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Rheology Control of UHPC

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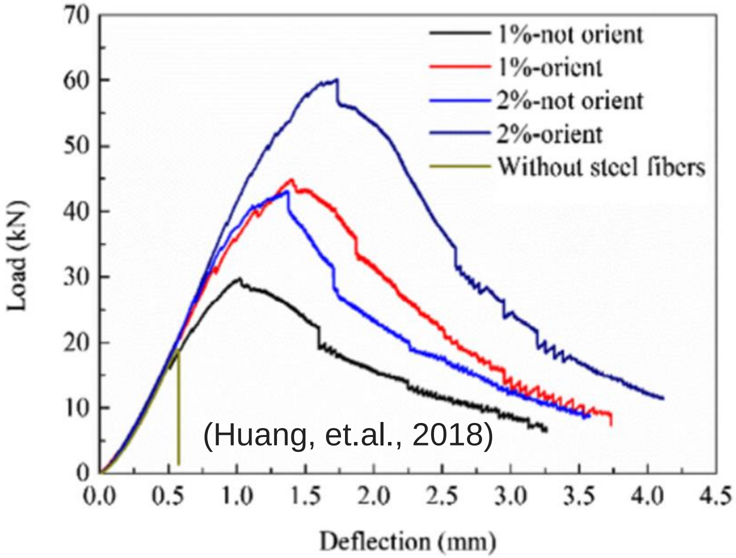
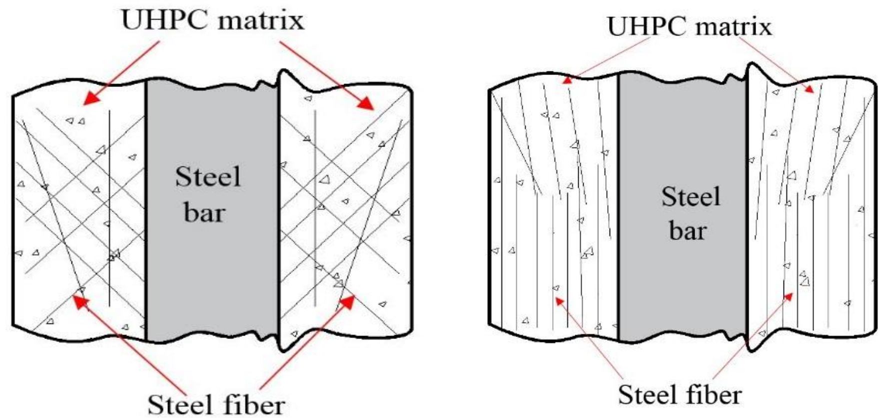
Outline

- ❑ Rheology control of UHPC for different applications
  - ✓ For better fiber distributions (i.e., orientation and dispersion)
  - ✓ For slope casting (UHPC overlay)
  - ✓ For ease of large-scale production
- ❑ Real-time monitoring of rheology
- ❑ Conclusions

Why better fiber distribution?

- Better-distributed fibers lead to greater flexural performance
- When fibers are well oriented along the steel bar direction, as there is less contact between steel fibers and steel bar, the galvanic corrosion was not observed





No galvanic corrosion when fibers are well oriented

Fan, L., Meng, W., Teng, L. and Khayat, K.H., 2019. Effect of steel fibers with galvanized coatings on corrosion of steel bars embedded in UHPC. *Composites Part B: Engineering*, *177*, p.107445.

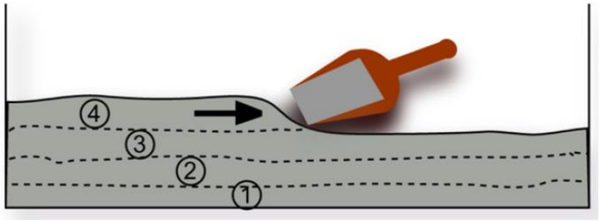
Fan, L., Meng, W., Teng, L. and Khayat, K.H., 2020. Effects of lightweight sand and steel fiber contents on the corrosion performance of steel rebar embedded in UHPC. *Construction and Building Materials*, *238*, p.117709.

How to achieve better fiber distribution?

- Improve casting methods

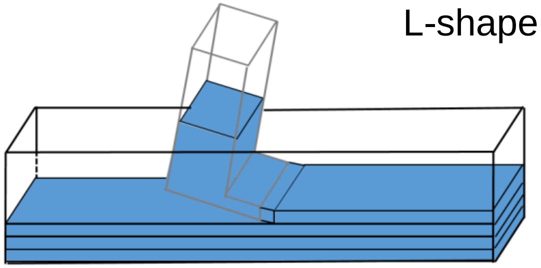
- Fibers are re-oriented during casting UHPC in a formwork, due to gradient of flow velocity, which is controlled by viscosity of suspending mortar

Place UHPC along longitudinal direction



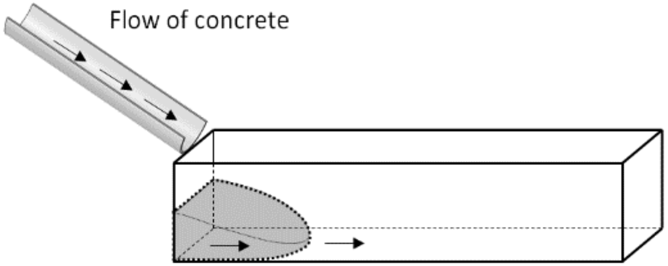
Kang et al., Construction and Building Materials, 25(5), 2011, 2450-2457.

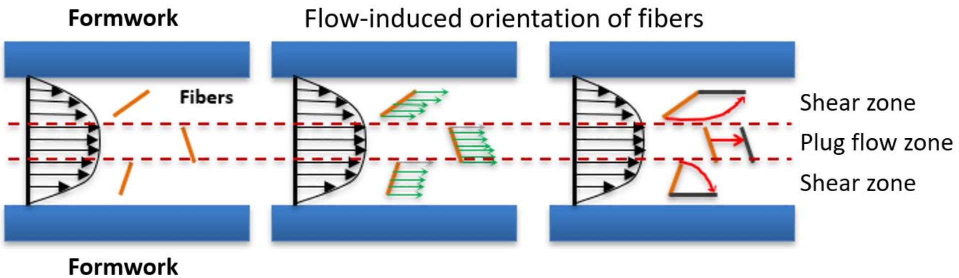
L-shape device



Huang et al., Construction and Building Materials, 188, 2018, 709-721.

Self-adaptive fiber orientation in flowing UHPC

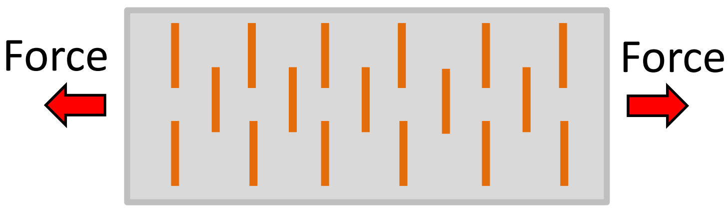




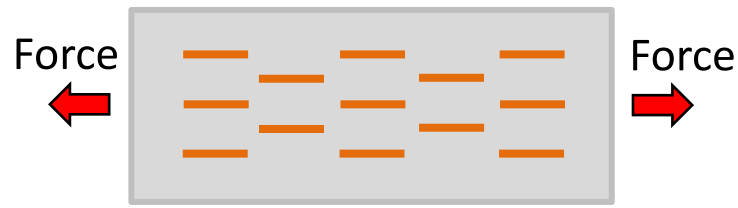
Meng and Khayat., Composites Part B: Engineering, 117, 2017, 26-34.

Rheology control for better fiber distribution

- Both fiber dispersion and orientation are controlled by the rheological properties of UHPC suspending mortar/matrix
- Improve fiber orientation and dispersion by optimizing plastic viscosity
  - Fiber orientation
    - ✓ Fibers along the loading direction can help resist tensile force.

