# Recent development and application of 3D printing concrete in China

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# Outline

0 ACI China Chapter

1 3D Printing Concrete and its Advantages

2 Mix Design of 3DPC

3 3DPC with Coarse Aggregate

4 3DPC under Different Curing Conditions

5 Applications of 3DPC

6 Challenges of 3DPC application

# ACI China Chapter (ACICC)

## History

- Founded in 2002,with headquarter in Hong Kong, China
- Now 111 members in total, the current President is Prof. Xianglin  GU from Tongji University

## Mission

- Carry forward the purpose of American Concrete society;
- Promote education, technical practice, scientific research; Improve the design, construction, use and durability of concrete structures and products by collecting, sorting and publishing relevant information.


ACI China Chapter meeting in 2016

# ACI China Chapter (ACICC)

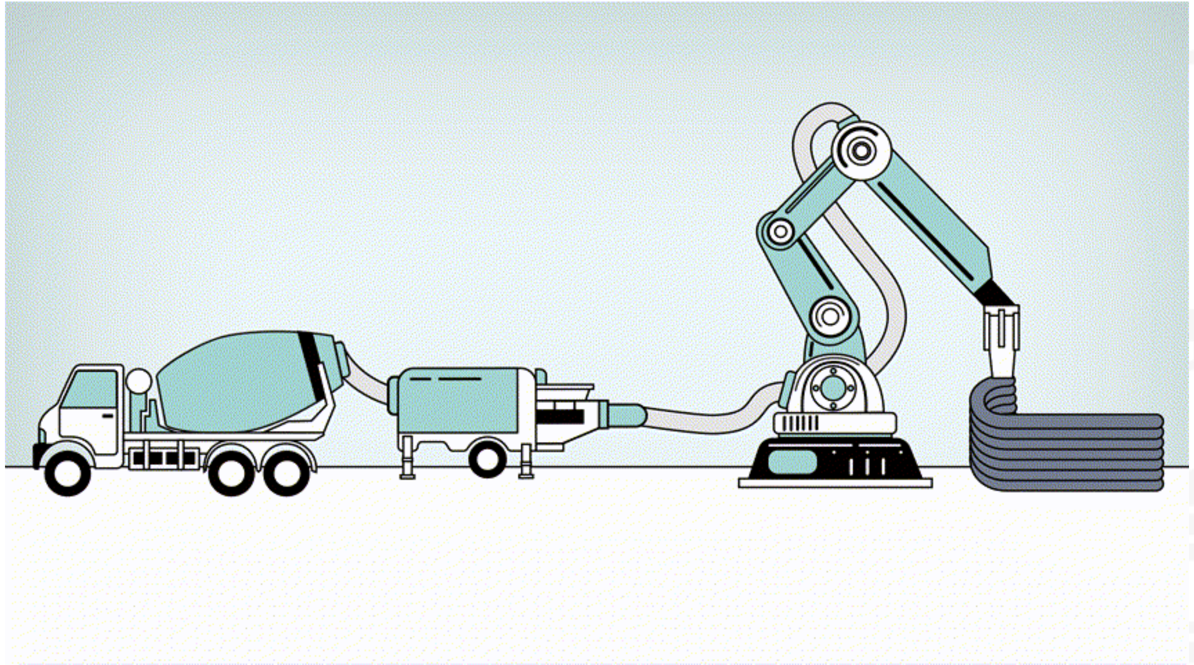
- Organized ACI certification in China “Concrete Laboratory Testing Technician - Level 1” since 2011
- Attended ACI leadership training in 2016
- Attended ACI spring/fall conventions on behalf of China
- Established ACI Tongji Student Chapter in 2019
- Co-organizing academic conferences and communication in China

ACI Certification training course 2011


ACI spring convention 2016


ACI China Chapter meeting 2019

# 1. 3D printing concrete and its advantages



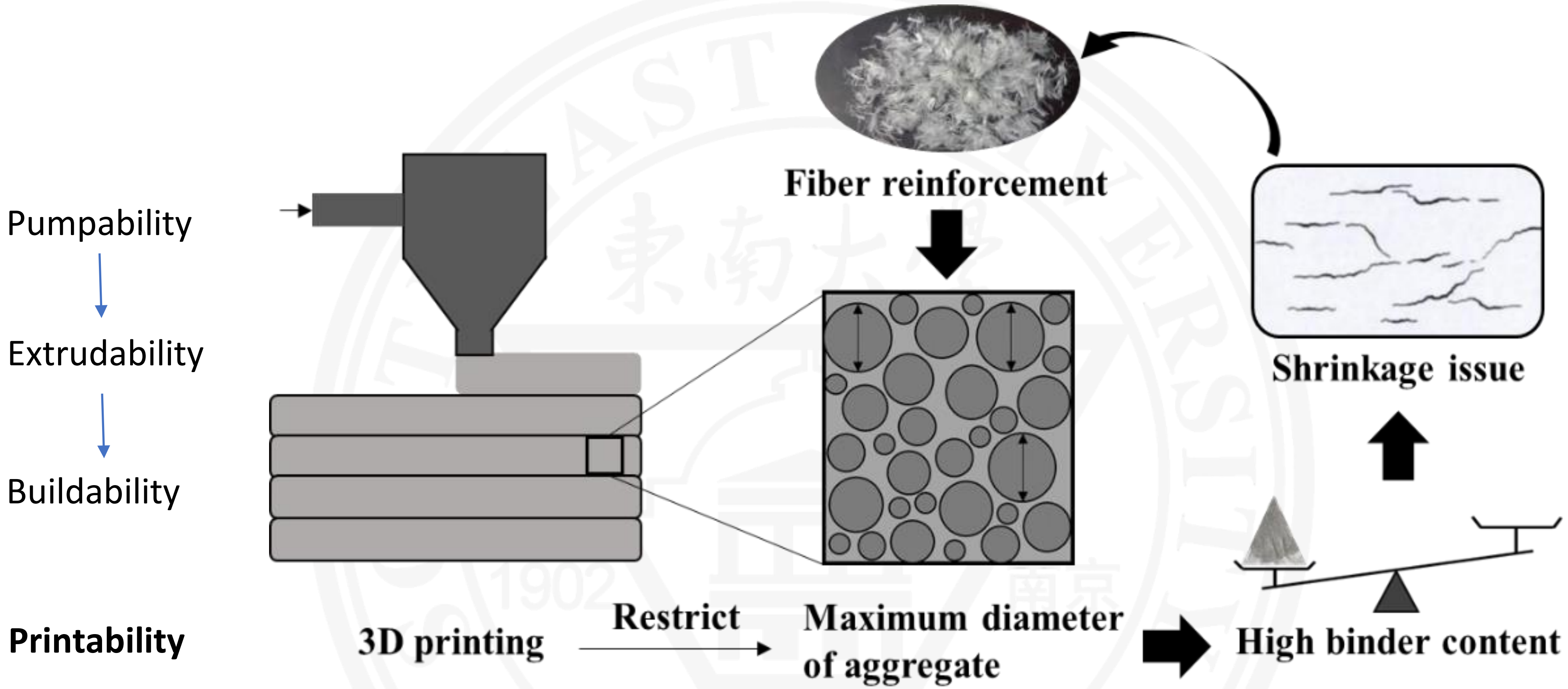
Prototype-3D printing the first 10m wind turbine base

https://cobod.com/ge-tower/

- No formwork
- Flexible design
- Labor saving
- Material saving

- Safe construction
- High construction efficiency
- Low cost
- Low carbon footprint

# 2. Mix design of 3DPC



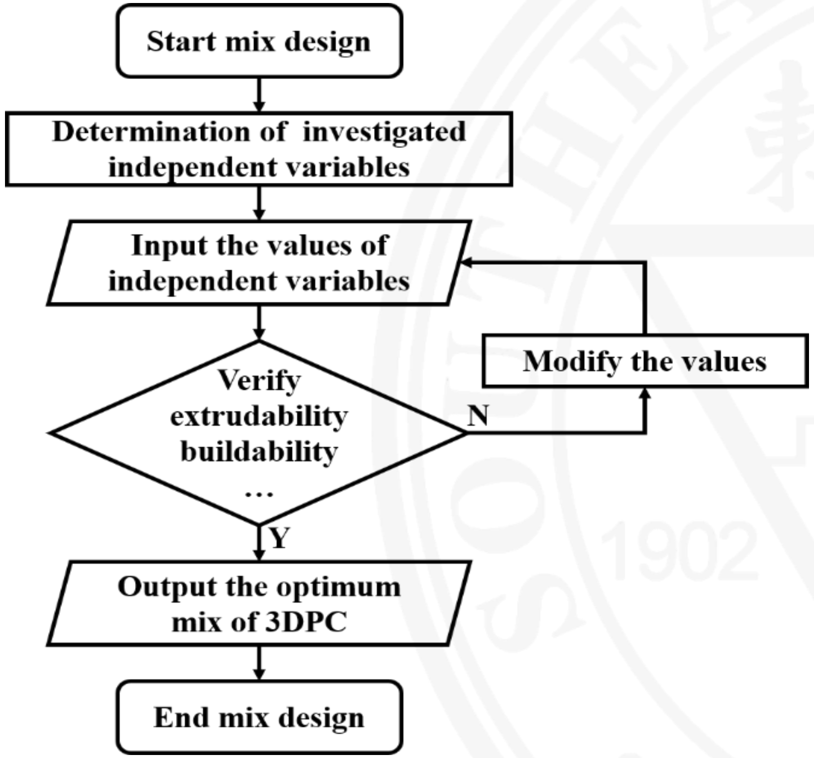

- Printability is the basic requirement for printing
- The extrusion process limits the material choice of concrete: lack of coarse aggregate
- The mix design based on the requirement of flowability and strength is not suitable for 3DPC

