KAIST College of Engineering Department of Civil and Environmental Engineering jae.kim@kaist.ac.kr

Matric suction and its effect on the shape stability of 3D printed concrete

Jae Hong Kim, PhD

Associate Professor – Department of Civil and Environmental Engineering
Director – Research Center for Underground City of the Future

Korea Advanced Institute of Science and Technology

ACI Fall 2023 Convention, Boston, MA

미래지하도시연구센터

1. Introduction
2. Matric suction
3. Matric suction, its effect on yield stress
4. Matric suction, other considerations
5. Conclusions

Introduction: Additive construction

Additive manufacturing		Formwork manufacturing	Slip-form method
Layer extrusion	Binder-jetting		
 Concrete printing (TU/e)  Contour crafting (USC)	 D-shape printing (Monolite)	  Polyurethane Form (MIT media lab)	 Smart Dynamic Casting (ETH Zurich)

Layer deposition

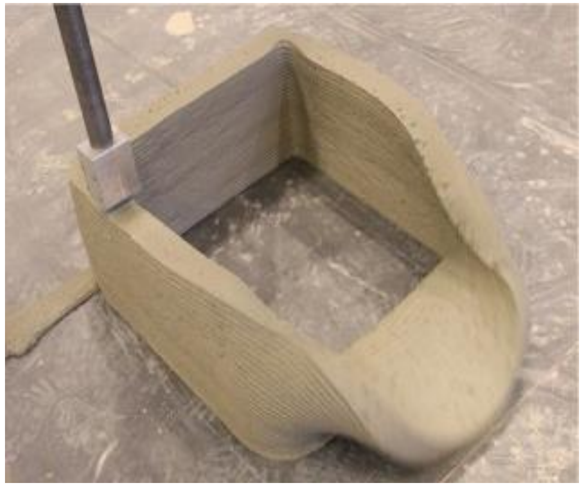
- Most common construction method of 3D concrete printing

Problems to be solved

- Size of equipment is proportional to structure scale
- Decreasing strength between layers
- Difficulties in placing rebar assembly

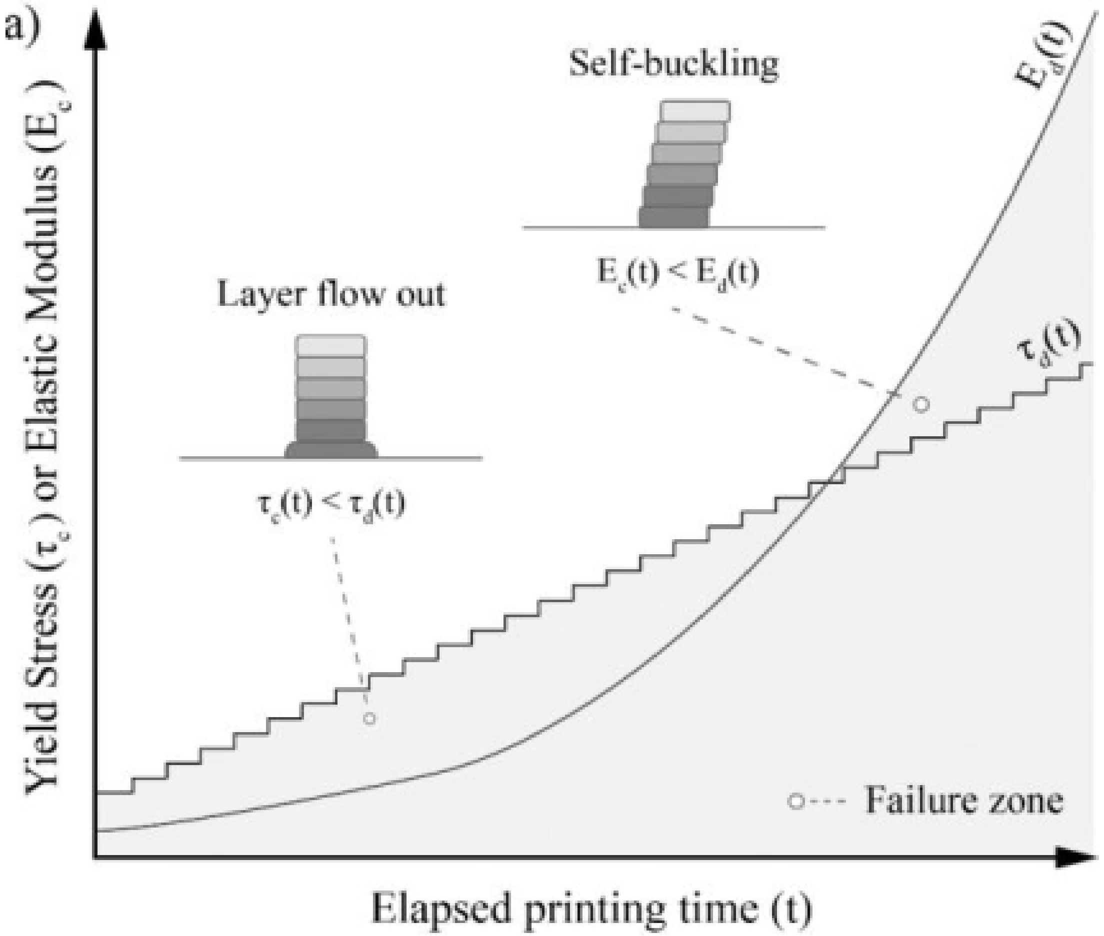
Labonnote, N., Rønnquist, A., Manum, B., & Rüther, P. (2016). Additive construction: State-of-the-art, challenges and opportunities. Automation in Construction, 72, 347–366.
Ahmed, G. H. (2023). A review of "3D concrete printing": Materials and process characterization, economic considerations and environmental sustainability. Journal of Building Engineering, 66, 105863.

Failure modes related to the shape stability



Layer flow out ~ yield stress

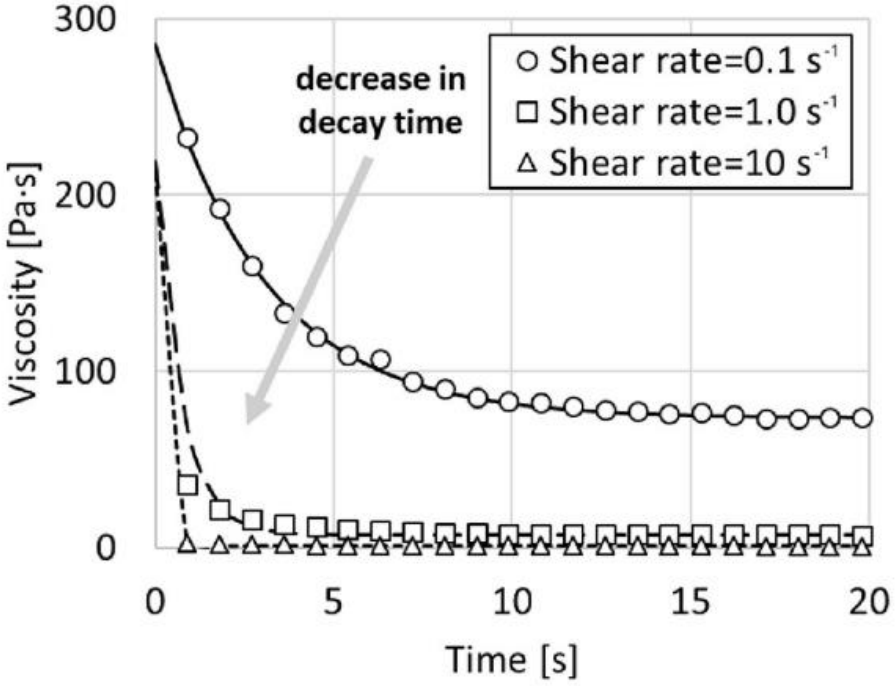
Self-buckling ~elastic modulus

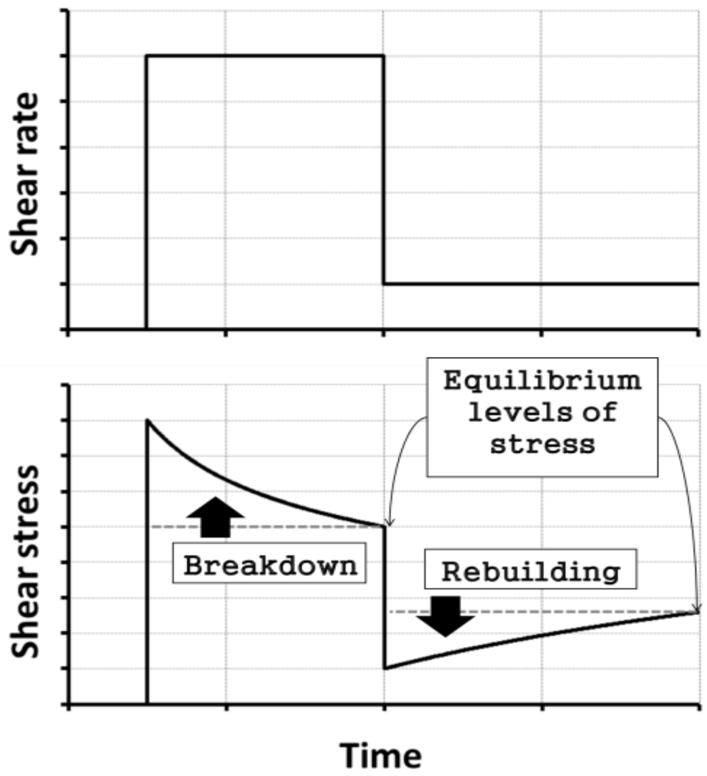


Suiker, A. S., Wolfs, R. J., Lucas, S. M., & Salet, T. A. (2020). Elastic buckling and plastic collapse during 3D concrete printing. Cement and Concrete Research, 135, 106016.
Leal da Silva, Fryda, Bousseau, Andreani, Andersen (2019). Evaluation of early-age concrete structural build-up for 3D concrete printing by oscillatory rheometry. International Conference on Applied Human Factors and Ergonomics