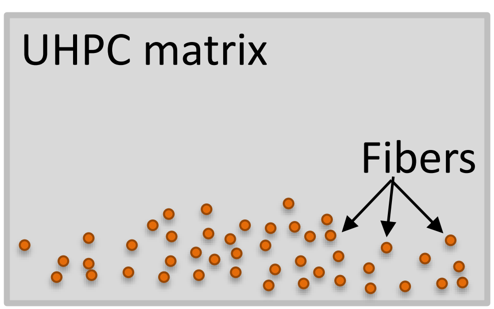


Perpendicular to loading

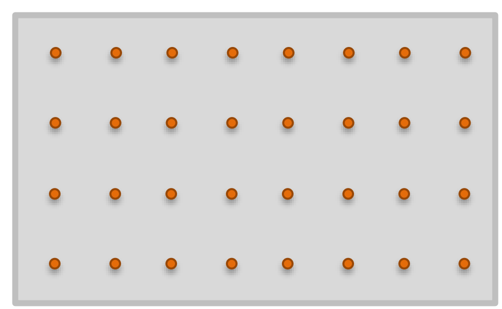


Along loading direction

  - Fiber dispersion
    - ✓ A uniform fiber dispersion is preferred for the quality of UHPC



Non-uniform

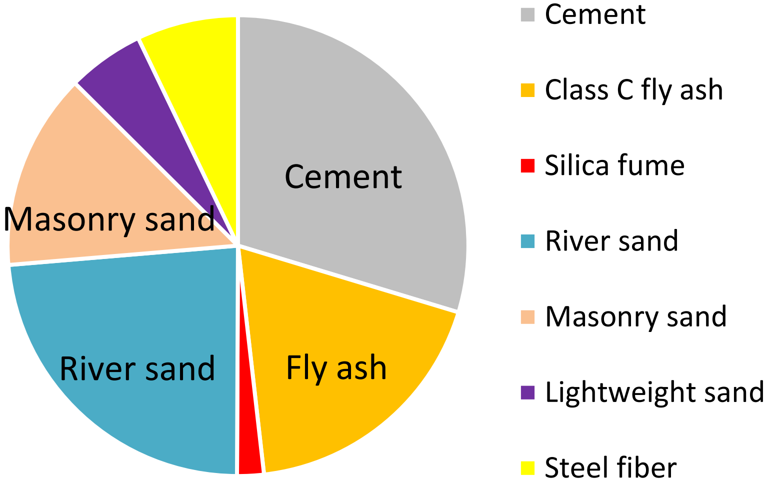


Uniform

Mixture design of UHPC

UHPC mixture design (unit: kg/m^3), **steel fiber is fixed at 2%**, by volume

Fiber	Cement	Fly ash	Silica fume	River sand	Masonry sand	Lightweight sand
156	649	405	41	516	302	118



Reference UHPC mixture, by mass

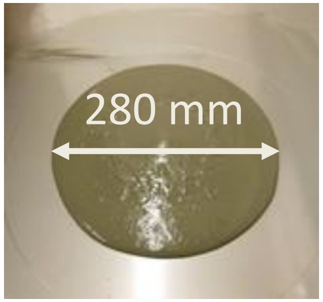
Six mixtures with different viscosity modified admixture (VMA)

VMA-0.0 (Reference),
VMA-0.5 (0.5%, mass),
VMA-1.0,
VMA-1.5,
VMA-2.0,
VMA-2.5

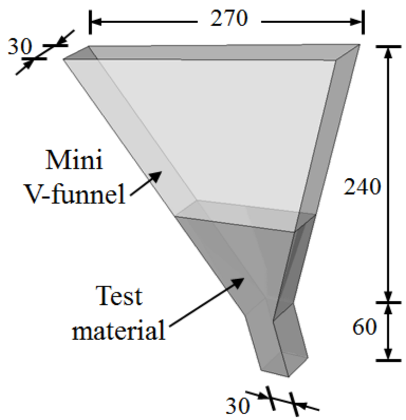
Meng, W. and Khayat, K.H., 2017. Improving flexural performance of ultra-high-performance concrete by rheology control of suspending mortar. *Composites Part B: Engineering*, *117*, pp.26-34.

Experimental method

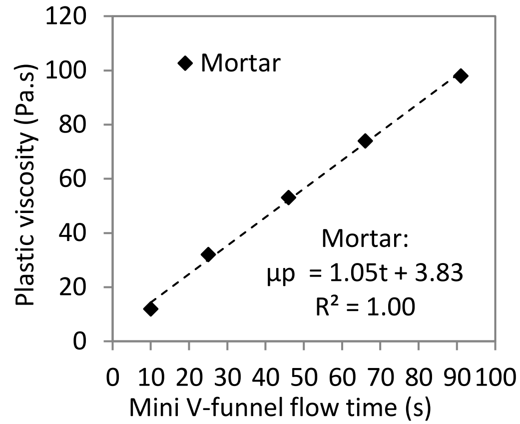
1. Before adding fibers



High mini-slump for low yield stress

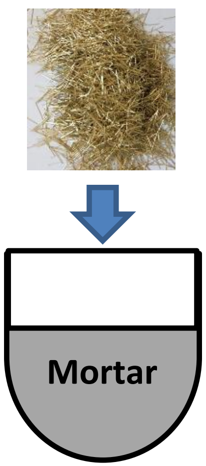


Mini V-funnel flow time



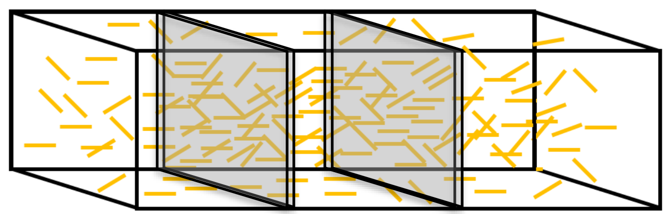
Plastic viscosity (µp)

2. After testing of 1, adding fibers into mortar



Flexural properties (ASTM C1609)

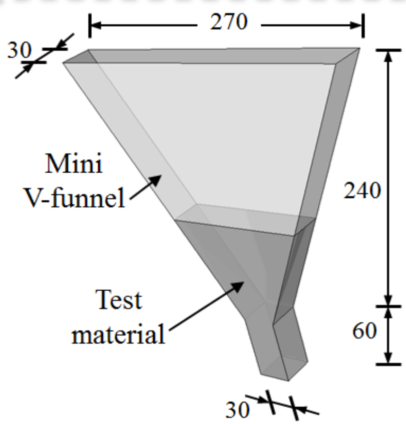
Cut sections for image analysis



Fiber distribution (orientation and dispersion)

Rheology control for better fiber distribution

- Establish relations of rheological properties (use viscosity modified admixture), flexural properties, and fiber distribution



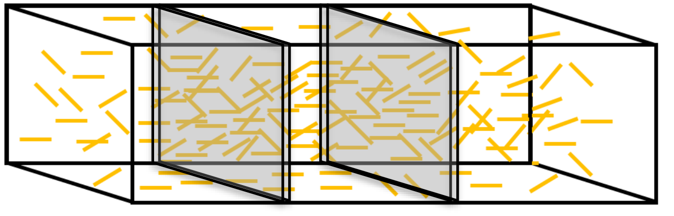
Flow time

Linear relationship

Plastic viscosity (μp)

Flexural properties (with fibers)

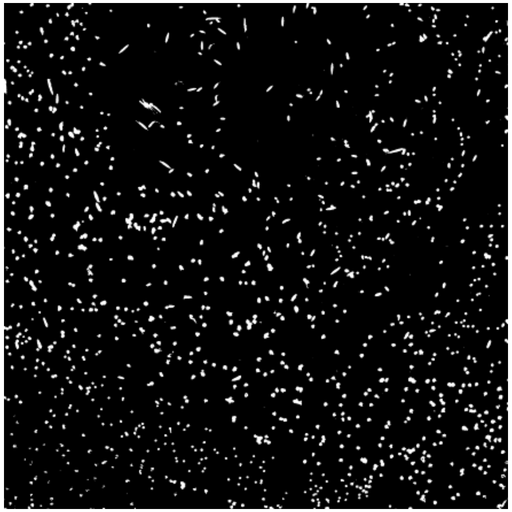
Fiber distribution (orientation and dispersion)