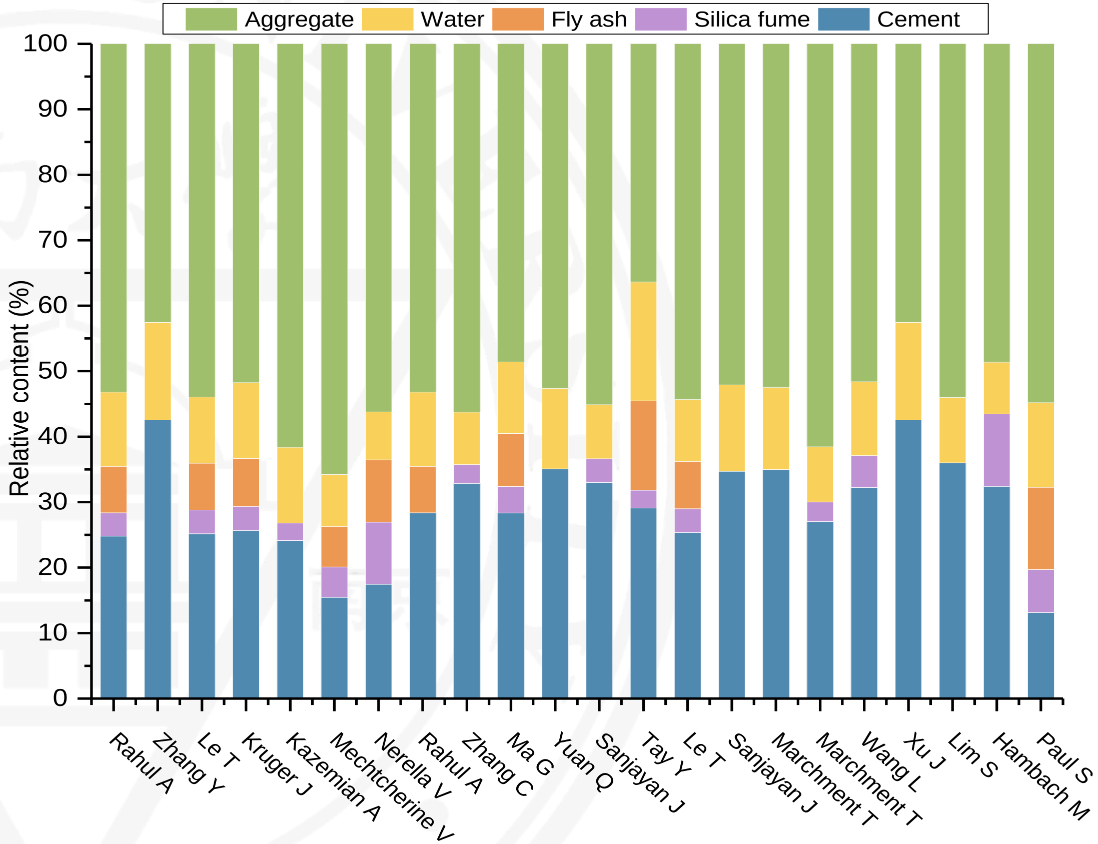


C Zhang, YM Zhang, et al, CCC SI, 2021

# 2. Mix design of 3DPC

## Empirical mix design methods for 3D printable concrete




- Silica fume, fly ash, bentonite, attapulgite, VMA, superplasticizer, etc. are often used for preparing 3DPC
- The average dosage of aggregate, water, and binder are approximately 1220±300 kg/m³, 250±115 kg/m³, and 830±230 kg/m³



C Zhang, YM Zhang, et al, CCC SI, 2021

# 2. Mix design of 3DPC

## Mix design method based on rheological model

Coussot model

$$\tau_m = \tau_f \left(1 - \frac{\emptyset}{\emptyset_{max}}\right)^{-m}$$

$\tau_m$ and $\tau_f$ are the yield stress of mortar and paste

$\emptyset$ and $\emptyset_{max}$: the fraction of aggregates and the maximum packing fraction of aggregates

m: a coefficient.

Chateau–Ovarlez–Trung model:

$$\frac{\tau_c(\emptyset)}{\tau_c(0)} = \sqrt{\frac{1-\emptyset}{\left(1 - \frac{\emptyset}{\emptyset_{max}}\right)^{2.5\emptyset_{max}}}}$$

$\tau_c(\emptyset)/\tau_c(0)$ : the yield stress ratio of the suspensions of monodisperse rigid noncolloidal particles to suspending fluids

Modified Chateau-Ovarlez-Trung model

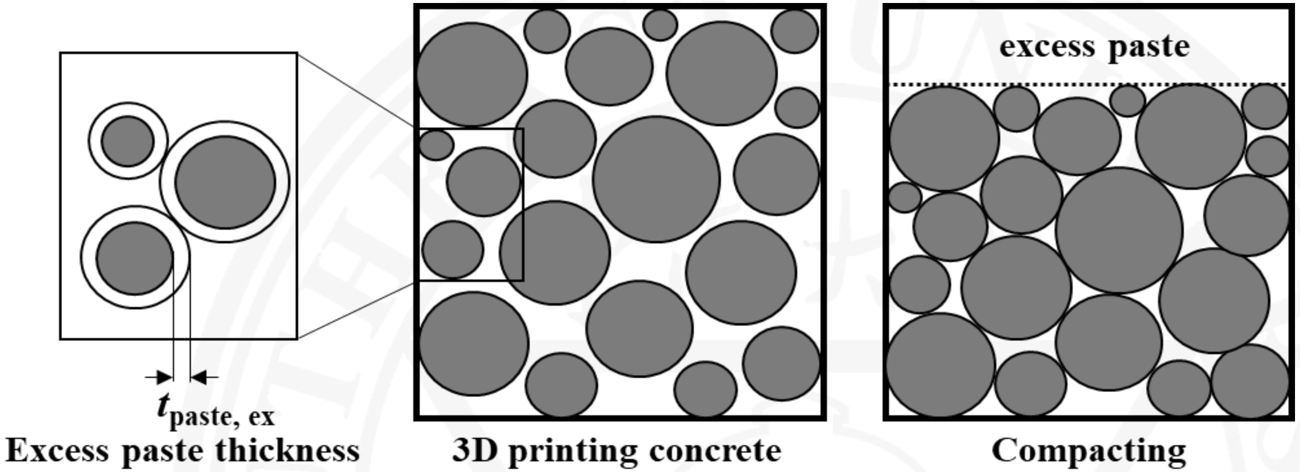
$$\frac{\tau_c(\emptyset)}{\tau_c(0)} = \sqrt{\frac{1-\emptyset}{\left(1 - \frac{\emptyset}{\emptyset_{RLP}}\right)^{5.1\emptyset_{RLP}}}}$$

The influence of volume fraction and surface area of aggregate is considered

$\emptyset_{RLP}$ is the random loose packing fraction of aggregate

- Quantitative relationship between two phases: aggregate and paste
- Advantages: Independent of the parameters and chemical composition of raw materials

# 2. Mix design of 3DPC




Excess paste theory: $$t_p = \frac{V_{paste} - V_{void}}{6\beta \frac{M}{\rho} \sum_{i=1}^{n} \left(\frac{k_i}{d_i}\right)}$$

X. Xie, Constr. Build. Mater., 2018

$t_p$: thickness of excess paste layer
$V_{paste}$ and $M$: volume of paste and mass content of
$V_{void}$ is the volume of space between aggregates
$\rho$ is the apparent density of aggregates
$k_i$ and $d_i$ : mass fraction and mean size of the aggregates
$B$: the coefficient for considering the shape of aggregates

- The excess paste layer acts as a lubricant between aggregates enhancing the flowability of concrete
- The excess paste layer thickness can reflect not only the volume fraction, but also the fineness, shape and particle size distribution of aggregates

C Zhang, YM Zhang, et al, CCC, 2019

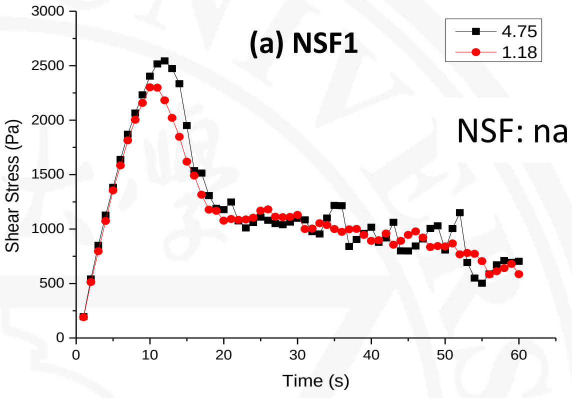
# 2. Mix design of 3DPC

**Mixture proportion and flowability of the cement paste with different rheological modifiers**

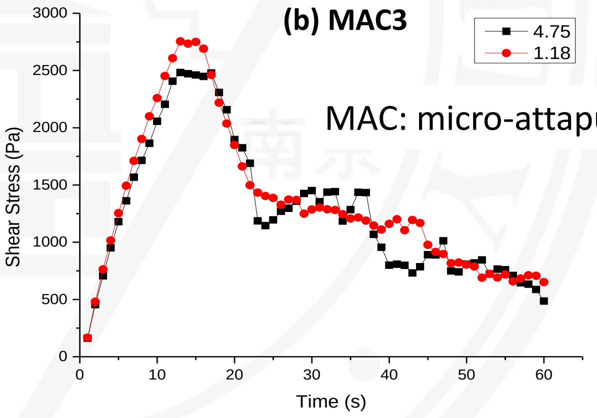
| Labels | Cement (g) | Water (g) | W/C ratio | Flowability (mm) |
|---|---|---|---|---|
| NS1R30 | 500 | 150 | 0.30 | 215 |
| MAC3R30 | 500 | 150 | 0.30 | 144 |

**Calculated mixture proportion of 3DPC with different fineness of sand and rheological modifiers**

| Labels | Cement (g/L) | Water (g/L) | Sand (g/L) | W/C ratio |
|---|---|---|---|---|
| NS1R30-4.75 | 712 | 213 | 1374 | 0.30 |
| NS1R30-1.18 | 801 | 240 | 1258 | 0.30 |
| MAC3R30-4.75 | 914 | 274 | 1112 | 0.30 |
| MAC3R30-1.18 | 1032 | 310 | 958 | 0.30 |




