Research Progress on 3D Printed Concrete with Recycled Materials

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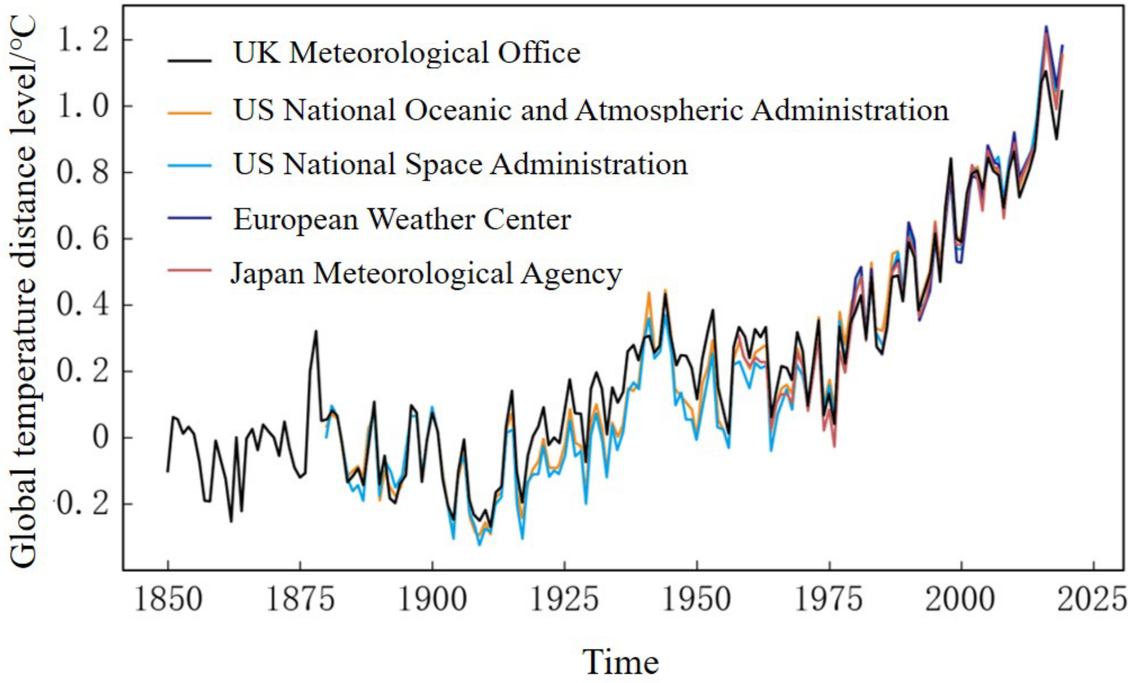
Outline

1. Background
2. 3DPC with Recycled Powder
3. 3DPC with Recycled Fine Aggregate
4. 3DPC with Recycled Coarse Aggregate
5. Conclusion

Background

❑ **Resource and environmental issues are becoming more prominent along with development**



Temperature rise caused by environmental pollution

Large volume mining and the shortage of natural resources

Increasing construction and demolition waste

Background

❑ Recycled Materials: a way to alleviate resource scarcity and waste pollution

Construction waste recycling

Construction waste crushing

Aggregate sorting

Recycled powder

Recycled fine aggregate

Recycled coarse aggregate

Resourceization of Construction Solid Waste

Recycled coarse aggregate (RCA)

↓ replace

Natural crushed stone (NCA)

Recycled fine aggregate (RFA)

↓ replace

Natural river sand (NFA)

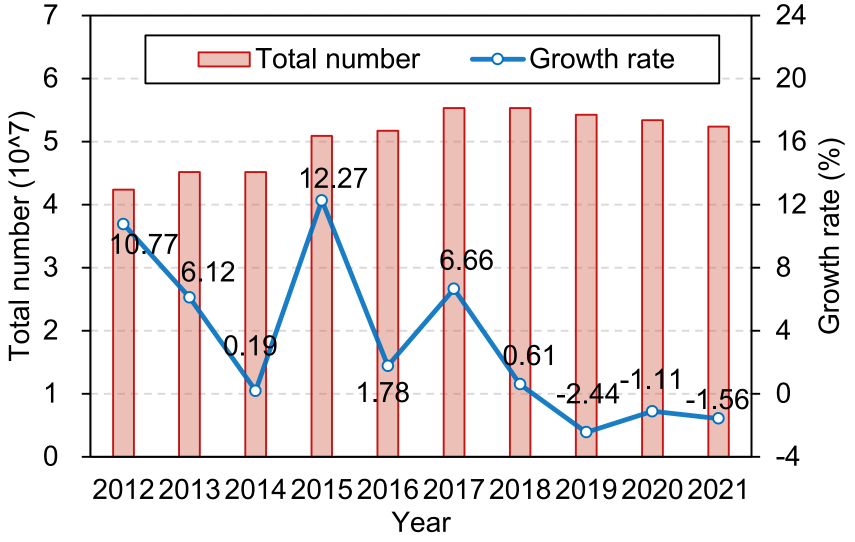
Recycled powder (RP)

↓ replace

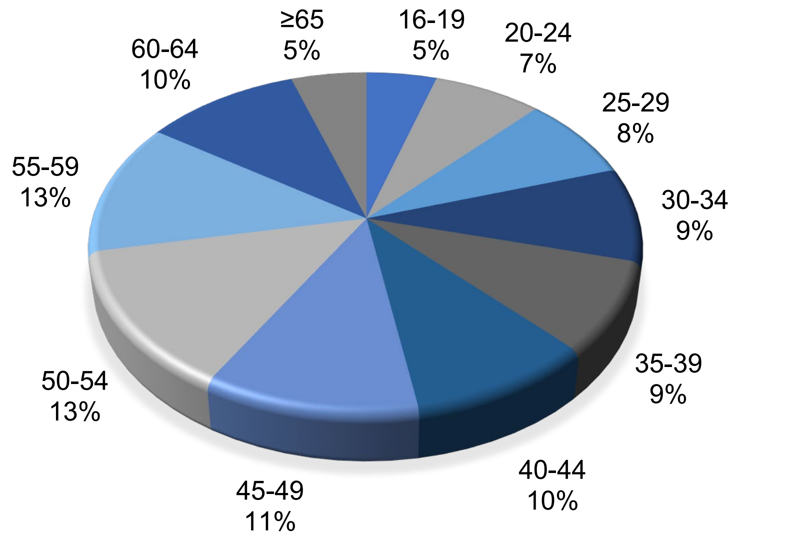
Cementitious materials

Background

❑ Low level of automation in the construction industry



Number of employees in the construction industry

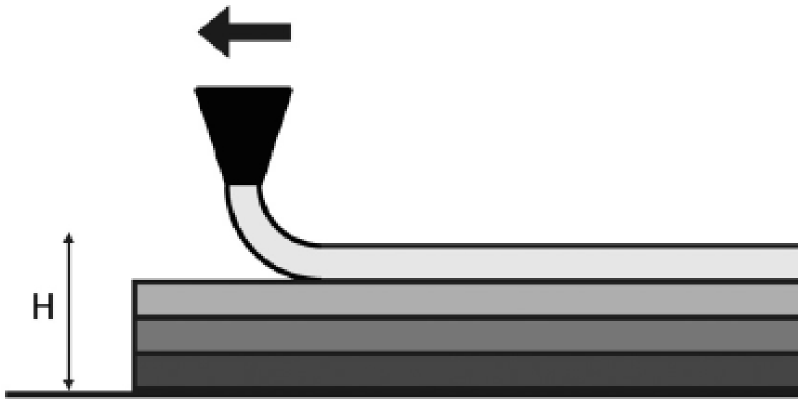


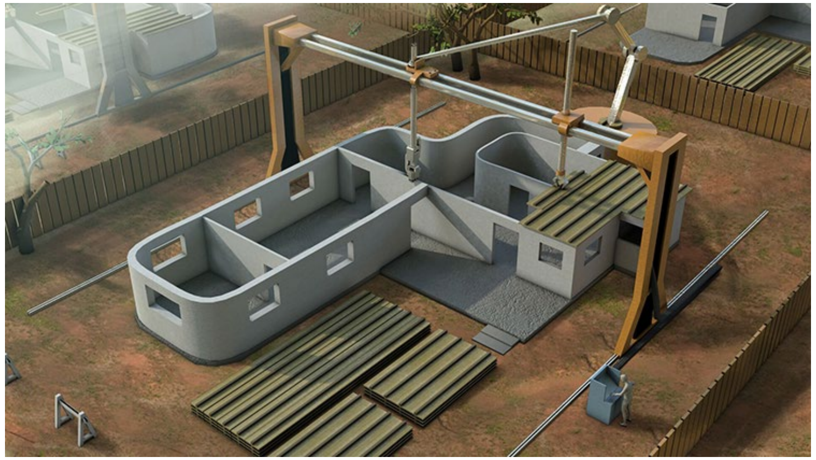
Age composition of construction workers in 2021

- ❑ **In the past 30 years, China's population growth trend has slowed down. There is a negative growth in the number of employees in the construction industry.**
- ❑ **The age composition of construction workers is gradually aging. In 2021, the proportion of construction workers over 50 years old has reached 41%.**

Background

Contour crafting



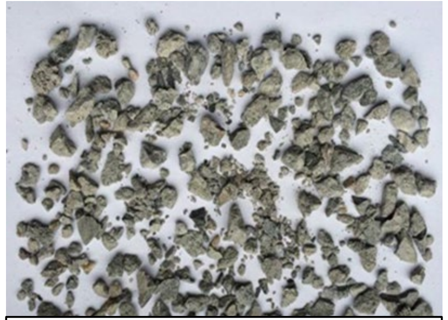


- 3D concrete printing construction, also known as additive construction, is a technique for printing out buildings by stacking materials layer by layer based on a 3D digital model.
- Prof. Khoshnevis invented the Contour Crafting. The concrete material is continuously extruded with the aid of a computer-controlled nozzle and built up layer by layer.

Advantages

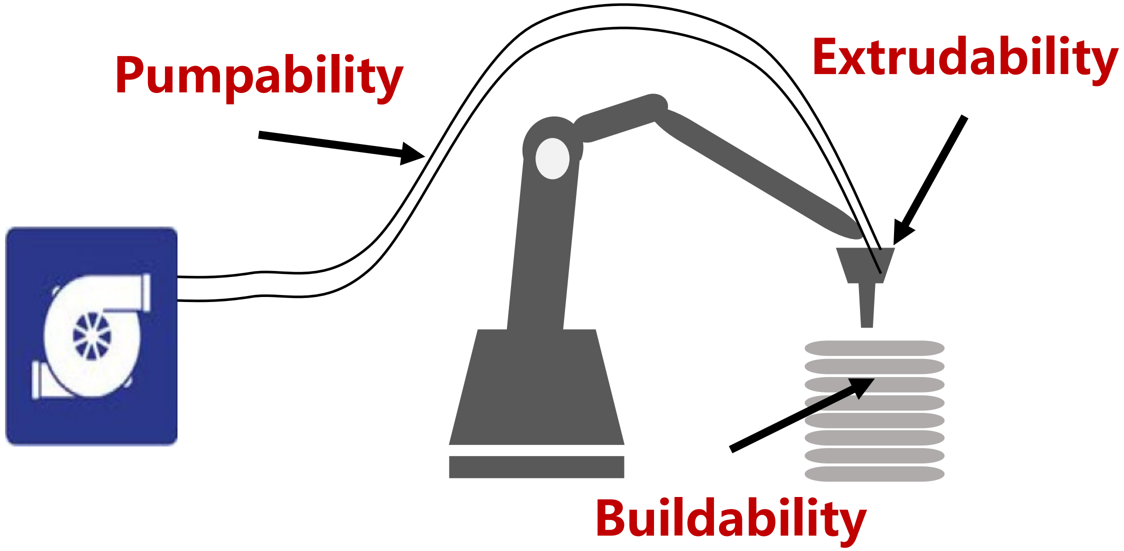
- Saving labor
- No formwork
- Personalization and digitalization

Background


Recycled sand (RS)


Recycled powder (RP)


RS and RP



Recycled materials

+

3D printing

↓

3D-printed recycled concrete

- ☐ **The research aims to apply recycled materials to 3D-printed concrete.**

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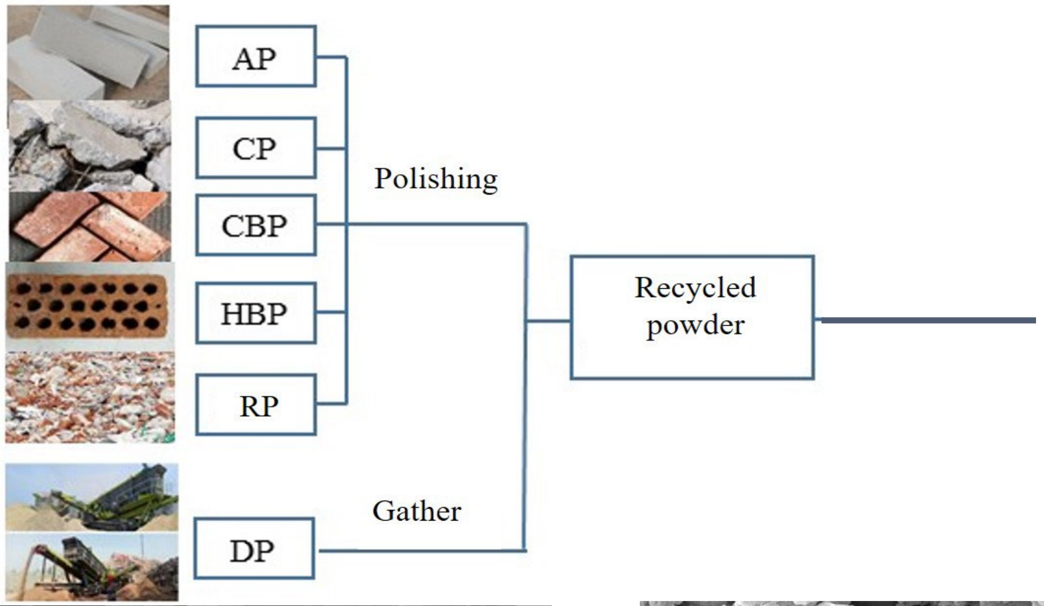
1. Background
2. **3DPC with Recycled Powder**
3. 3DPC with Recycled Fine Aggregate
4. 3DPC with Recycled Coarse Aggregate
5. Conclusion

Characteristics of Recycled Materials

Production and microstructure of recycled powder



AP: aerated brick powder

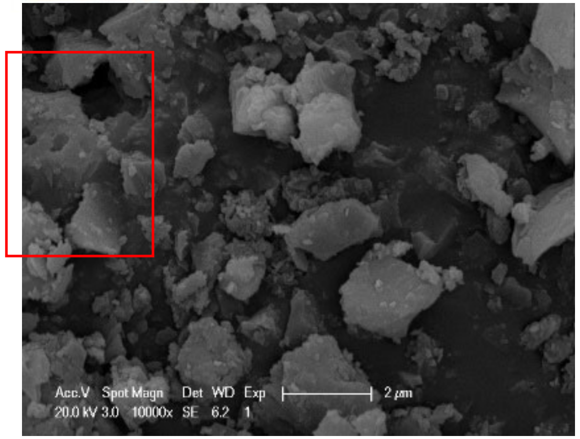
CP: concrete powder

CBP: clay brick powder

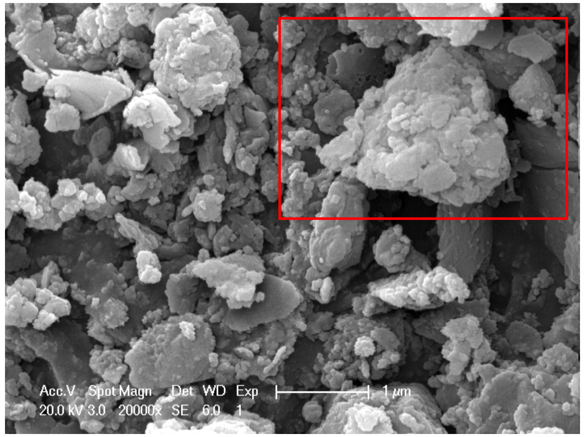
HBP: hollow brick powder

DP: dust powder

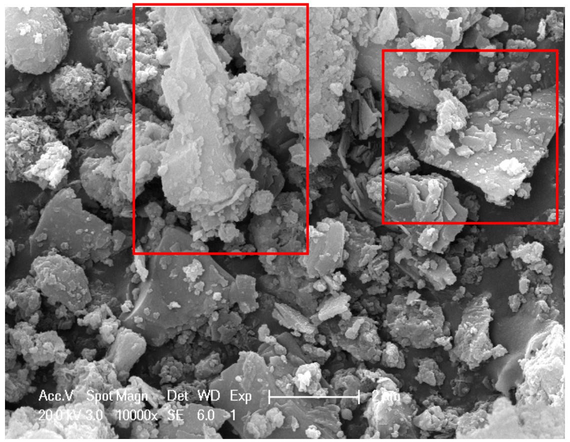
RP: recycled powder from mixed waste brick and concrete



