Mixture Design of Sustainable Nano-Engineered High-Performance Concrete (nHPC) Overlay for Concrete Bridge Decks in Cold Regions

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Table of Content

Background

- What is concrete bridge deck overlay?

- hot mix asphalt (HM
- organic/polym
- latex m ... e overlay
- ...ified concrete overlay
- ...mp concrete overlay

lower w/c ratio

UHPC Overlay

- Potential reasons causing overlay to crack

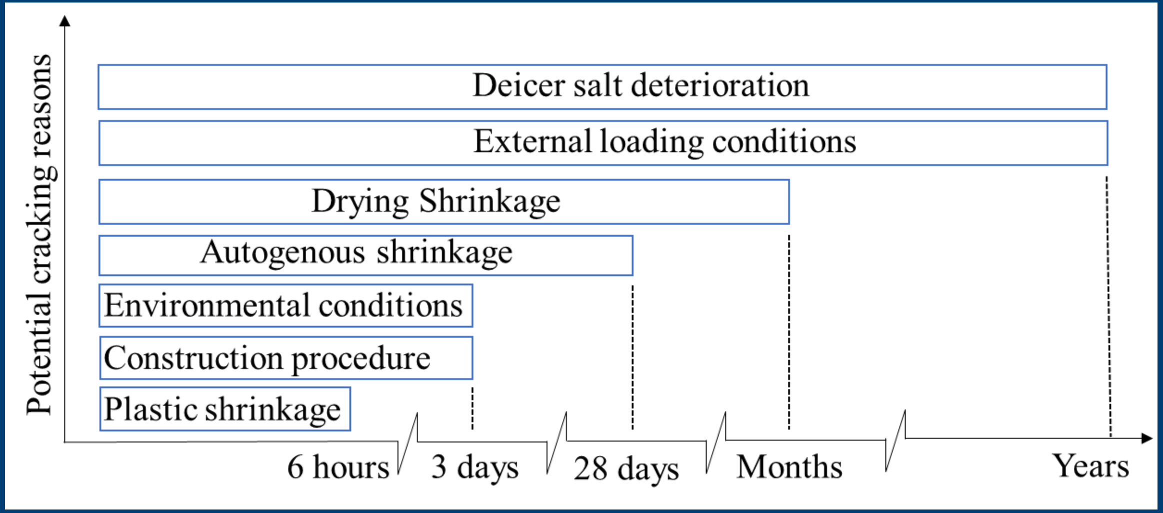
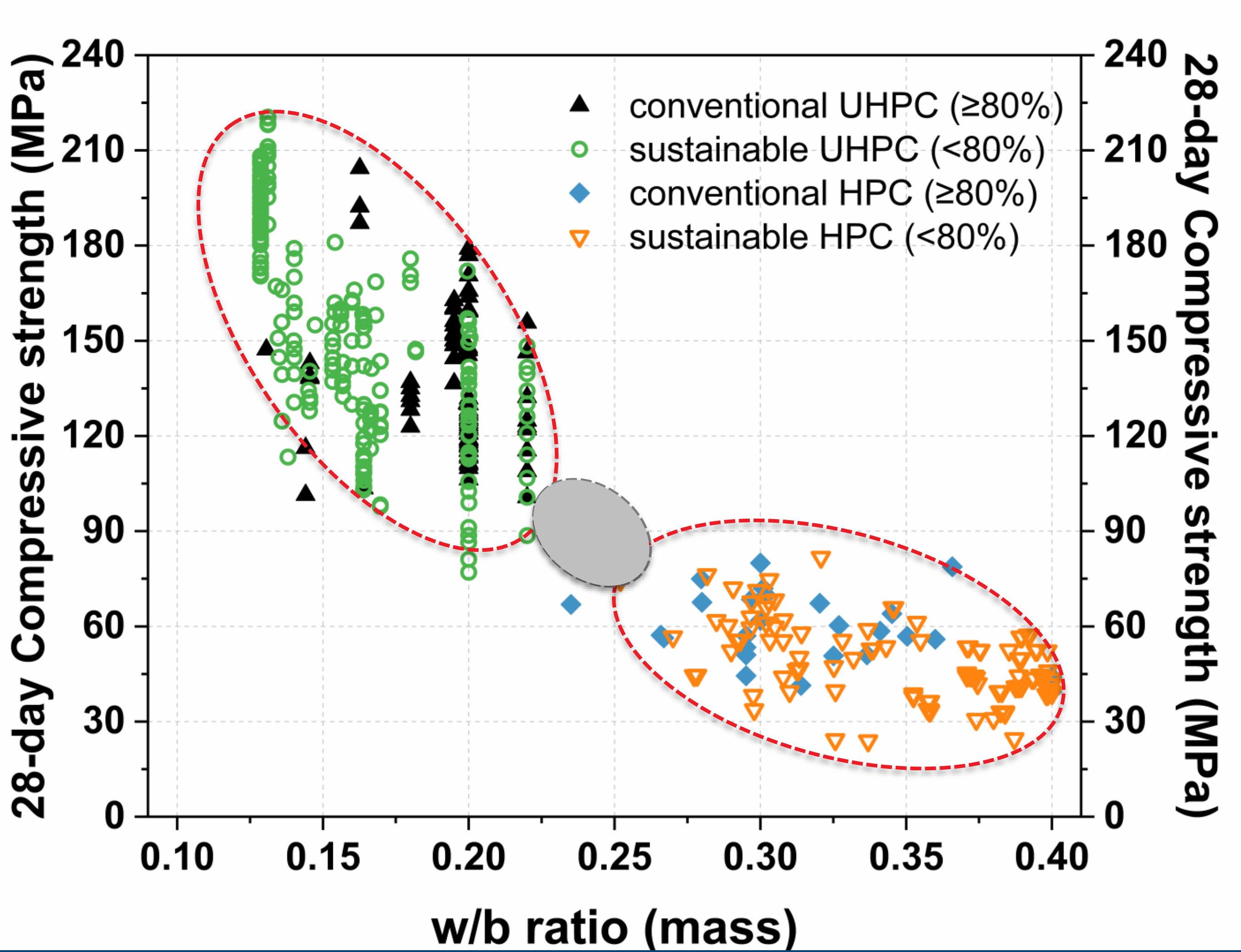


Image source:
https://www.uhpcsolutions.com/blog/when-is-a-deck-overlay-applied-to-a-bridge-deck

Objective



FHWA (2019):