NSF: nano silica




MAC: micro-attapulgite clay

(a) NS1R30-4.75

(b) NS1R30-1.18

(c) MAC3R30-4.75

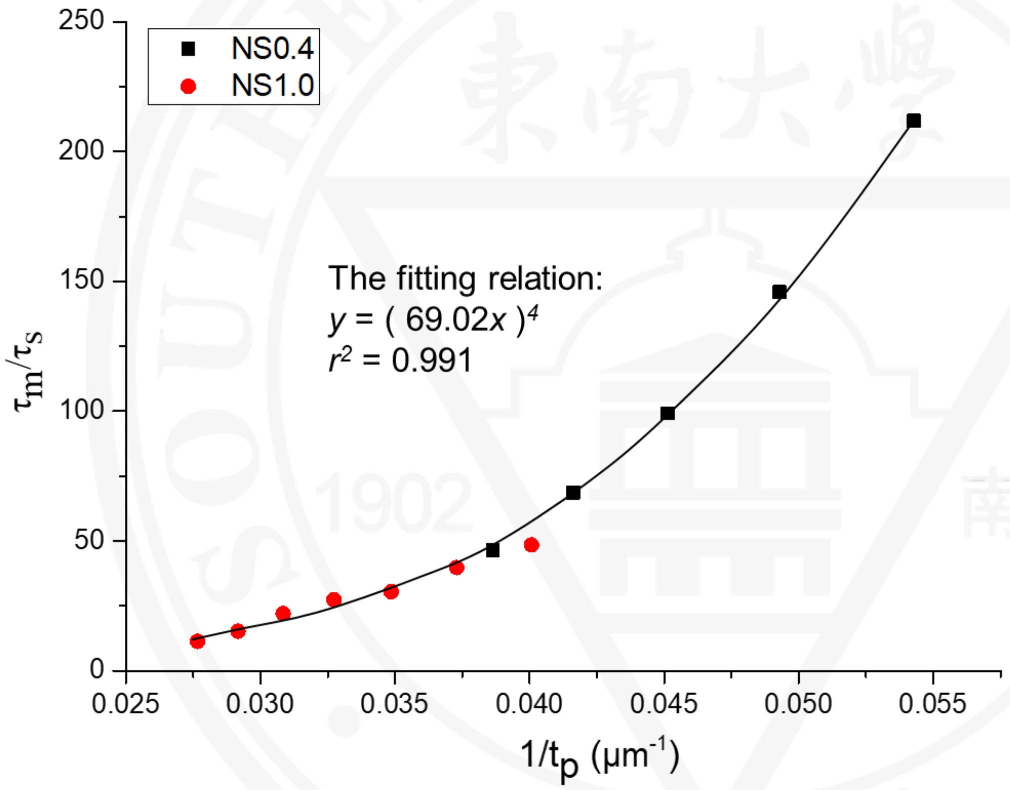
(d) MAC3R30-1.18

- Mortars with the same excess paste thickness and paste flowability exhibit similar rheological behavior as well as similar printability.

C Zhang, YM Zhang, et al, CCC, 2019

# 2. Mix design of 3DPC

Prediction of static yield stress of mortar based on $t_p$ :




$$\frac{\tau_c}{\tau_s} = f(\emptyset) = f'(t_p)$$

$$\tau_m = \tau_s \left(\frac{69.02}{t_p}\right)^4$$

- The $\tau_c/\tau_s$ ratio has an exponential relation with the thickness of excess paste layer $t_p$

C Zhang, YM Zhang, et al, 2021

# 2. Mix design of 3DPC

Prediction of static yield stress of mortar:

$$t_p = \frac{V_{paste} - V_{void}}{6\beta \frac{M}{\rho} \sum_{i=1}^{n} \left(\frac{k_i}{d_i}\right)}$$

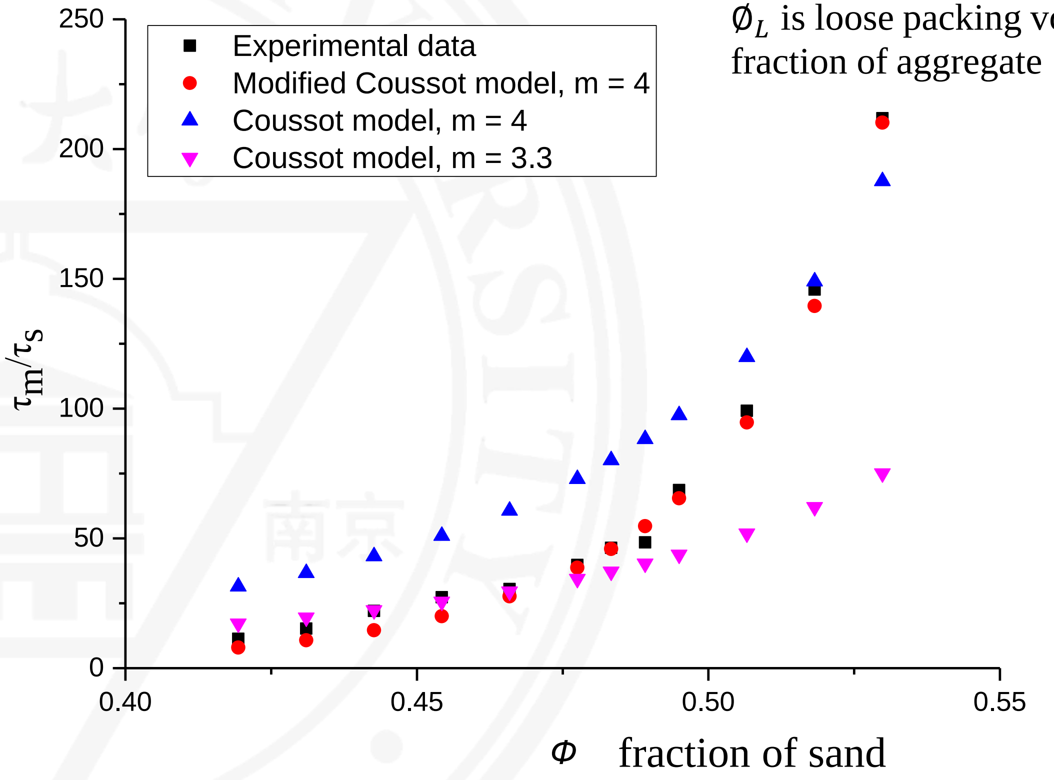
$$t_p = \frac{\emptyset_L - \emptyset}{A\rho\emptyset}$$

$$\tau_m = \tau_s \left(\frac{69.02}{t_p}\right)^4$$

$$t_p = 69.02 \frac{\emptyset_L - \emptyset}{\emptyset}$$

$$\tau_m = \tau_s \left(\frac{\emptyset_L}{\emptyset} - 1\right)^{-m}$$

Modified Coussot model



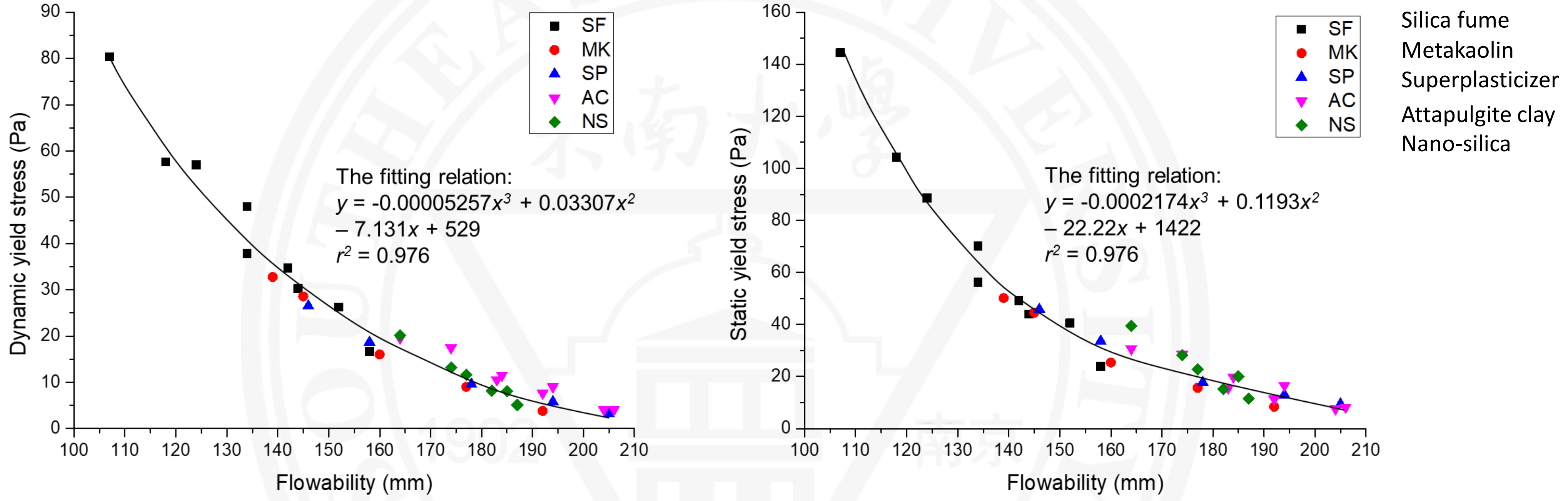

$\emptyset_L$ is loose packing volume fraction of aggregate

- The static yield stress of paste, the thickness of excess paste layer and packing fraction of aggregate can be used as key parameters to predict the yield stress of mortar based on modified Coussot model

C Zhang, YM Zhang, et al, 2021

# 2. Mix design of 3DPC

## Relation between flowability of paste and static yield stress of mortar




Relationship between the dynamic/static yield stress and flowability of paste

- The flowability of paste is strongly linked to its yield stress even if the paste consists of different rheology modifying agents
- Flowability of paste can be used instead of the static yield stress in the modified Coussot model to predict the static yield stress of 3DPM

C Zhang, YM Zhang, et al, 2021

# 3. 3D printing concrete with coarse aggregate

Drying plastic shrinkage induced cracks G. De Schutter, etc. CCR, 2018

Cracking of 3D printed mortar elements after long time exposure in the air

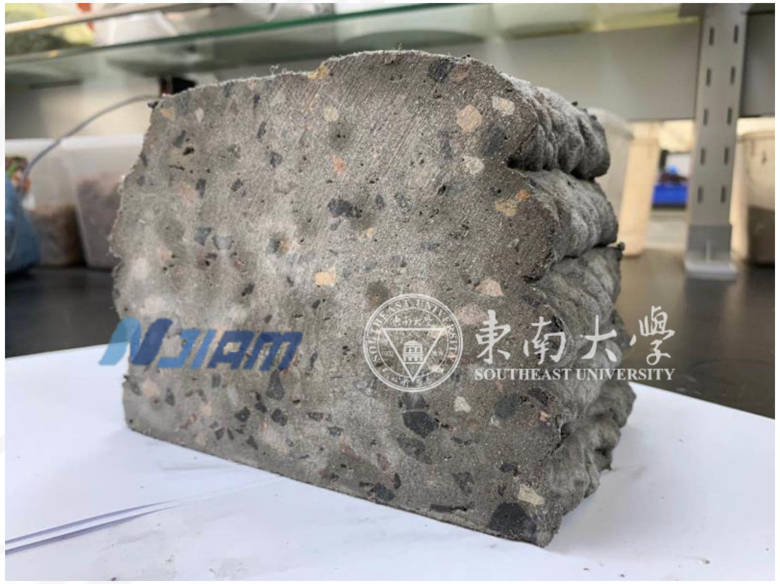
XG Wang, YM Zhang, et al, 2021

**Why printing with coarse aggregate?**

- Reduce shrinkage and creep
- Reduce risk of cracking
- Improve durability
- Reduce cost
- Lower carbon footprint

# 3. 3D printing concrete with coarse aggregate






- Continuously 3D printed concrete with coarse aggregate: nozzle diameter 40mm; coarse aggregate 5-10mm; filament height 25mm, width 65mm; printing speed 3.8m/min.