KAIST

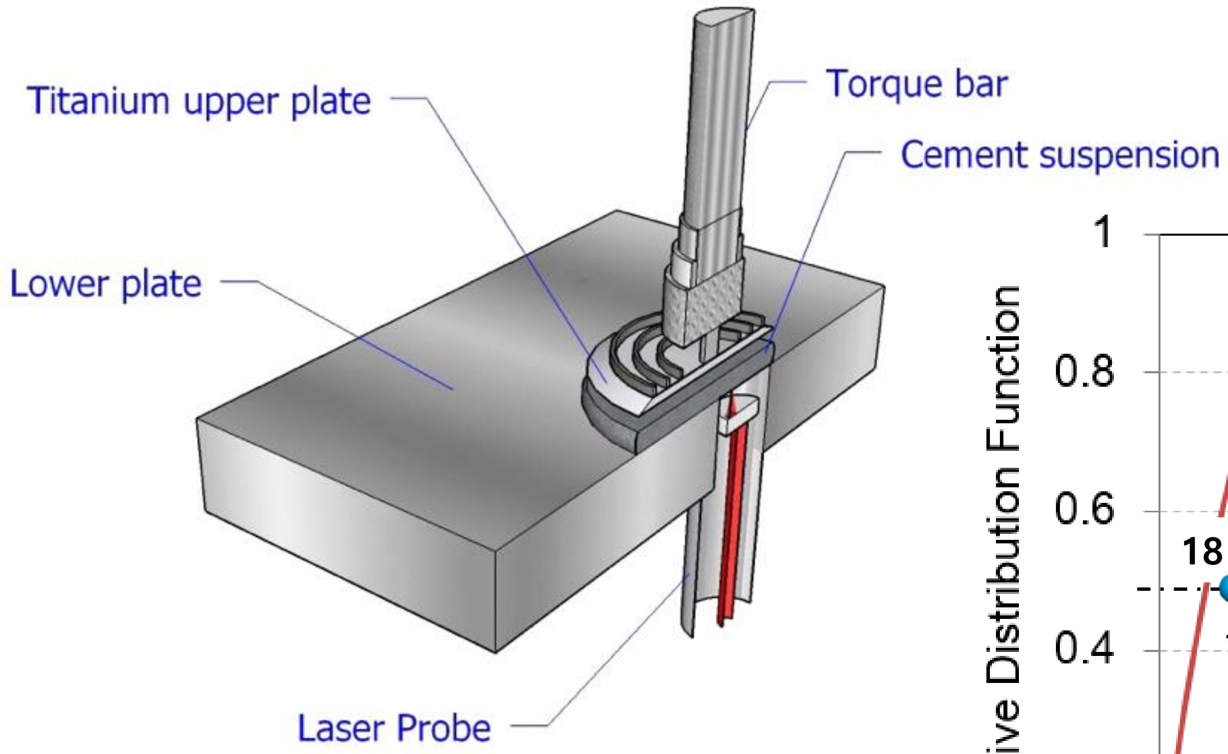
$$\eta_t(t;\dot{\gamma}) = \eta(\dot{\gamma}) + a\exp(-b(\dot{\gamma})t)$$

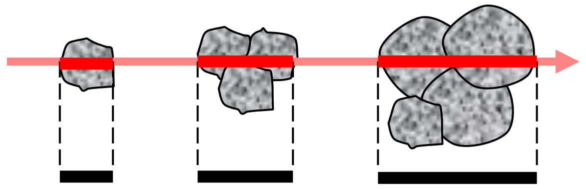


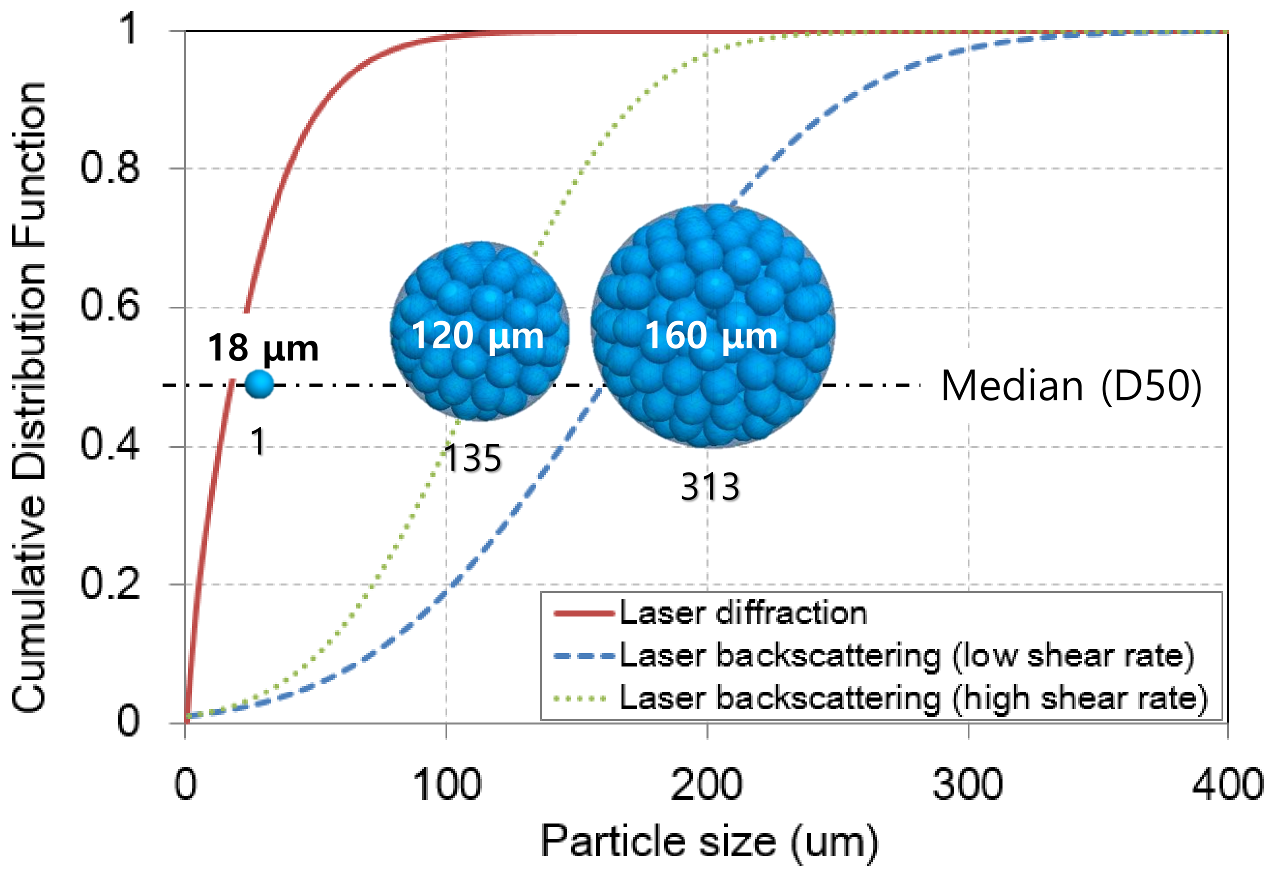


KAIST Choi, BI, **Kim, JH**, Shin, TY (2019). Rheological model selection and a general model for evaluating the viscosity and microstructure of a highly-concentrated cement suspension, CEMENT AND CONCRETE RESEARCH, 123: 105775.