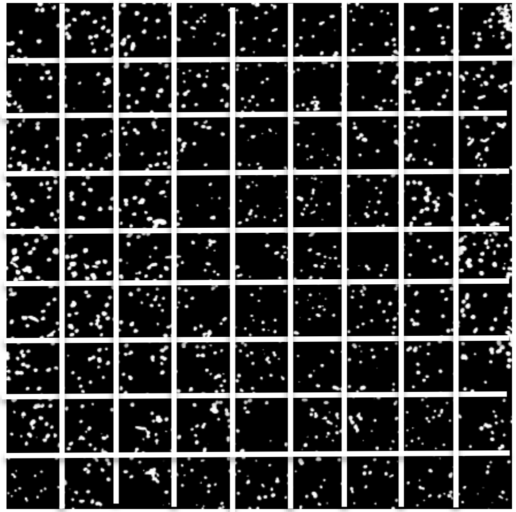
Cut sections

Image analysis for fiber dispersion and orientation

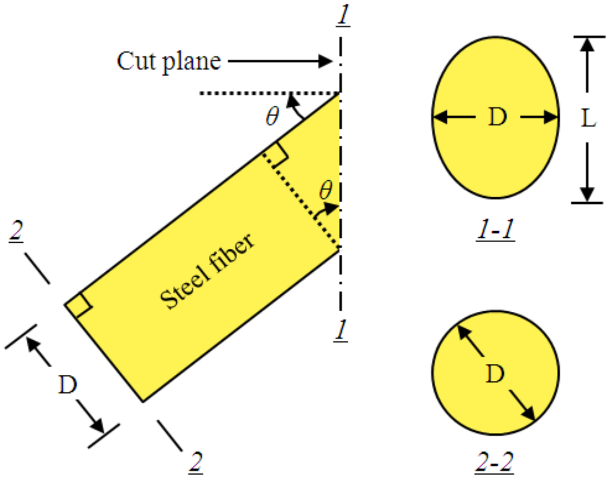
- Binary images of the cross sections of beam specimens



VMA-0



VMA-1.0



Fiber orientation coefficient (η):
η = 1, fibers aligned perpendicular to cross section

$$\theta = \arccos\left(\frac{D}{L}\right)$$

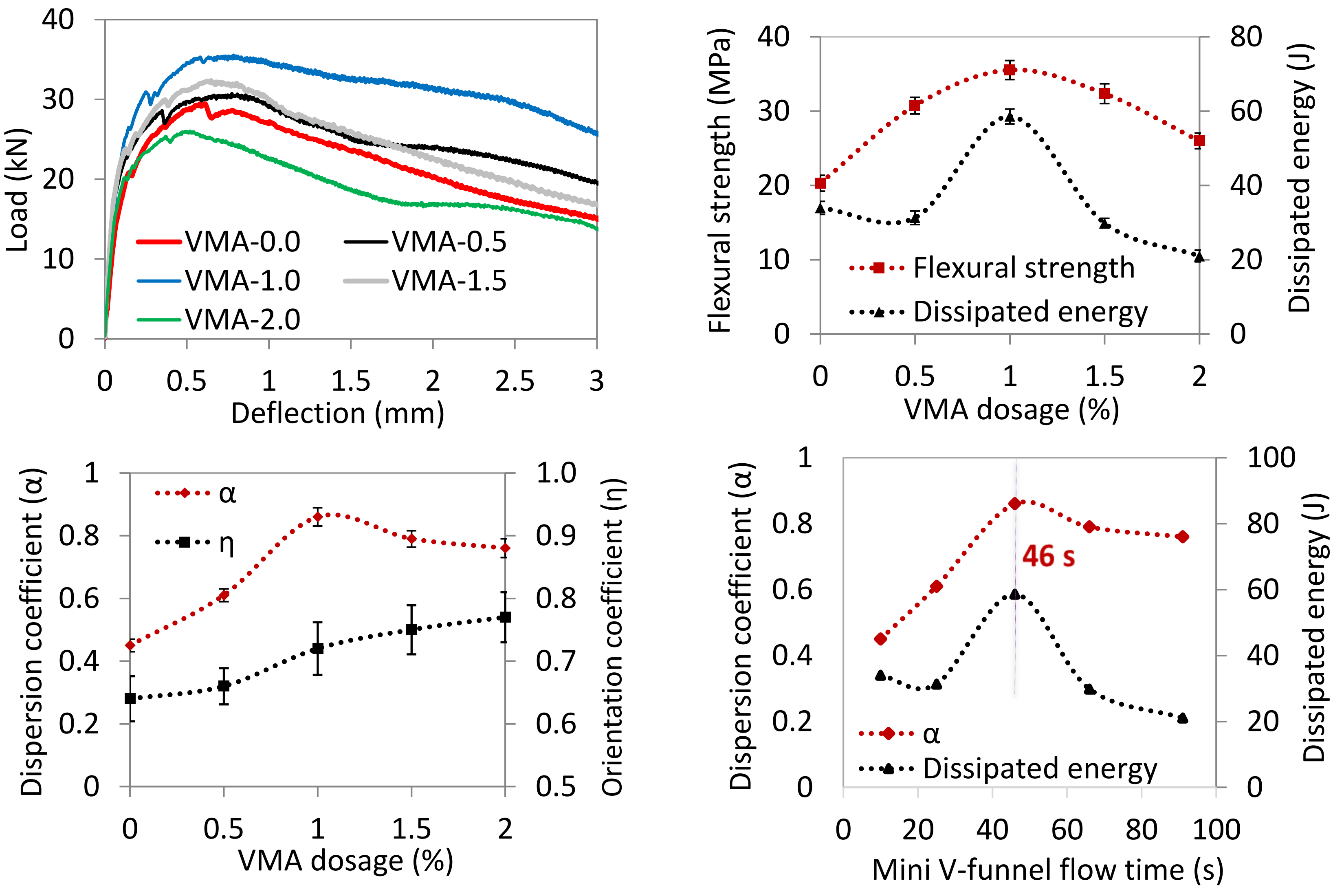
$$\eta = \int_{\theta_{min}}^{\theta_{max}} p(\theta)\cos^2\theta \, d\theta$$

Fiber dispersion coefficient (α):
α = 1, fibers uniformly dispersed

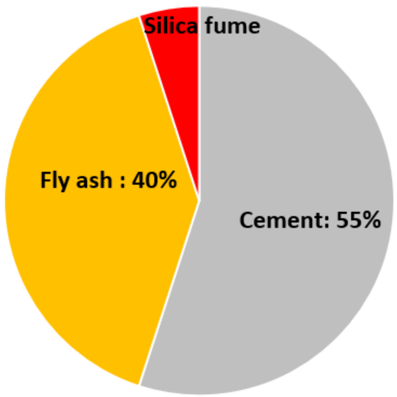
$$\alpha = \exp\left[-\frac{1}{x_0}\sqrt{\frac{\sum(x_i - x_0)^2}{n}}\right]$$

Effect of rheology on flexural properties of UHPC

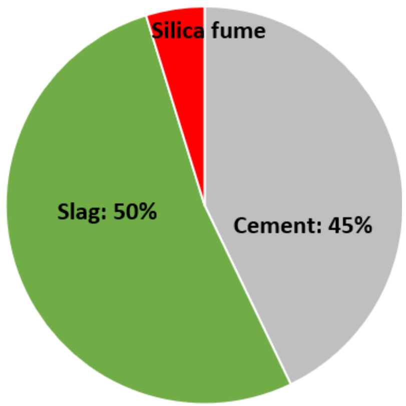
- Control rheological properties to optimize flexural properties