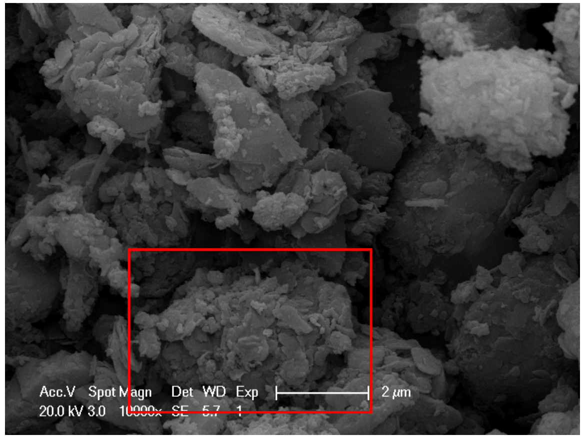
CBP



RP



CP



DP

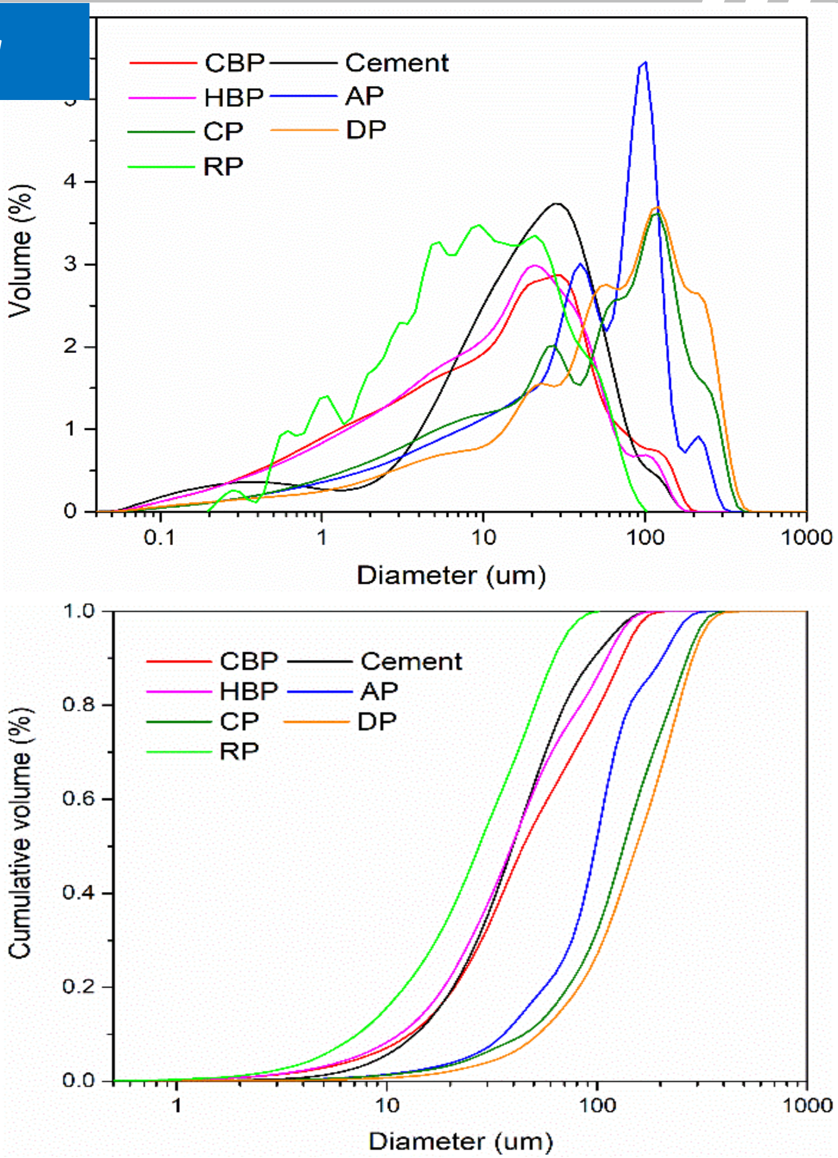
Characteristics of Recycled Materials

Chemical composition and particle size of recycled powder

Chemical composition

	CaO	SiO_2	Al_2O_3	Fe_2O_3	SO_3	MgO	K_2O	Na_2O	TiO_2
C	58.02	23.18	9.31	3.56	2.62	1.36	1.02	0.411	0.40
MBP	21.99	45.71	**15.83**	**6.77**	2.29	2.71	2.56	1.14	0.85
CBP	**2.49**	**64.11**	**18.77**	**7.35**	0.20	1.93	2.53	1.64	0.91
HBP	**2.33**	**62.03**	**19.87**	**8.56**	0.19	2.02	2.51	1.51	0.88
CP	21.30	57.01	**10.93**	3.45	1.17	1.82	2.22	1.58	0.45
DP	30.61	43.28	**12.80**	4.67	1.57	2.54	2.03	1.03	0.70
AP	30.57	37.51	**20.95**	4.79	2.62	1.22	0.99	0.44	0.84

- **Low content of CaO (calcium oxide), higher content of SiO_2 and Al_2O_3 of recycled powder**
- **The average particle size of RP is the smallest, and the particles are all below 100μm, mostly distributed in the range of 5-20μm**



Particle size distribution

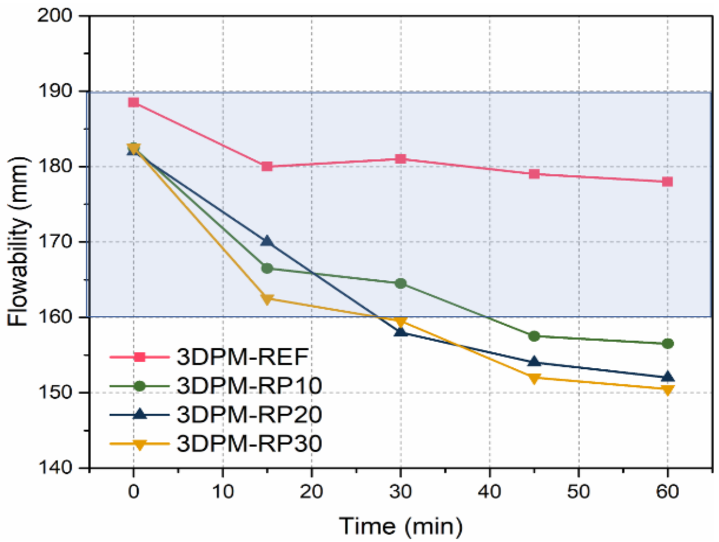
3DPC with RP – Fresh properties

Fluidity, consistency, penetration resistance

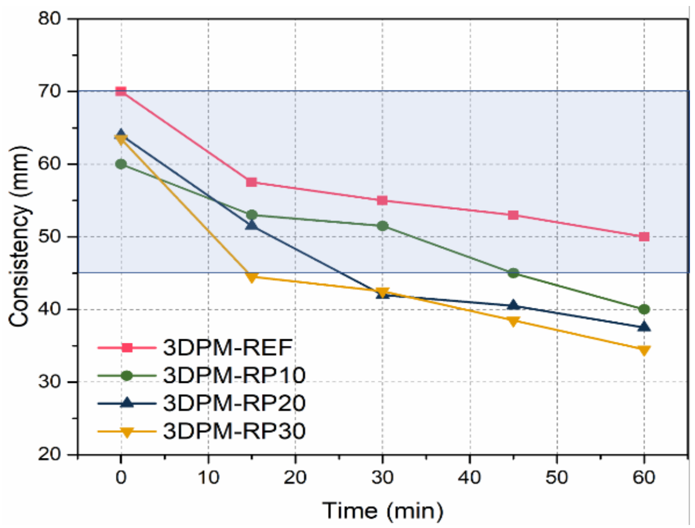
The mix ratio of 3DPC specimen

Group	Water	Cement	RP	Sand	HPMC	SP
3DPM-Ref	350	1000	0	1000	1	0.07
3DPM-RP10	350	900	100	1000	1	0.12
3DPM-RP20	350	800	200	1000	1	0.19
3DPM-RP30	350	700	300	1000	1	0.29

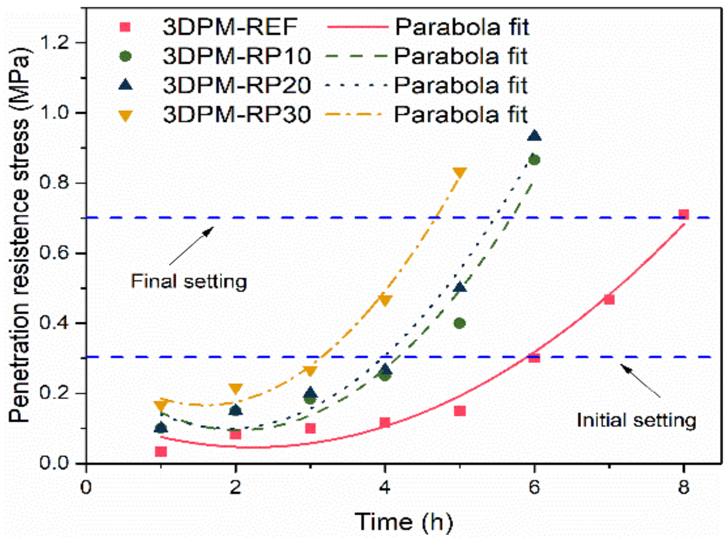
The higher the replacement rate of recycled raw materials, the greater the value of penetration resistance and the faster the growth rate



Fluidity



Consistency

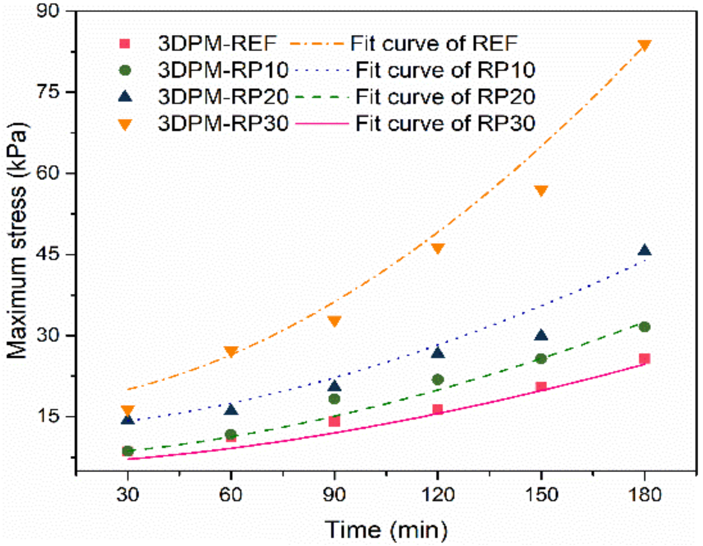


Penetration resistance

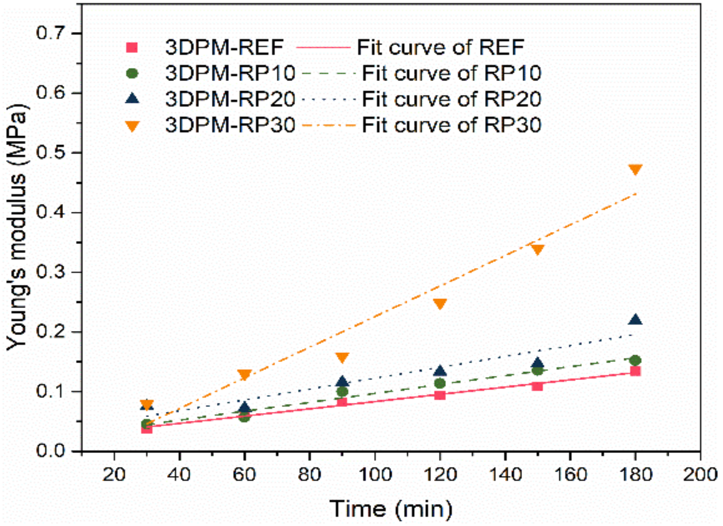
3DPC with RP – Fresh properties

Green strength and Young's modulus

Compressive strength



Elastic modulus



Fitting parameters

$$\sigma(t) = \sigma_0 + k \cdot t^n$$

	σ_0	k	n
3DPM-REF	6.25	0.0030	1.68
3DPM-RP10	7.52	0.0033	1.72
3DPM-RP20	12.81	0.0041	1.72
3DPM-RP30	17.51	0.0052	1.82

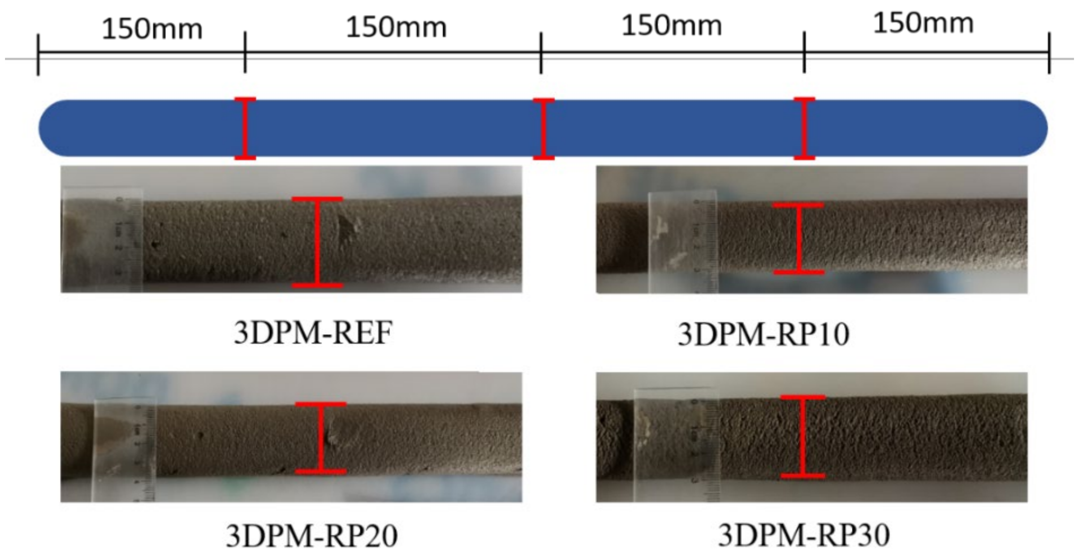
$$E(t) = E_0 + k \cdot t$$

	E_0	k
3DPM-REF	0.023	6.08×10^{-4}
3DPM-RP10	0.022	7.46×10^{-4}
3DPM-RP20	0.034	9.01×10^{-4}
3DPM-RP30	0.038	21.00×10^{-4}

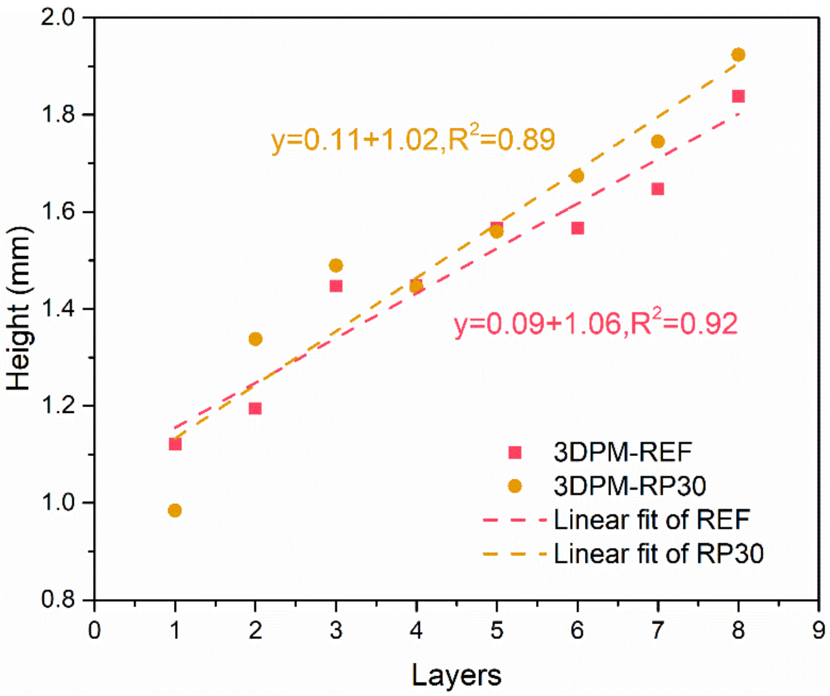
- **When the replacement ratio of RP was higher than 30%, the increase ratio of compressive strength and elastic modulus enhanced quickly**

3DPC with RP – Printability

Extrudability and buildability



No damage, separation and clogging after extrusion



Different layer heights

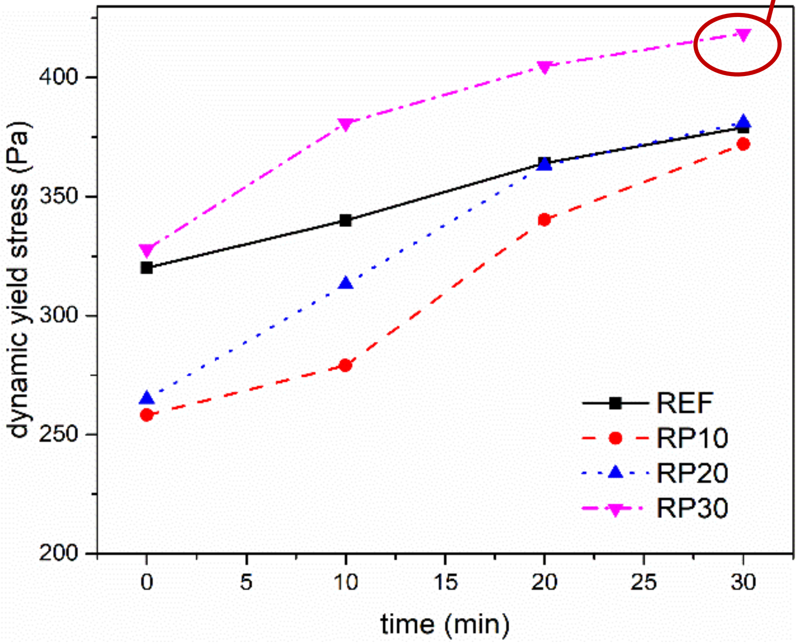
Destruction mode

The addition of the recycled powder has less effect on the maximum print layer height, which is 11-13 layers, and the damage mode is flexural damage.

3DPC with RP – Rheology

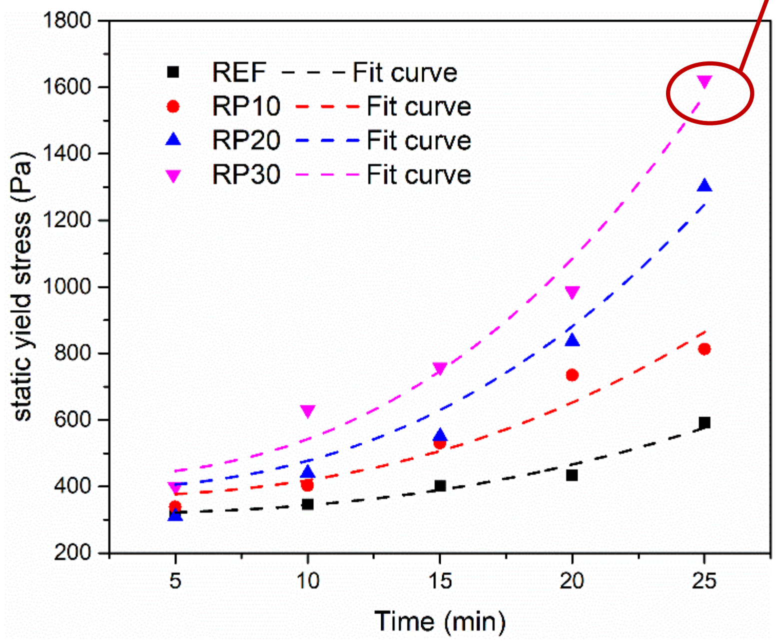
Dynamic and static Yield stress

27.8% increase in 30min



Dynamic yield stress changes over time

416.5% increase in 20min



Static yield stress changes over time

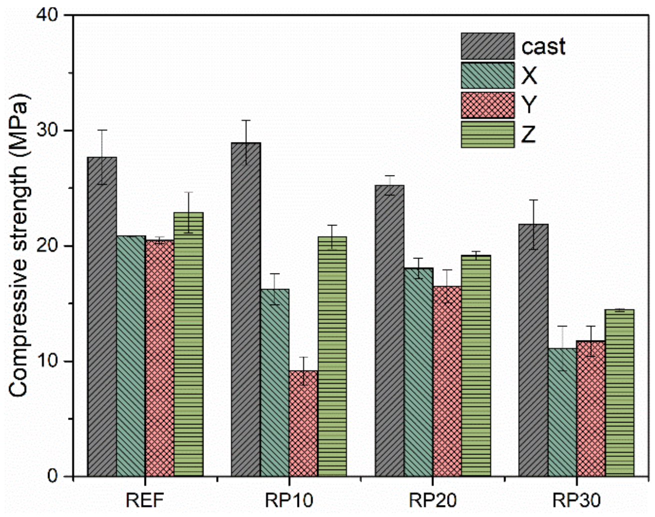
Fitting Equ. and parameters

$$\tau_s(t)=\tau_{s,0}+kt^{2.5}$$

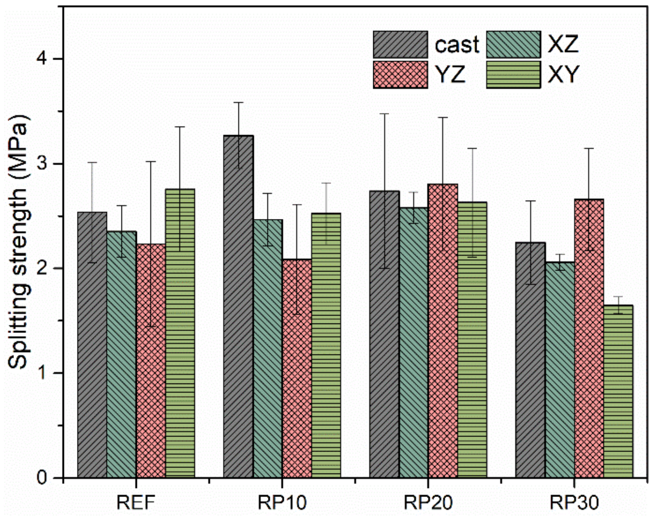
		k	R^2
3DPM-REF	317.69	0.083	0.96
3DPM-RP10	368.70	0.159	0.91
3DPM-RP20	390.49	0.275	0.96
3DPM-RP30	426.21	0.368	0.97

Static yield stress increases significantly faster with time than dynamic yield stress, which is positive to the development of buildability

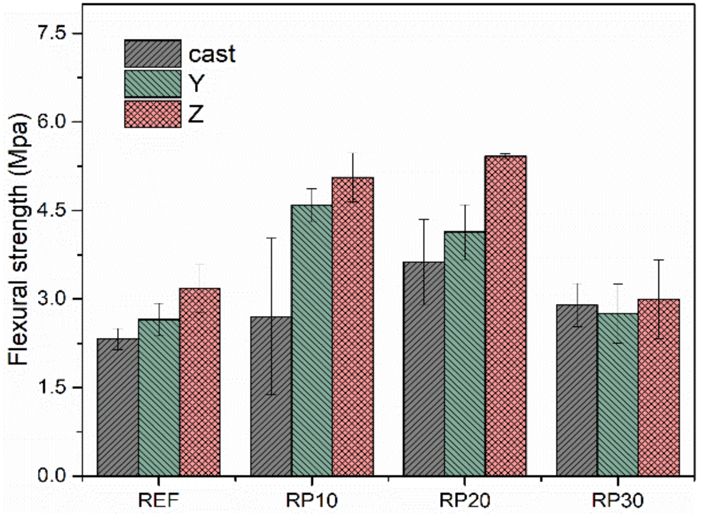
3DPC with RP – Hardened mechanical properties



Compressive strength



Splitting tensile strength



Flexural strength

- The highest compressive strength of the 3D printed specimens was obtained on the X direction.
- When the RP replacement ratio was 20%, the X-direction compressive strength of 3DPM was 24.11% lower than that of cast samples
- The splitting tensile strengths of 3DPM were closed to and the flexural strengths of 3DPM were higher than that of cast samples regardless of the loading directions.