Thixotropy, its relation with flocculation (1)



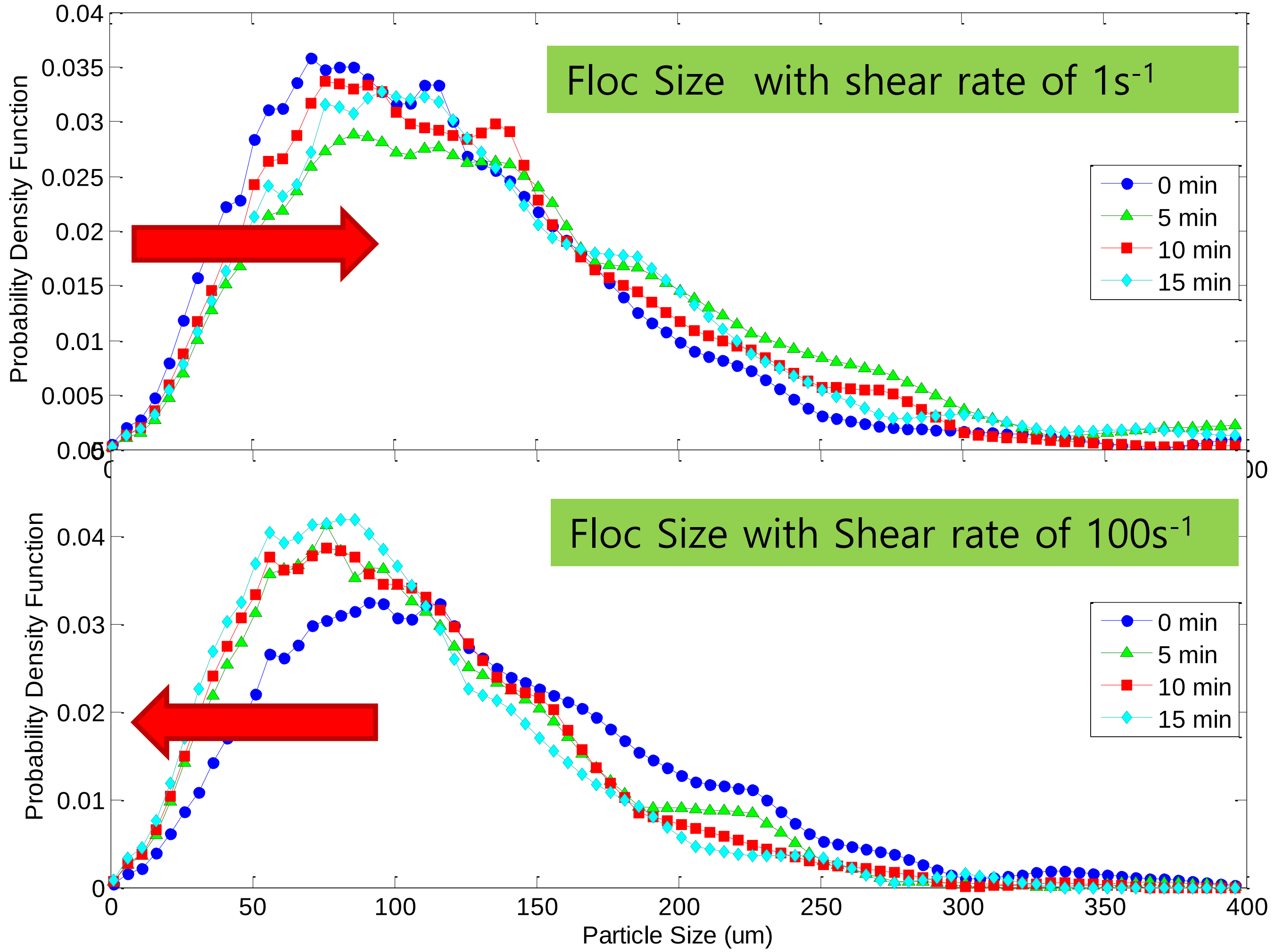


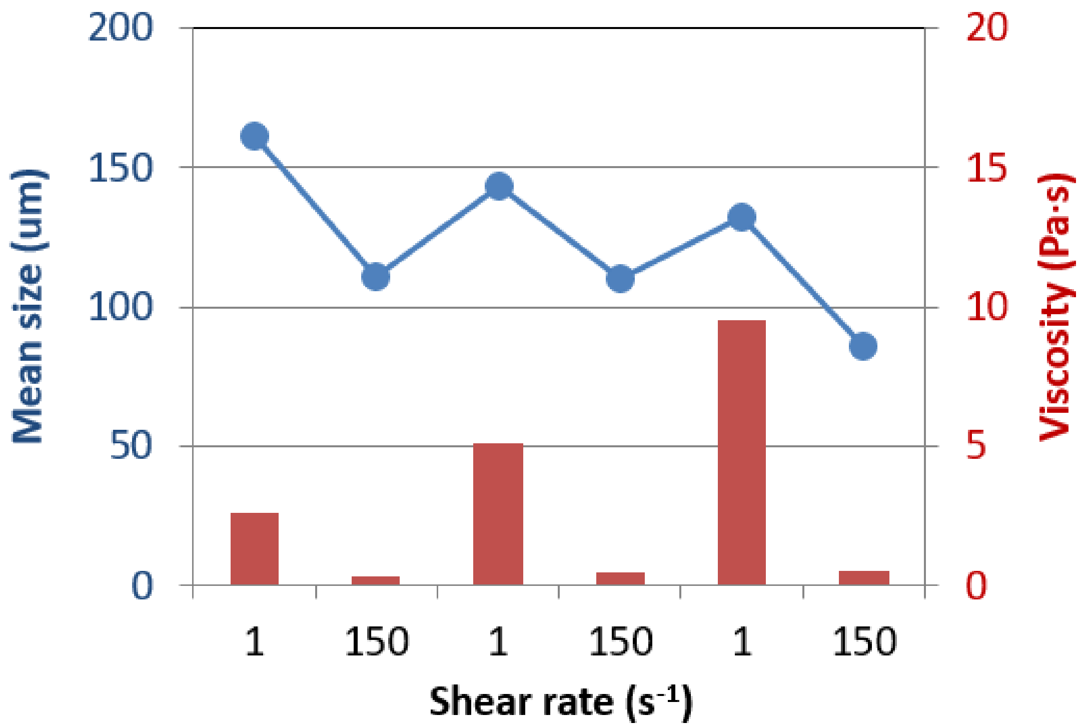


KAIST

Yim, HJ, **Kim, JH**, Shah, SP (2013). Cement particle flocculation and breakage monitoring under Couette flow, CEMENT AND CONCRETE RESEARCH, 53: 36~43.

Thixotropy, its relation with flocculation (2)