Validation of rheology control concept



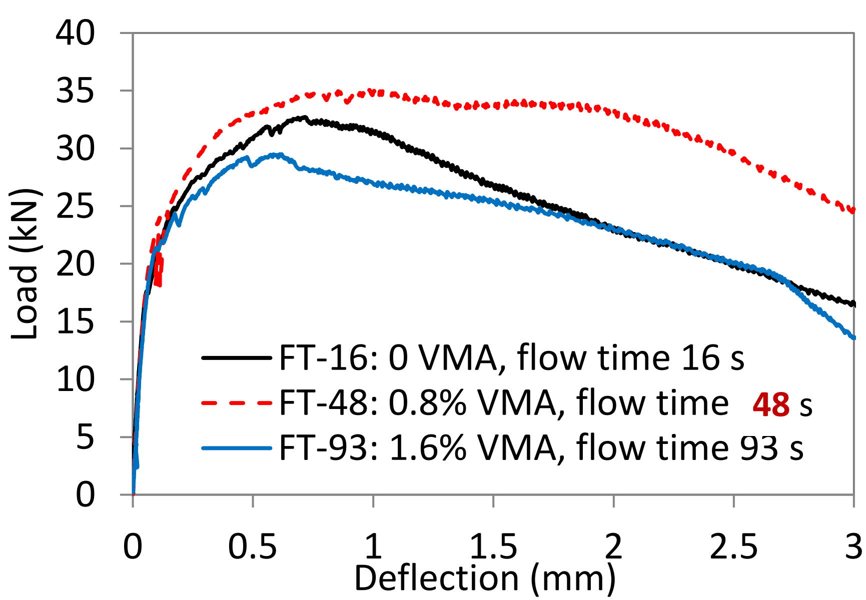
Control binder, by volume

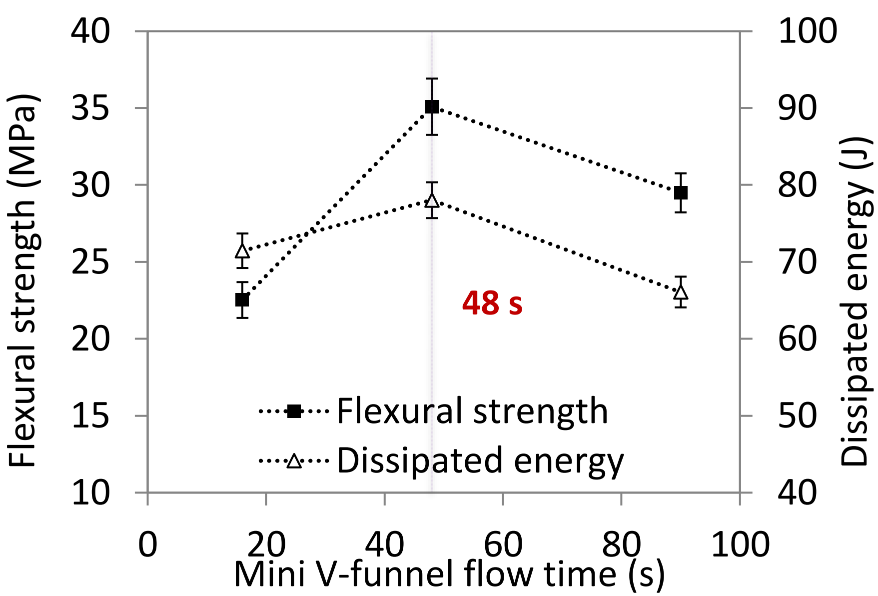


Binder for validation, by volume

3 mixtures
The flow time of each mortar was controlled to:

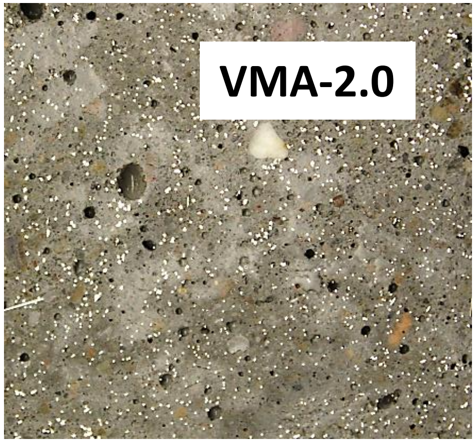
1. 16 s
2. 48 s ≈ **46 s**
3. 93 s

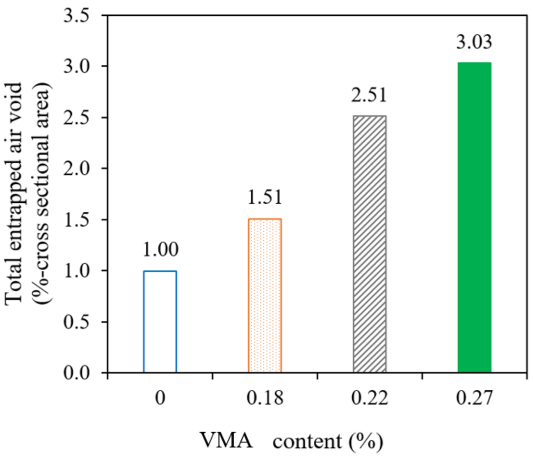




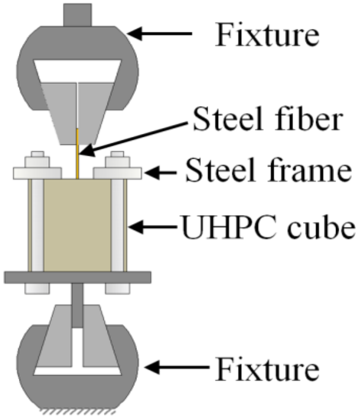
Effect of VMA

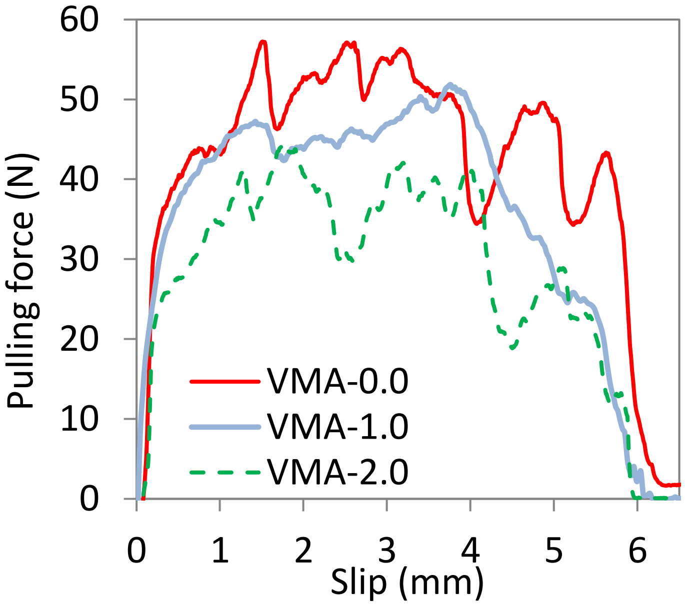
- More VMA, more air void





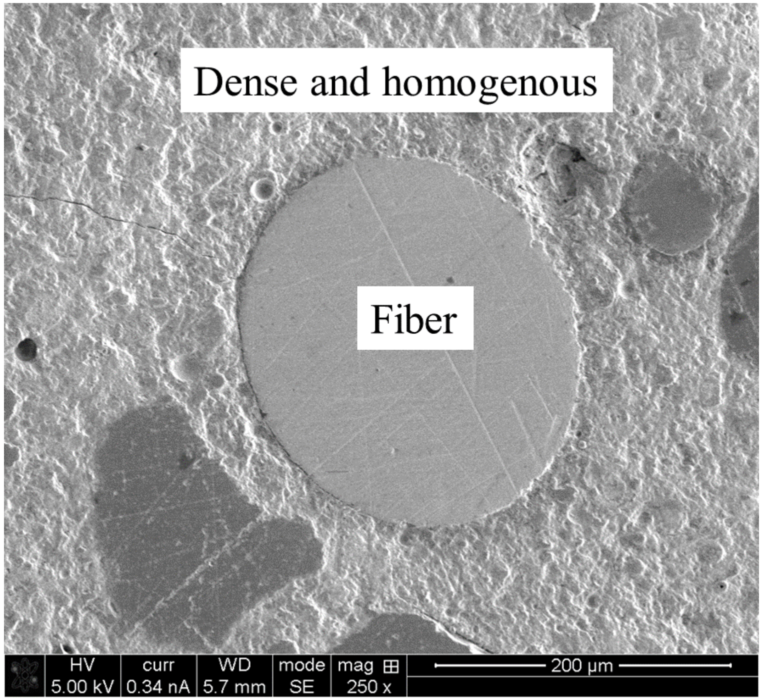
- More VMA, lower bond strength and pull-out energy