XG Wang, YM Zhang, et al, 2021

# 3. 3D printing concrete with coarse aggregate


Coarse aggregate: 5-10mm

Slump

Cylinder height

P/A=1.4 P/A=1.3 P/A=1.2 (mass ratio)


P/A=1.4

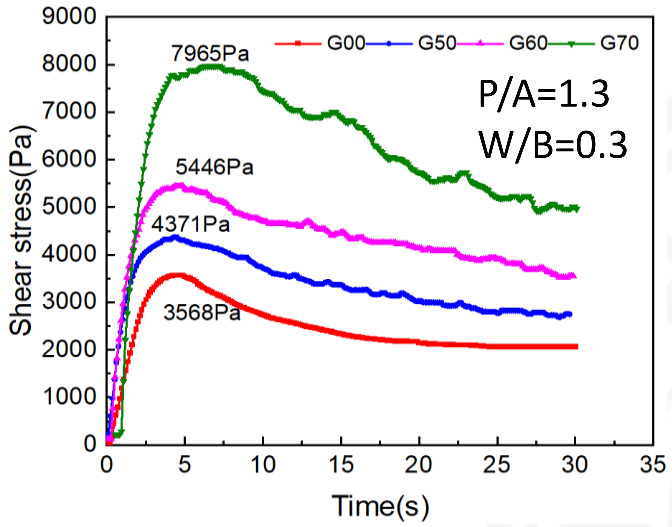
P/A=1.3

P/A=1.2

- Paste to aggregate (coarse and fine) ratio (P/A) is an important parameter determining the printability of concrete.

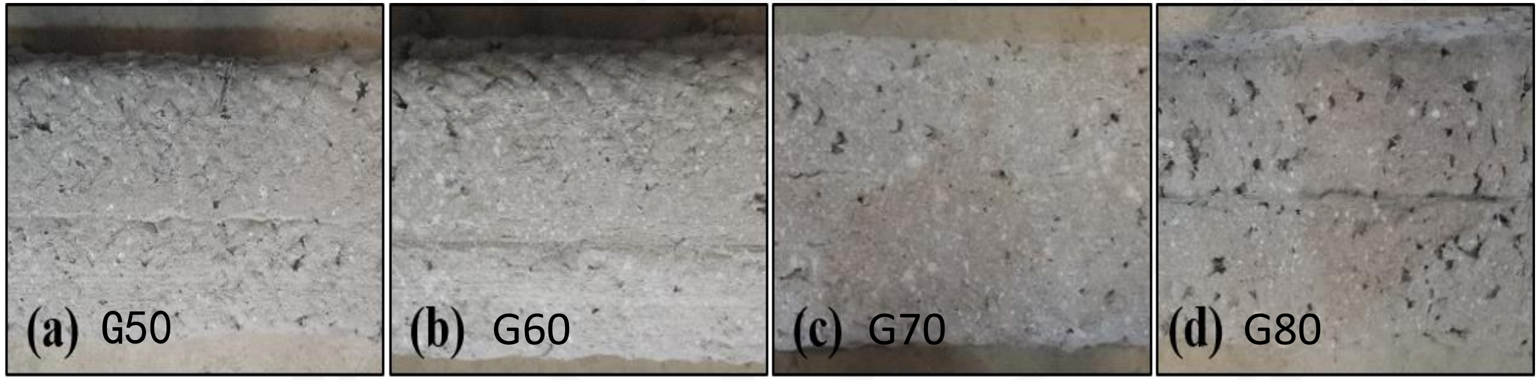
XG Wang, YM Zhang, et al, 2021

# 3. 3D printing concrete with coarse aggregate




Effect of coarse aggregate content on rheological properties

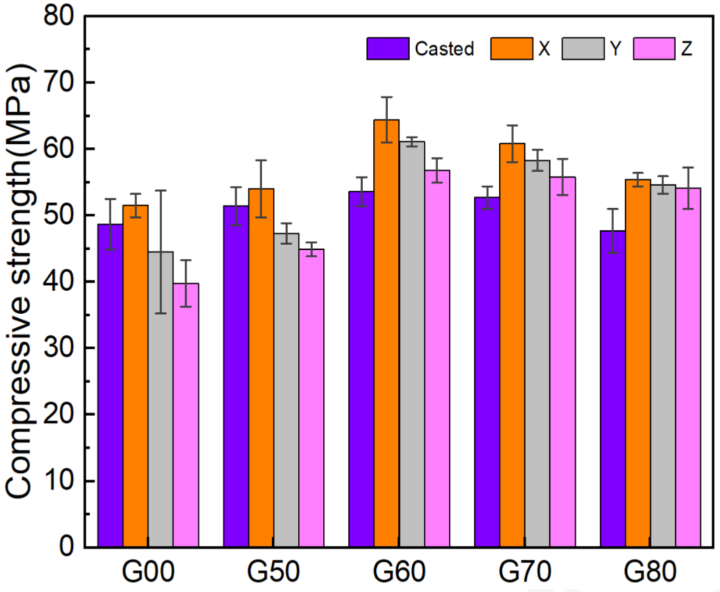
| | Linear fitting equation | $R^2$ | Dynamic yield stress （Pa） | Plastic viscosity （Pa·s） |
|---|---|---|---|---|
| G00 | $\tau=87.5\gamma + 829.86$ | 0.965 | 829.86 | 87.5 |
| G50 | $\tau=128.4\gamma + 1120.82$ | 0.986 | 1120.82 | 128.4 |
| G60 | $\tau=167.9\gamma + 1.25.47$ | 0.969 | 1325.47 | 167.9 |
| G70 | $\tau=295.4\gamma + 2003.56$ | 0.974 | 2003.56 | 295.4 |

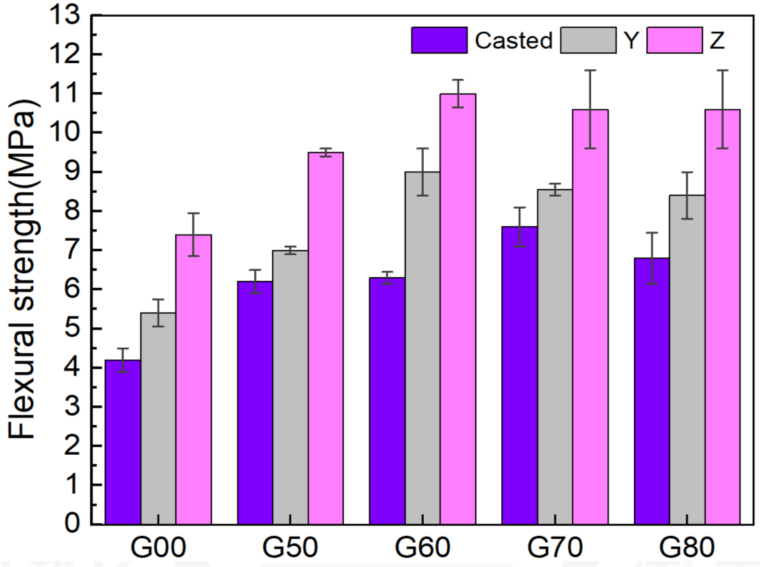


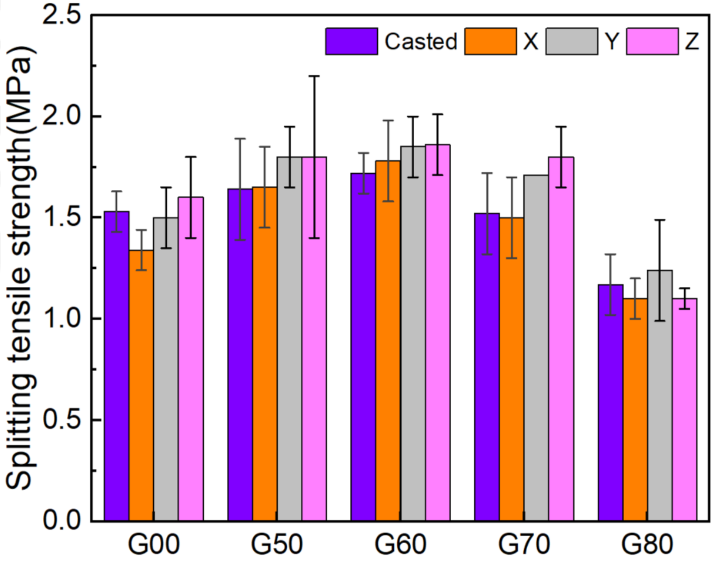

- At optimal paste/aggregate ration, the increase of coarse aggregate to aggregate ratio greatly increases the static yield stress, dynamic yield stress and plastic viscosity
- Too high yield stress and plastic viscosity causes defects of printed filaments

XG Wang, YM Zhang, et al, 2021

# 3. 3D printing concrete with coarse aggregate




- The compatibility of printing parameters and rheological properties of 3DPC is the key to print good quality concrete
- Under favorable printing condition, coarse aggregate can enhance the interlay properties, the anisotropy of mechanical properties is mitigated

XG Wang, YM Zhang, et al, 2021

# 4. 3DPC under different curing conditions

3D printing

Traditional casting

- The joint research with the research center of Holcim Group
- Understand the influence of RH, air convection and exposure area on properties of 3DPC.