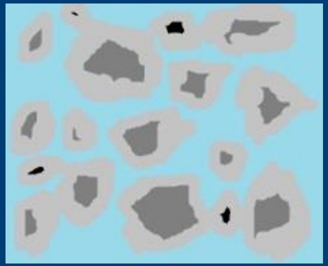
UHPC is a cementitious composite material having a typical 28-d compressive strength (f_c') greater than 150 MPa under heat curing (or 120 MPa under standard curing) ……

data source:
Marani et al. (2020) Materials, 13(21), 4757; Yeh (1998) Cement and Concrete Research, 28(12), 1797-1808

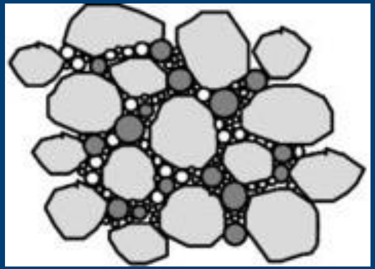
Stepwise Method for Mix Design

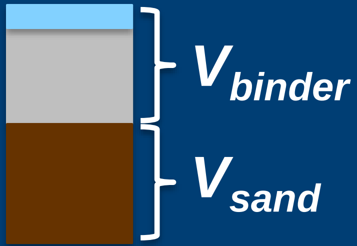
SCMs

28-day f_c'



packing model





PE fiber

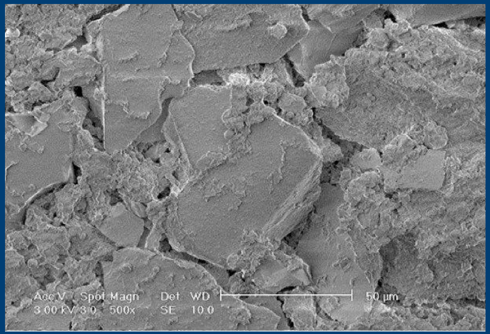
Step 1 — **binder combination**

Step 2 — **w/b ratio**

Step 3 — **sand gradation**

Step 4 — **volume fraction**

Step 5 — **fiber content**



nano montmorillonite

steel fiber

Image source:
R Ahmed et al. (2019) IOP Conference Series: Earth and Environmental Science, 357 012016
Vale et al. (2005) Journal of Macromolecular Science Part B Physic, 44(6) 821-831
Dhir et al. (1997) Challenges in designing concrete durability: a sustainable approach, University of Dundee

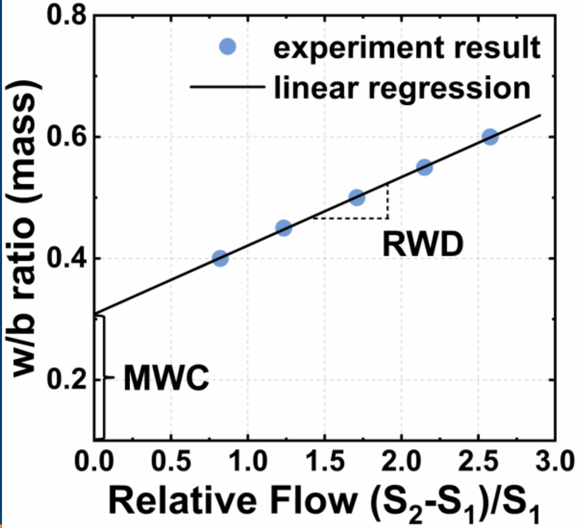
Step 1 binder combination | Step 2 w/b ratio | Step 3 sand gradation | Step 4 volume fraction | Step 5 fiber content

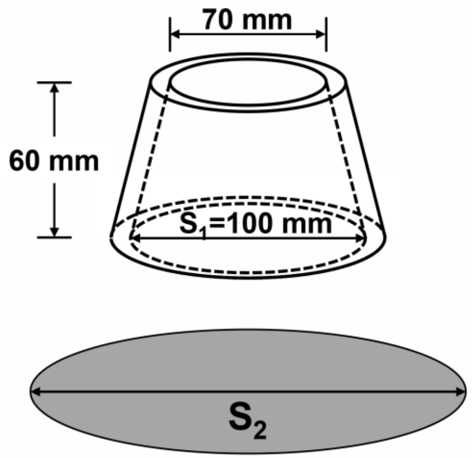
Substep 1: Narrow down the range of SCMs contents in nHPC binder (ASTM C230)