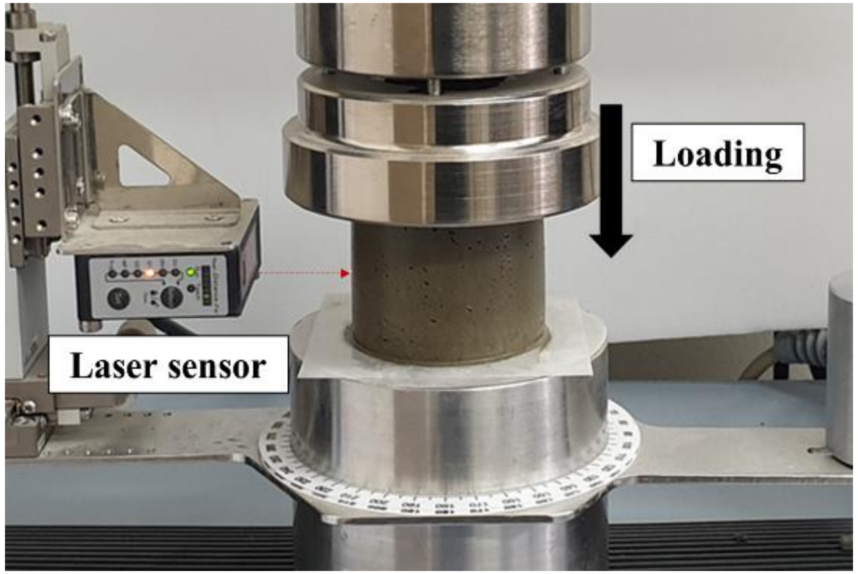


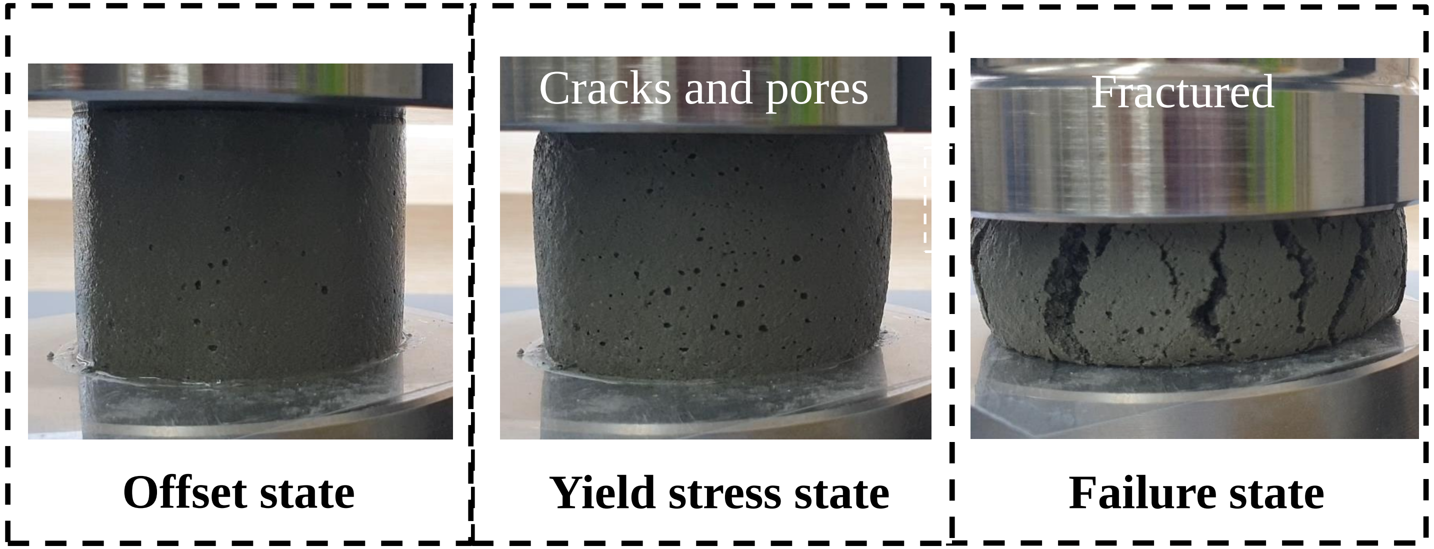


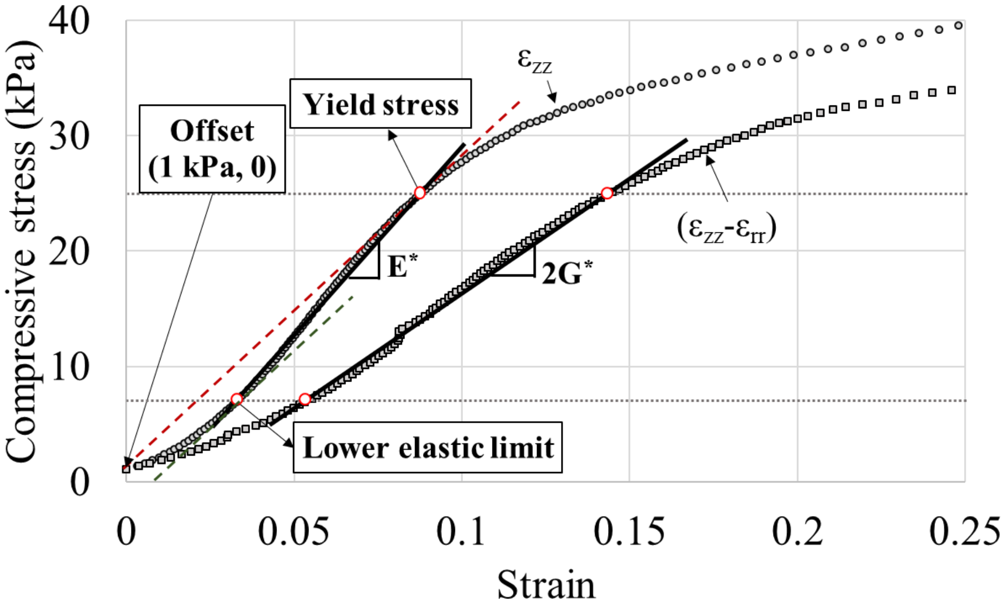
Kim, JH, Yim, HJ, Ferron, RD (2016), In situ measurement of the rheological properties and agglomeration on cementitious pastes, JOURNAL OF RHEOLOGY, 60(4): 695~704.

Yield stress measurement through the squeeze flow test

- Sample placed using a cylindrical mold, φ60×45
- Radial strain as well as vertical stress and strain
- Loading rate: 1.5 N/s

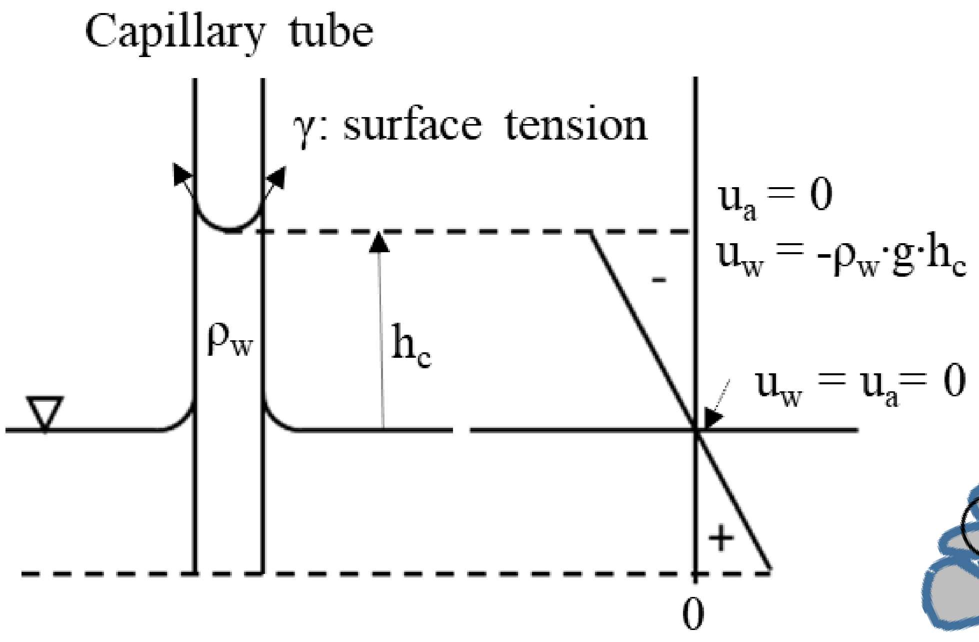


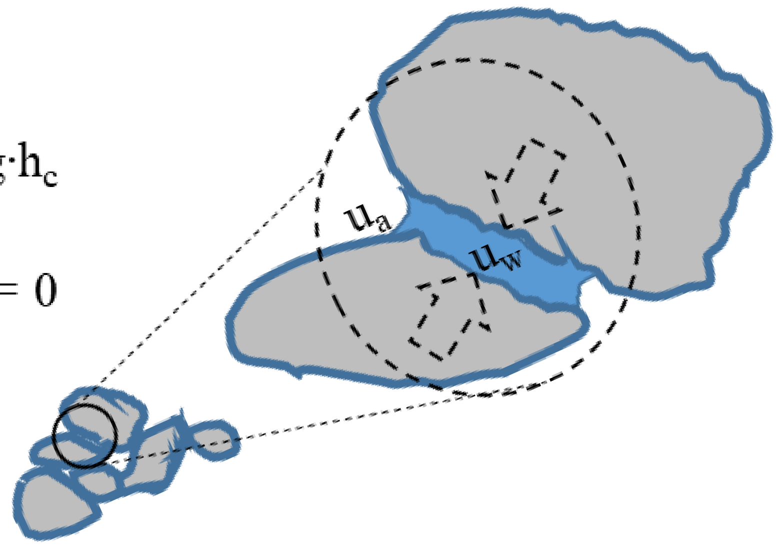




Surface tension of water induces a capillary rise, which results in the negative pore water pressure

- The negative pore water pressure on between particles makes them attractive each other