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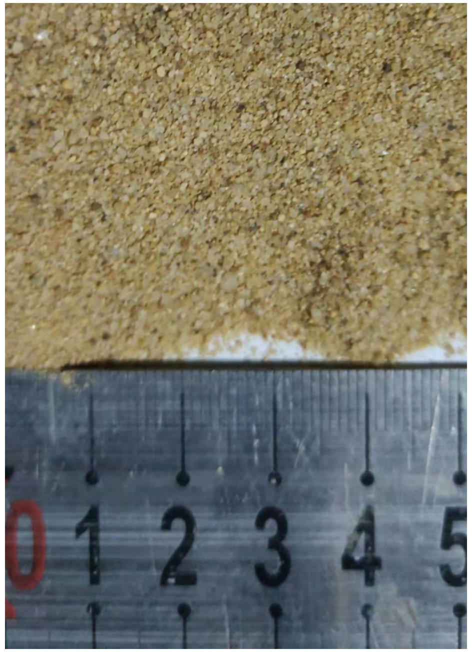
Characteristics of Recycled Materials

Appearance of coarse and fine aggregates

Natural coarse aggregate

Recycled coarse aggregate



Natural fine aggregate

Recycled fine aggregate

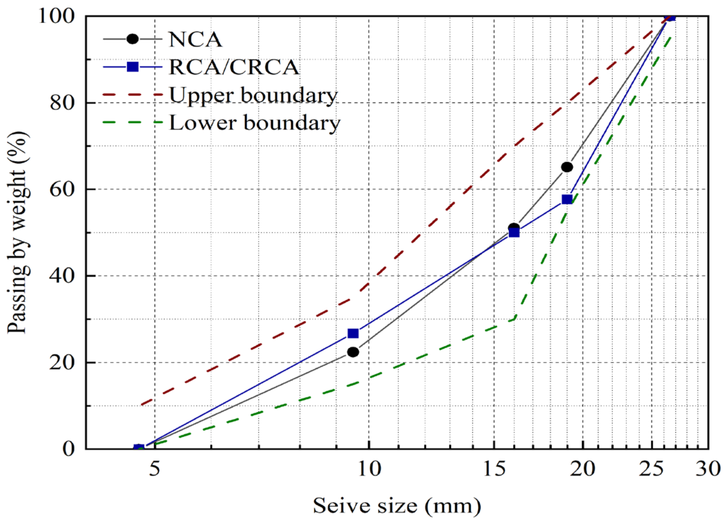
Compared to natural aggregates, recycled coarse aggregate and recycled fine aggregates have loose and porous old adherent mortar on the surface

Characteristics of Recycled Materials

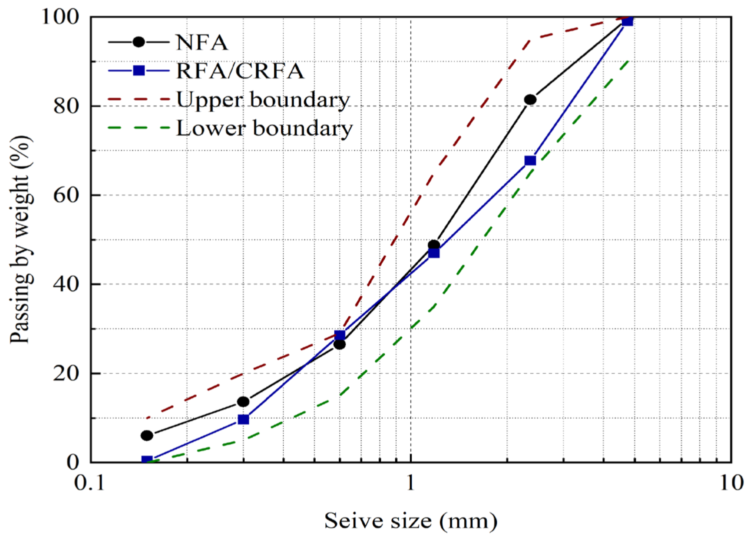
Properties of coarse and fine aggregate

Aggregate physical property parameters

Aggregate type	Fineness modulus	Crush index (%)	Apparent density (kg/m^3)	Water absorption (%)	Moisture content (%)
RFA	3.4	-	2236	13.3	6.6
NFA	3.2	-	2610	1.0	0.9
RCA	-	13.8	2614	7.7	4.5
NCA	-	5.1	2782	0.9	0.8



Particle distribution of RCA



Particle distribution of RFA

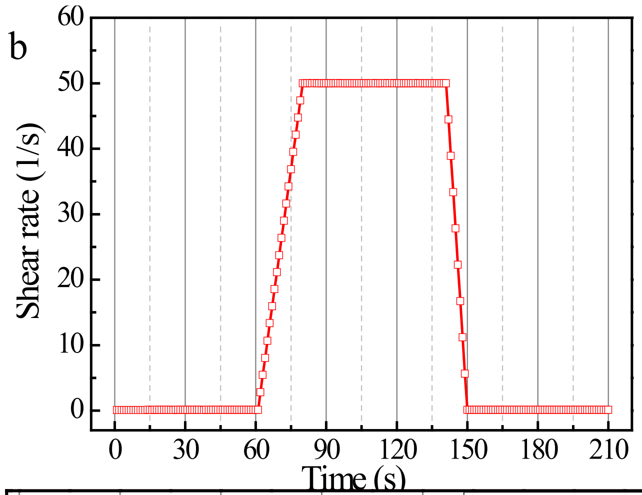
High water absorption of recycled material due to old mortar

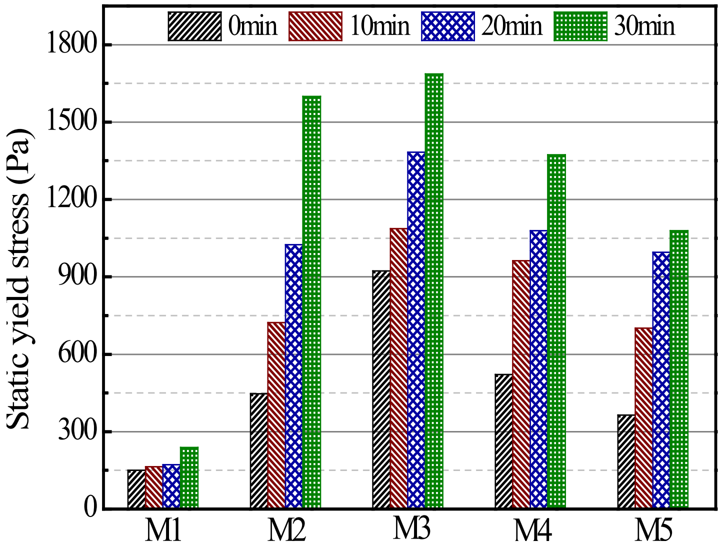
3DPC with RFA – Fresh properties

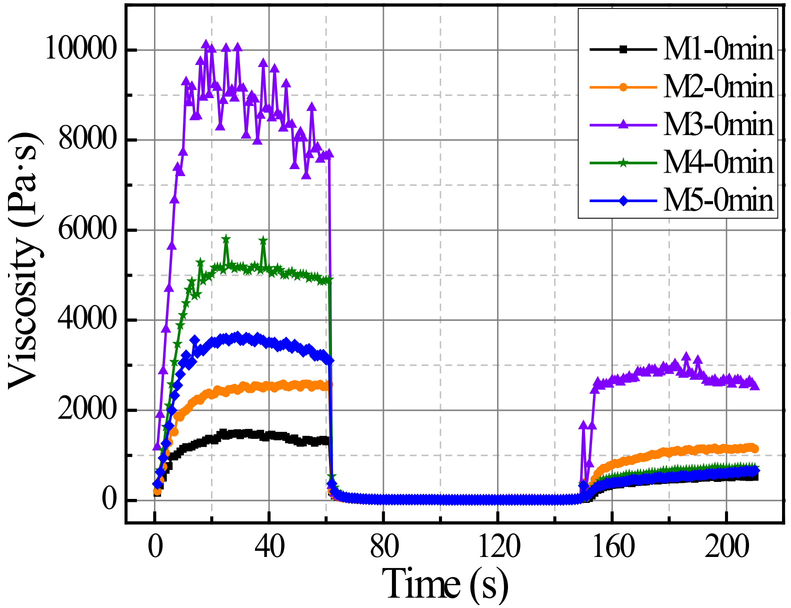
Rheology

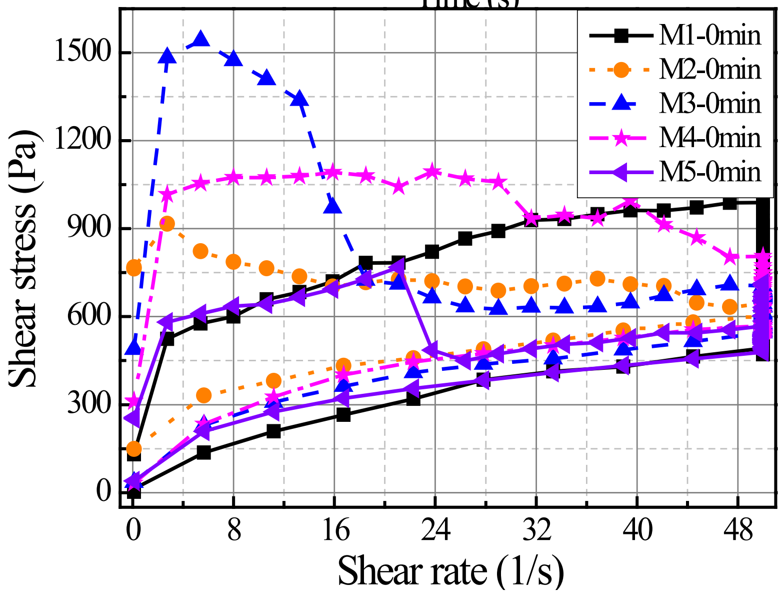
Mix design for the printing mixtures (g)

Mix	RFA ratio (%)	OPC	River sand	RFA	HPMC	Super-plasticizer	Sodium gluconate	Water
M1	0	1000	1000	0	1.28	0.83	0	350
M2	50	1000	500	500	1.28	0.83	0	418
M3	100	1000	0	1000	1.28	0.83	0	485
M4	100	1000	0	1000	1.28	0.83	0.6	485
M5	100	1000	0	1000	1.28	0.83	1.2	485





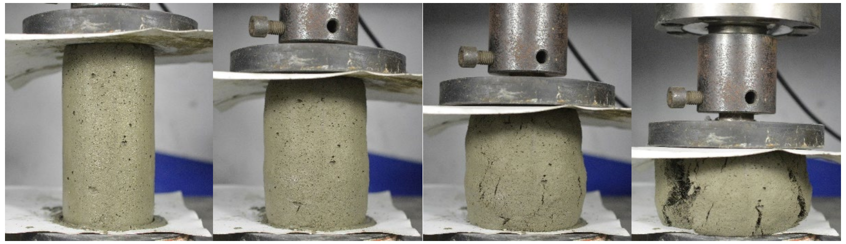




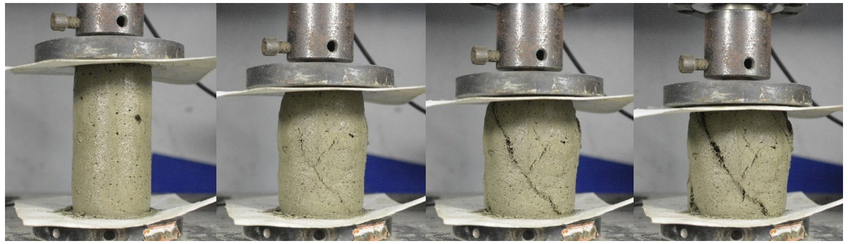
The incorporation of RFA highly increased the 3DP mixture's static yield stress, viscosity, thixitropy

3DPC with RFA – Fresh properties

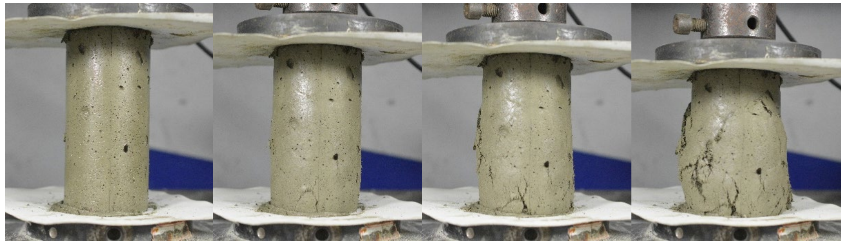
Green Strength



(a) 3DMP1 at 90 mins

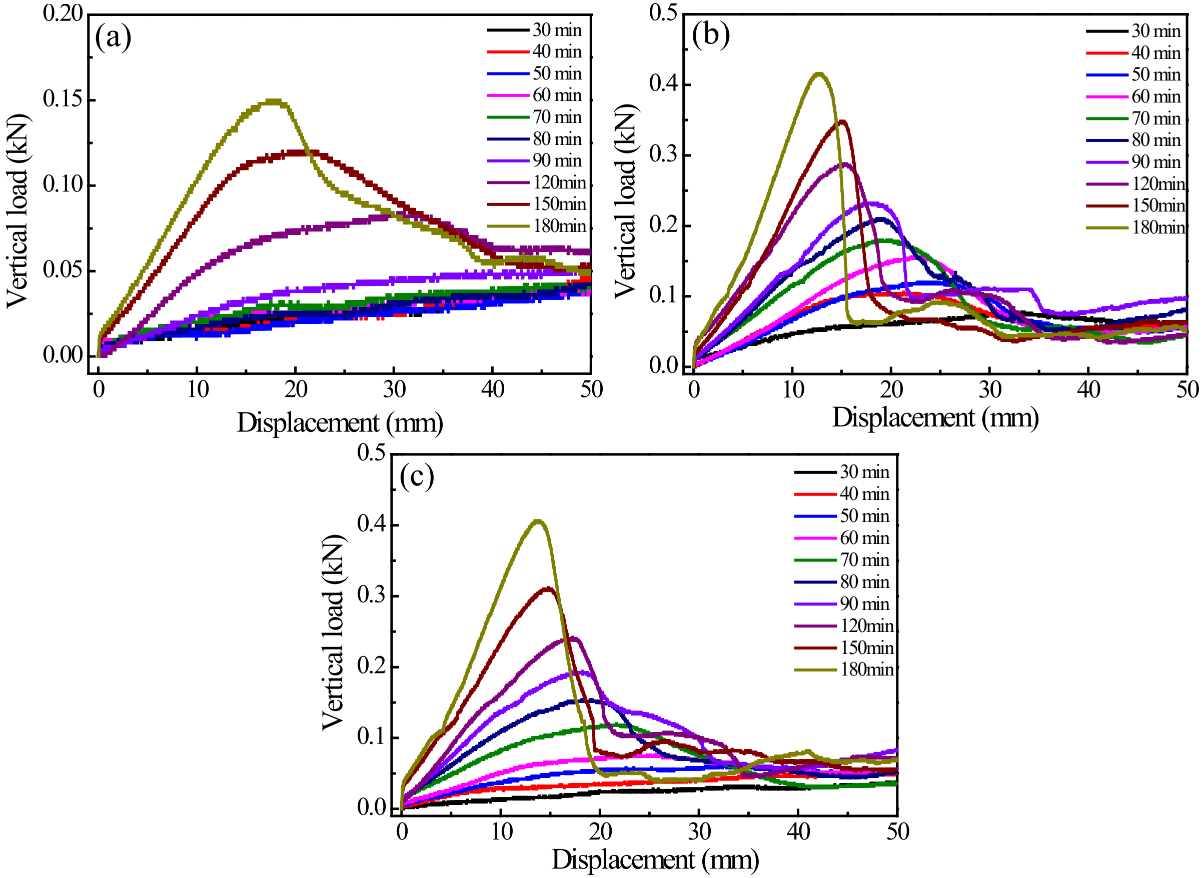


(b) 3DMP1 at 180 mins



(c) 3DMP5 at 90 mins

Fig. 7. Uniaxial unconfined compressive testing process of specimens at different resting time: (a) 3DMP1 at 90 mins; (b) 3DMP1 at 180 mins; (c) 3DMP5 at 90 mins