nHPC binder = UHPC binder (base) + SCMs

UHPC binder:
- 60 wt% cement
- 35 wt% class C fly ash
- 5 wt% silica fume

LP: limestone powder; FAF: class F fly ash

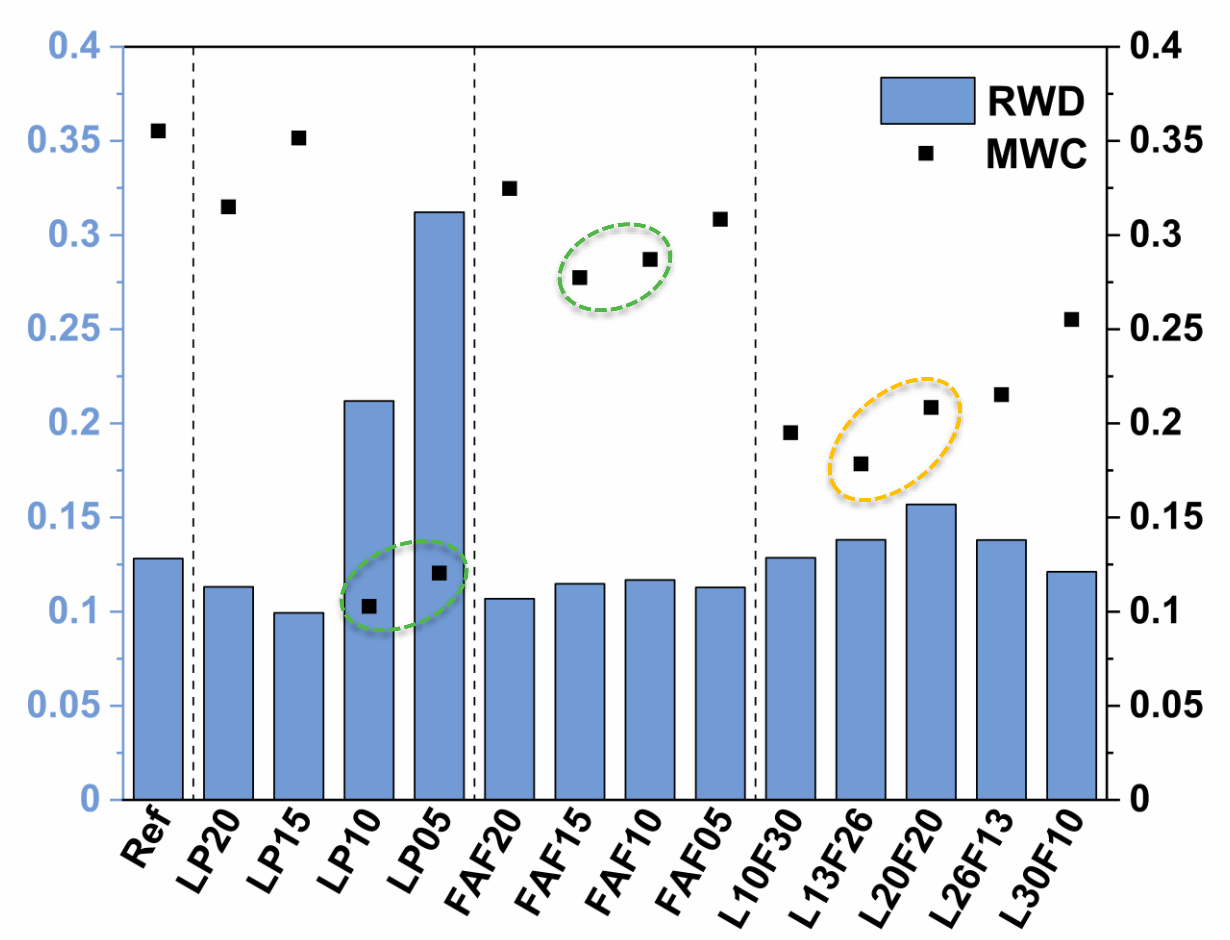




Group	Code	UHPC (wt%)	LP (wt%)	FAF (wt%)
1	Ref	100	-	-
2	LP20	80	20	-
	LP15	85	15	-
	LP10	90	10	-
	LP05	95	5	-
3	FAF20	80	-	20
	FAF15	85	-	15
	FAF10	90	-	10
	FAF05	95	-	5
4	L20F20	60	20	20
	L13F26	61	13	26
	L26F13	61	26	13
	L30F10	60	30	10

Step 1 binder combination | Step 2 w/b ratio | Step 3 sand gradation | Step 4 volume fraction | Step 5 fiber content

Substep 1: Narrow down the range of SCMs contents in nHPC binder (ASTM C230)



Preliminary w/b mass ratio: 0.24

LP: 5 wt% ~ 10 wt%

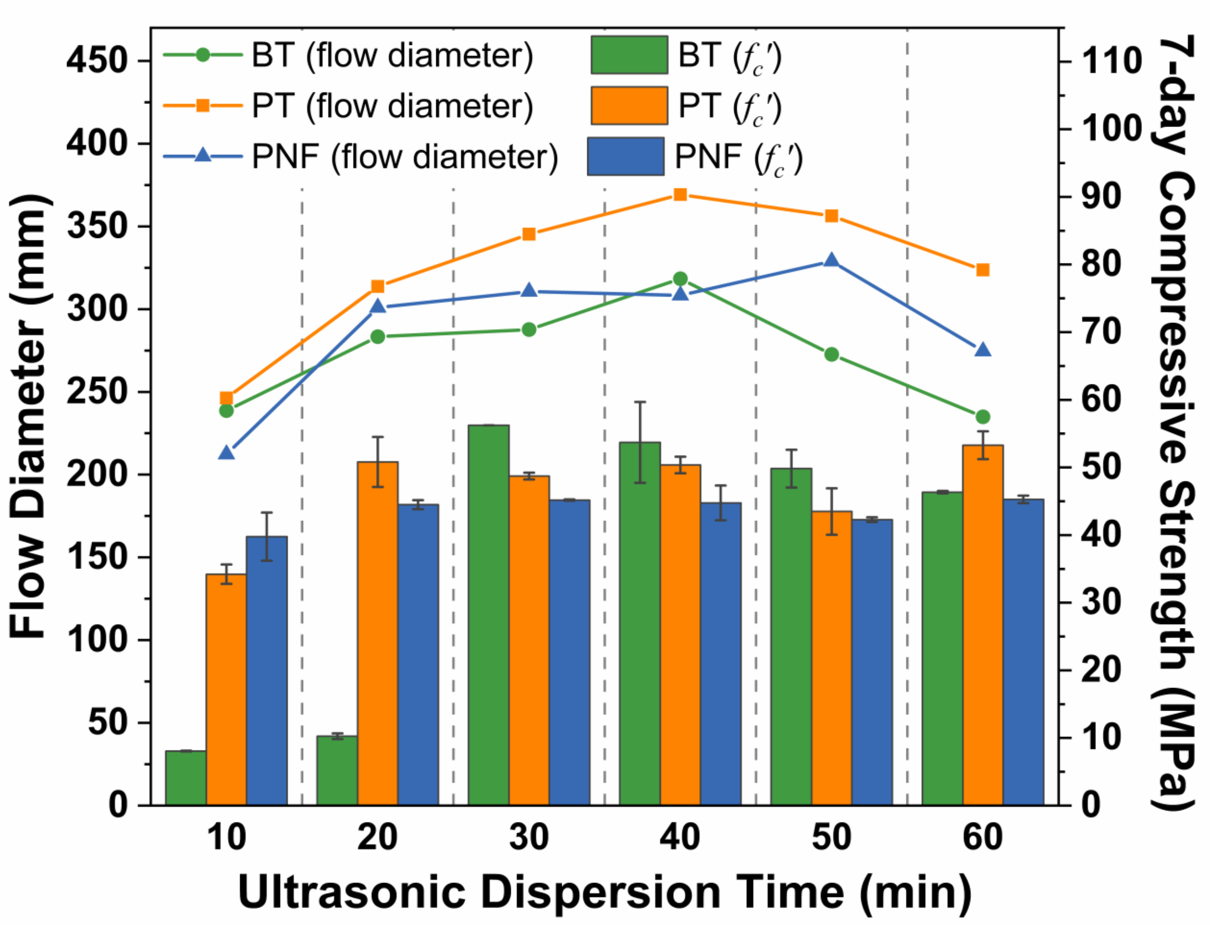
FAF: 10 wt% ~ 15 wt%

nano montmorillonite: 0 wt% ~ 2.5 wt% (nanoclay)

Substep 2: Optimize nHPC binder combination (Central Composite Design Method)