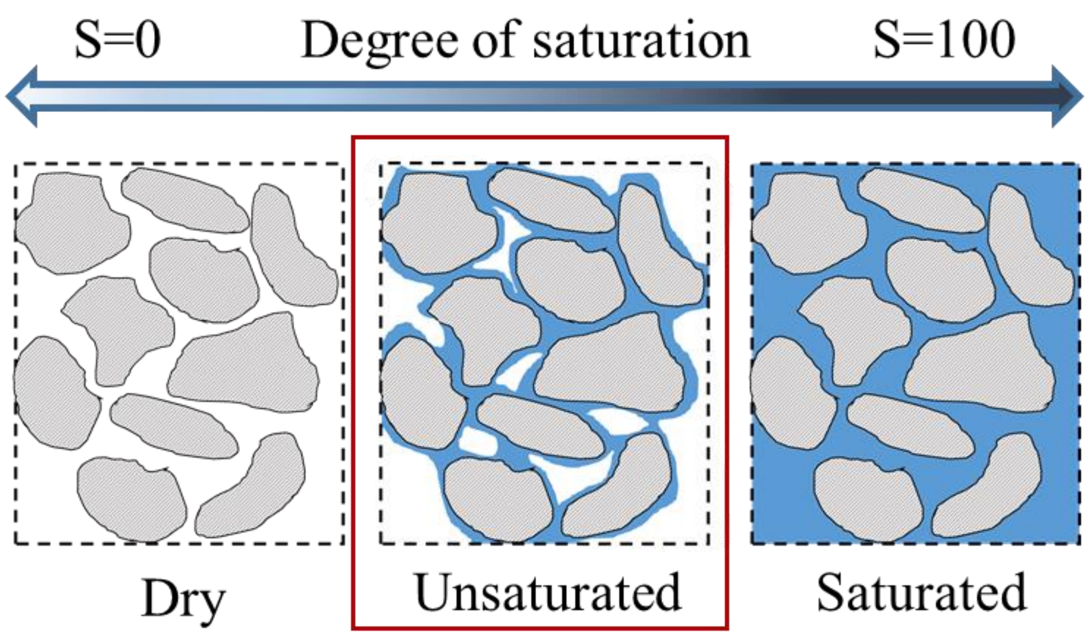


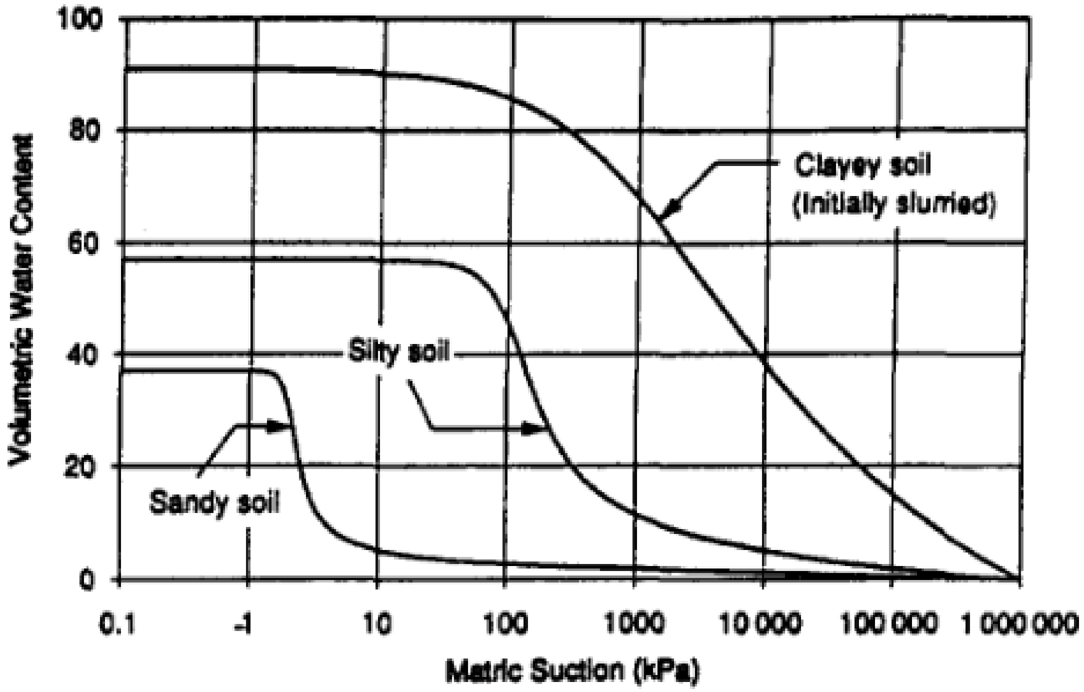


jae.kim@kaist.ac.kr

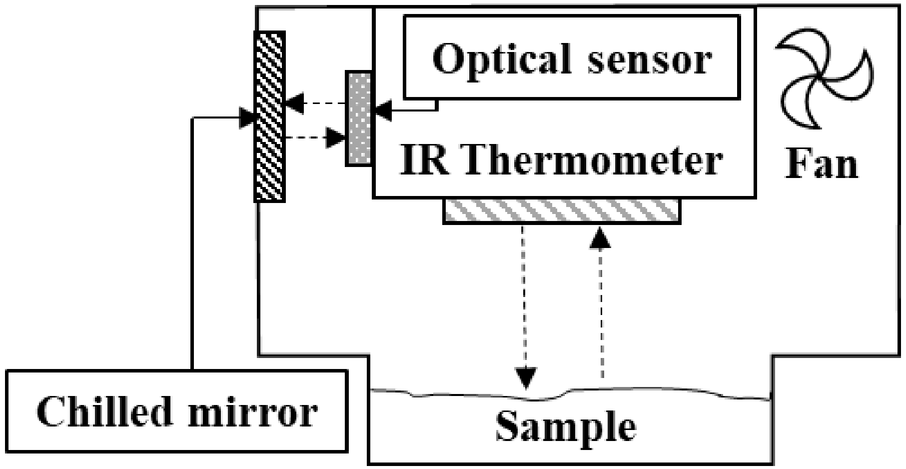
Soil water characteristic curve (SWCC)

- Relation between 'matric suction' and 'volumetric water content'
- As water content decreases, matric suction increases

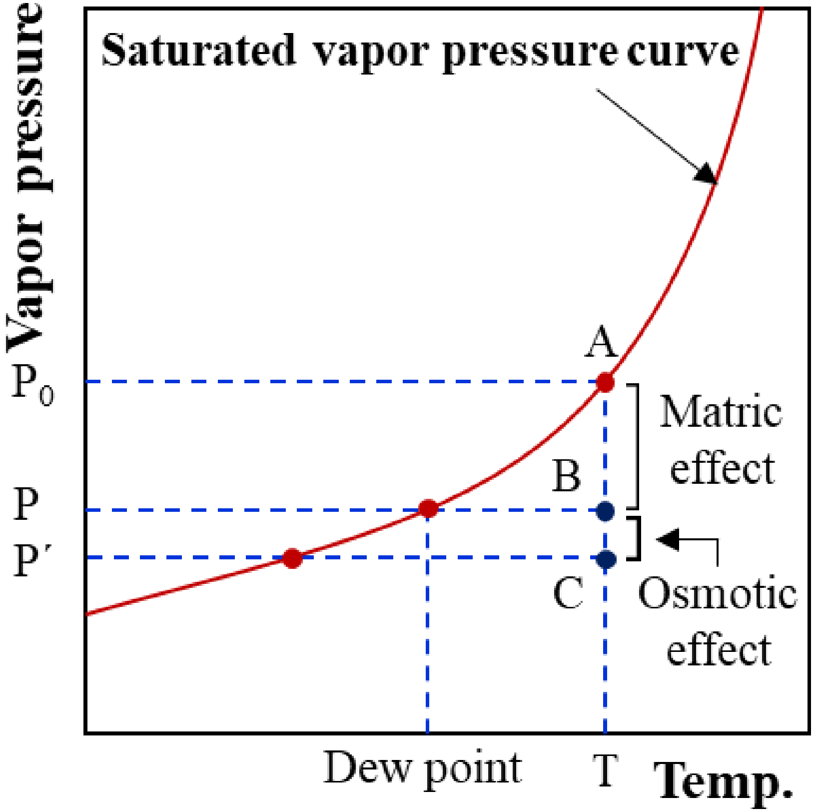


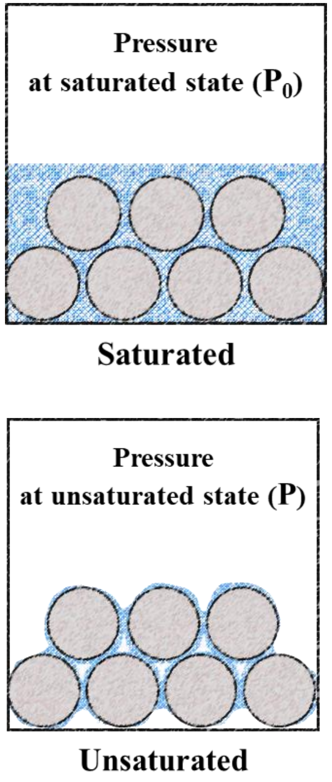


Chilled mirror hygrometer for measuring the matric suction of cement paste



Kelvin equation $$\psi = \frac{RT_s}{V_w} \ln \frac{P}{P_0} = \frac{RT}{V_w} \ln(RH)$$