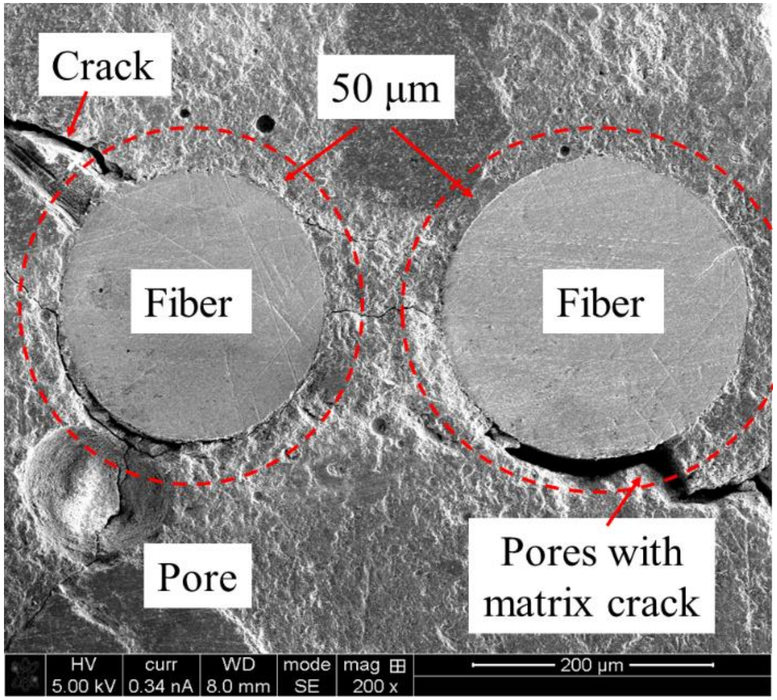


Microstructure

- More VMA, higher plastic viscosity of the matrix, more pores observed between the interface of fiber and matrix



Low and optimum viscosity

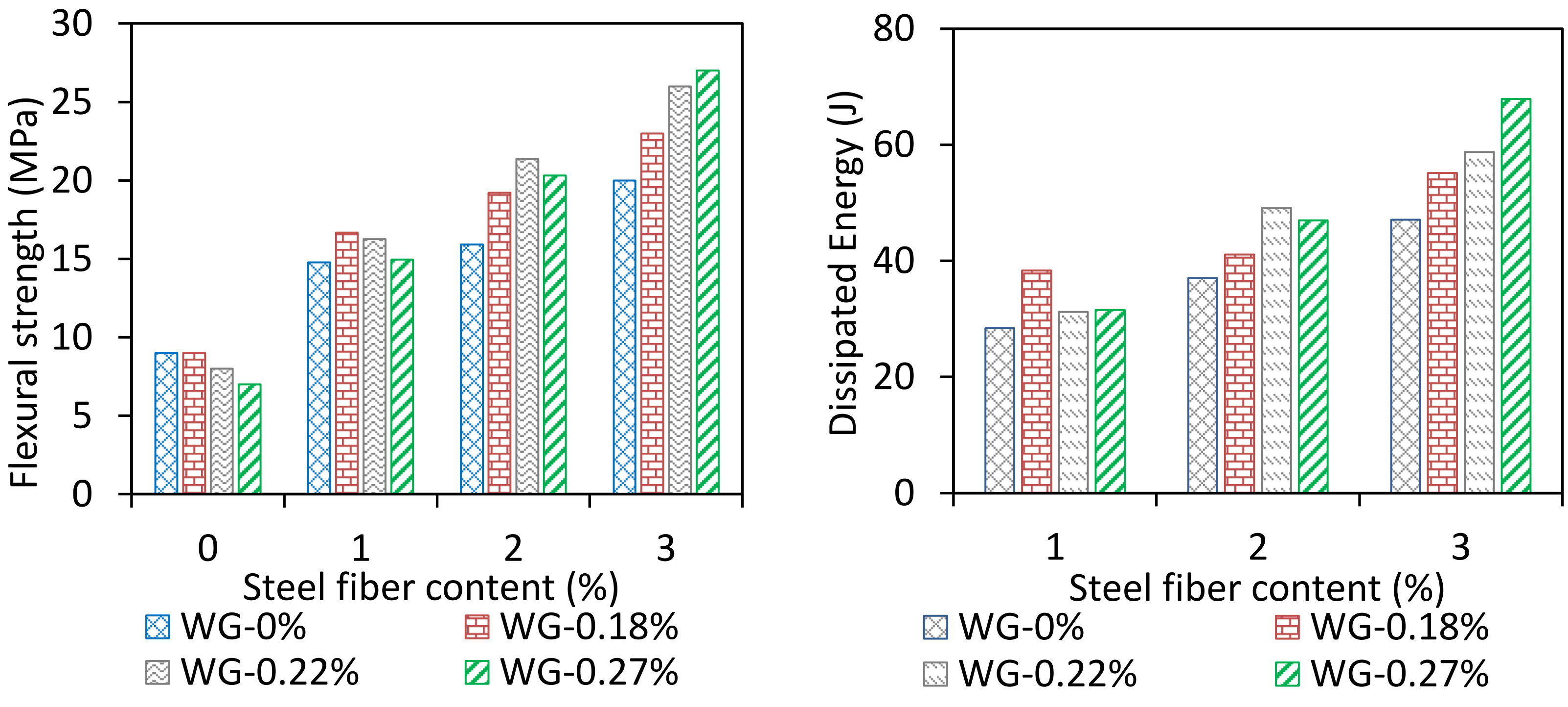


High viscosity

Teng, L., Meng, W. and Khayat, K.H., 2020. Rheology control of ultra-high-performance concrete made with different fiber contents. *Cement and Concrete Research*, *138*, p.106222.

Effect of fiber contents on rheology control

- UHPC with higher fiber content requires higher viscosity of suspending mortar to secure the highest flexural properties



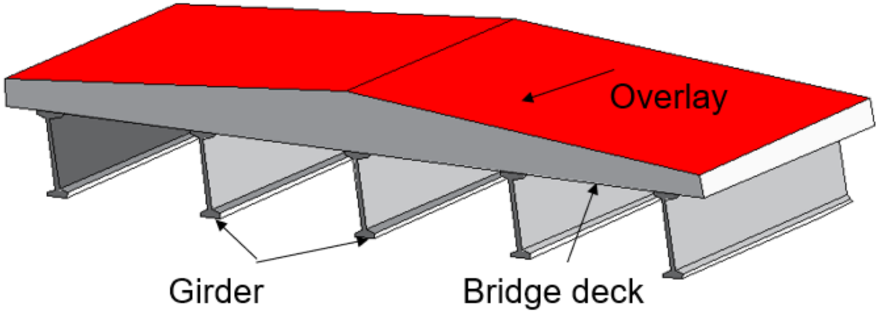
- Optimum viscosity: 36 Pa·s for V_f = 1%; 52 Pa·s for V_f = 2%; 66 Pa·s for V_f = 3% (WG: welan gum, one type of VMA)

Teng, L., Meng, W. and Khayat, K.H., 2020. Rheology control of ultra-high-performance concrete made with different fiber contents. *Cement and Concrete Research*, *138*, p.106222.

Rheology control for slope casting

- Bridge deck is sloped structures: 2%~5%.
- Typical UHPC is flowable and hard to stay still on decks
- Rheology of UHPC needs to be controlled for ease of mixing and casting, but stay still after casting

Flowable UHPC



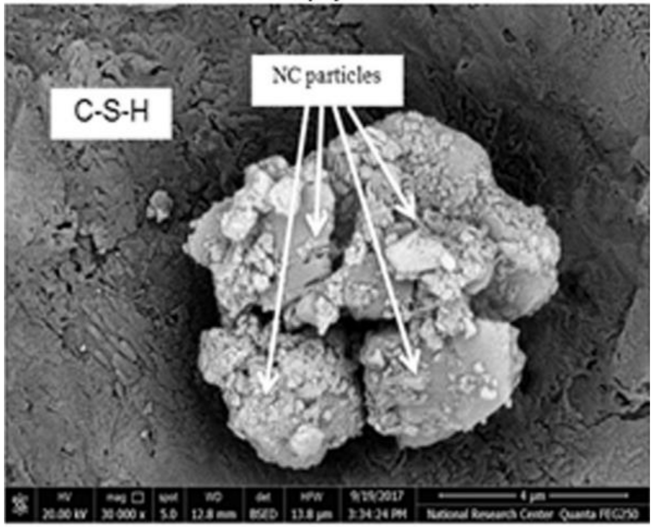
Labors and formworks

Sritharan, S., & Wibowo, H. (2018).