Run	LP (wt%)	FAF (wt%)	nanoclay (wt%)	Run	LP (wt%)	FAF (wt%)	Nanoclay (wt%)
1	7.5	12.5	1.25	**11**	5	15	2
2	11.7	12.5	1.25	**12**	7.5	12.5	1.25
3	5	10	0.5	**13**	10	15	0.5
4	3.3	12.5	1.25	**14**	7.5	12.5	2.5
5	7.5	12.5	1.25	**15**	7.5	16.7	1.25
6	7.5	12.5	1.25	**16**	10	15	2
7	7.5	12.5	0	**17**	7.5	12.5	1.25
8	7.5	12.5	1.25	**18**	5	15	0.5
9	10	10	2	**19**	10	10	0.5
10	7.5	8.3	1.25	**20**	5	10	2

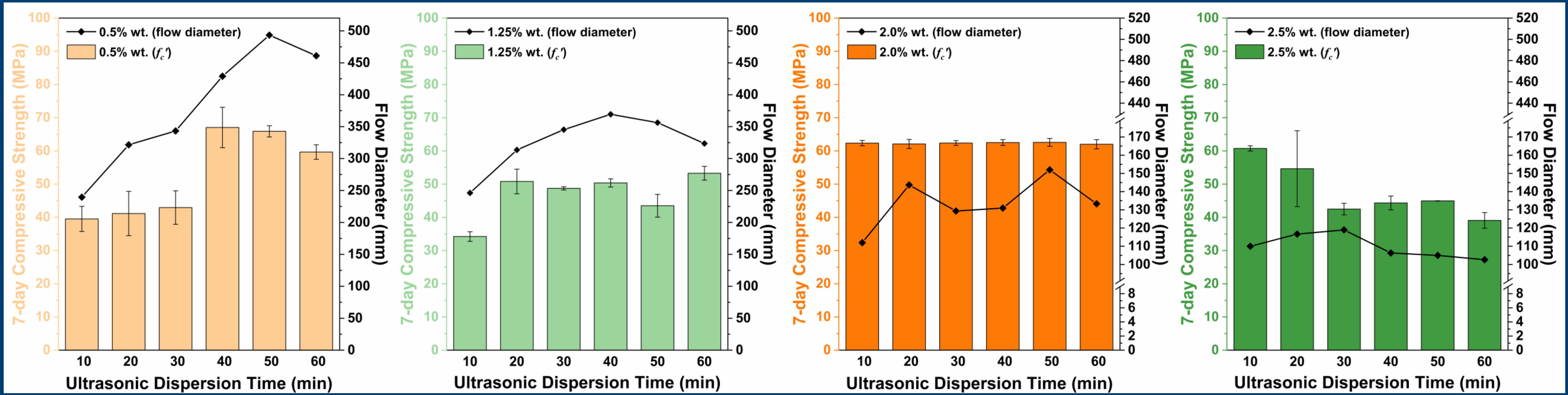
Step 1 binder combination | Step 2 w/b ratio | Step 3 sand gradation | Step 4 volume fraction | Step 5 fiber content



Run 1: 1.25 wt% nanoclay with a w/b ratio of 0.24
HRWRA: fixed @ 0.74% (by weight of total binder)
Flow Diameter: S_2

Selection: PT nanoclay
Best dispersion time: 40 minutes for 1.25 wt%

Step 1 binder combination → Step 2 w/b ratio → Step 3 sand gradation → Step 4 volume fraction → Step 5 fiber content



Best dispersion time:

50 minutes for 0.5 wt%
40 minutes for 1.25 wt%
50 minutes for 2.0 wt%
20 minutes for 2.5 wt%