L Ma, Q Zhang, YM Zhang, et al, 2021

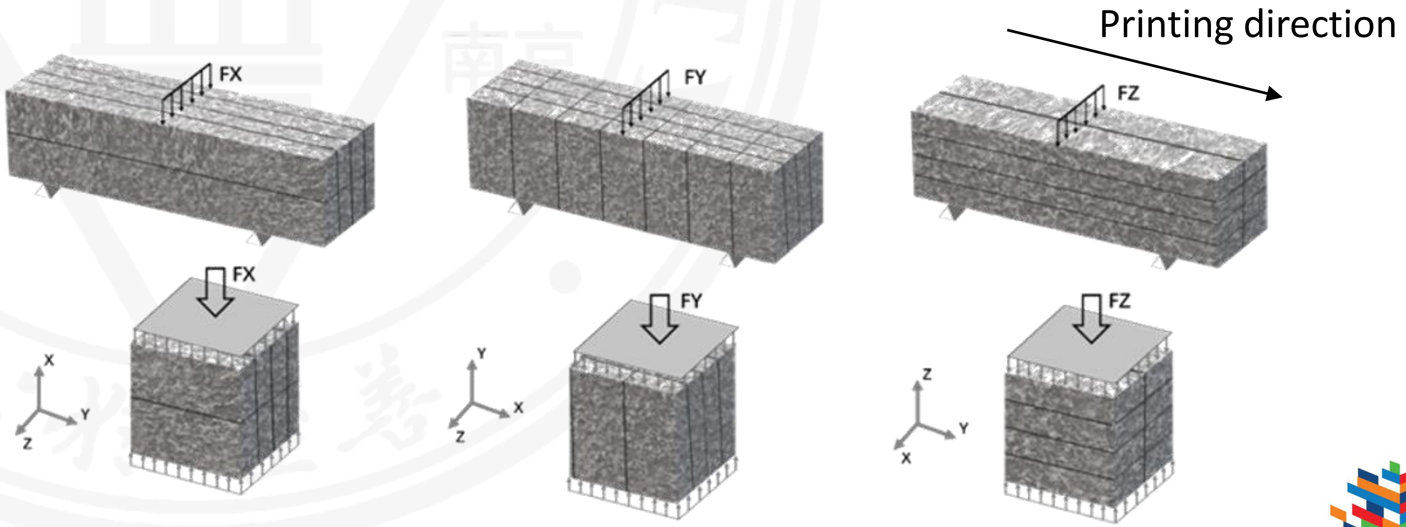
# 4. 3DPC under different curing conditions

**Environmental factors:**

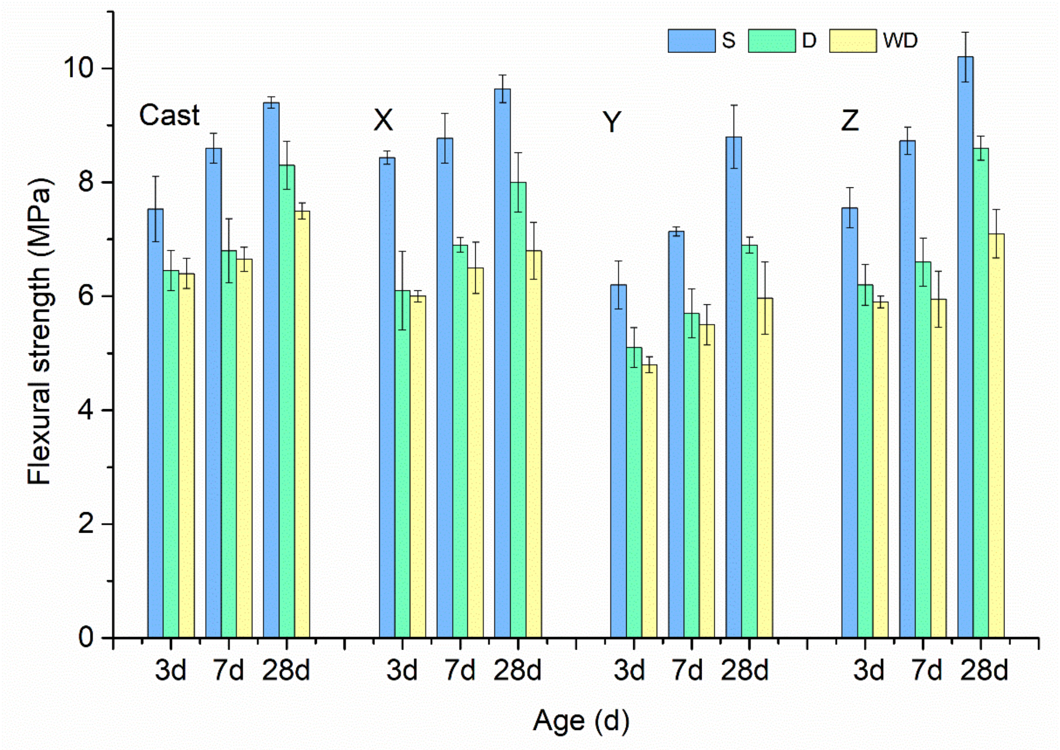
| | Relative humidity | | Air convection | |
|---|---|---|---|---|
| | RH>95% | RH=60%±5% | Wind speed= 0 m/s | Wind speed= 3 m/s |
| Standard curing condition (S) | √ | - | √ | - |
| Drying condition (D) | - | √ | √ | - |
| Wind condition (WD) | - | √ | - | √ |

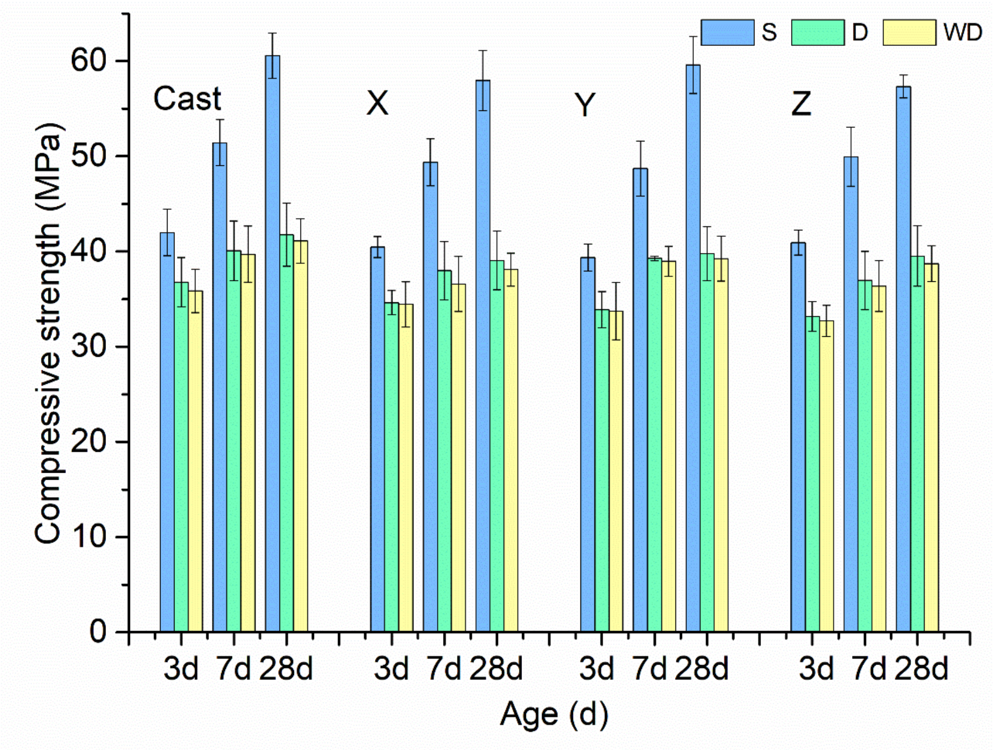
**Ambient control**
(environmental case):

**Loading directions** of 3DPC for flexural strength and compressive strength:



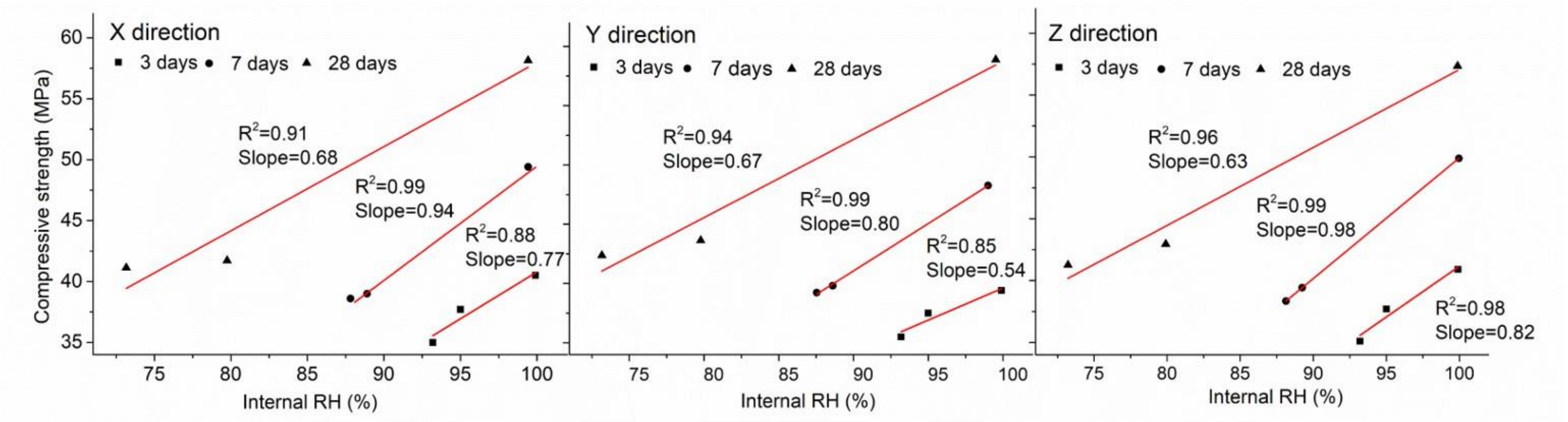
# 4. 3DPC under different curing conditions




- RH reduces from 95% to 60%, the flexural strength drops by 24.6%, and the compressive strength by 32. 3%.
- The addition of wind (3m/s) declines the flexural strength by 30.7%, and the compressive strength by 33.6%.
- The strength of printed specimen is more vulnerable to drying and wind compared with the cast specimen.