Enhance the thixotropic properties

- Why thixotropy?
  - ✓ Thixotropy enables the shape stability of UHPC after casting.
- Thixotropy-enhancing admixture
  - ✓ Nanoclay powders: magnesium alumina silicate - agglomerate

Enhanced shape stability

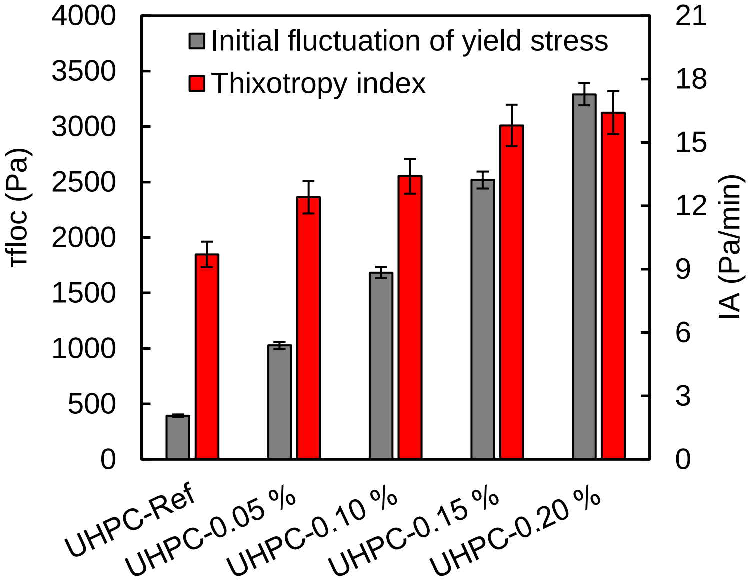


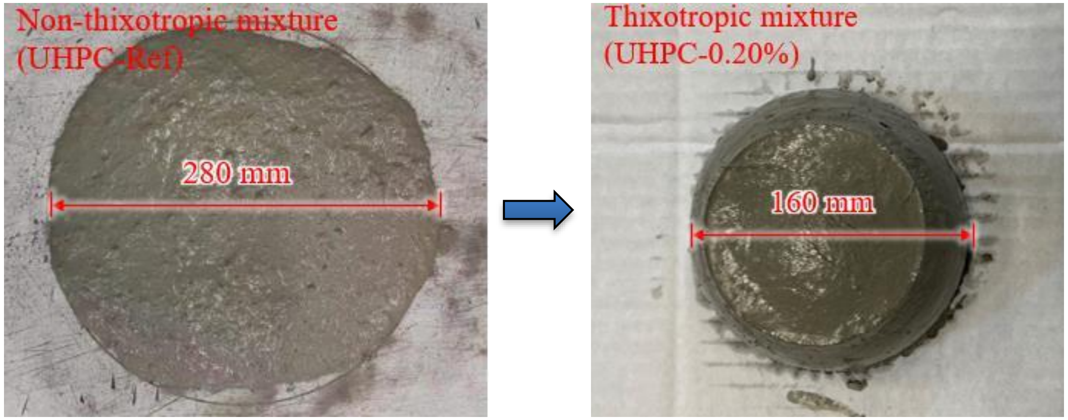
Sritharan, S, et al. (2018)   Hamed, N., et al. (2019)

A water-based nanoclay suspension is used

- With the enhanced shape stability, fresh UHPC can stay still on the ground without external supports.

Mixture design	UHPC-Ref	UHPC-0.05	UHPC-0.10	UHPC-0.15	UHPC-0.20
NC content	0	0.05%	0.10%	0.15%	0.20%



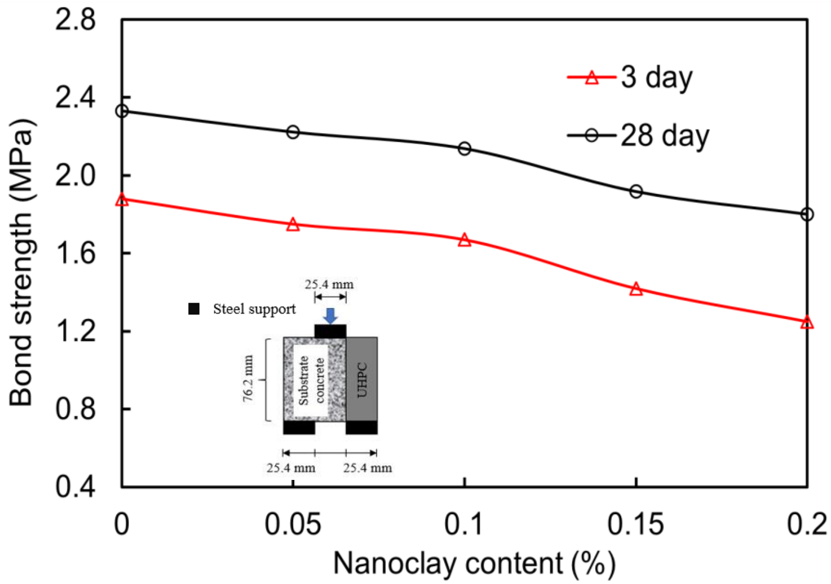


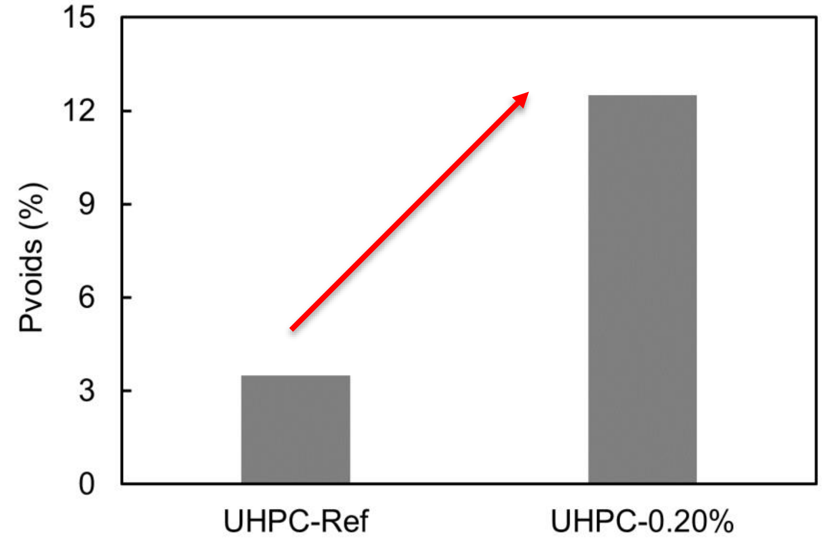
Note: τ_{floc} is the initial fluctuation of yield stress; I_A is the thixotropy index

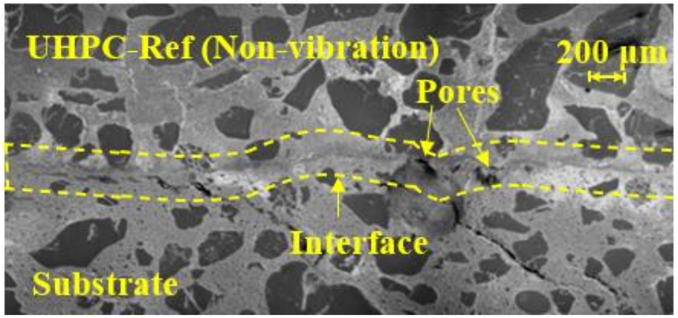
Du, J., & Meng, W. (2023).

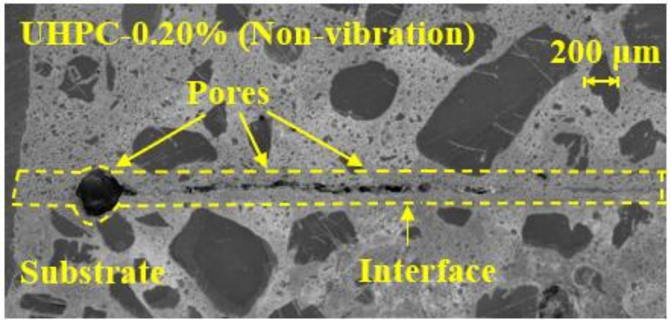
Effect of thixotropy on bond behaviors

- High thixotropy reduces the bond strength on the interface.
- High thixotropy results in high voids on the interface.