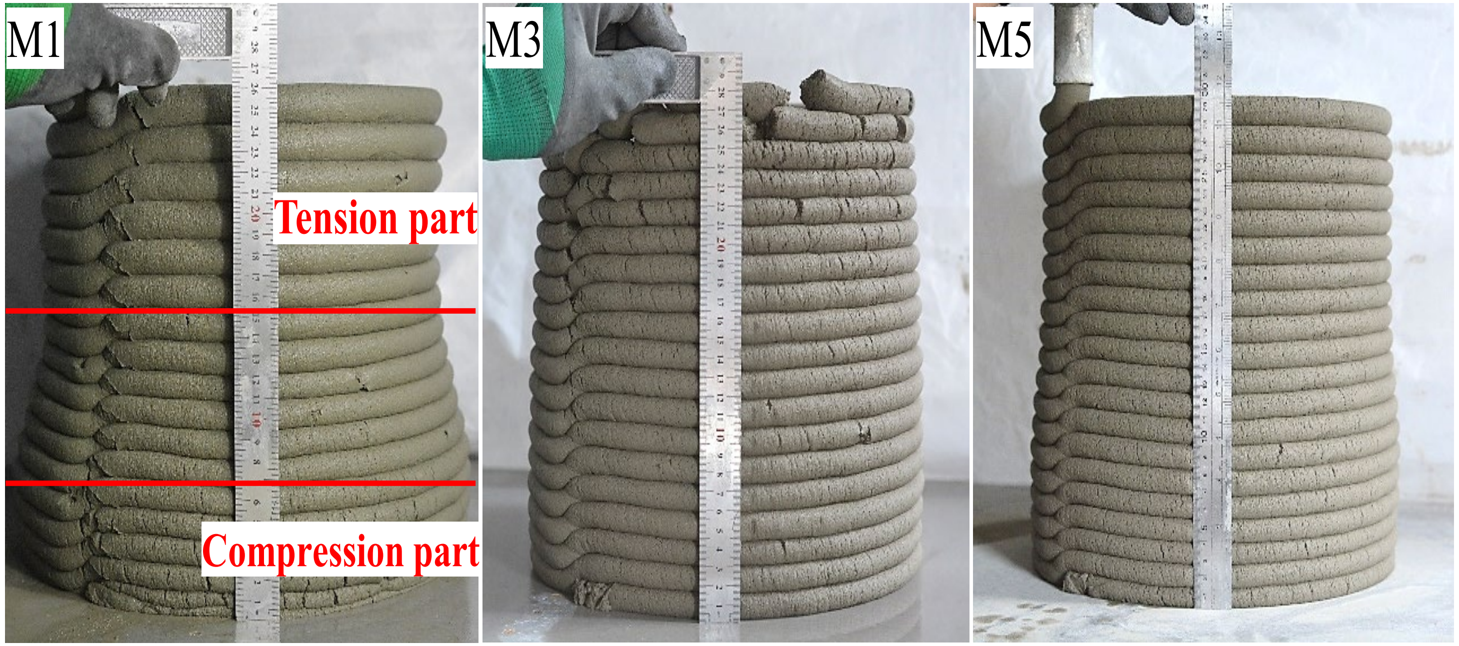


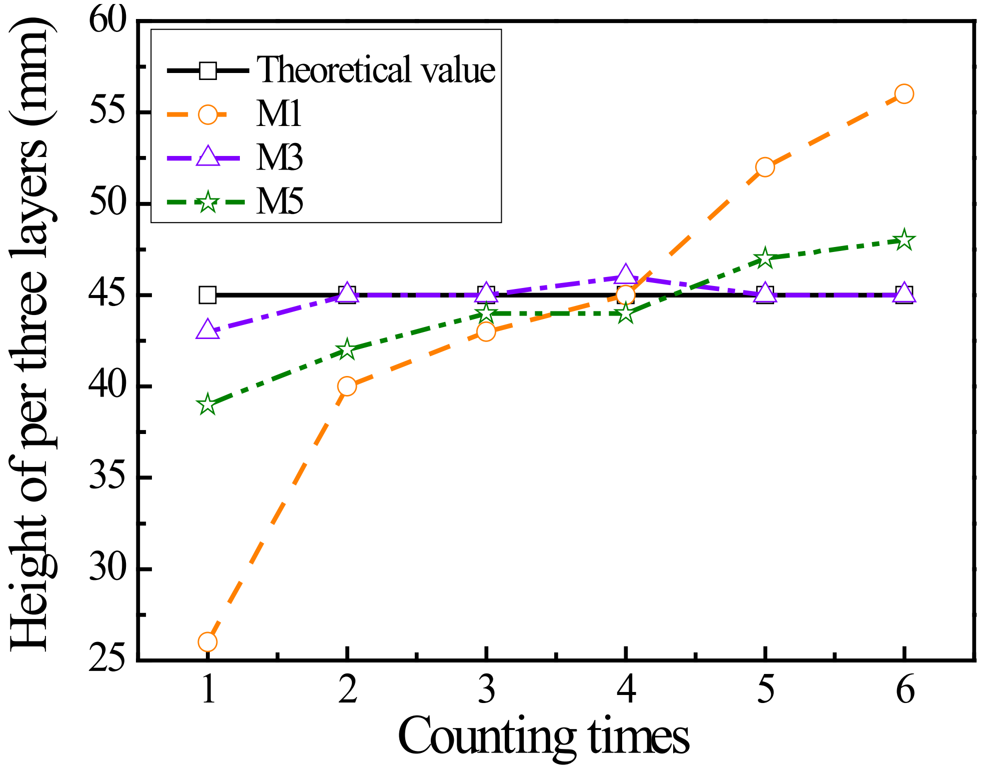
Vertical load to displacement curves: (a) 3DPM1, (b) 3DPM2, (c) 3DPM5

RFA improves deformation resistance and accelerated the hardening process of 3DPC

3DPC with RFA – Printability

Buildability



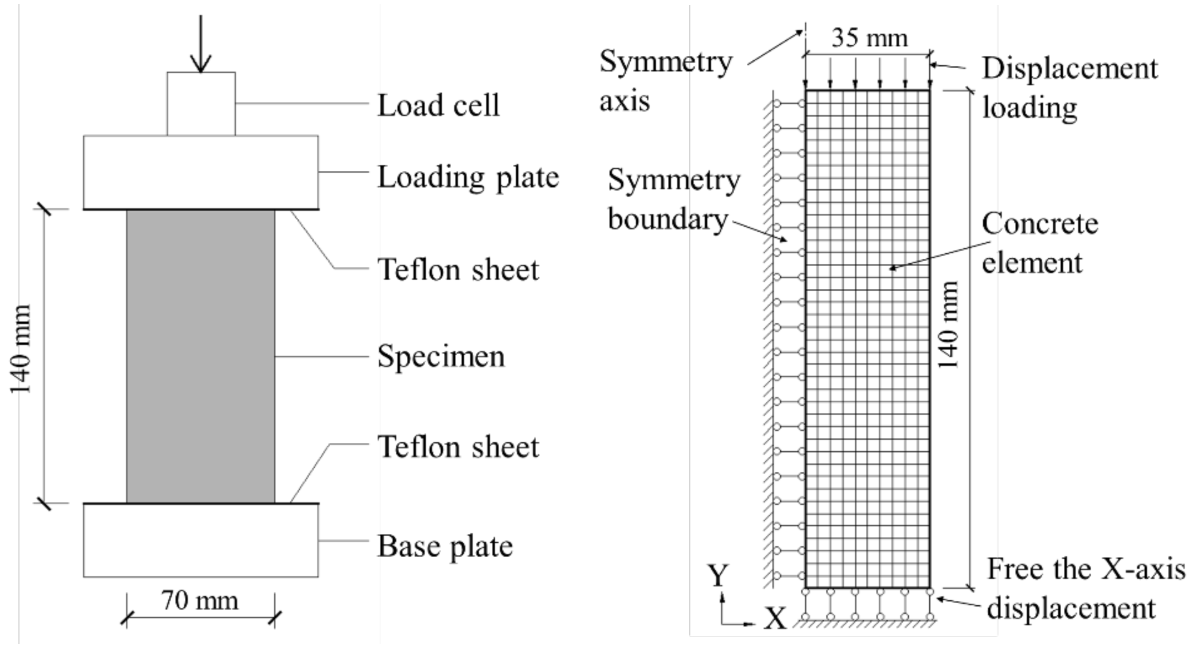


RFA improved the buildability of 3DPC, especially when considering both compression and tension deformations during the printing.

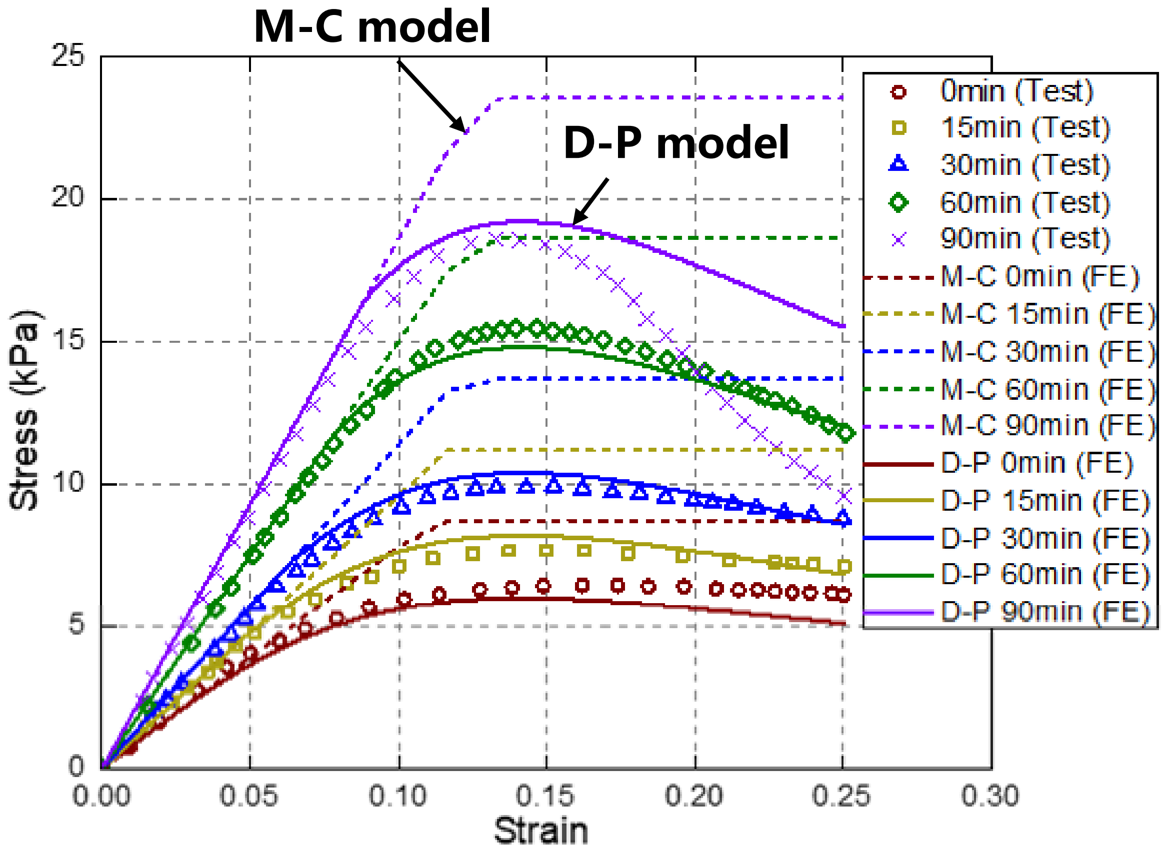
3DPC with RFA – Buildability prediction

Case 1: uniaxial compression test

Test **FE model**



Schematic diagram of test and FE model

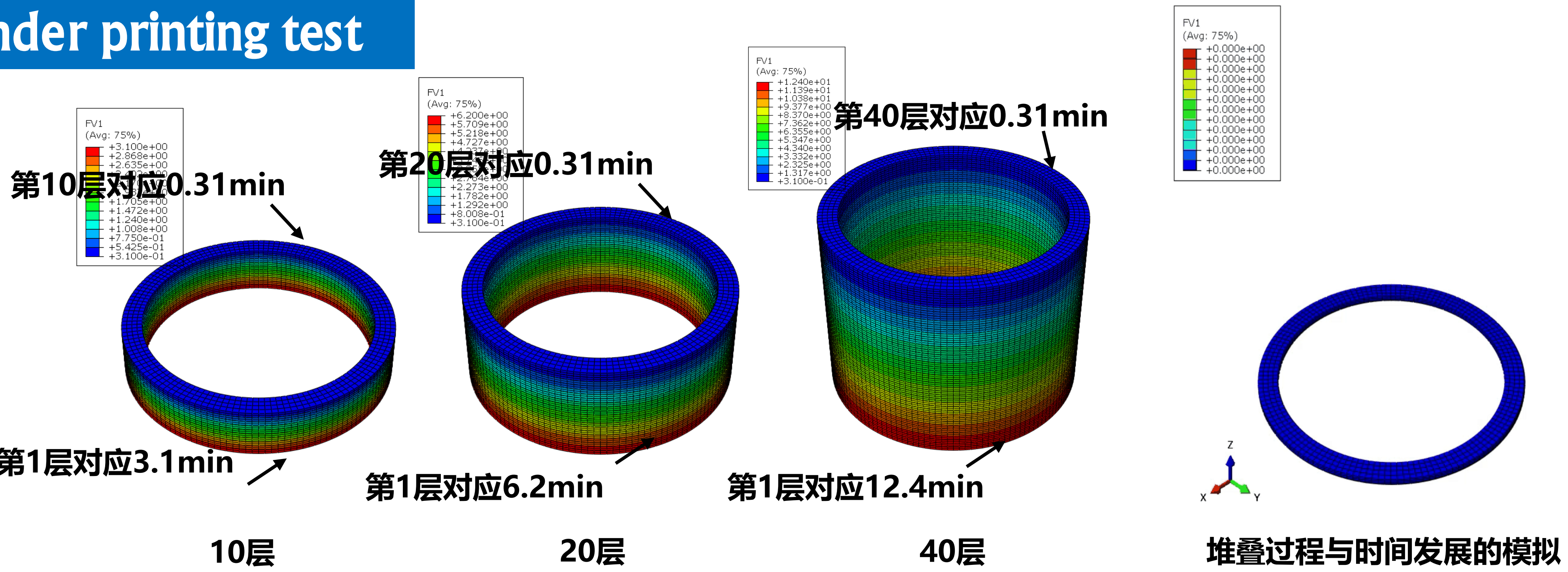


The comparison between FE and test results

R.J.M. Wolfs, F.P. Bos, T.A.M. Salet, Cement and Concrete Research. 106 (2018) 103–116.
H. Liu, T. Ding, J. Xiao, V. Mechtcherine, Additive Manufacturing. 55 (2022) 102821.

3DPC with RFA – Buildability prediction

Case 2: hollow cylinder printing test



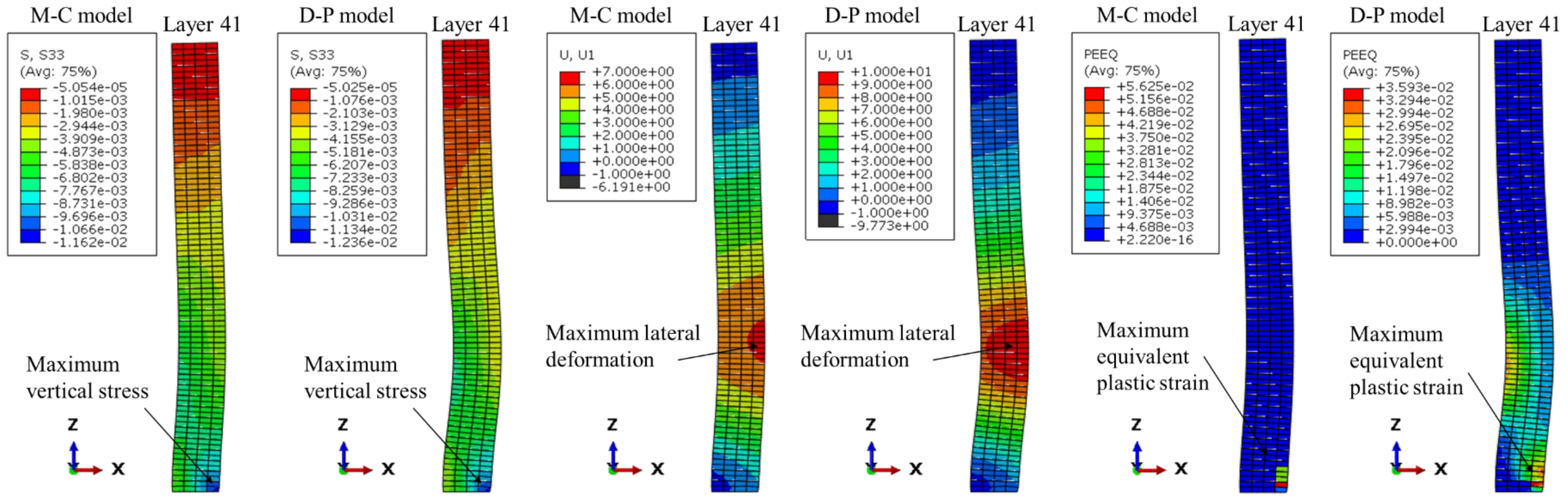
- Centerline radius: 250 mm
- Layer width: 40 mm
- Layer height: 10 mm
- Printing speed: 5000 mm/min
- Time interval: 0.31 min

- Solid elements (C3D8R) were used.
- The model change option was adopted to realize the deposition of printed filaments layer-by-layer.
- The field variable was employed in the FE model to realize the variation of material parameters over time.

H. Liu, T. Ding, J. Xiao, V. Mechtcherine, Additive Manufacturing. 55 (2022) 102821.

3DPC with RFA – Buildability prediction

Case 2: hollow cylinder printing test



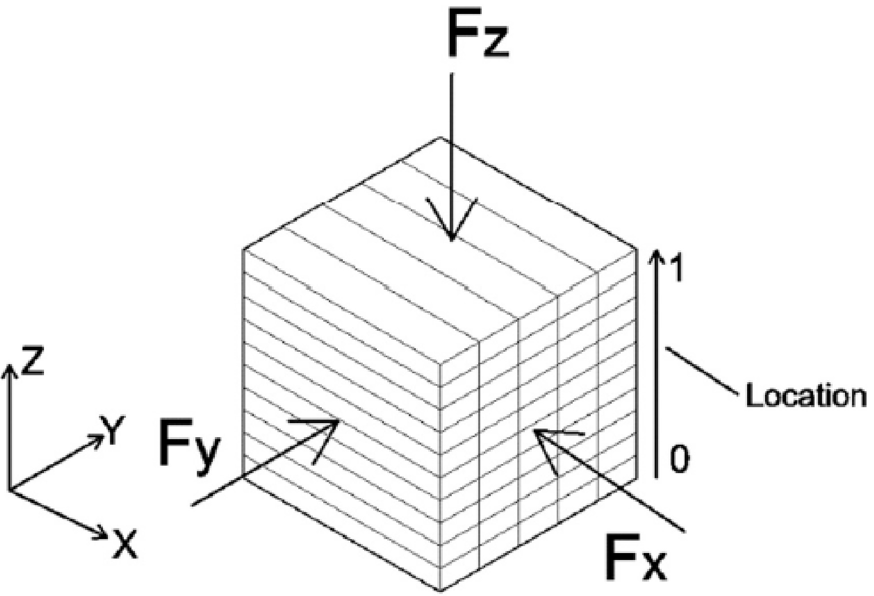
Vertical stress **Lateral deformation** **Equivalent plastic strain**

- Before the collapse of the hollow cylinder, a large plastic strain has occurred in the middle and lower parts, and the concrete has reached yield stress.