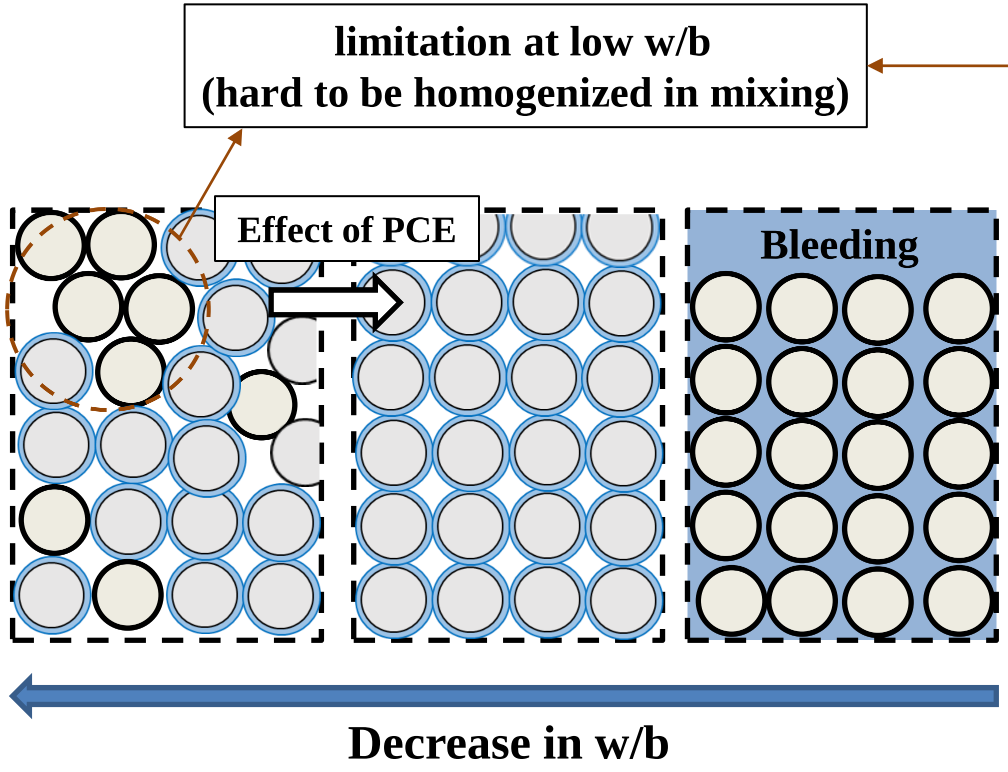


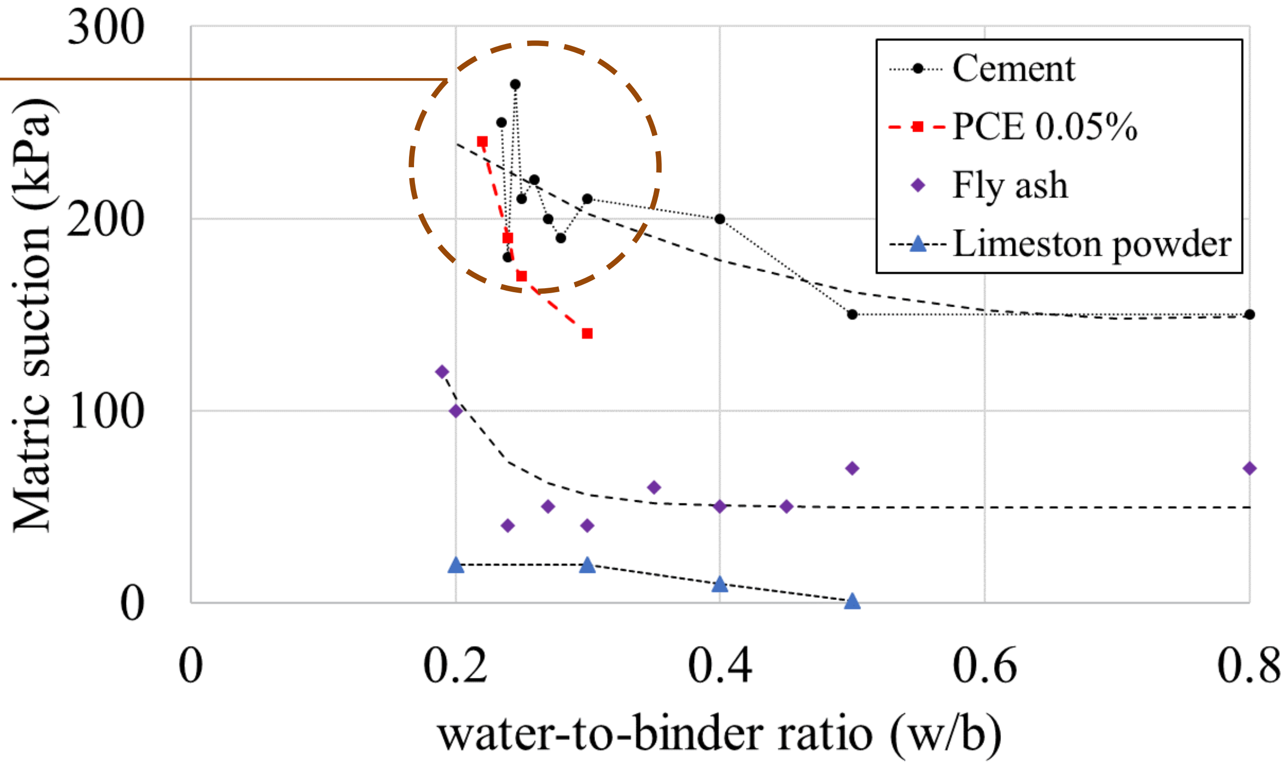


Matric suction (1), the effect of binder, water-to-binder ratio and PCE

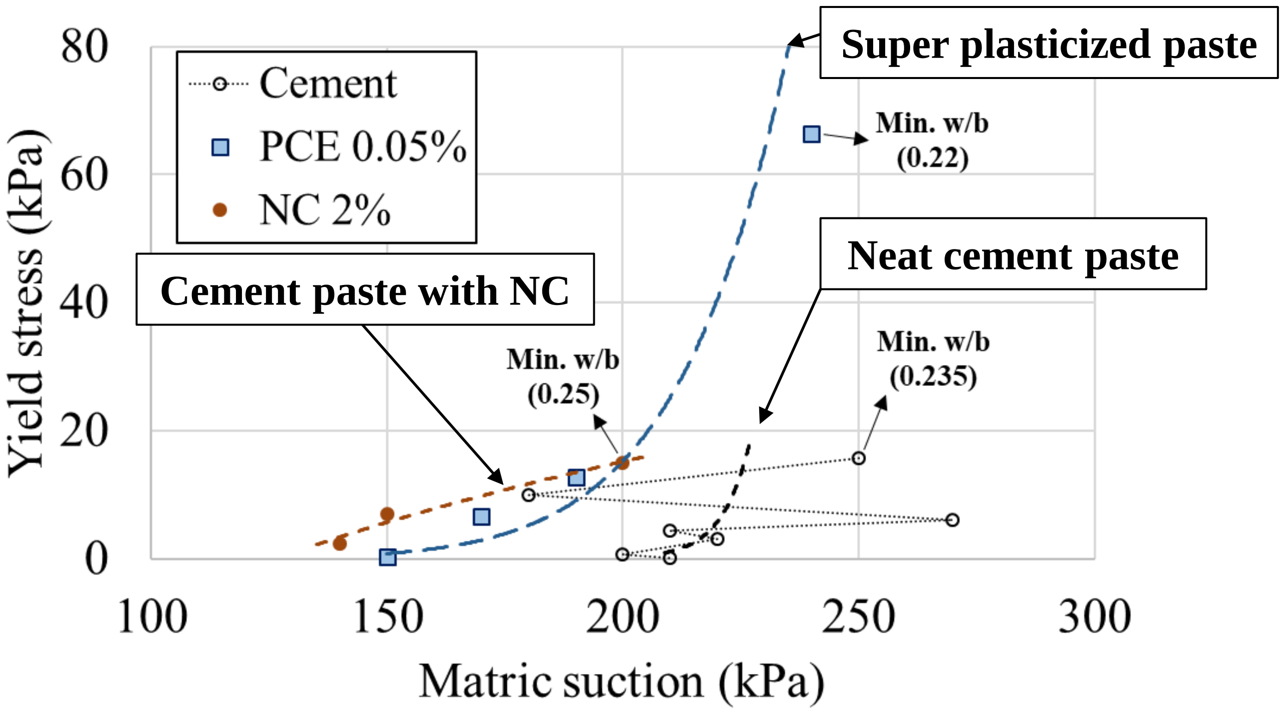
- Matric suction: Cement > Fly ash > Limestone powder
- A higher matric suction with a lower w/b.
- Steric hindrance of PCE increases the homogeneity

	Specific density	Blaine number
Cement	3.11	3,470
Fly ash	2.36	7,570
LSP	2.73	410





- A lower water-to-cement ratio → a higher matric suction → a higher yield stress
- Both PCE and nanoclay increases the yield stress at the same matric suction

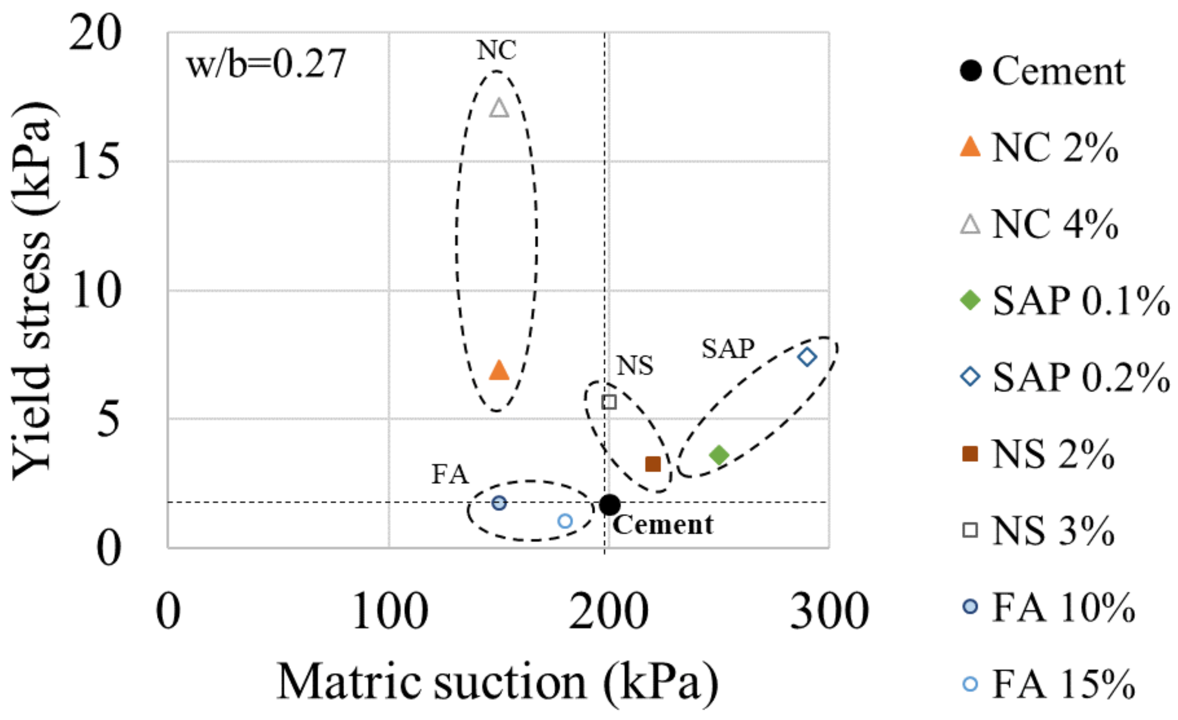


Lee, JH; Kim, JH*; "Matric suction and its effect on the shape stability of 3D printed concrete", CEMENT AND CONCRETE RESEARCH, vol.159, 2022.09

Matric suction (3), the effect of additives

	Type
PCE	Solution (TSC:0.25)
Nano clay	Powder
SAP	Powder
Nano silica	Suspension (φ_s=0.50)