# 4. 3DPC under different curing conditions

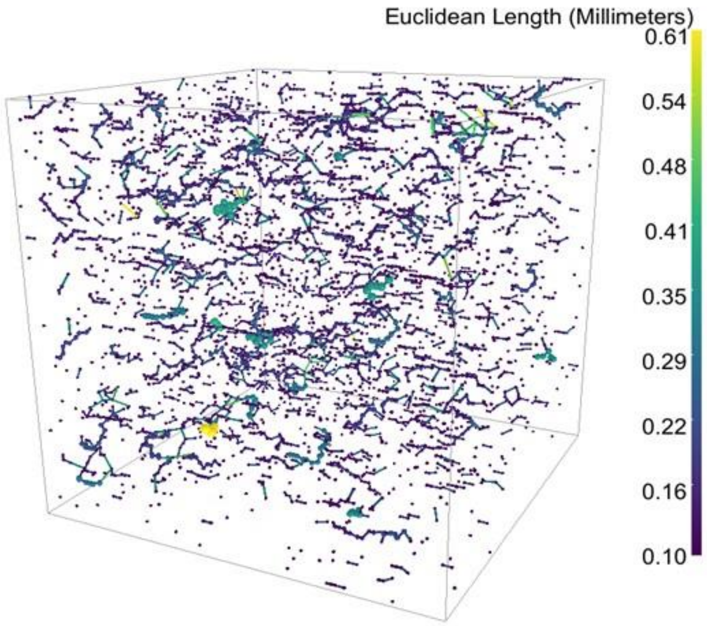



Correlation between compressive strength and internal RH of printed specimens of 3 days, 7 days and 28 days under three curing conditions

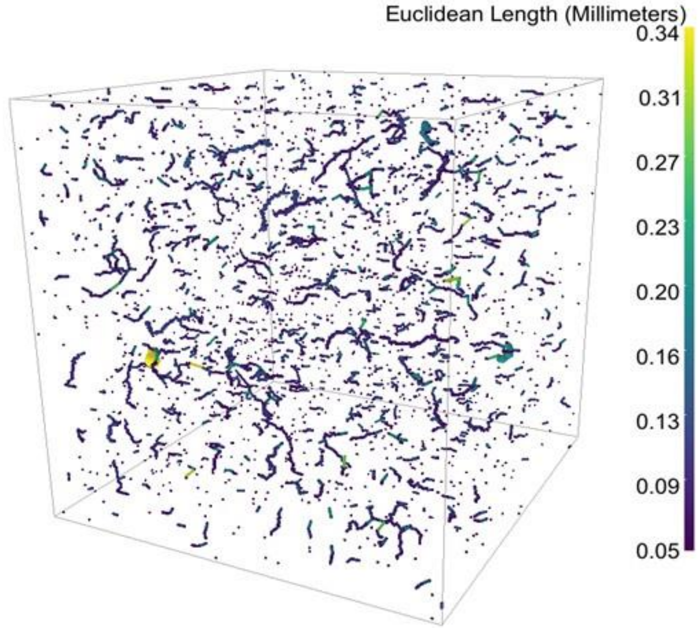
- Mechanical properties is proportional to internal relative humidity
- The early curing condition is significant to the strength development of 3DPC, for which early curing is often not available, especially in the case of on-site 3D printing

# 4. 3DPC under different curing conditions

Printed specimen




Casted specimen



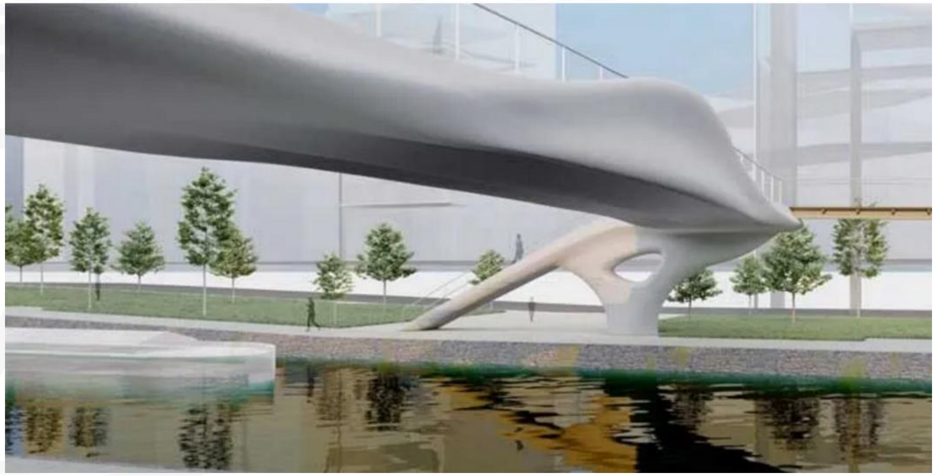

- The pores with connected length of 0.1mm-0.22mm increase significantly
- The maximum connected length increases from 0.34mm (casted specimen) to 0.61mm (printed specimen)

# 5.1 3D printed projects around the world

3D printing camp at night in Texas, by ICON

Project by the Block Research Group at ETH Zurich and Zaha Design Group (ZHACODE), in collaboration with incremental3D, made possible by Holcim, 2021


The Dubai Municipality: on-site 3D printed building, standing tall at 9.5 m with an area of 640 m2



40 m long foot bridge, to be built for the 2024 Olympic game in Paris
Freyssinet, Levigne, Cheron Architects, Quadric, Holcim and XtreeE

# 5.2 On-site printing and fabrication of 3DPC elements

## On-site 3D printing

- Install & disassemble 3D printer
- Large enough printing range
- Transportation of fresh concrete
- Printing process influenced by wind, temperature, humidity
- On-situ curing issue
- Strength development dependent on ambient environment
- No additional transportation

## On-site fabrication of 3D printed elements

- Elements printed in factory
- Short-time transportation of fresh concrete
- Curing can be executed
- Printing process less dependent on ambient
- Printing quality guaranteed
- Transportation from factory to construction site
- Joints between elements needed
- …….