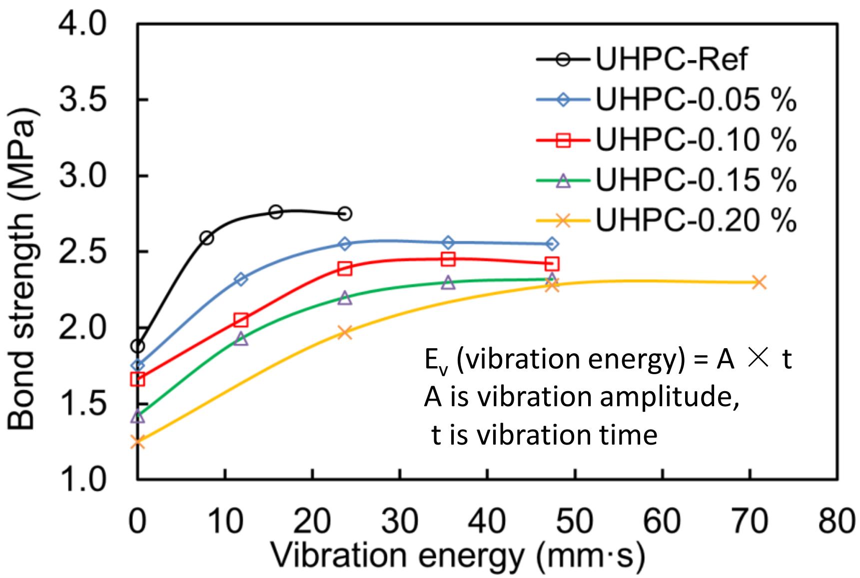


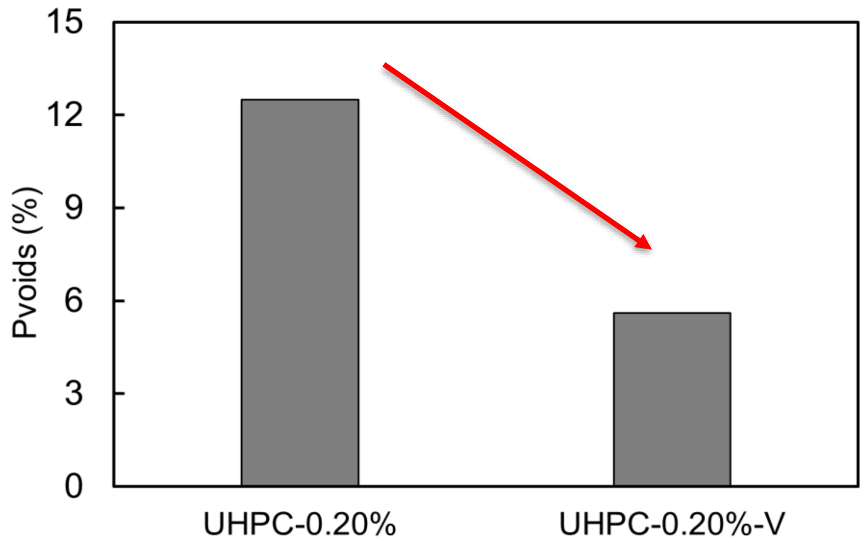


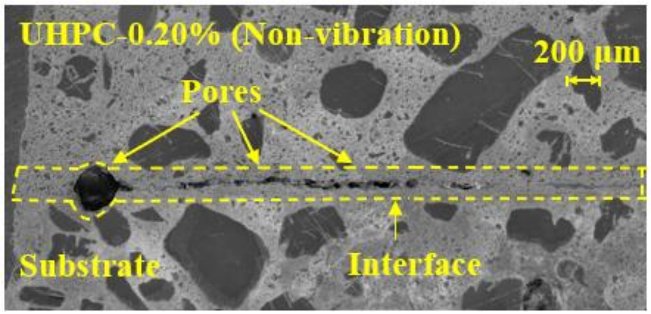
Du, J., & Meng, W. (2023).

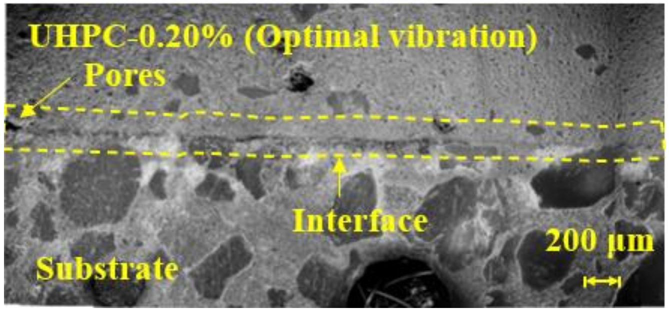
Vibration needs to be optimized

- Vibration restores UHPC flowability and reduces air voids on interface.
- Optimal vibration improves bond strengths on the interface.



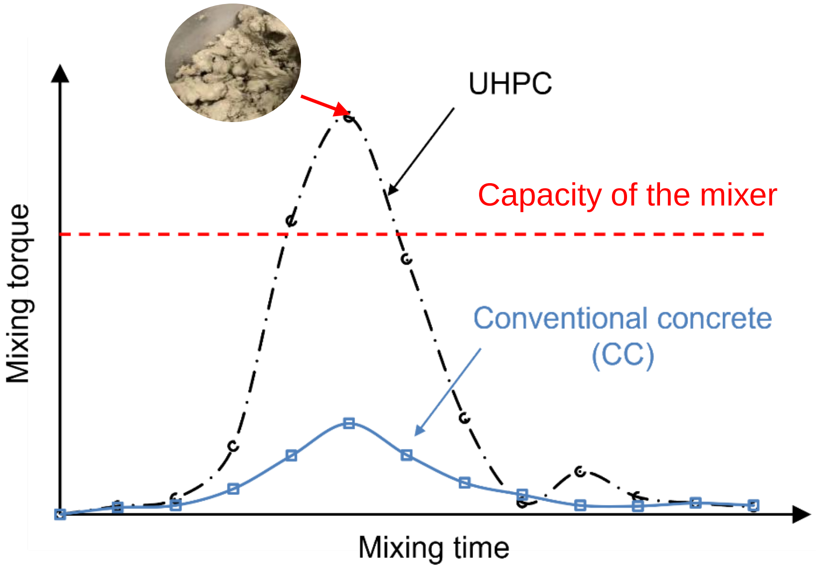






Rheology control for large-scale production

- The mixer might be shutdown due to the excessive mixing torque
  - ✓ High-volume binders: CC ≈ 500 kg/m^3 and UHPC ≈ 1200 kg/m^3
  - ✓ Low w/b: CC ≈ 0.45 and UHPC ≈ 0.20
- The stoppage damages the engine and wastes raw materials.