- At w/b=0.27, PCE: unable to measure (too low yield stress)
- Nanoclay: Matric suction (↓) and yield stress (↑)
- Super-absorbent polymer: Matric suction (↑), but hard to control due to its swelling



Lee, JH; Kim, JH*; "Matric suction and its effect on the shape stability of 3D printed concrete", CEMENT AND CONCRETE RESEARCH, vol.159, 2022.09

Generalized Hook's law considering matric suction

$$\varepsilon_{rr} = \frac{(\sigma_{rr} - u_a)}{E} - \frac{\nu}{E}(\sigma_{zz} + \sigma_{rr} - 2u_a) + \frac{\psi_m}{H}$$

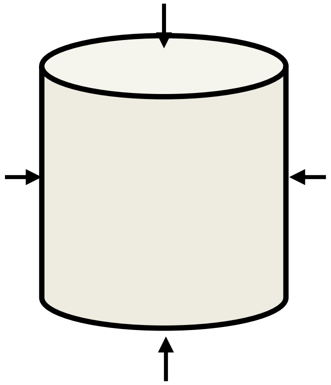
Total stress **Matric suction**

Radial strain in the test

$$\varepsilon_{rr} = -\frac{\nu\sigma_{zz}}{E} + \frac{\psi_m}{H}$$

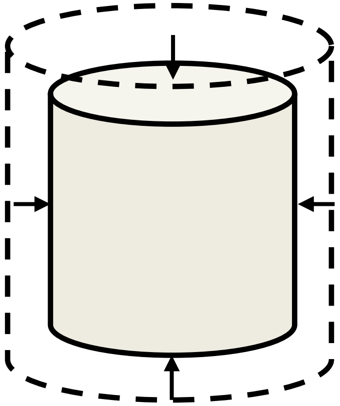
Matric suction effect
(Confining stress)

More stress is required to overcome the matric suction effect



Effect of matric suction as confining stress increases yield stress

Matric suction effect
(Eigenstrain)

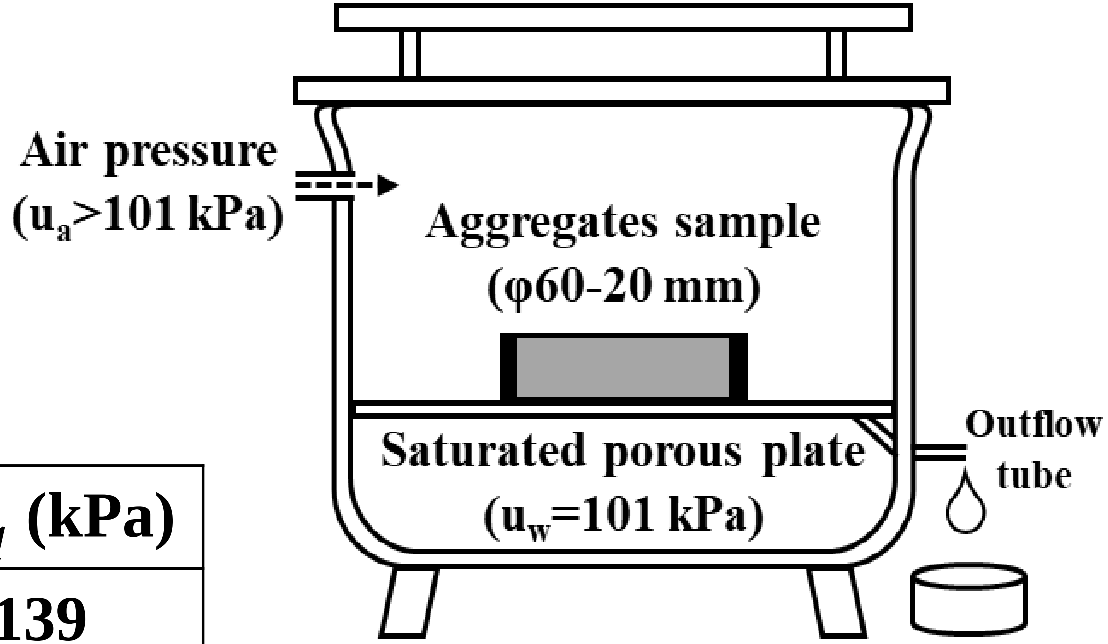


Apparent elastic modulus increases in the view of strain energy equivalence

Effect of matric suction as Eigenstrain increases elastic moduli

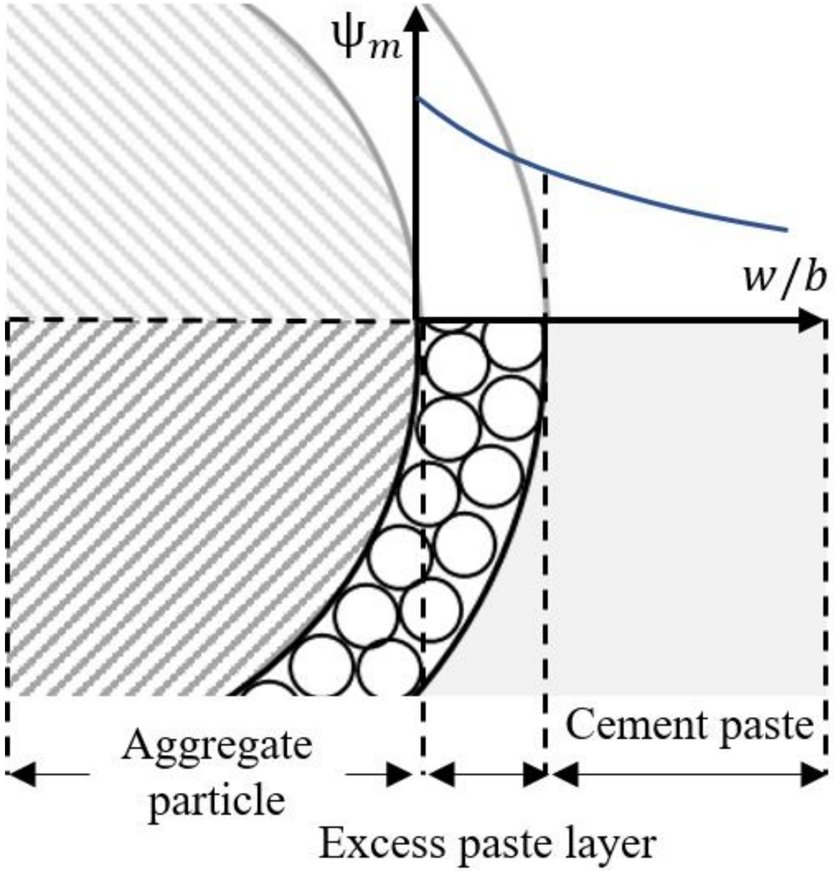
Matric suction of fine aggregates

Pressure plate extractor (ASTM D6836)



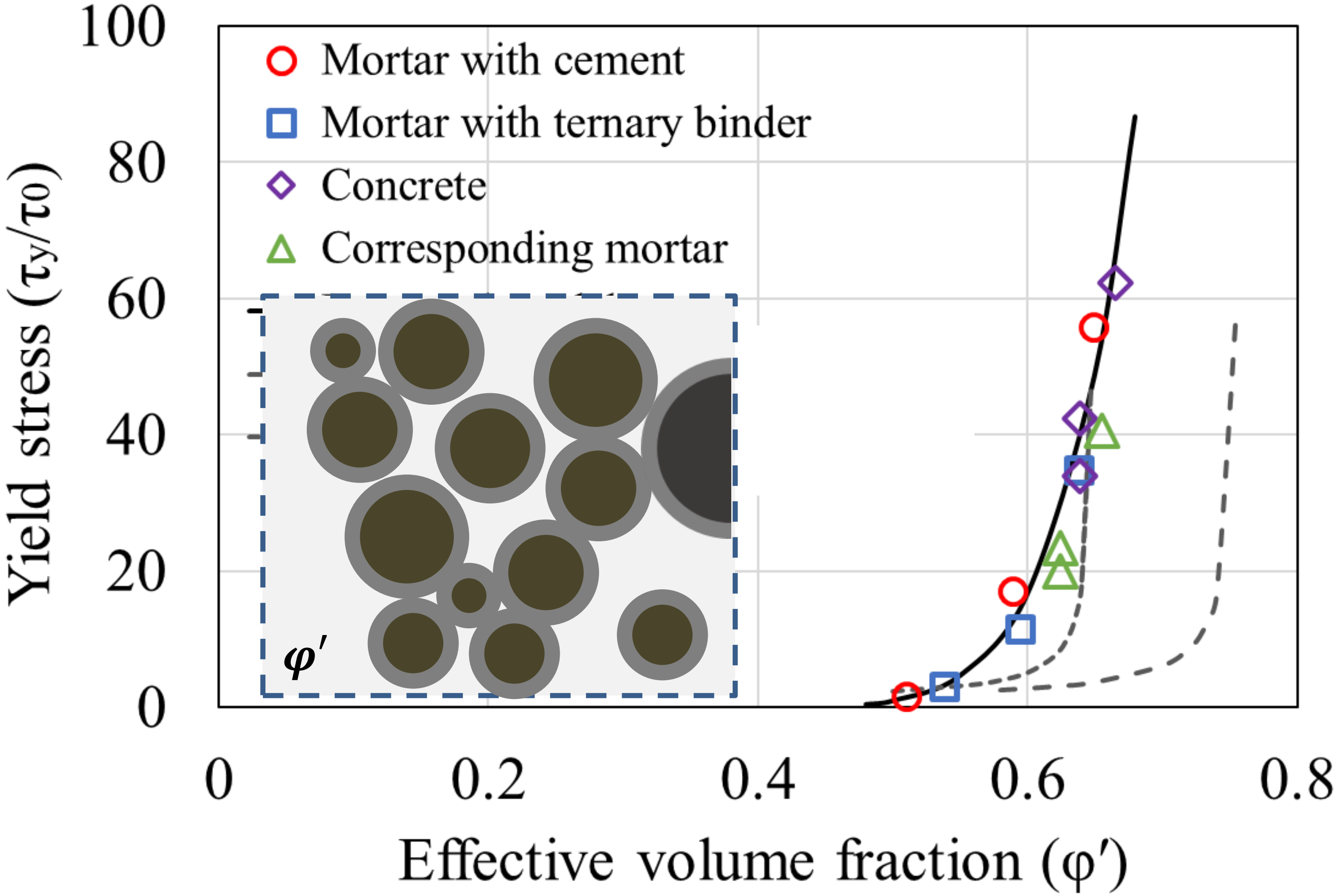
Sample	k (%)	ψ_{eq} (kPa)
Cement paste	-	**139**
Control mortar	1.3	**141**
10% silica sand replacement	5.3	**147**
20% silica sand replacement	4.6	**146**
30% silica sand replacement	16.4	**164**