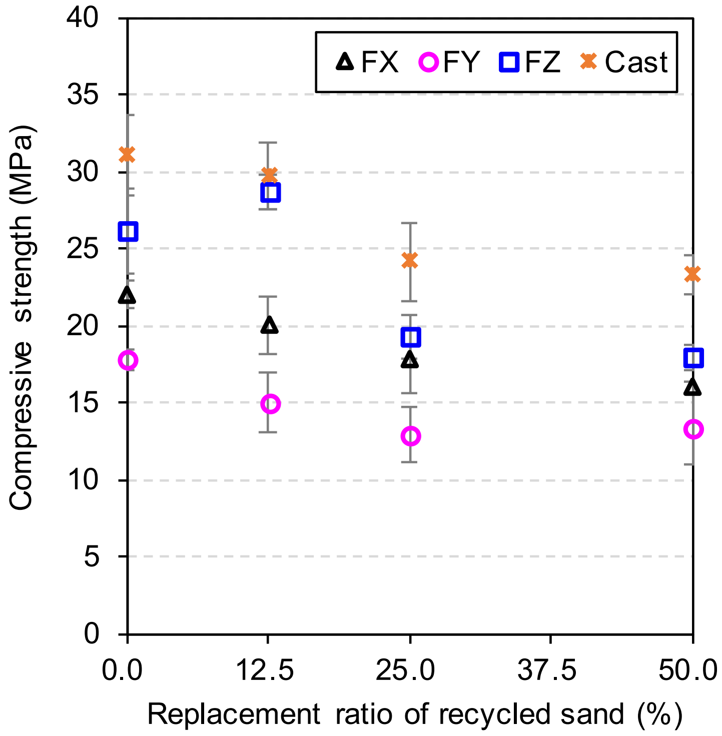
H. Liu, T. Ding, J. Xiao, V. Mechtcherine, Additive Manufacturing. 55 (2022) 102821.

3DPC with RFA – Hardened properties

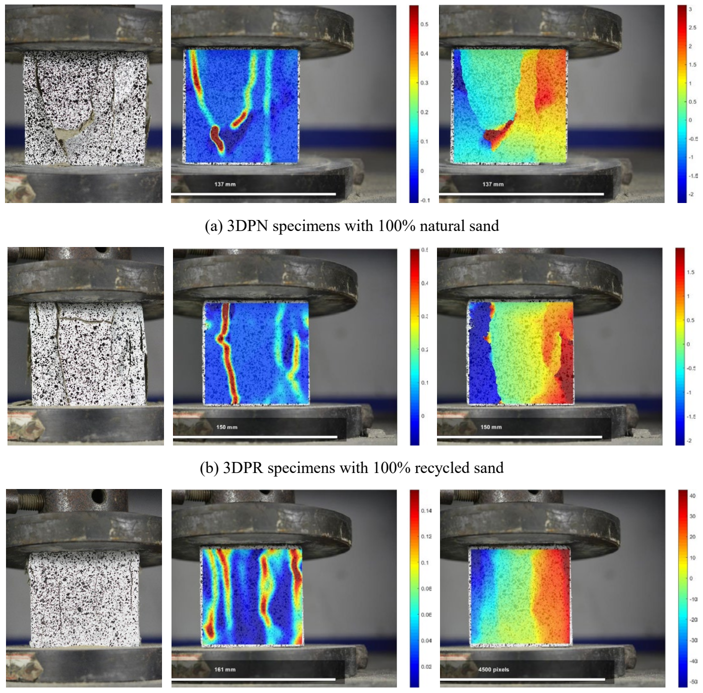
Compressive, tensile splitting and flexural strengths



加载方向示意图



抗压强度



(a) 3DPN specimens with 100% natural sand

(b) 3DPR specimens with 100% recycled sand

(c) 3DPRF specimens with 100% recycled sand and 1% fiber

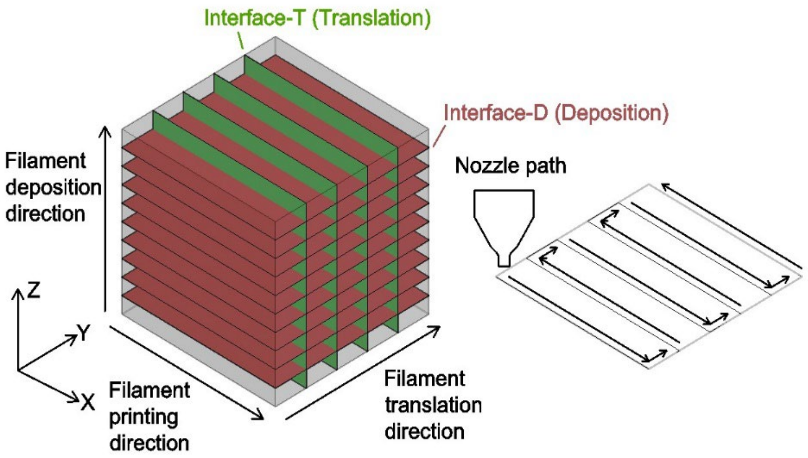
Fig. 7. Failure patterns of compressive test: (a) 3DPN; (b) 3DPR; (c) 3DPRF

裂缝开展情况

- 进行了抗压强度、抗弯强度和劈裂抗拉强度等力学性能试验
- 试验结果表明，**3D打印再生混凝土具有明显的各向异性。**

3DPC with RFA – Finite element simulation

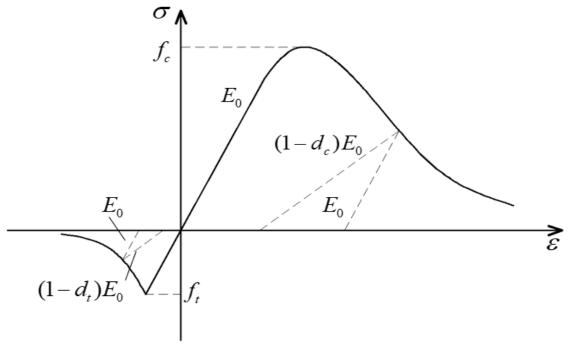
Finite element simulation for 3DPC hardening properties



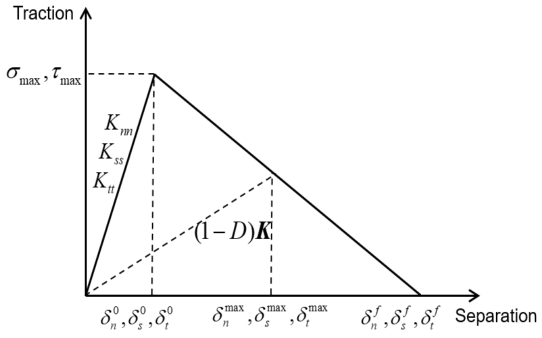
Interface distribution form

When the print strips are stacked in the Z-axis direction, the interface between the strips is the stacking interface (Interface-D).

When the print strips are translated in the XY plane, the interface between the strips is the translation interface (Interface-T).



Concrete damaged plasticity model



Traction-separation law

The concrete plastic damage model is used, and the concrete material itself is considered to be isotropic.

The anisotropy of 3DPC is due to stacking and is not related to the material itself.

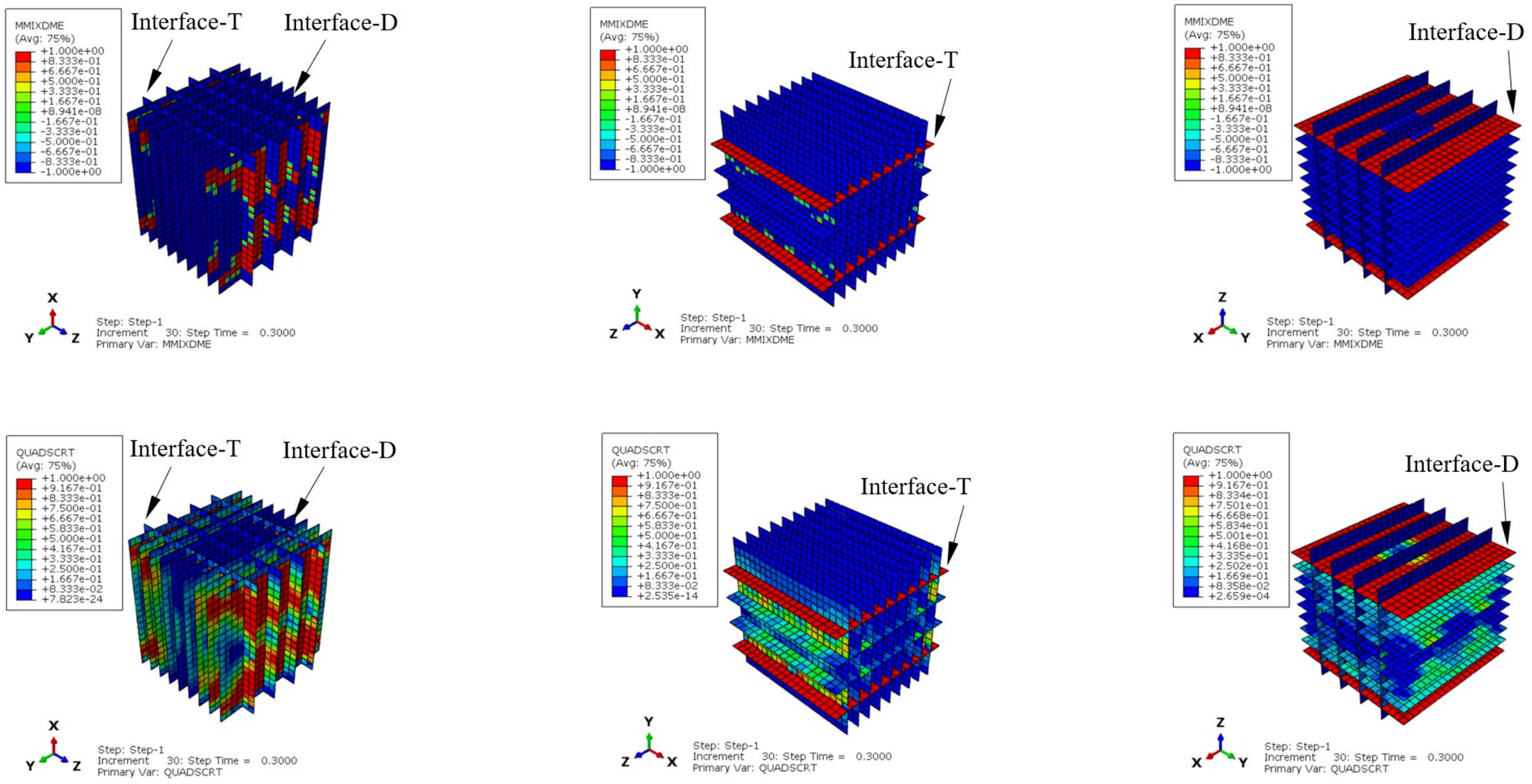
Traction-separation law is used to simulate the binding slip at the interface.

3DPC with RFA – Finite element simulation

Finite element simulation for compressive damage pattern

Mode mix ratio during damage evolution

Interface damage



X-direction loading

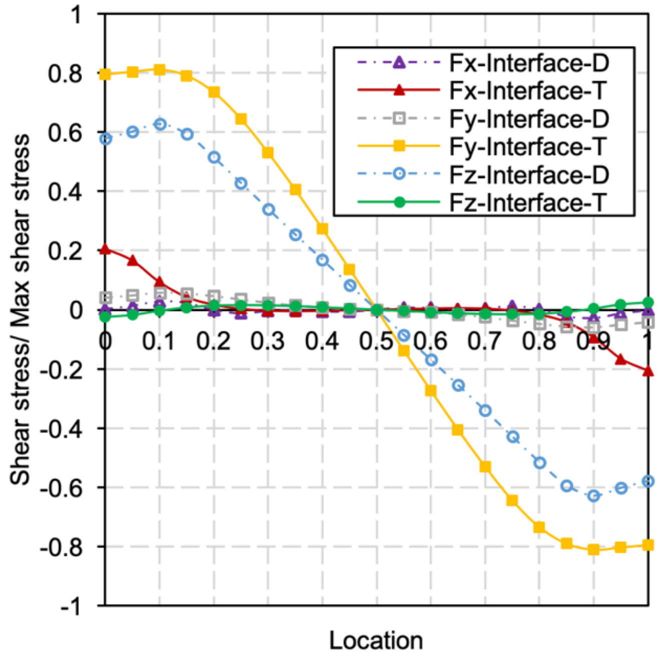
Y-direction loading

Z-direction loading

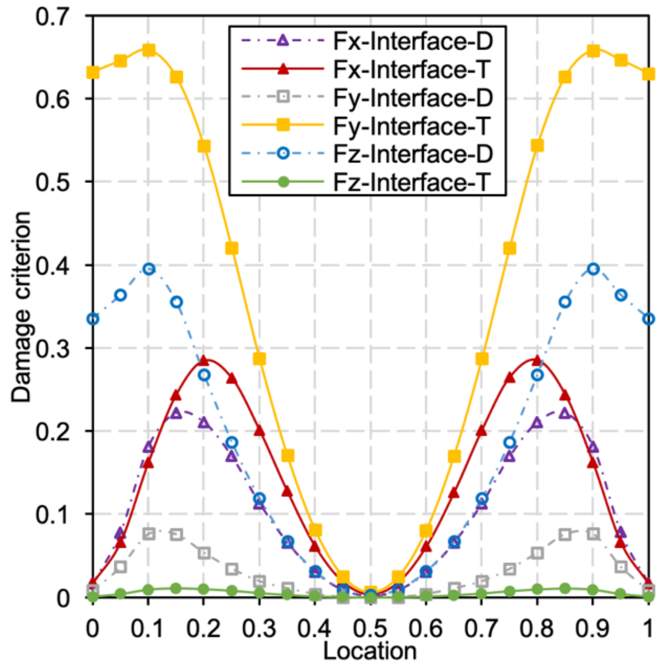
The damage pattern shows that Y and Z are horizontally oriented interfacial shear damage.

3DPC with RFA – Finite element simulation

Stress and damage distribution



Shear stress

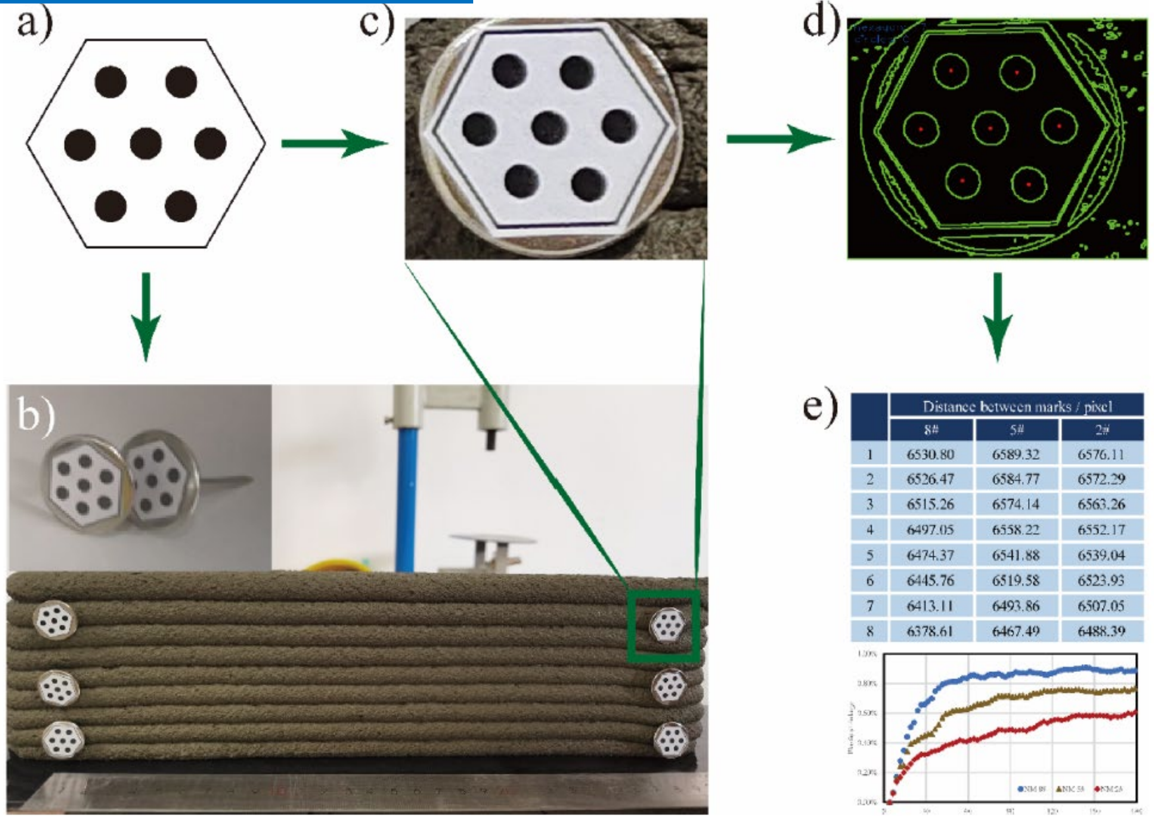


Damage

The shear stress and damage of the Interface-T when loaded in the Y direction is the largest, followed by the Interface-D when loaded in the Z direction and the Interface-T when loaded in the X direction.