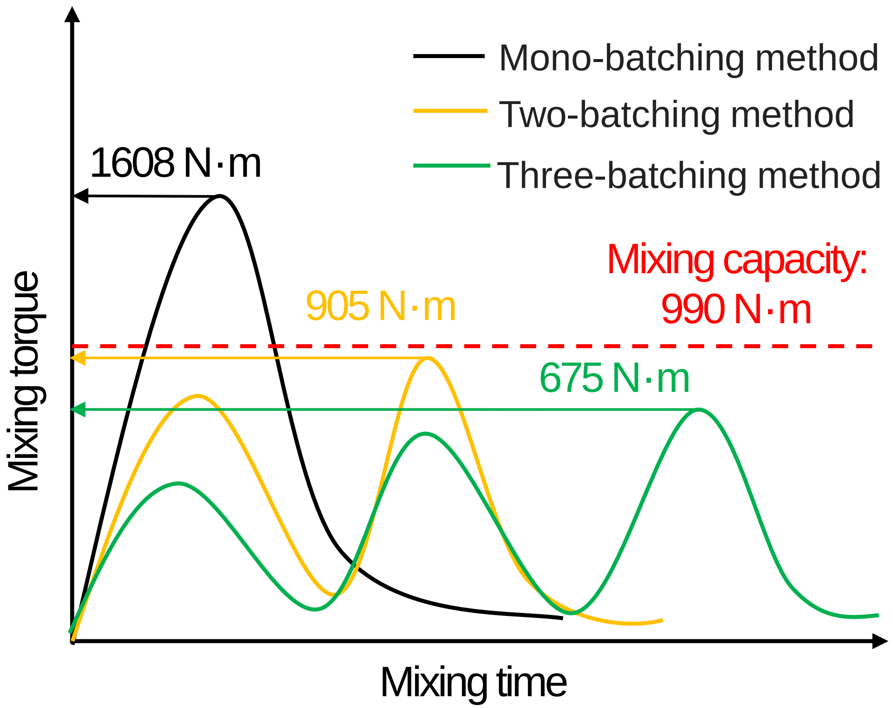


Malfunction of the mixer during the mixing process

Note: w/b is the water-to-binder ratio

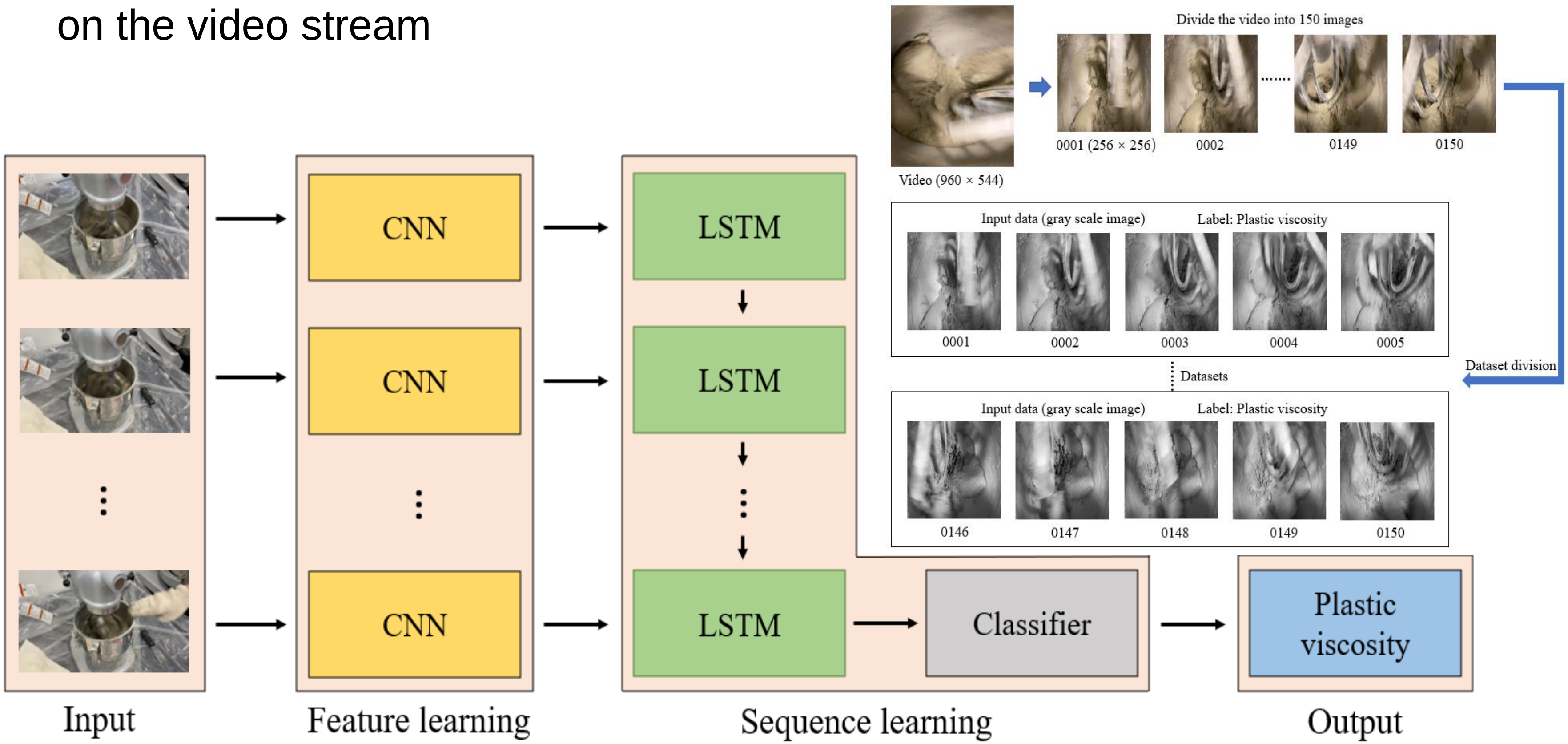
Control rheology by multi-batching method

- Divide one batch into two or three to reduce the peak mixing torque
  - ✓ Mixing capacity: 990 N·m



Rheology assessment using videos

- A deep learning method (i.e., long-term recurrent convolutional network (LRCN)) has been developed to assess the plastic viscosity of UHPC based on the video stream

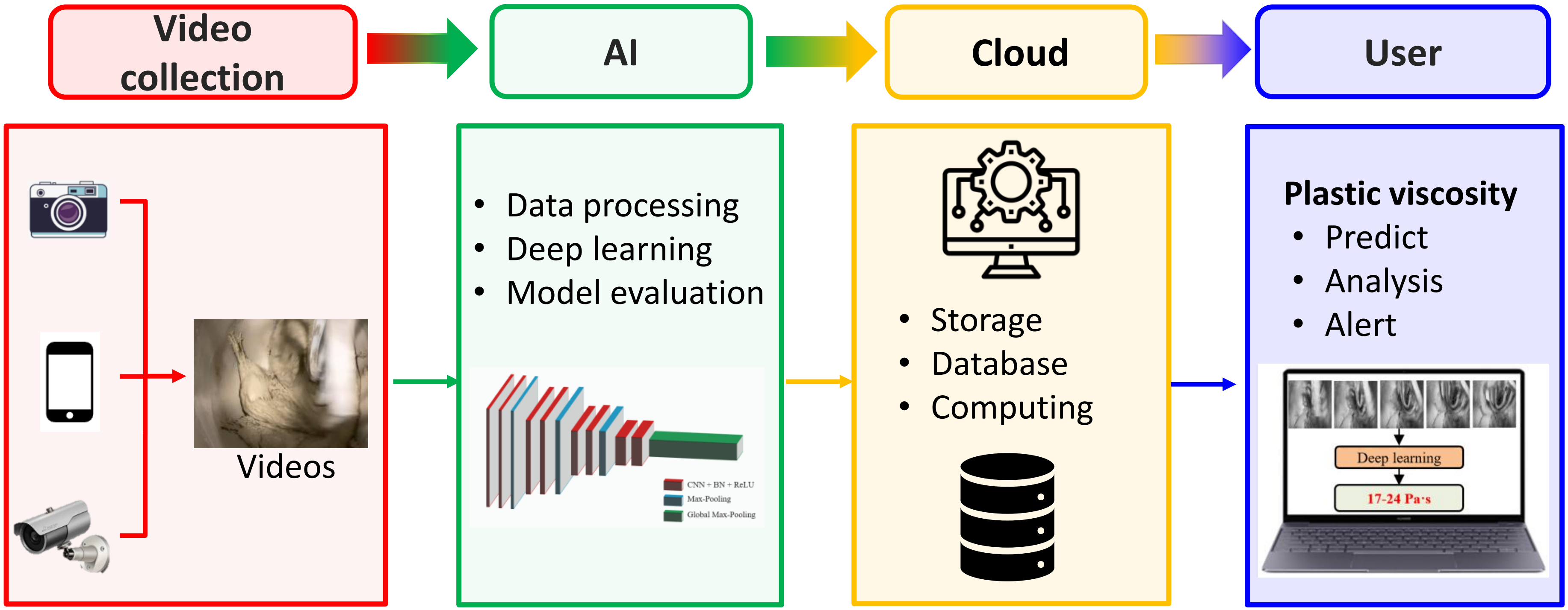


Architecture of long-term recurrent convolutional network

Guo, P., Du, J., Bao, Y. and Meng, W., 2022. Real-time video recognition for assessing plastic viscosity of ultra-high-performance concrete (UHPC). *Measurement*, *191*, p.110809.

AI-aided plastic viscosity monitoring

- AI-aided rheology monitoring and control



Method	Time	Human action
Rheometer	10-30 min	Need manual operation
Flow time method	10 min	Need manual operation
Deep learning method	< 1 s	Without human intervention

Conclusions

1. The dispersion and orientation of steel fibers in UHPC are dependent on the rheological properties of the suspending mortar. Optimum plastic viscosity results in highest flexural properties.
2. Water-based nanoclay can effectively enhance the thixotropic properties of UHPC. Vibration can improve the interfacial properties between thixotropic UHPC and substrate
3. Mixing procedures need be optimized for ease of large-scale mixing of UHPC.
4. AI-based method monitors the viscosity in real time.

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Dr. Le Teng

Thank you!
Q&A

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