Step 1
binder combination

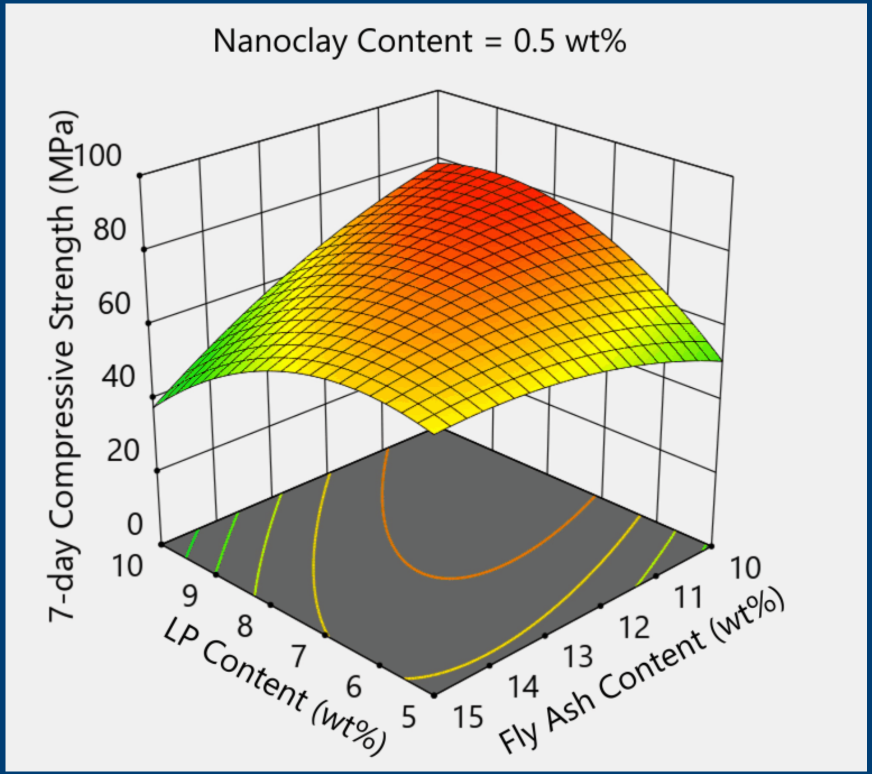
Step 2
w/b ratio

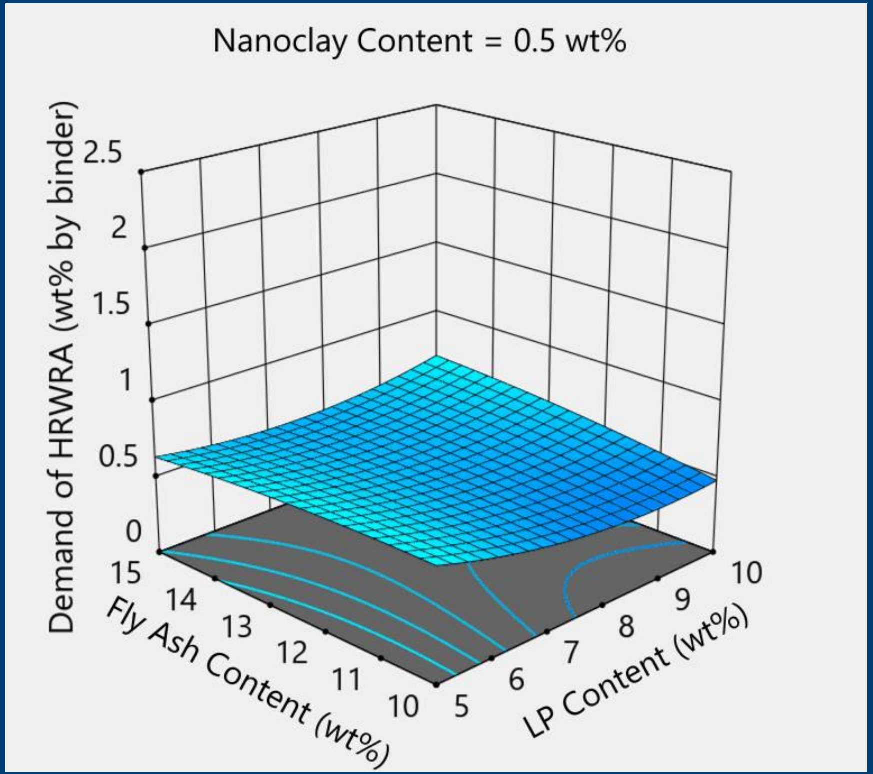
Step 3
sand gradation

Step 4
volume fraction

Step 5
fiber content

Substep 2 Optimize nHPC binder combination (Central Composite Design Method)





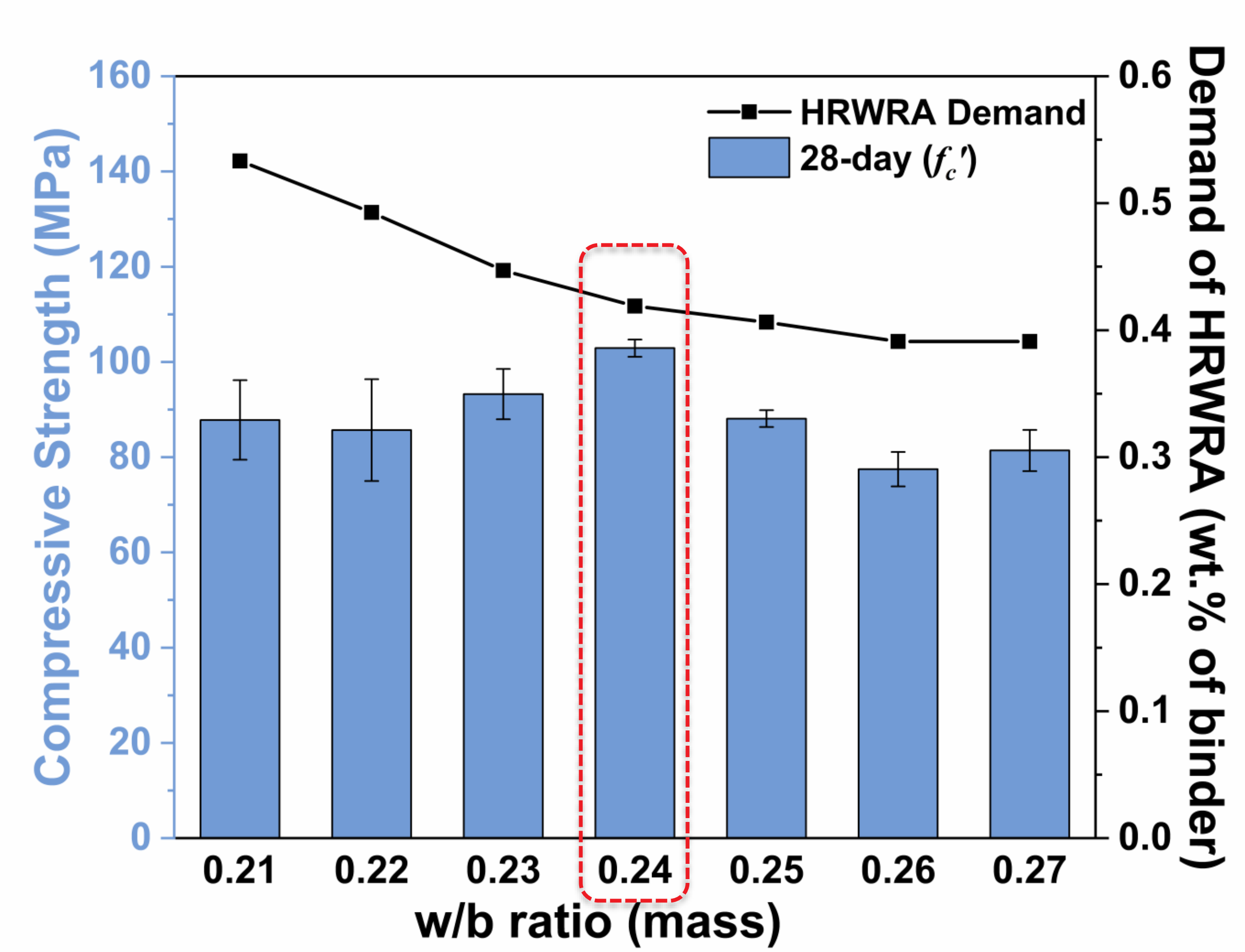
Demand of HRWRA:
To make S_2 of fresh mixture in the range of 280±10 mm

7-day f_c' of the mixture with desired workability (280±10 mm)

Optimal binder combination

UHPC: 80.6 wt%
LP: 9 wt%
FAF: 10 wt%
nanoclay: 0.6 wt%

Step 1 binder combination | **Step 2 w/b ratio** | Step 3 sand gradation | Step 4 volume fraction | Step 5 fiber content



Demand of HRWRA:
To make S_2 of fresh mixture in the range of 280±10 mm

28-day f_c' of the mixture with desired workability (280±10 mm)