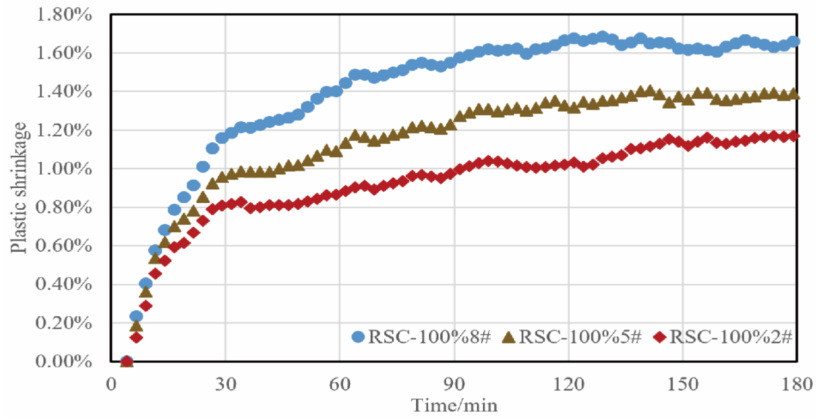
3DPC with RFA - Shrinkage

Plastic shrinkage

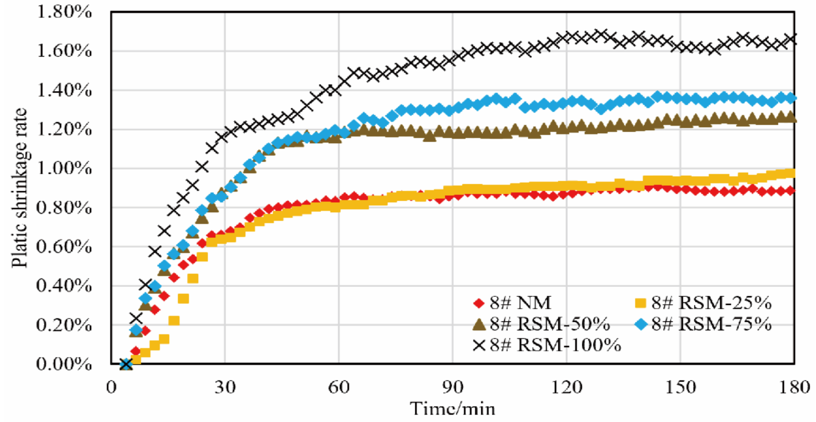


	Distance between marks / pixel		
	8#	5#	2#
1	6530.80	6589.32	6576.11
2	6526.47	6584.77	6572.29
3	6515.26	6574.14	6563.26
4	6497.05	6558.22	6552.17
5	6474.37	6541.88	6539.04
6	6445.76	6519.58	6523.93
7	6413.11	6493.86	6507.05
8	6378.61	6467.49	6488.39

Testing method for plastic shrinkage of 3DPC



Plastic shrinkage of 3DPC in different layers

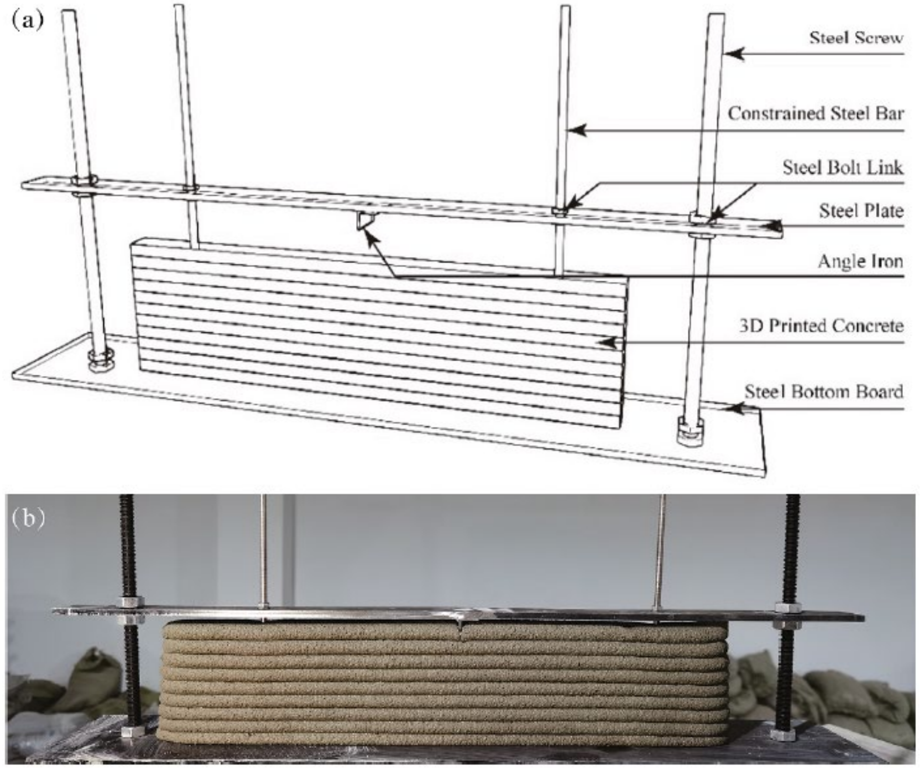


Plastic shrinkage of 3DPC with different RA contents

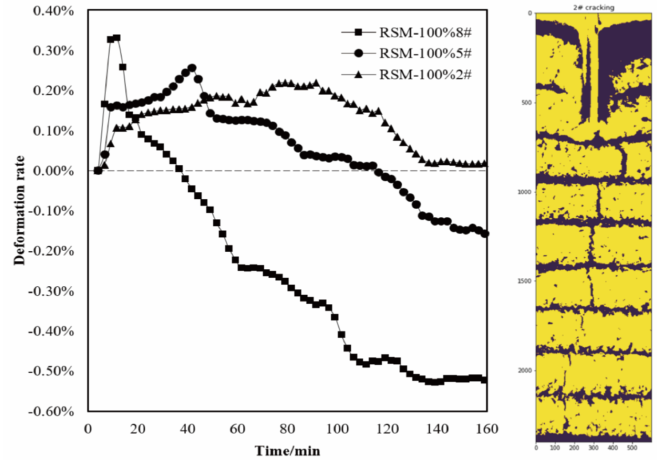
The shrinkage trend of different layers was measured by contactless image recognition method

3DPC with RFA - Shrinkage

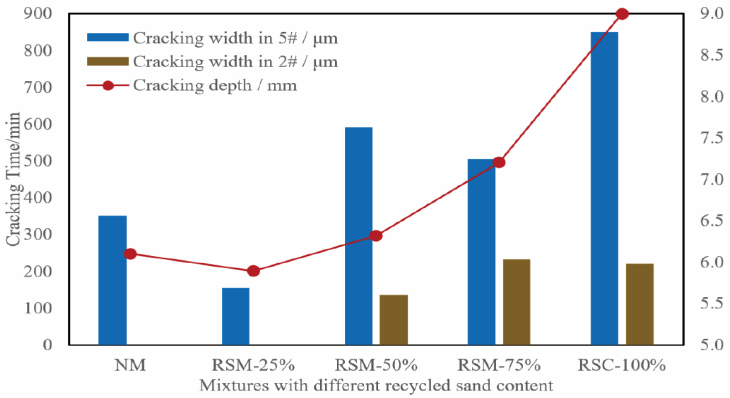
Plastic shrinkage cracking



Testing method for plastic shrinkage cracking of 3DPC



Plastic shrinkage cracking and the length change between the markers

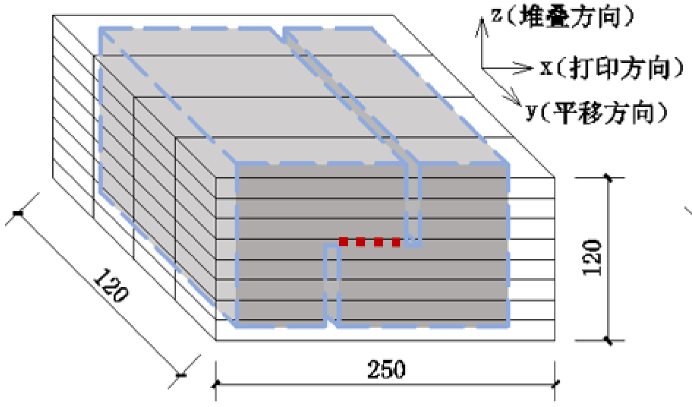


Effects of RA on plastic shrinkage cracking width of 3DPC

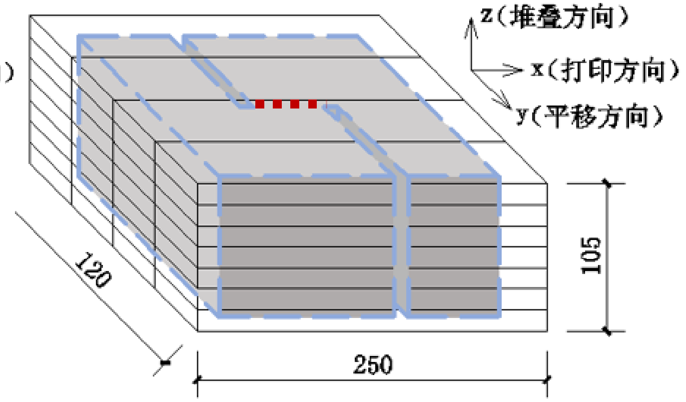
With the increase of RA doping, the plastic shrinkage crack width of 3DPC decreases and then rises

3DPC with RFA – Interface shear strength

Specimen size

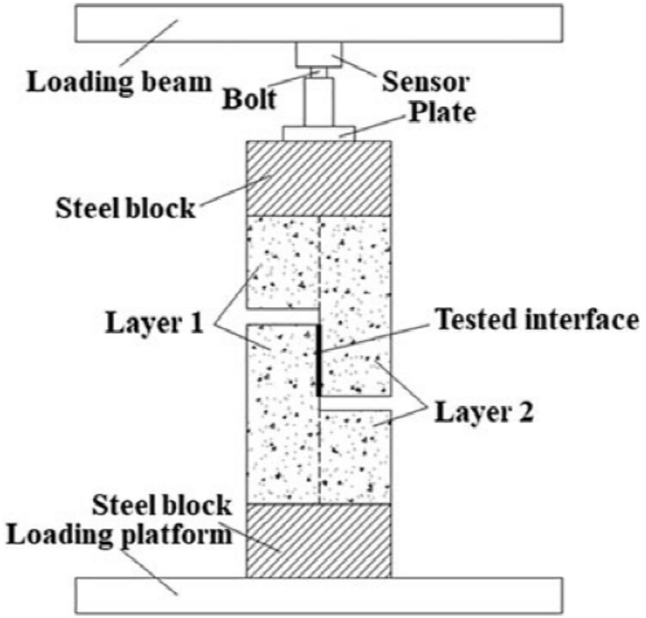


Interlayer interface



Interstrip interface

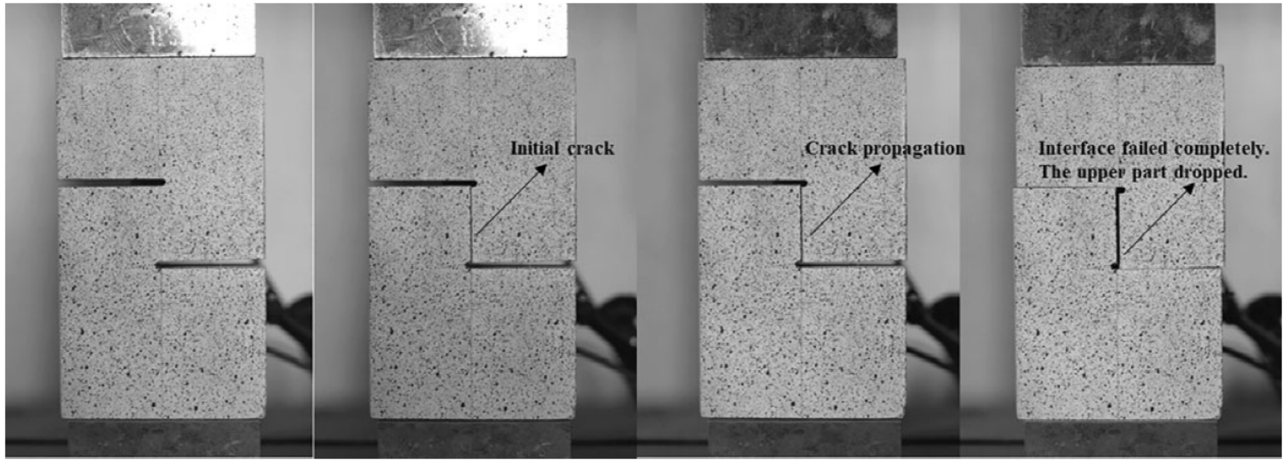
Test set-up



Experimental variables

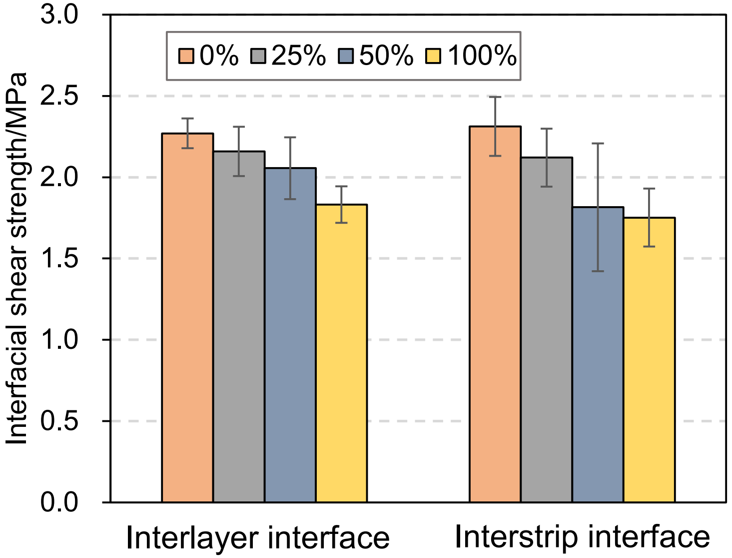
- Replacement ratio of RS（0%, 25%, 50%, 100%）
- Time interval（0, 30min, 60min, 120min）
- Surface treatment（cement paste, epoxy paste, wetting）

Failure pattern

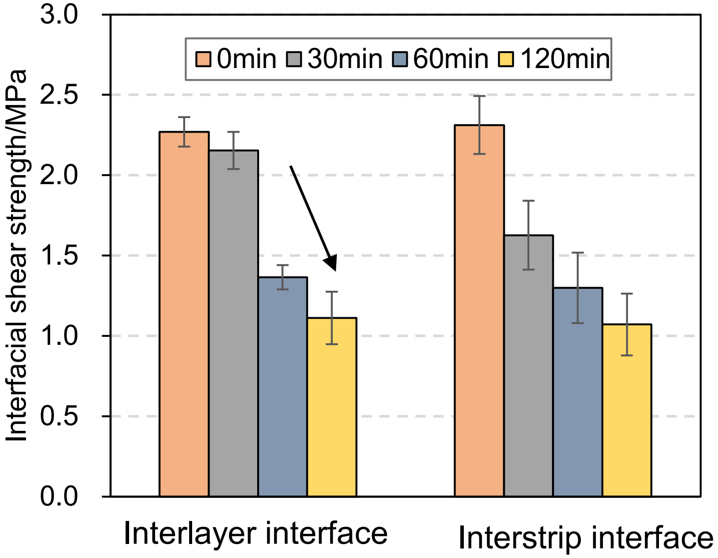


3DPC with RFA – Interface shear strength

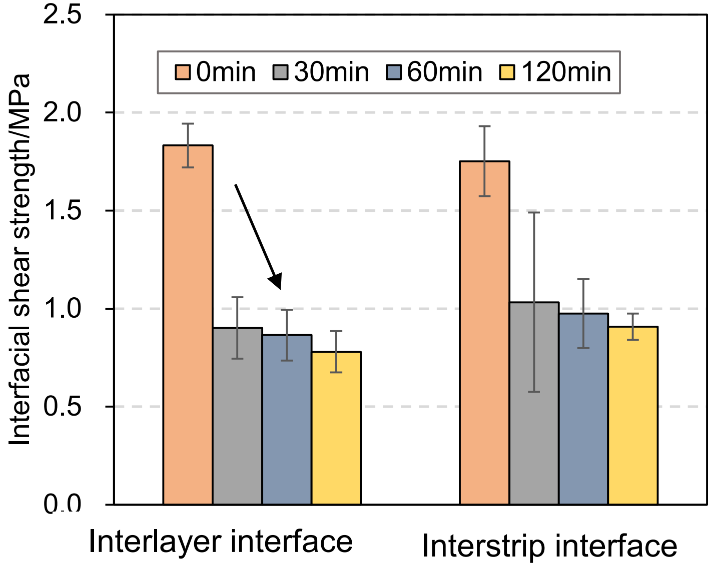
Effect of RS replacement ratio



Effect of time interval



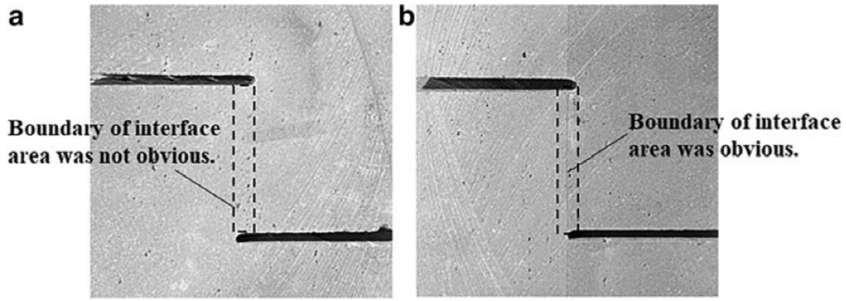
Natural sand



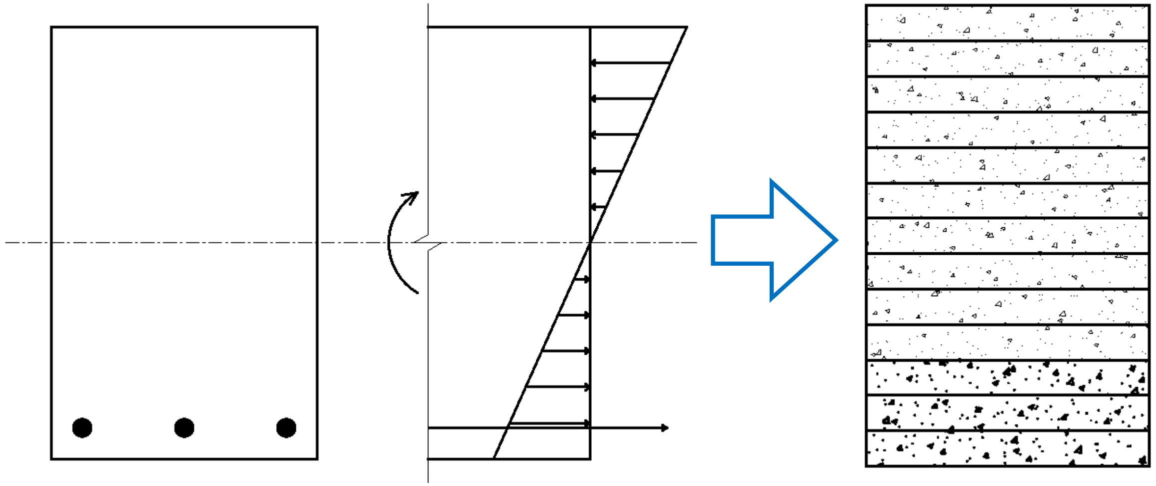
Recycled sand

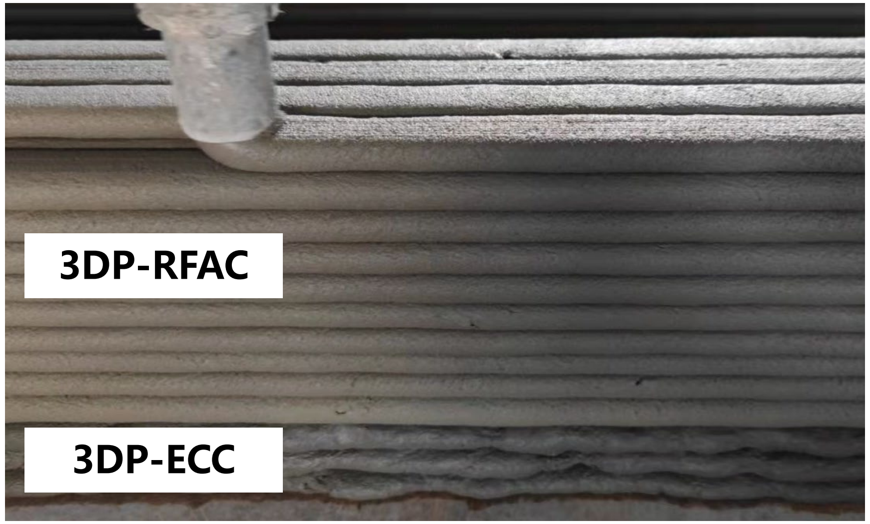
- Interfacial shear strength decreases slightly with the increase of recycled sand replacement ratio.

- Interfacial shear strength decreases significantly with increasing print interval.