Lee, JH; Kim, JH; "Matric suction of fine sand and its effect on the shape stability of 3D printed cement mortar", CONSTRUCTION AND BUILDING MATERIALS, vol.341, 2022.07



Schematic of interface of cement-aggregate

$$\tau_y/\tau_0 = 10^{4.87}(\varphi'(b) - \varphi_c)^{7.17}$$

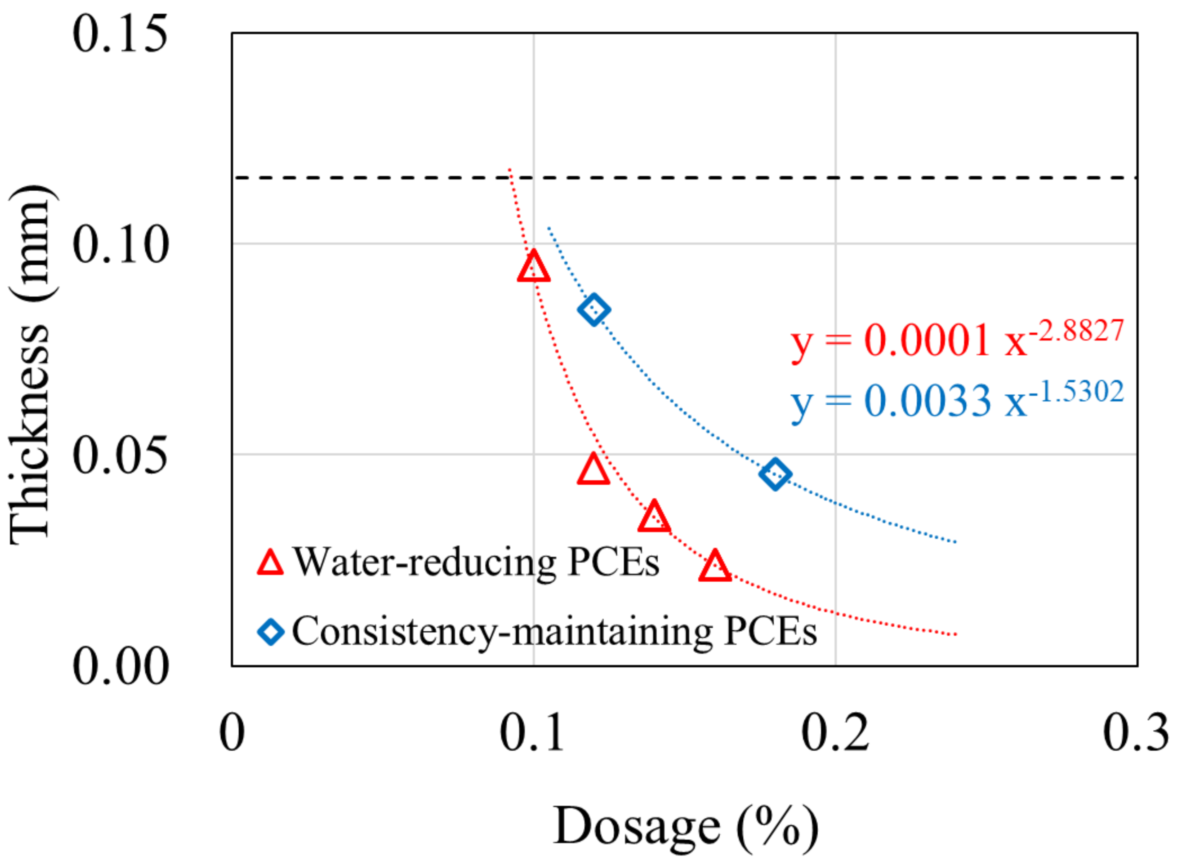


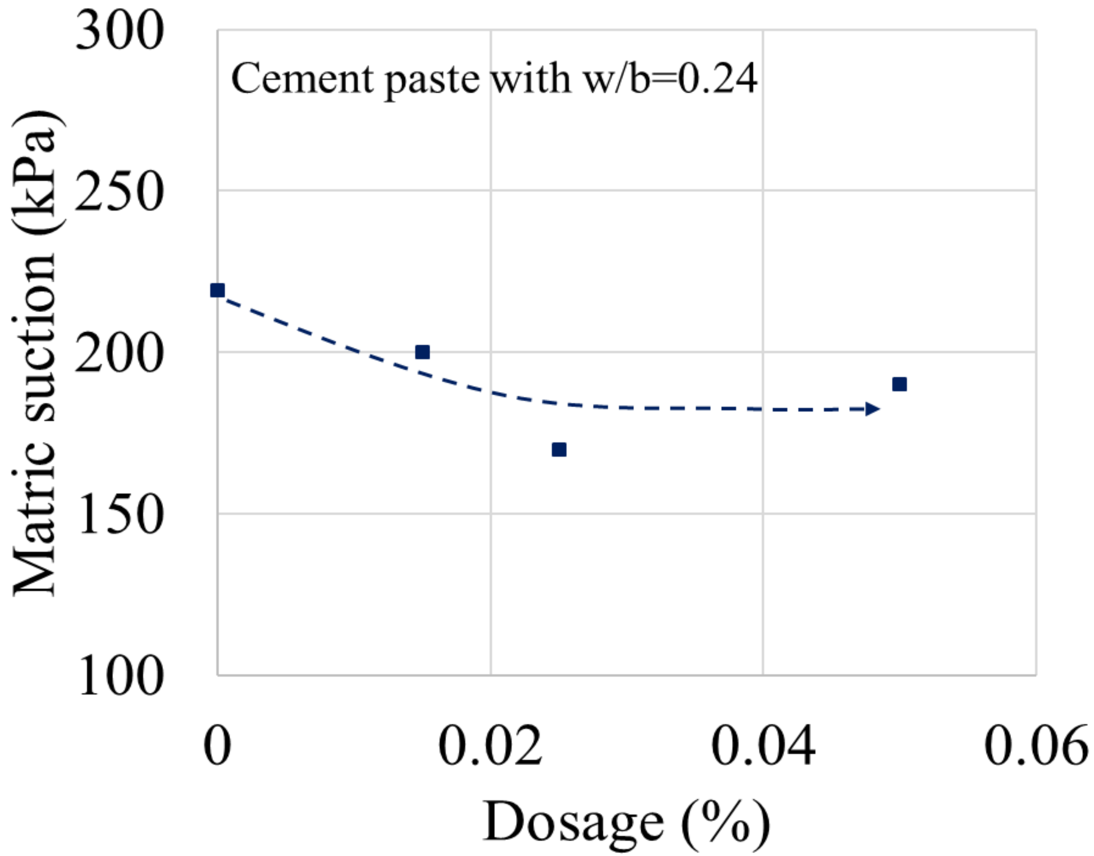
$$\varphi' = (1 + b/d_s)^3\varphi_s + (1 + b/d_g)^3\varphi_g$$

Lee, J, Kim, JH, Yoon,JY, "Prediction of the yield stress of concrete considering the thickness of excess paste layer", CONSTRUCTION AND BUILDING MATERIALS, 173: 411-418, 2018.06

Excess paste layer and matric suction (2)

$$\varphi' = (1 + b/d_s)^3\varphi_s + \left(1 + b/d_g\right)^3\varphi_g$$





jae.kim@kaist.ac.kr

- Matric suction is an additional contribution to the shape stability of 3D concrete printing
- Theory of elasticity can consider it as confining stress and eigenstrain
    - Matric suction acts as confining stress,
      contributing to the enhancement of yield stress
    - Matric suction induces Eigenstrain,
      contributing to the enhancement of elastic moduli
- Matric suction of fine aggregates is less than 10% of that of cement binder
- Matric suction is a cause to develop the excess paste layer in SCC

Thank You for Your Attention.

NRF 한국연구재단

KAIST College of Engineering Department of Civil and Environmental Engineering jae.kim@kaist.ac.kr