieved by PVA 33% mixture.
- All the PVA modified UHPC mixtures have lower sorptivity than the control and carbon fiber modified UHPC mixtures.

# Conclusions

- PVA and carbon fibers can be sustainable alternatives to steel fibers.
- All mixtures maintained the target compressive strength of 120 MPa by 28 days, except at 75% PVA replacement.
- Carbon fiber mixtures demonstrated better compressive strengths than PVA mixtures.
- Splitting tensile strength and modulus of elasticity decreased with increasing replacement levels; carbon fibers outperformed PVA.
- PVA improved flexural performance under WB curing, while carbon fiber modified UHPC mixtures showed comparable performance to control mixtures.
- PVA fiber mixtures showed better shrinkage resistance and durability performance than carbon mixtures highlighting their long-term sustainability potential.

# Thank You

**Acknowledgement:** We sincerely acknowledge NEx (ACI Center of Excellence for Nonmetallic Building Materials) for their financial support of this research. Their funding has been instrumental in advancing our study on the use of nonmetallic fibers in ultra-high-performance concrete.



**“Alone we can do so little; together we can do so much.” – Helen Keller**

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