3DPC with RFA – composite beam





Mix	OPC	SS	RFA	FA	SF	HPMC	NC	SG	PE	SP	Water
RFAC	1000	-	1000	-	-	1.28	5.63	0.7	-	0.9	485
ECC	656	604	-	118	246	-	-	-	15	3	275

Fibre type	Length (mm)	Diameter (μm)	Tensile strength (GPa)	Elastic modulus (GPa)	Density (g/cm³)
PE	12	20	2.9	116	0.97

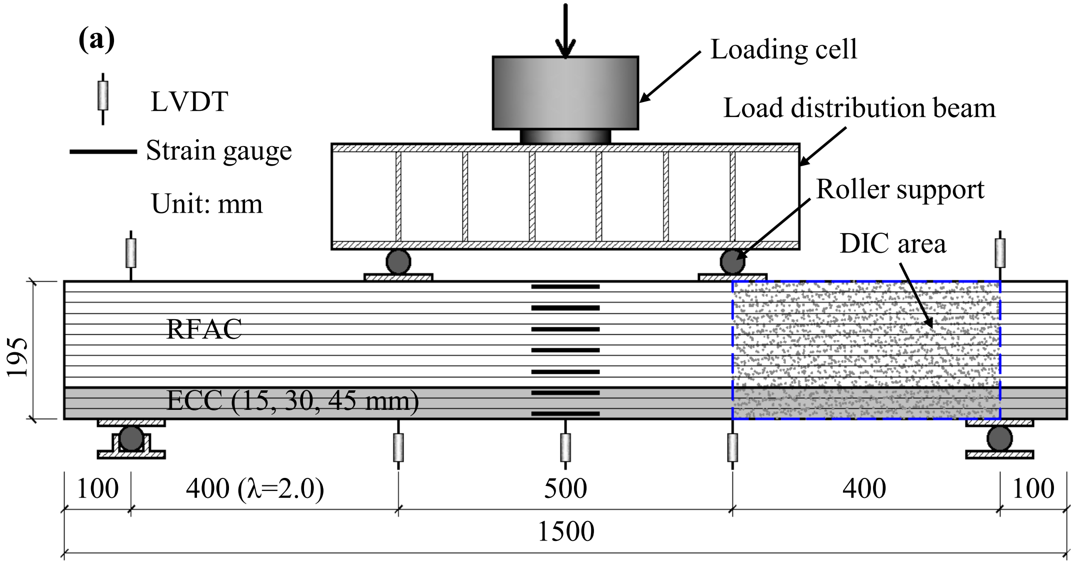
- ECC high tensile strength was combined with recycled fine aggregate concrete to manufacture 3D-printed concrete composite beams.

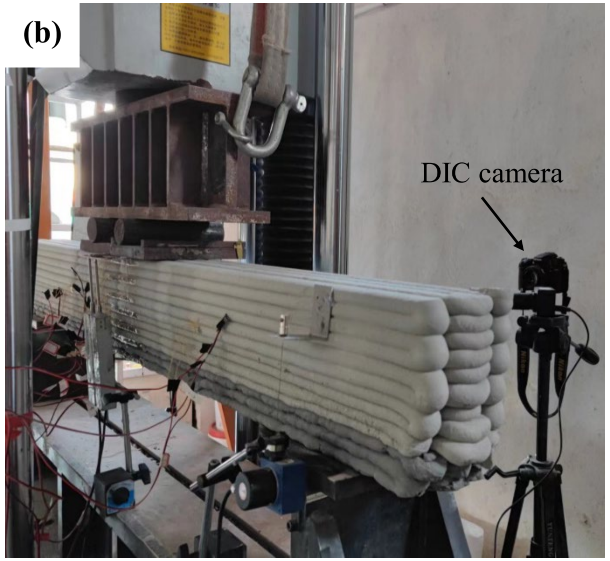
➢ Liu H, Xiao J, Ding T. Engineering Structures, 2023, 283: 115865.

3DPC with RFA – composite beam

Specimen design

Specimen ID	ECC height (mm)	Shear-span ratio
B-15-2.0	15	2.0
B-15-2.5		2.5
B-15-3.0		3.0
B-30-2.0	30	2.0
B-30-2.5		2.5
B-30-3.0		3.0
B-45-2.0	45	2.0
B-45-2.5		2.5
B-45-3.0		3.0



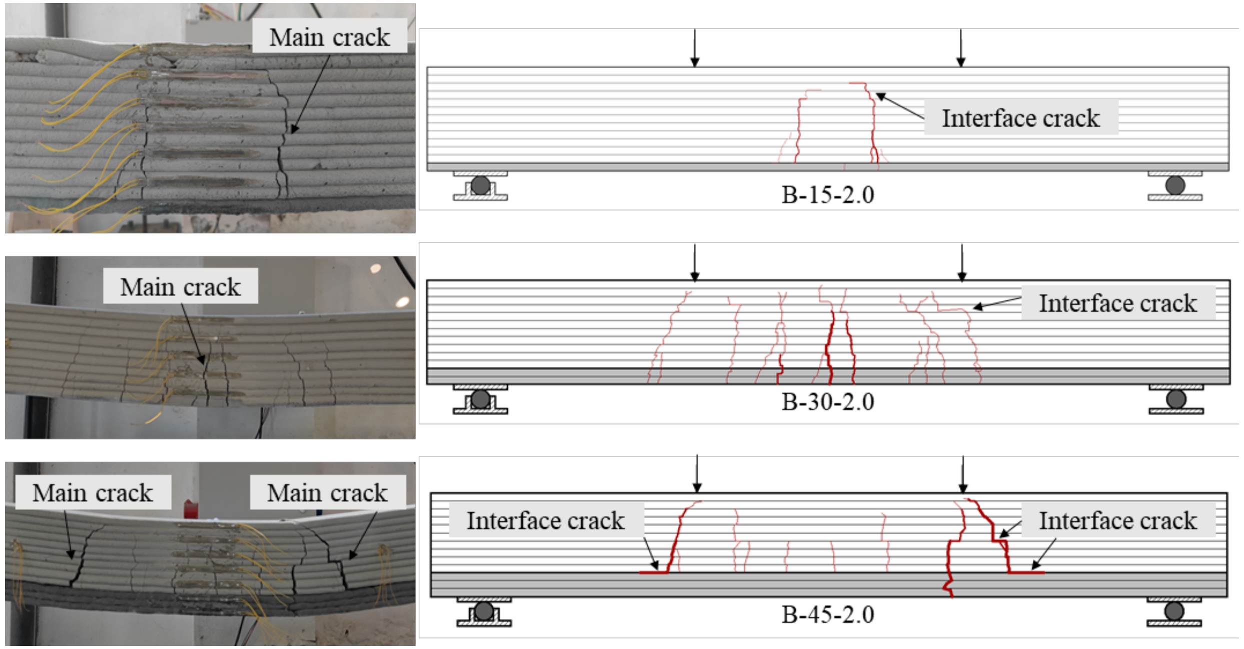


- Nine 3D-printed composite beams were designed for this experiment.
- The variables included shear-span ratios λ (2.0, 2.5, and 3.0) and ECC heights (15, 30, and 45 mm).

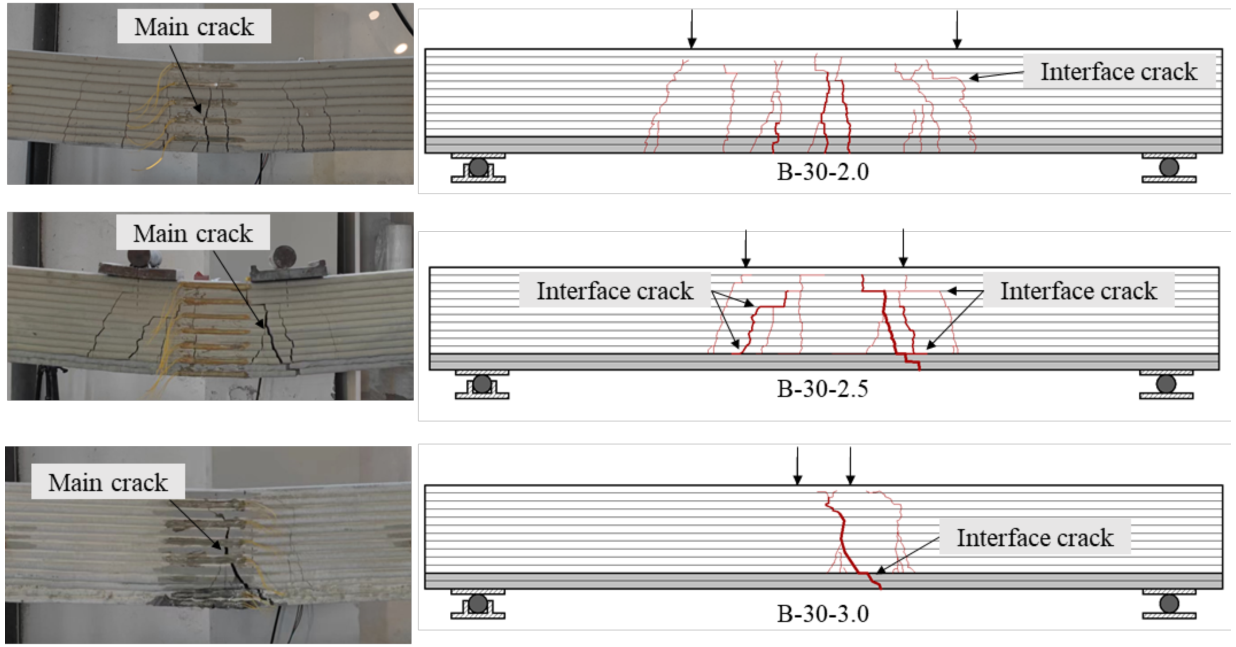
➢ Liu H, Xiao J, Ding T. Engineering Structures, 2023, 283: 115865.

3DPC with RFA – composite beam

Crack patterns



Different ECC heights



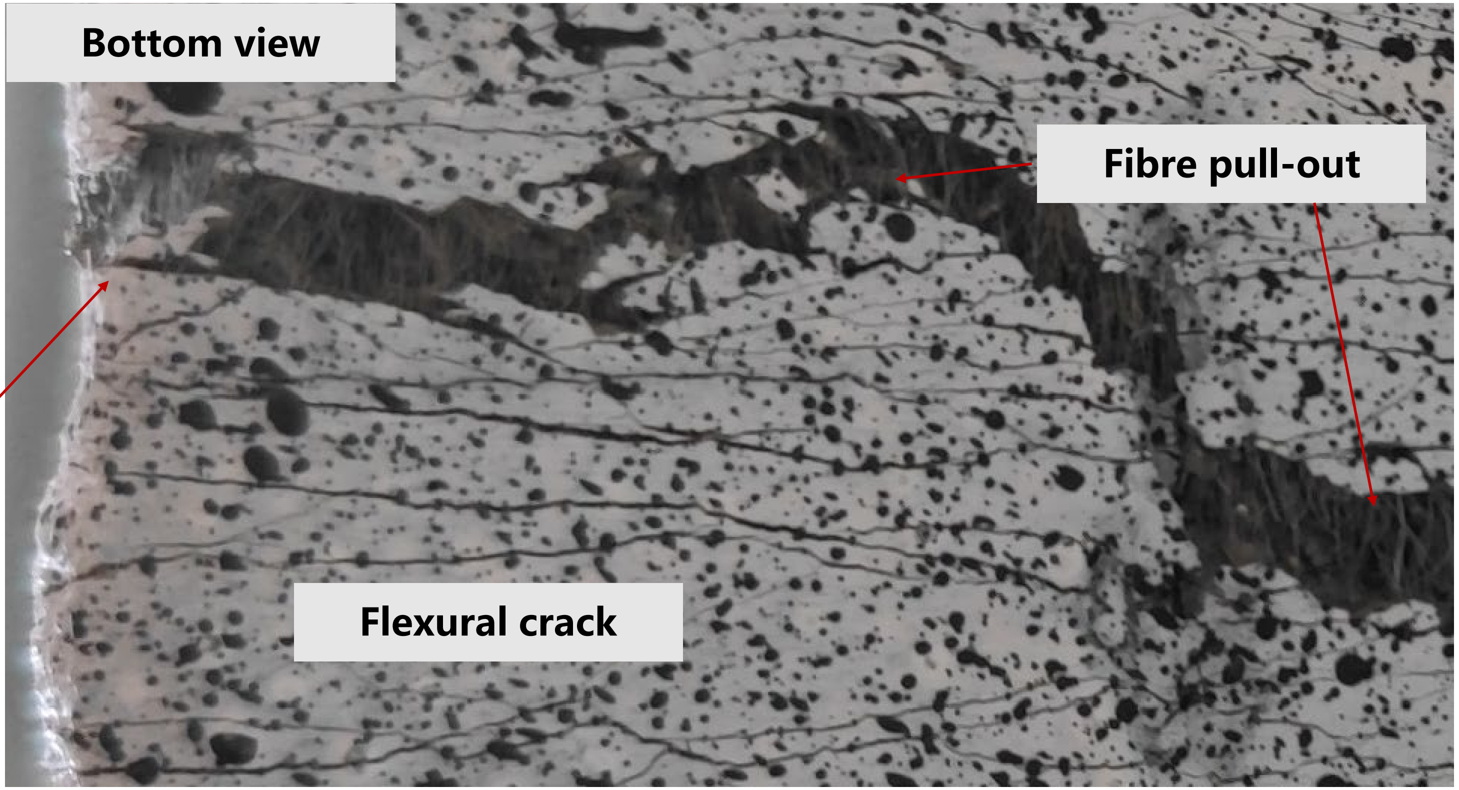
Different shear-span ratios

- ☐ The majority of crack types were flexural cracks.
- ☐ The distribution of cracks gradually increased with an increase in ECC height and a decrease in shear-span ratio.

➢ Liu H, Xiao J, Ding T. Engineering Structures, 2023, 283: 115865.

3DPC with RFA – composite beam

Crack patterns

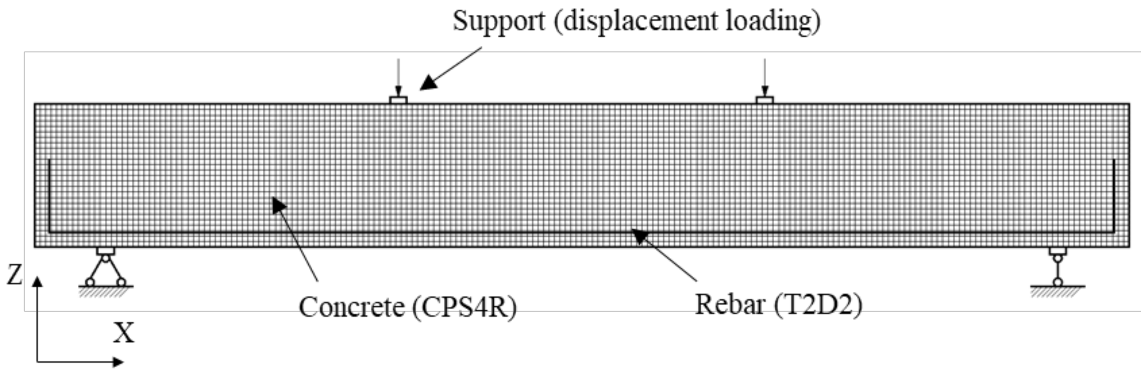


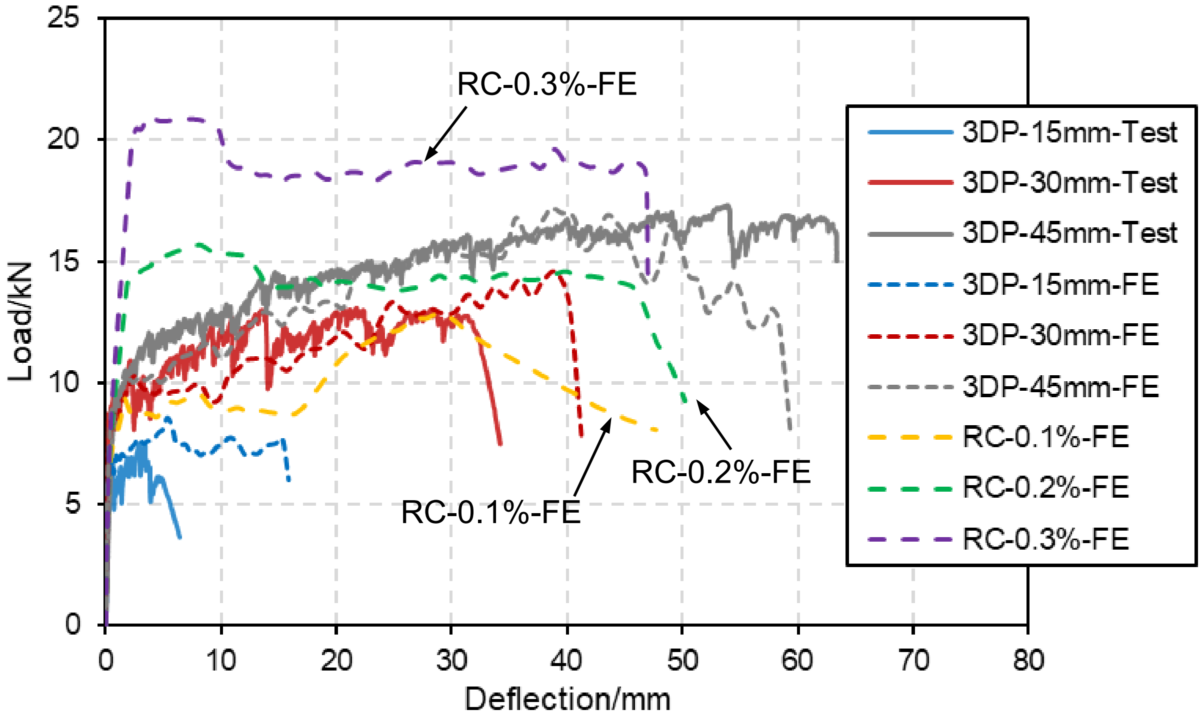
- The fiber bridging effect can be observed at the location of the main crack of the ECC.

➢ Liu H, Xiao J, Ding T. Engineering Structures, 2023, 283: 115865.

3DPC with RFA – composite beam

Comparison with RC beams



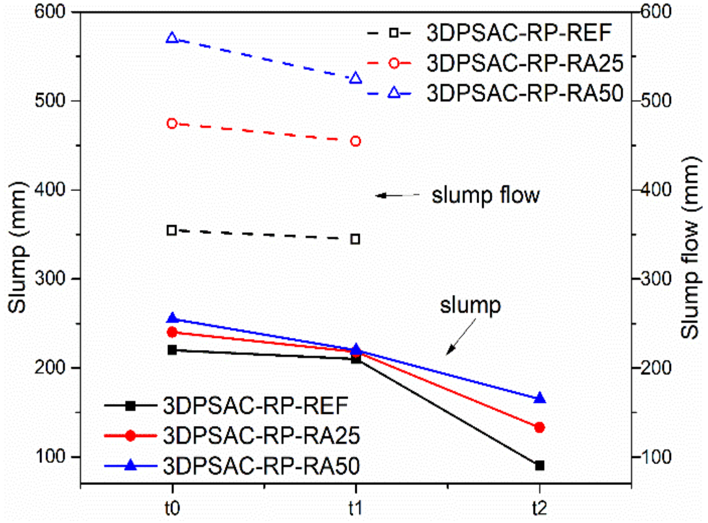


- Three reinforcement rates of 0.1-0.3% of cast-in-place RC beams were considered.
- Steel bars are of HRB335 grade with yield tensile strength of 335 MPa, ultimate tensile strength of 455.
- The load carrying capacity and deformation capacity of the 3D-printed composite beams (ECC heights of 30 and 45 mm) can be equivalent to that of a RC beam with a reinforcement ratio of 0.2%, which meets the lower limit of the reinforcement ratio requirement for RC beams in the design code.