Optimal w/b ratio: 0.24

The modified Andreasen and Andersen Model

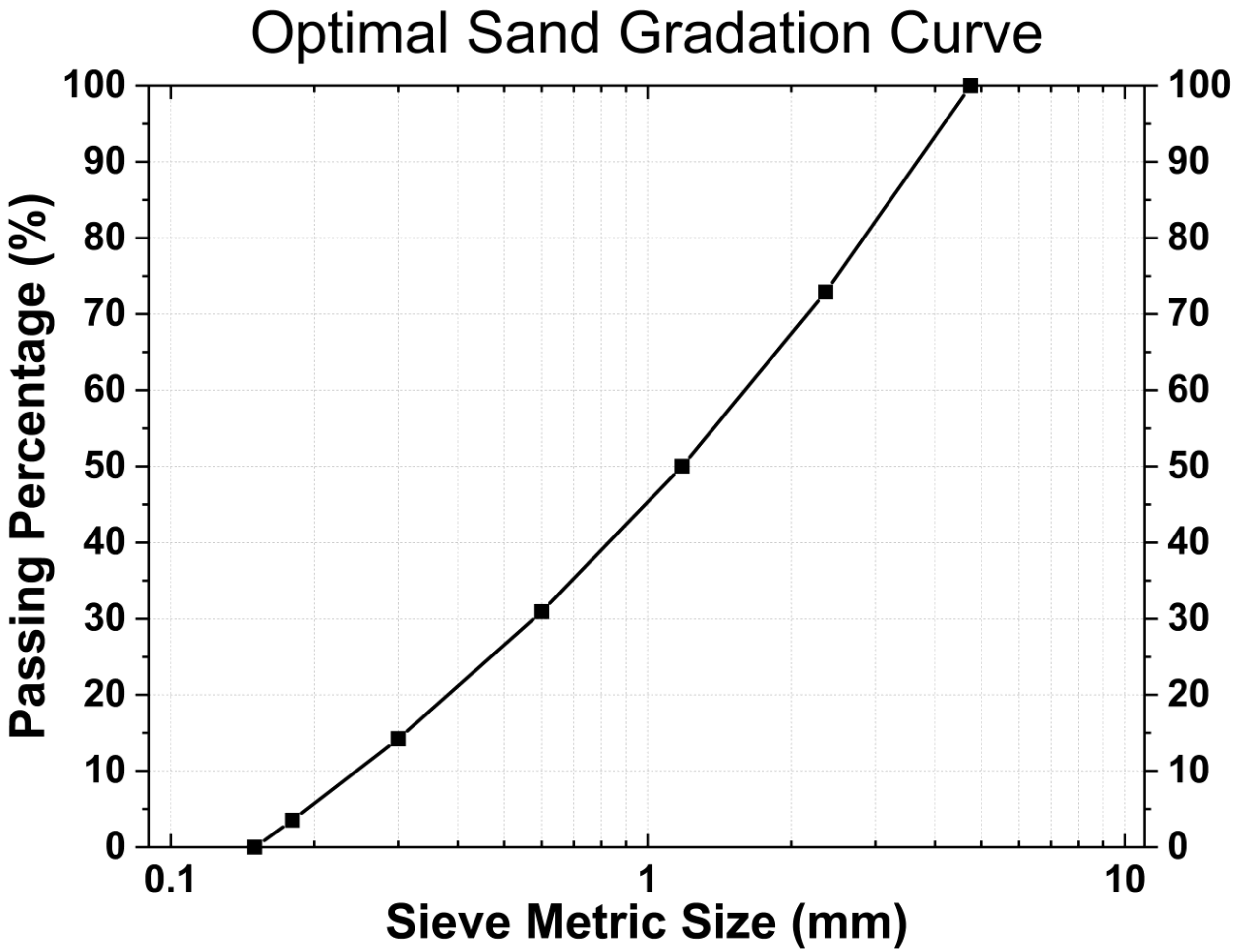
$$P(D) = \frac{D^q - D^q_{min}}{D^q_{max} - D^q_{min}}$$

$P(D)$: the weight percentage of sand passing the sieve with size D

D_{min} : the minimum particle size (4.75 mm)

D_{max} : the maximum particle size (0.15 mm)

q: the distribution modulus related to the sand particle size ($0.22 \sim 0.25$, $q = 0.23$)



paste for filling voids

excess paste for lubricating

Binder phase: $V_b = V_{exp} + V_{void}$

(volume %)

$$V_{exp} = 8 + \frac{(16-8)}{4} \times (R_{S,A} - 1)$$

$$V_{void} = \frac{\alpha \times (100 - V_{exp})}{100}$$

$R_{S,A} = 3\ (from\ 1\ to\ 5)$

$R_{S,A}$ is a coefficient related to the shape and angularity of sand

$$\alpha = \left(1 - \frac{\gamma_s}{\rho_s}\right) \times 100$$

α is the void content of compacted blended sand; γ_s and ρ_s are the bulk density and density of compacted blended sand, respectively

Sand phase: $V_s = \frac{V_{exp}+V_{void}}{100-V_{exp}-V_{void}}$

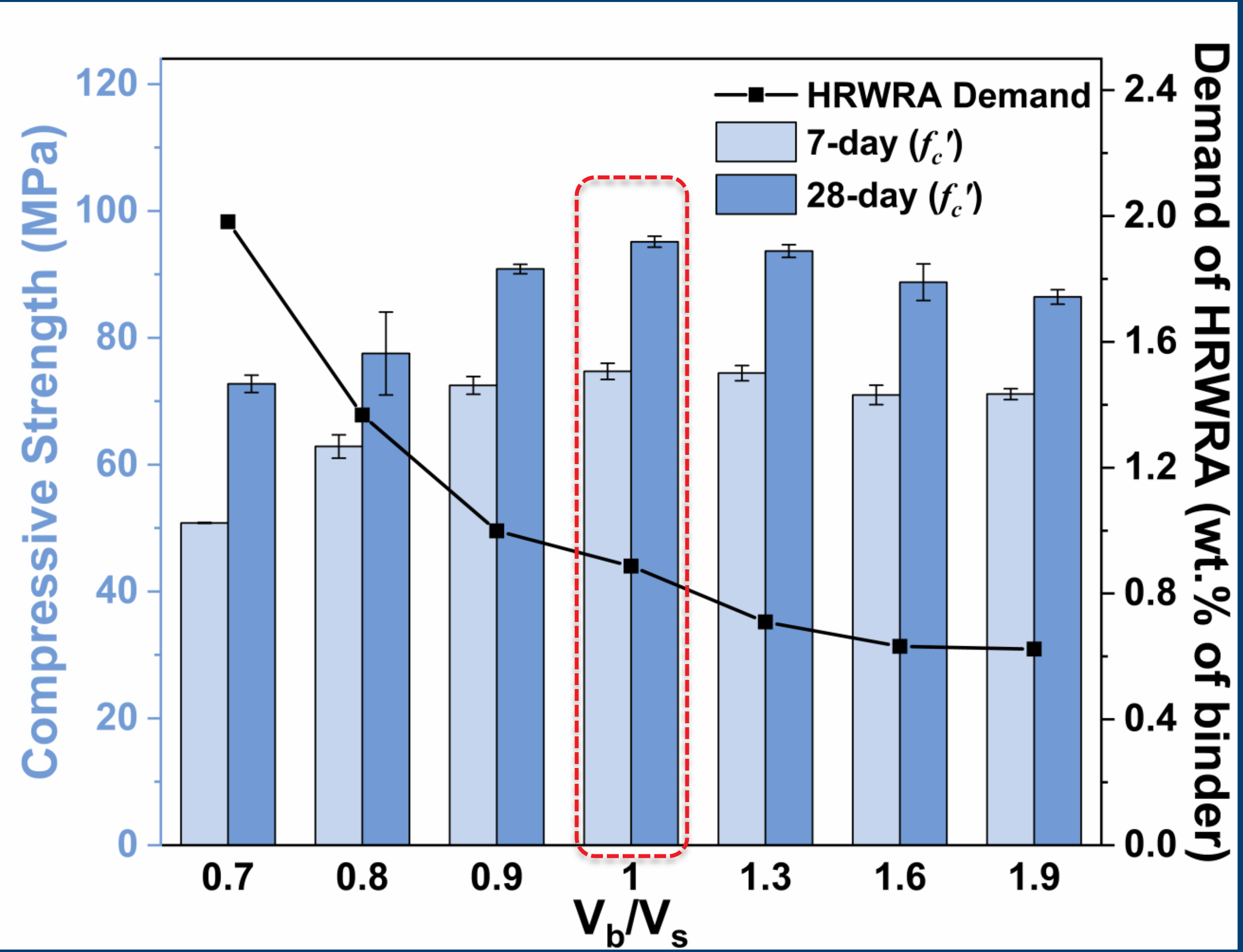
(volume %)