# 5.3 3D Printed Fabricated Building in Nanjing

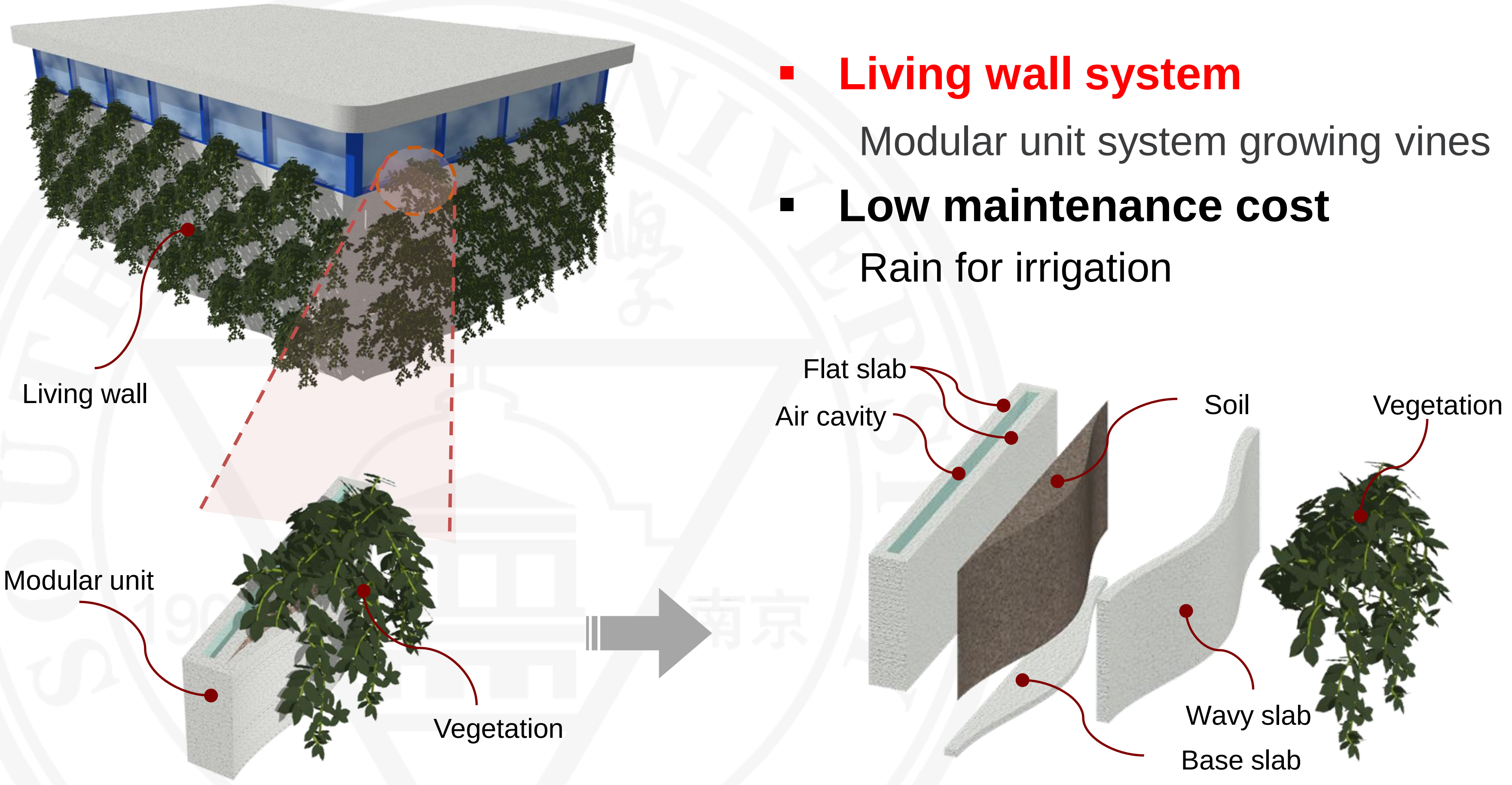
- **Location**

  Jiangbei, Nanjing, China
- **Floor area**

  50.46 $m^2$ for one building
- **Building type**

  Commercial
- **Type of construction**

  Steel frame structure with 3-D printed concrete walls




- **Living wall system**

  Modular unit system growing vines
- **Low maintenance cost**

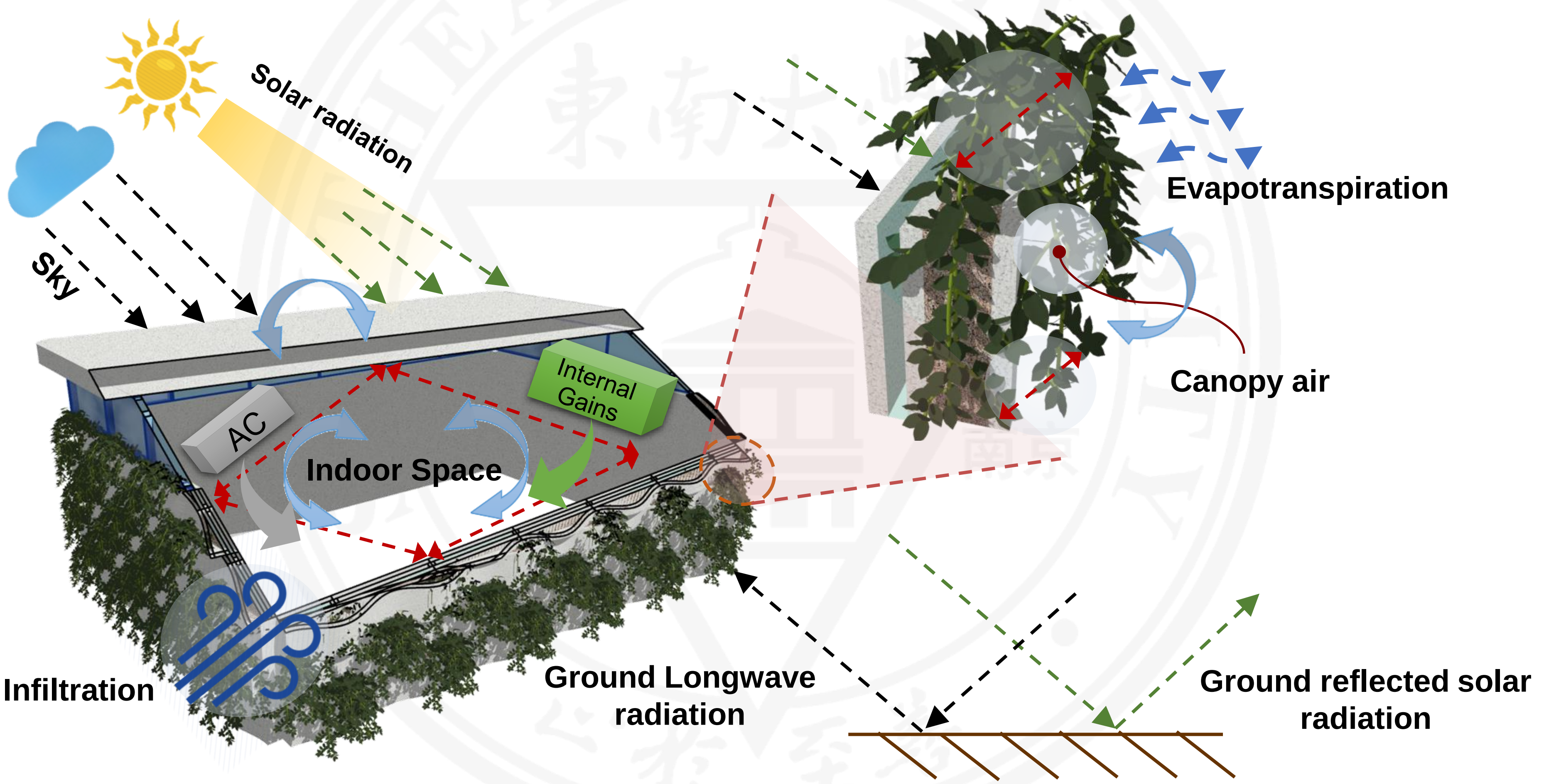
  Rain for irrigation

- The energy calculation was jointly completed by SEU and Hongyu Zhou's team at the University of Tennessee
- 3-D printed multifunctional wall assemblies serve both as the main structural components as well as the backbones for living wall system to achieve higher energy efficiency.

Yawen He, Yamei Zhang, Chao Zhang, Hongyu Zhou, Energy & Buildings, 2020

# 5.3 3D Printed Fabricated Building in Nanjing

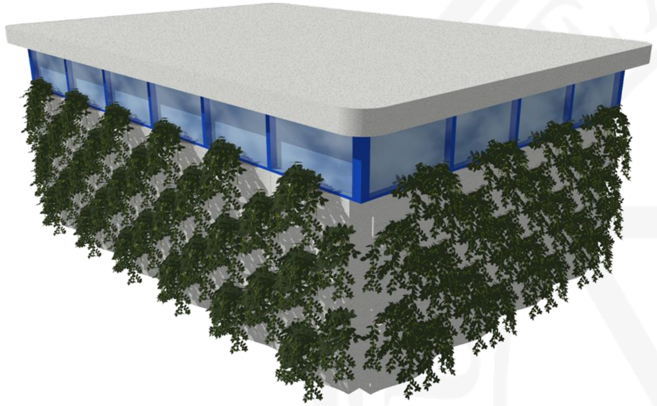
**Heat transfer process of building model with living walls**



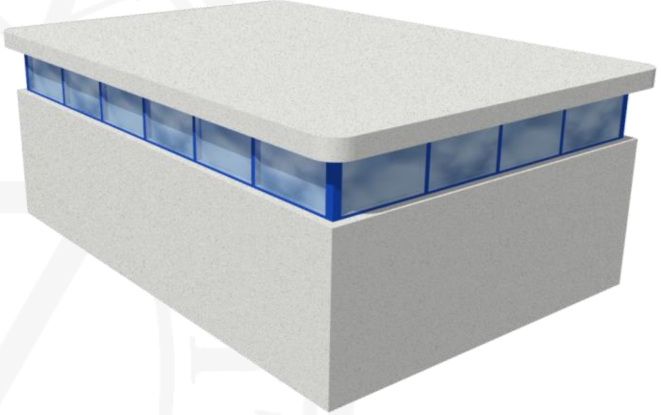

Yawen He, Yamei Zhang, Chao Zhang, Hongyu Zhou, Energy & Buildings, 2020

# 5.3 3D Printed Fabricated Building in Nanjing

**Case studies**



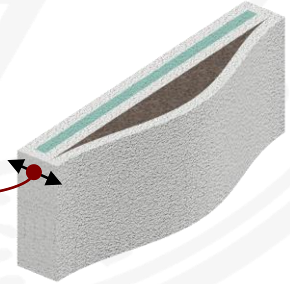
**vs**



- **Living wall system**

| | |
|---|---|
| Leaf area index (LAI) | 3 |
| Leaf emissivity | 0.9 |
| Leaf reflectivity | 0.2 |
| Conductivity of soil | 0.4 W/(m·K) |
| Thermal absorption | 0.96 |

Total thickness of concrete layer: 150mm



- **Baseline**

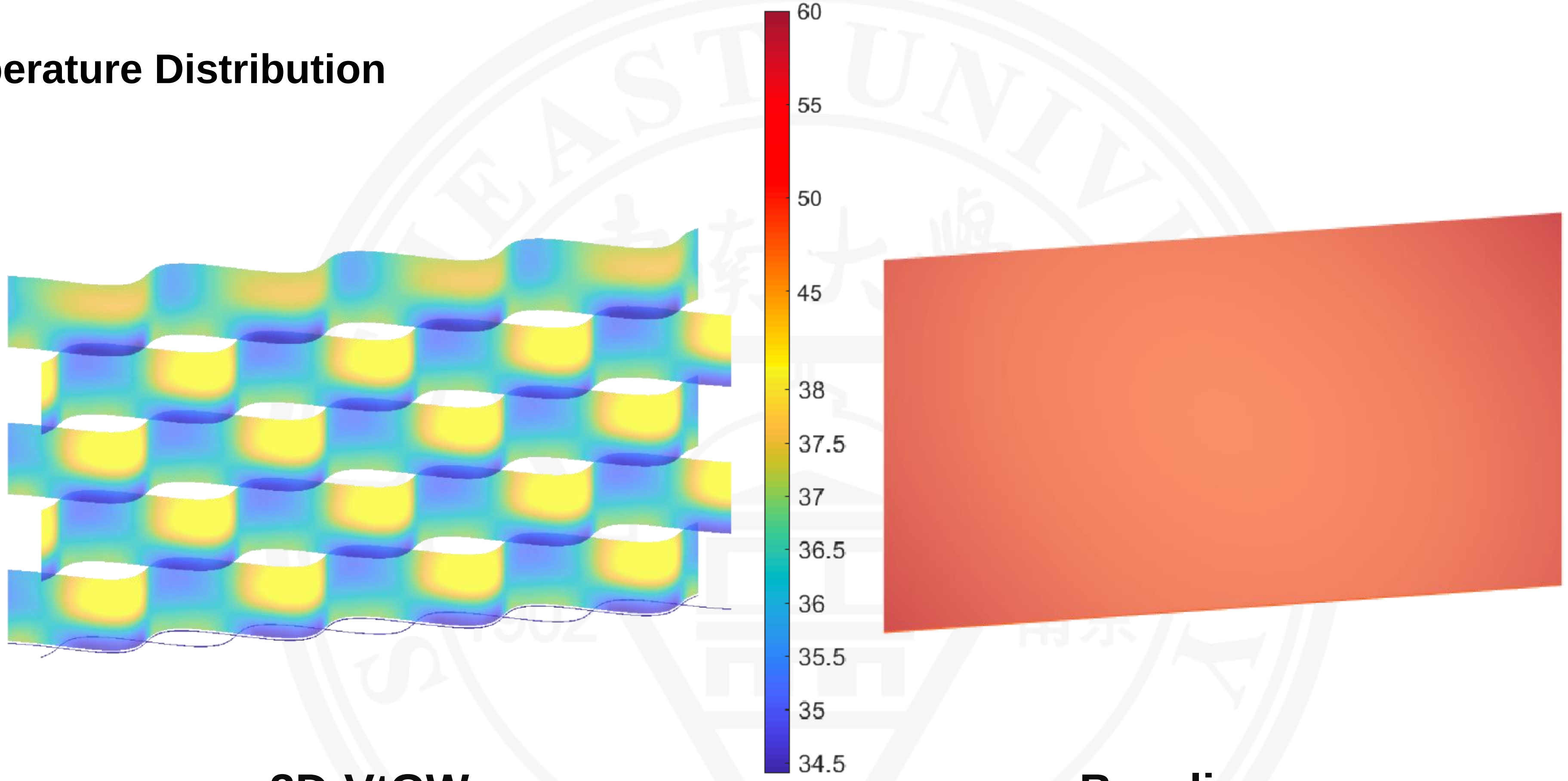
  Aerated concrete block

  Wall thickness 200 mm

Yawen He, Yamei Zhang, Chao Zhang, Hongyu Zhou, Energy & Buildings, 2020

# 5.3 3D Printed Fabricated Building in Nanjing

**Temperature Distribution**



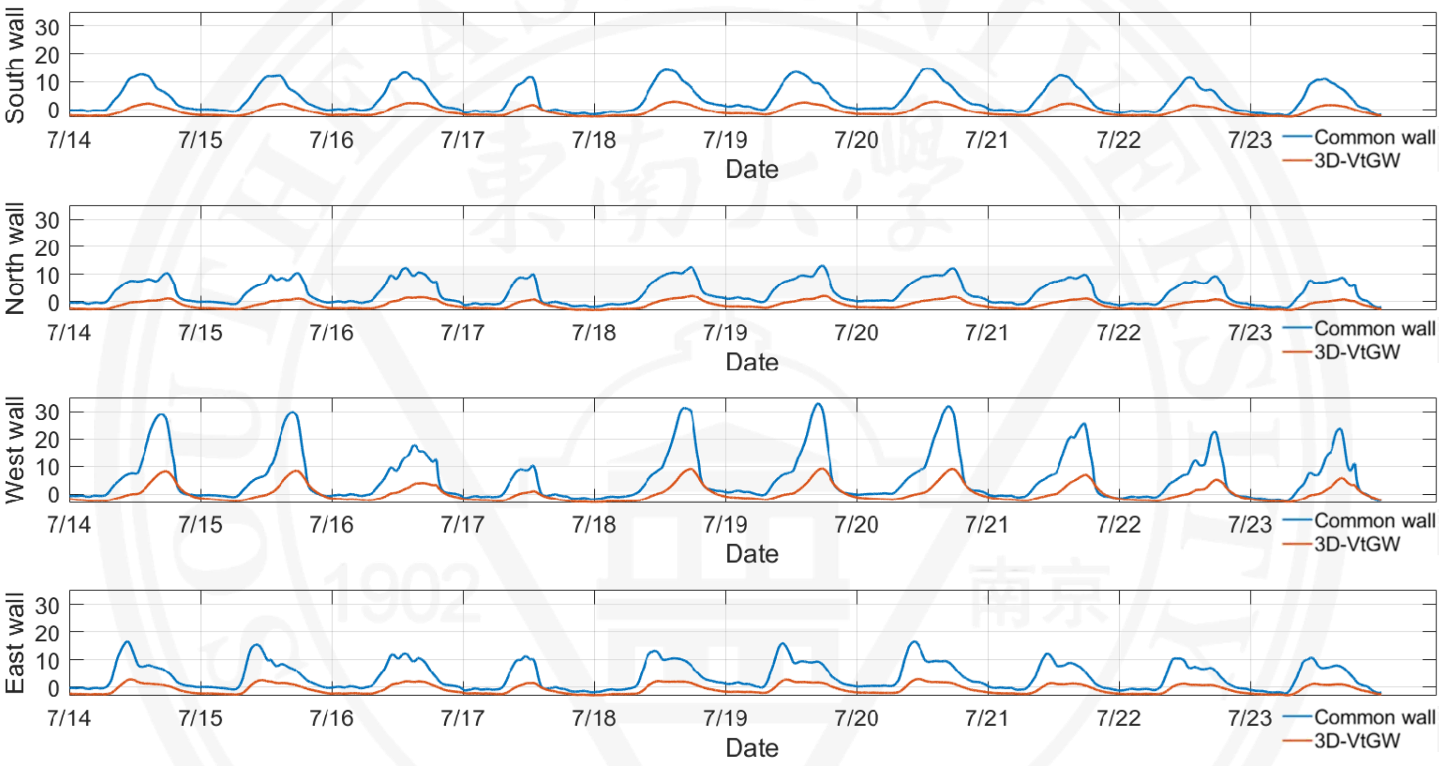

- **3D-VtGW** **VS** - **Baseline**

Comparison of temperature distribution of west wall external surface at noon on one day of July between building with 3D-VtGW and baseline.

Yawen He, Yamei Zhang, Chao Zhang, Hongyu Zhou, Energy & Buildings, 2020

# 5.3 3D Printed Fabricated Building in Nanjing

**Through Wall Heat Flux (W/m²) during Summer (July)**




- Heat flux through exterior walls in 3D-VtGW is 19.35 W/m² (66.82%) lower than that of the counterpart (the aerated concrete wall baseline).
- 3D-VtGW system exhibited improved energy performance in reducing and postpone peak load through walls, especially during summer daytime with high solar radiation.

Yawen He, Yamei Zhang, Chao Zhang, Hongyu Zhou, Energy & Buildings, 2020

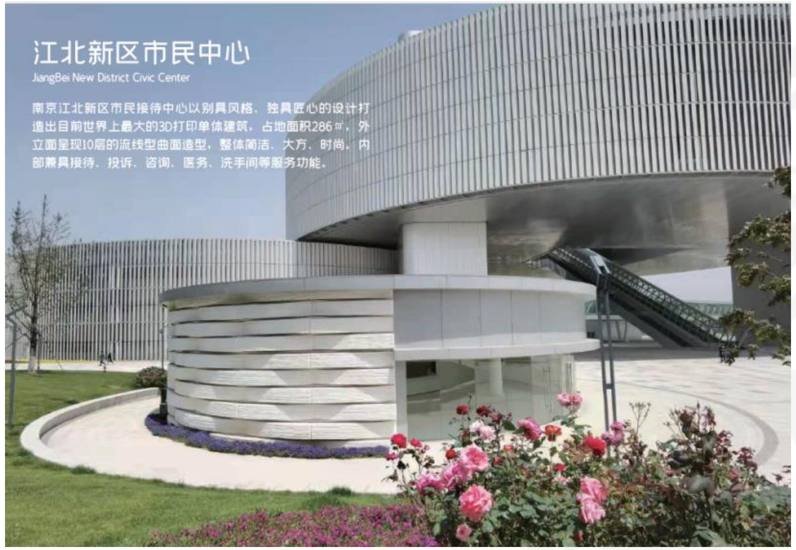
# 5.3 3D Printed Fabricated Building in Nanjing

3D printed elements in factory

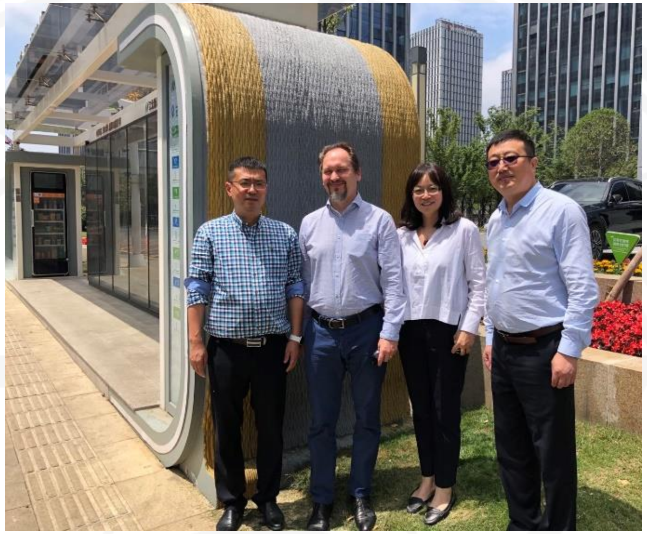
On-site construction

Finished buildings (before planting wall vegetation)

# 5.4 Applications of 3DPC finished by NJIAM




Reception civic center



Bus station

Farm shed


Public washing room


Coffee house

Guard house

# 5.4 Applications of 3DPC finished by NJIAM

Landscape in city

Landscape in city

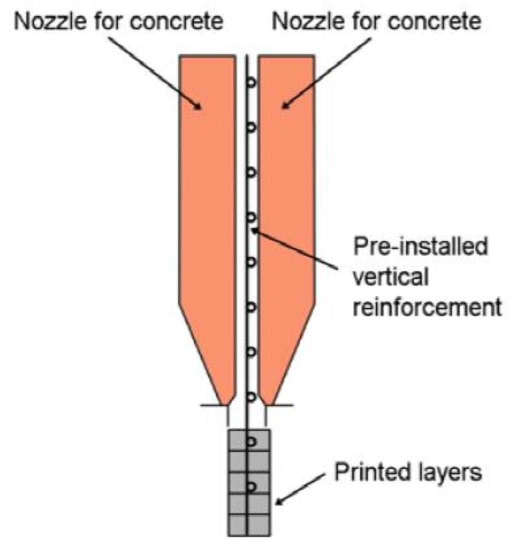

Epidemic shelter


River channel revetment

Seat in park

**3D printing makes our community different and beautiful!**

# 5.5 On-site 3D printed 2-storey building




- The Chinese company HuaShang Tenda demonstrated its novel technology by printing a two-storey, 400 m2 villa on the grounds of the company in Tongzhou, Beijing, in 2016
- The material used is ordinary vibrated concrete, conveyed vertically in the large printhead under gravity, assisted by vibration.
- The nozzle is forked and held by the printhead mounted on a large-scale gantry robot
- The vertical steel mesh reinforcement is fixed by hand prior to printing. The concrete is then deposited layer-by-layer, gradually enclosing the reinforcing bars from all sides

# 5.6 Fabricated 3D printed concrete bridge


From Li Wang, Guowei Ma

- Mimic Zhaozhou Bridge in campus of Hebei University of Technology, by Prof Guowei Ma's team in 2019.
- 28.1m long, 4.2 m wide, net span: 17.94 m
- Structural elements were produced by casting concrete in 3D printed permanent formwork and prestressed externally. Non-structural elements were totally 3D printed.

# 5.7 On-site 3D printed 2-storey building




- The 2-storey building was produced by the China State Construction Technology Center
- The printing of the wall took 48.5 hours and  was finished on November 17, 2019.
- Construction of the building took 4 months, including the waiting time for floor and roof installation
- Beams, floor and roof were precast concrete.

# 5.8 On-site 3D printed house in countryside

Designed and printed by Prof Weiguo Xu's team from Tsinghua University, 2021, Hebei, China

- Three robot printers were used. Robots were installed on the lifting platform.
- Both the foundation and walls were printed on-site. Roof was pre-printed on-site and installed.
- Insulation materials were inserted in the printed wall.
- No reinforcement

# 6 Challenges of 3DPC application

## Challenges of 3DPC mix design

- Printability (pumpability, extrudability and buildability) is the first concern in design of 3D printable concrete
- Strength, deformation, durability should be considered simultaneously

## Challenges of 3D printing with coarse aggregate

- Printing systems: suitable for printing with coarse aggregate
- Suitable printing technology: meeting the pumping, extrusion and buildability requirements
- Favorable surface of printing: rough surface with coarse aggregate may need to be treated

# 6 Challenges of 3DPC application

## Challenges of reinforcing 3DPC

- New structure independent of traditional reinforcing
- New reinforcement approach: coordinating 3D printing of concrete and layout of reinforcement, high efficiency

## Standards of 3DPC needed

- Testing methods are needed: printability, mechanical properties, sampling, etc.
- Design codes of 3D printed structures
- Quality acceptance of 3DPC elements, structures

# Thank you for attention

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