Step 1 binder combination | Step 2 w/b ratio | Step 3 sand gradation | **Step 4 volume fraction** | Step 5 fiber content

According to ASTM C29, $\gamma_s = 1701$;
According to ASTM C128, $\rho_s = 2511$;
Thereby, void ratio $\alpha = 32\%$

Since $R_{S,A} = 3$, $V_{exp} = 12\%$ and $V_{void} = 28.16\%$; thereby, $V_b = 40.16\%$ and $V_s = 67.11\%$, and the minimum value of $V_b/V_s = 0.6$. However, …

Slight bleeding and segregation, S_2=252 mm



Step 1 binder combination | Step 2 w/b ratio | Step 3 sand gradation | Step 4 volume fraction | **Step 5 fiber content**

Steel fiber:

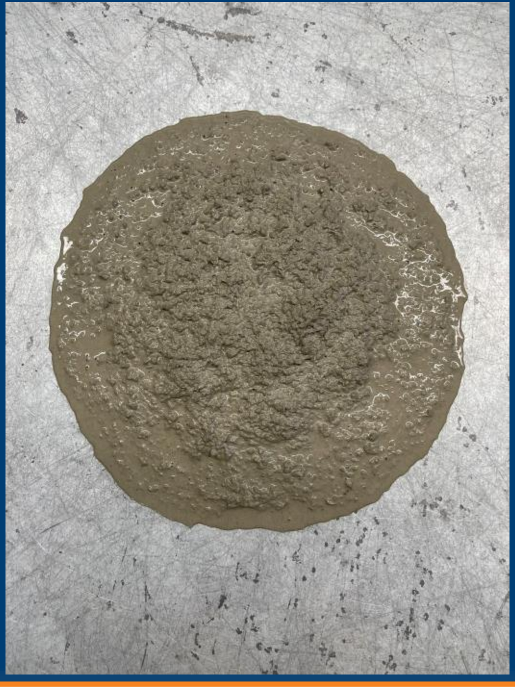
12 mm length, 200 µm diameter, 7.85 g/cm^3

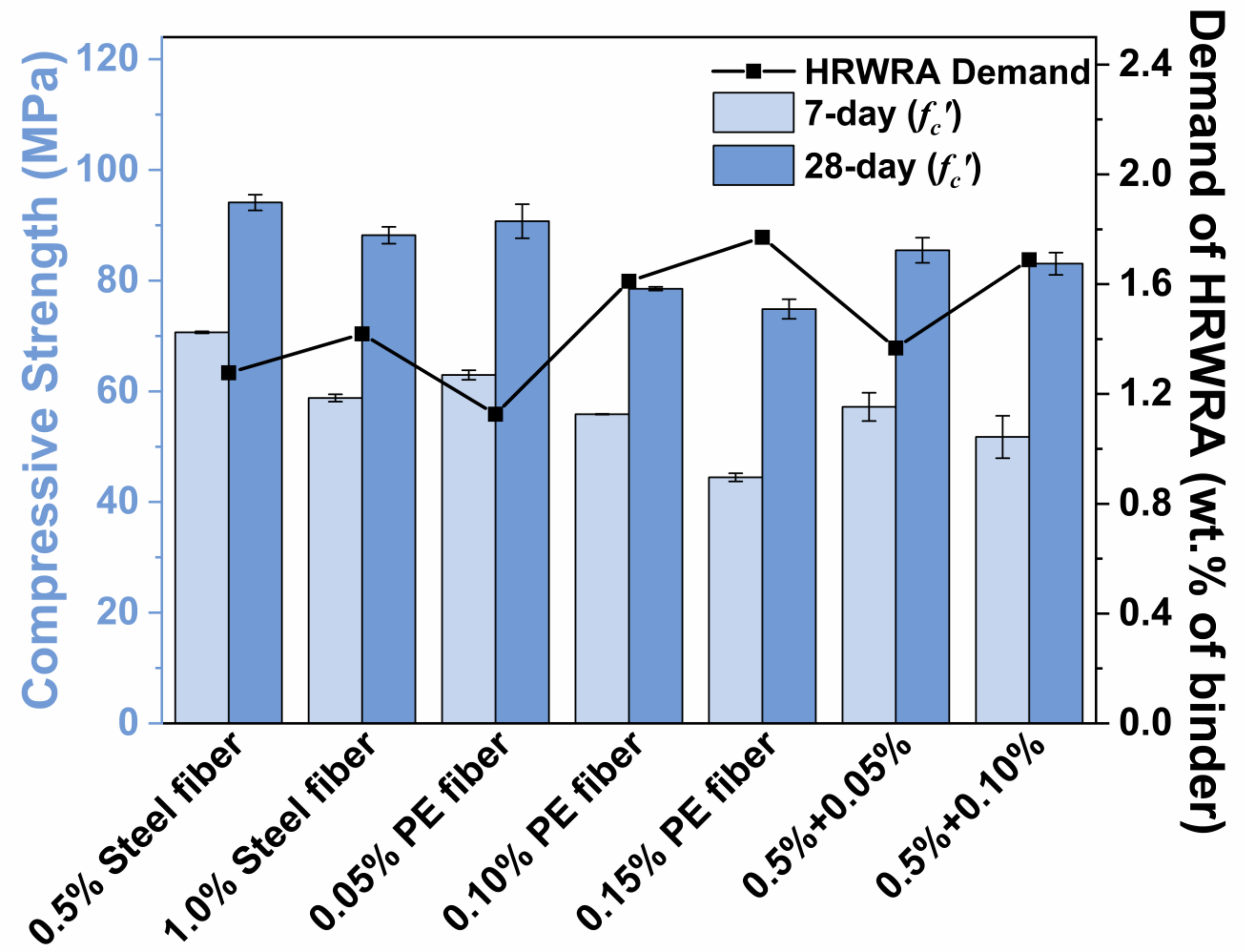
PE fiber:

12 mm length, 26 µm diameter, 0.97 g/cm^3

1.5 vol% Steel fiber

0.2 vol% PE fiber





Step 1 binder combination
Step 2 w/b ratio
Step 3 sand gradation
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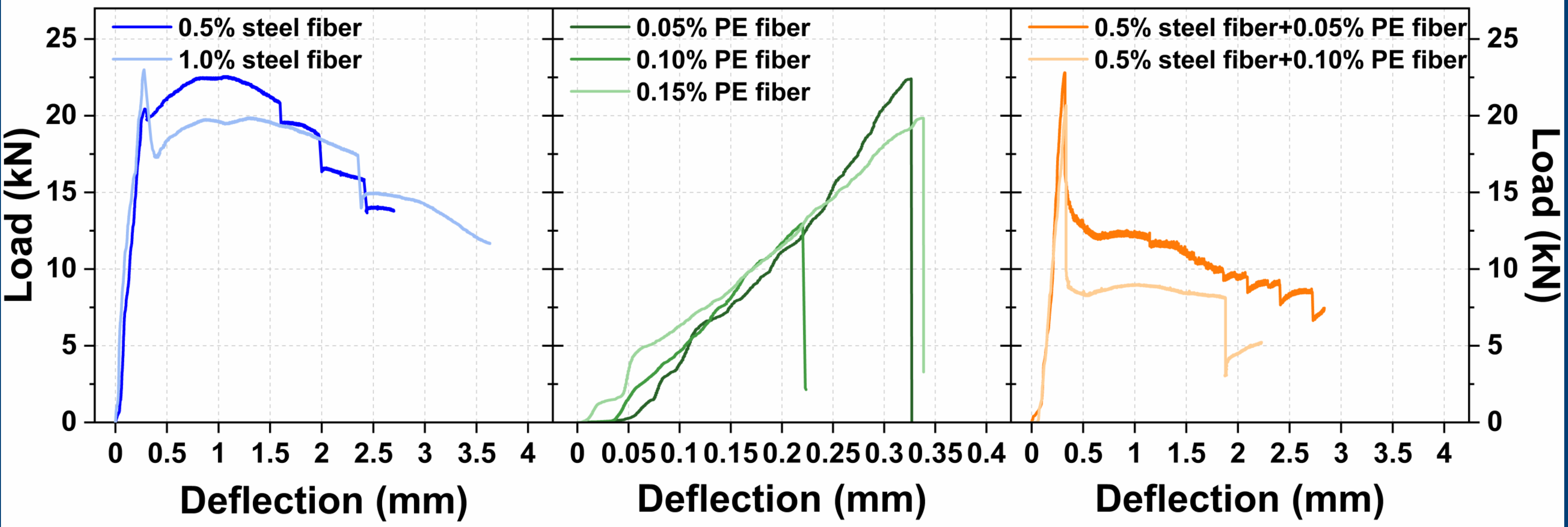

Step 1 binder combination | Step 2 w/b ratio | Step 3 sand gradation | Step 4 volume fraction | **Step 5 fiber content**

Group	f_c' (MPa)	HRWRA (wt%)	f_1 (MPa)	δ_1 (mm)	f_p (MPa)	δ_p (mm)	f_{600}^D (MPa)	T150 (J)
0.5% steel fiber	94.1	1.28	5.94	0.29	6.56	1.08	6.15	39.7
1.0% steel fiber	88.2	1.42	6.68	0.24	6.68	0.24	5.42	37.4
0.05% PE fiber	90.7	1.13	6.51	0.33	6.51	0.33	-	3.0
0.10% PE fiber	78.5	1.61	3.76	0.22	3.76	0.22	-	1.3
0.15% PE fiber	74.9	1.77	5.77	0.28	5.77	0.28	-	3.4
0.5%+0.05%	85.5	1.37	6.63	0.30	6.63	0.30	3.69	22.5
0.5%+0.10%	83.1	1.69	6.01	0.33	6.01	0.33	2.43	16.6

Comparison

Mix Design of nHPC

Binder

- Cement: Type I/II Portland Cement (48.36 wt%)
- SCMs: class C fly ash (28.21 wt%)
  class F fly ash (10 wt%)
  silica fume (4.03 wt%)
  limestone powder (9 wt%)
- Nanomaterial: nano montmorillonite (0.06 wt%, ultrasonic dispersion)
- Water-to-Binder mass ratio: 0.24

Fine Aggregate

- Blended sand (based on modified Andreasen&Andersen model)
- Optimal volume fraction: $V_b/V_s = 1$

Fiber

- Steel fiber
- Optimal fiber content = 0.5 vol%

Comparison

Mixture	Cost ($/m^3)	Strength Normalized Cost ($/m^3/MPa)	Energy Consumption (MJ/m^3)	Strength Normalized Energy Consumption (MJ/m^3/MPa)
nHPC	317.14	3.37	3706.44	39.38
UHPC-LCC	1733.09	14.2	7430.02	60.92
Control	874.57	6.52	5954.2	44.35
GM20	1111.83	8.72	5821.88	45.69
L0	789.62	6.7	4427.48	37.49
L25	850.01	6.8	4366.41	34.2
L100	1026.33	10.26	4193.38	41.95

UHPC-LCC: w/b ratio = 0.157, binder = cement + silica fume + glass powder/hollow glass microsphere; From Control to L100: w/b ratio = 0.2, binder = cement + slag (GM-glass microsphere), L means expanded glass to replace traditional river sand in UHPC;

data source:
Guo et al. (2023) Construction and Building Materials 371, 130441

Conclusions

- A sustainable and environmentally friendly nano-engineered high performance concrete mixture is developed for the overlay of concrete bridge deck

- The application of nano-montmorillonite in the cementitious mixture needs preliminary investigation of ultrasonic dispersion parameter to achieve well dispersion.

- In terms of cost and energy consumption, nHPC is approximately 25 to 50% lower than that of UHPC. Further durability experiments are necessary to evaluate the application of this nHPC mixture in the field.

Thank you very much!

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