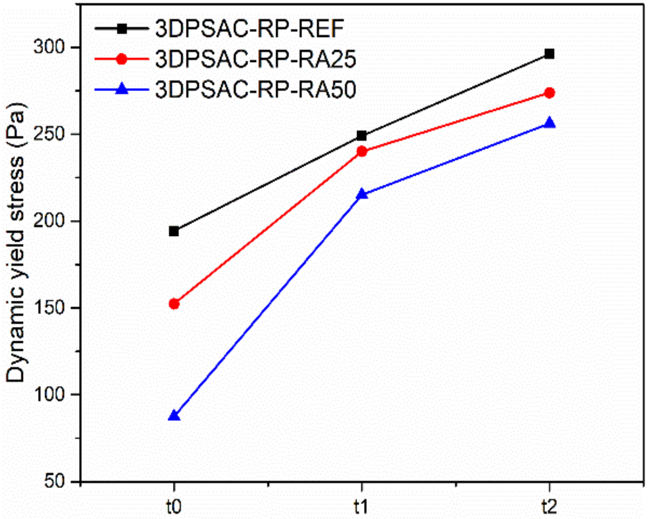
➢ Liu H, Xiao J, Ding T. Engineering Structures, 2023, 283: 115865.

3DPC with RCA - Rheology

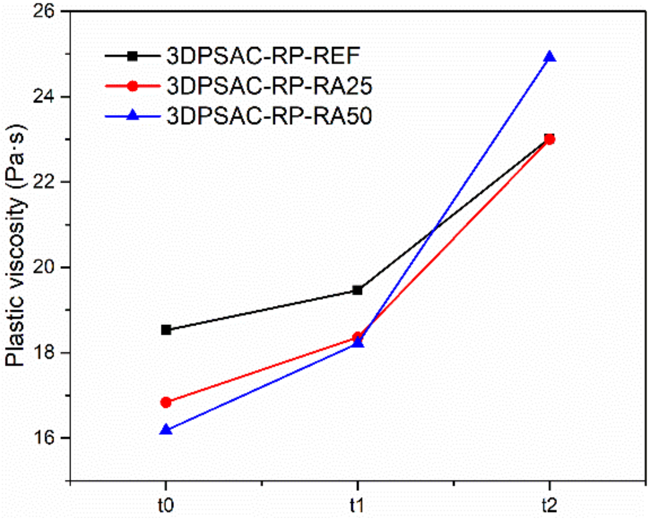
Rheology regulation during secondary mixing



Collapse and expansion



Dynamic yield stress



Plastic viscosity

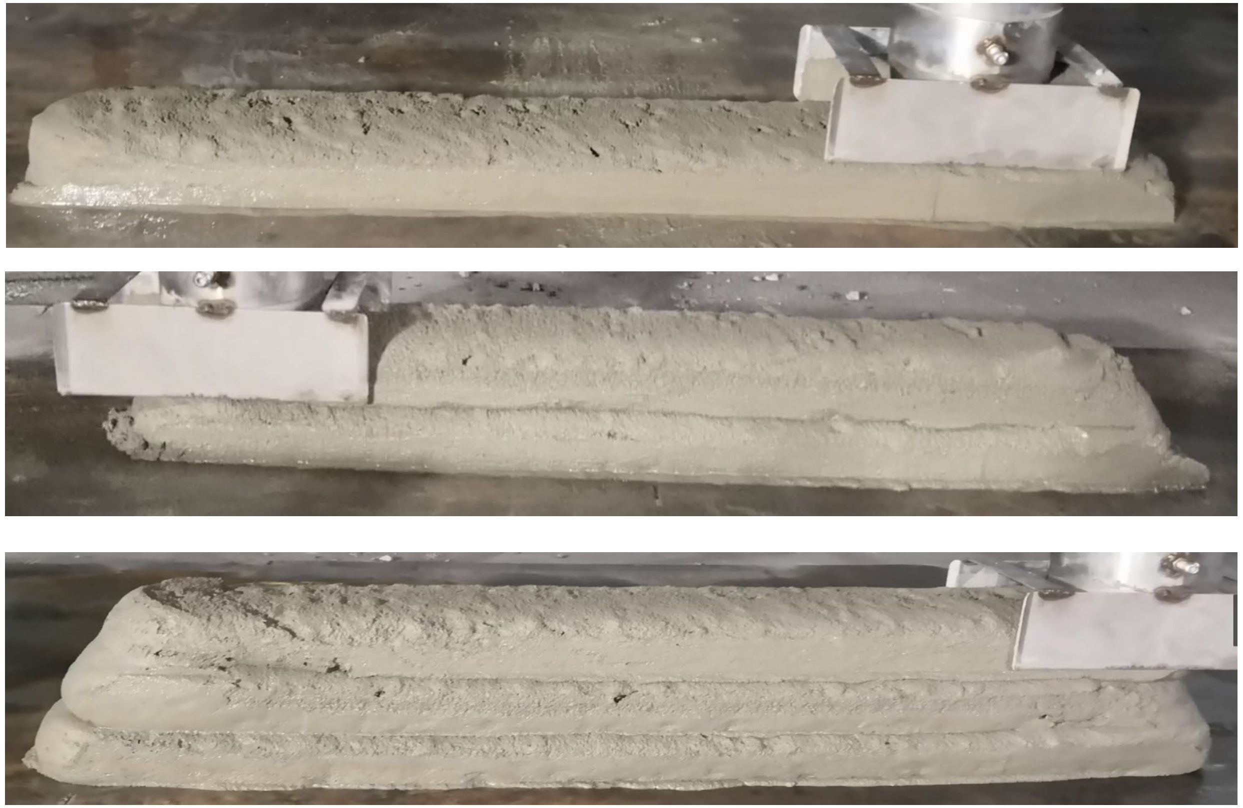
Degree of variation of rheological parameters

	Dynamic yield stress			Plastic viscosity		
	3DPSAC-RP-REF	3DPSAC-RP-RA25	3DPSAC-RP-RA50	3DPSAC-RP-REF	3DPSAC-RP-RA25	3DPSAC-RP-RA50
t0-t1	28.00%	57.58%	146.15%	5.02%	9.03%	12.61%
t1-t2	18.87%	14.11%	19.08%	18.29%	25.27%	36.77%

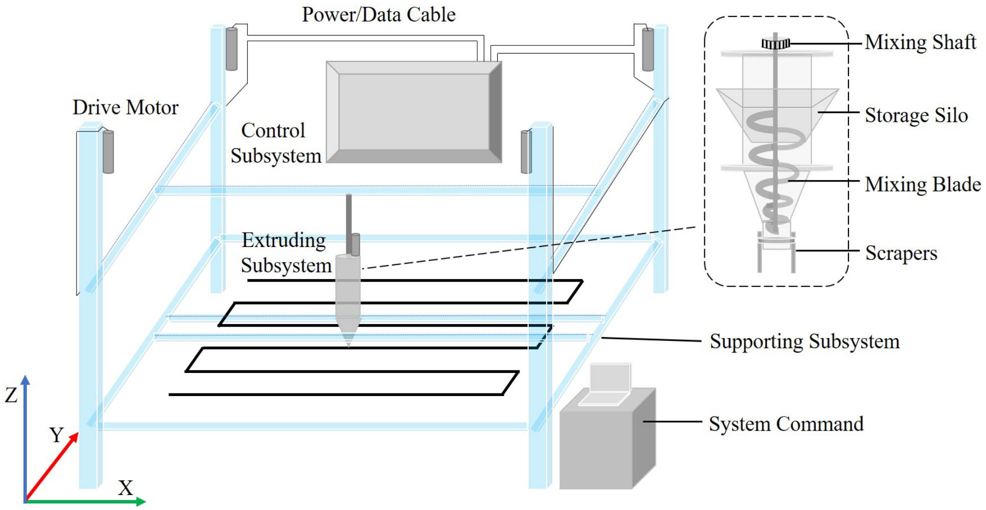
The higher the RCA replacement ratio, the greater the increase in dynamic yield stress of concrete during resting, with an increase of 28%-146%

3DPC with RCA - Printability

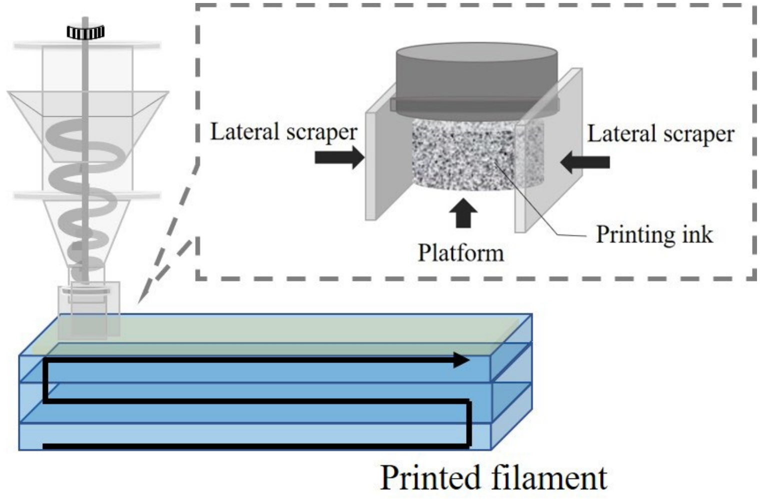
Extrudability



Coarse aggregate concrete ink print status



3D printer system



Print ink stacking path

Tests show good extrudability of concrete inks mixed with coarse aggregates

3DPC with RCA - Printability

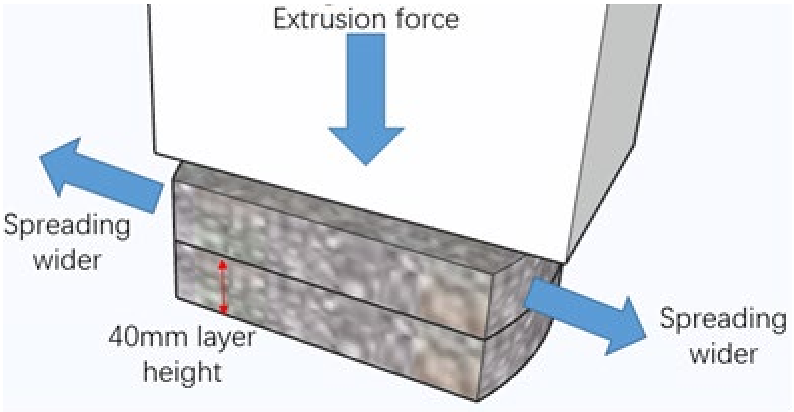
Buildability

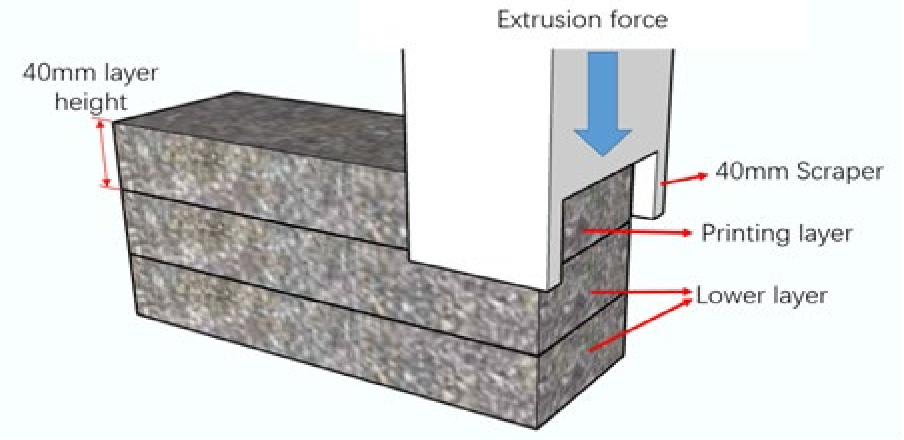
Analysis: the pressure on the printed layer can be expressed as:

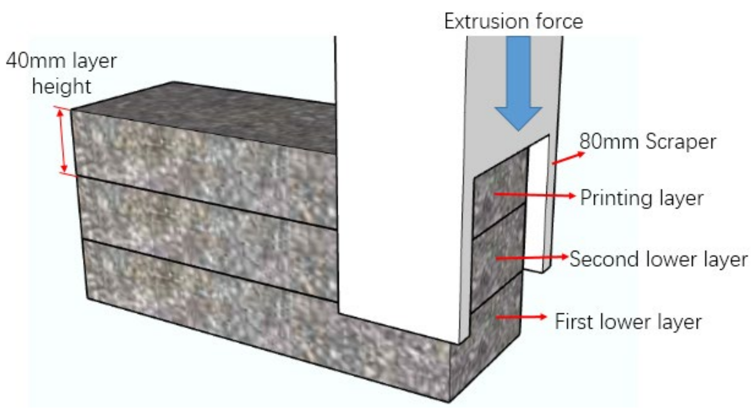
$$P = W + F \times \cos\theta$$

where P is the vertical pressure on the printed layer, W is the weight of the upper layer, F is the extrusion force, θ is the angle bend of the nozzle in the vertical direction.

- $\cos\theta=0$ for the horizontal nozzle system. In contrast, $\cos\theta=1$ for the vertical nozzle system. The pressure on the printed concrete is sum of the upper-layer weight and the vertical extrusion force.



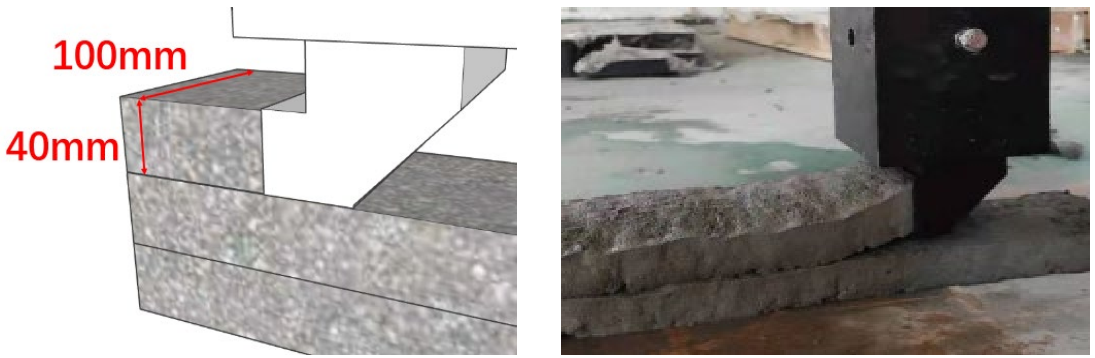




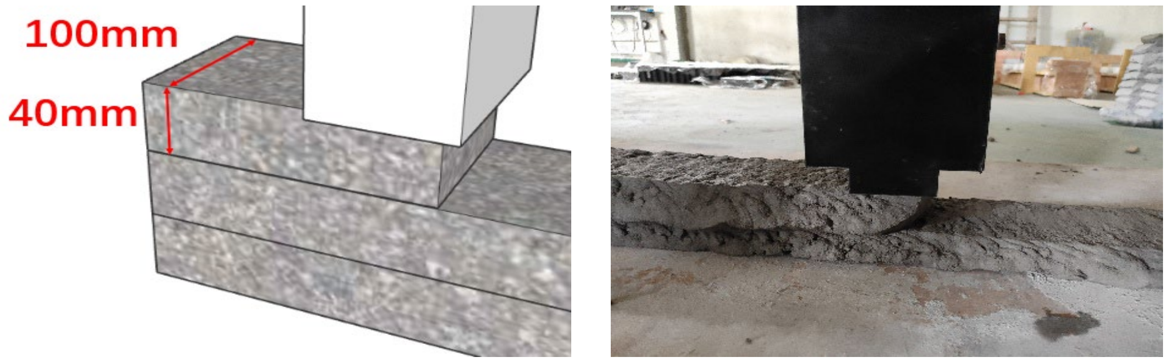
Scraper could prevent the printed concrete from spreading wider, and concrete ink is compacted by scraper

3DPC with RCA - Printability

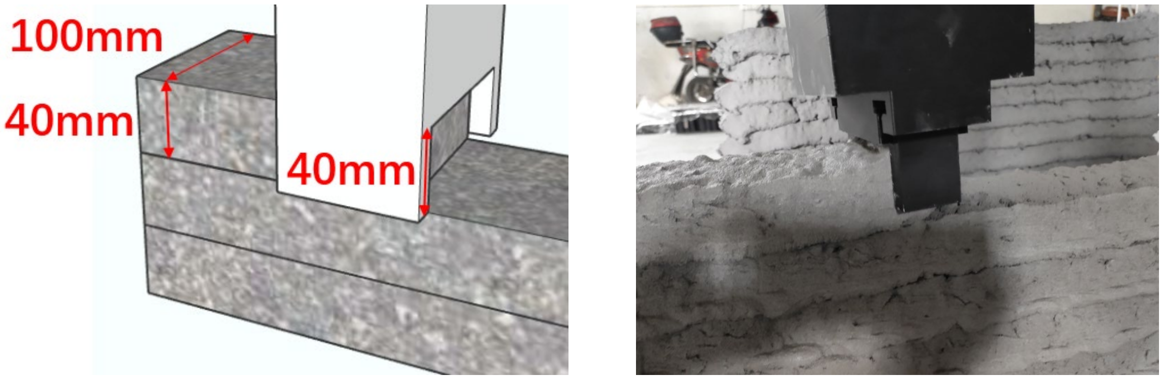
Effects by printer nozzle type



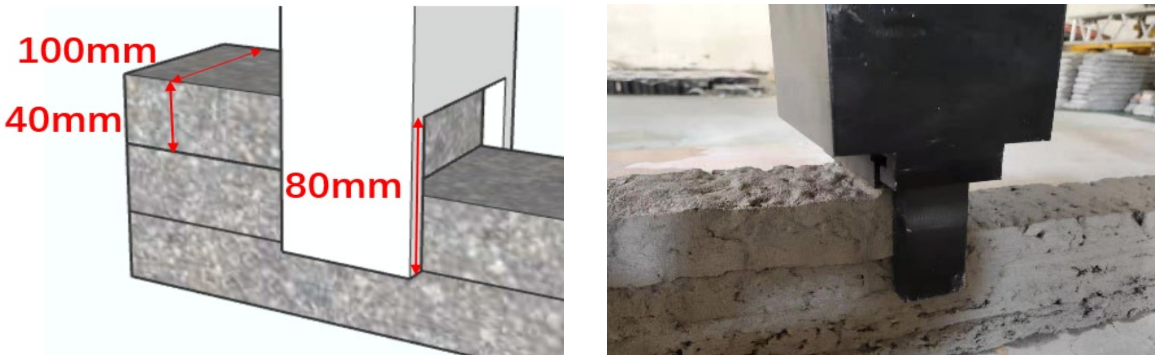
a) Horizontal nozzle (HN)



b) Vertical nozzle (VN)



c) Vertical nozzle with 40mm scraper (VN-40S)

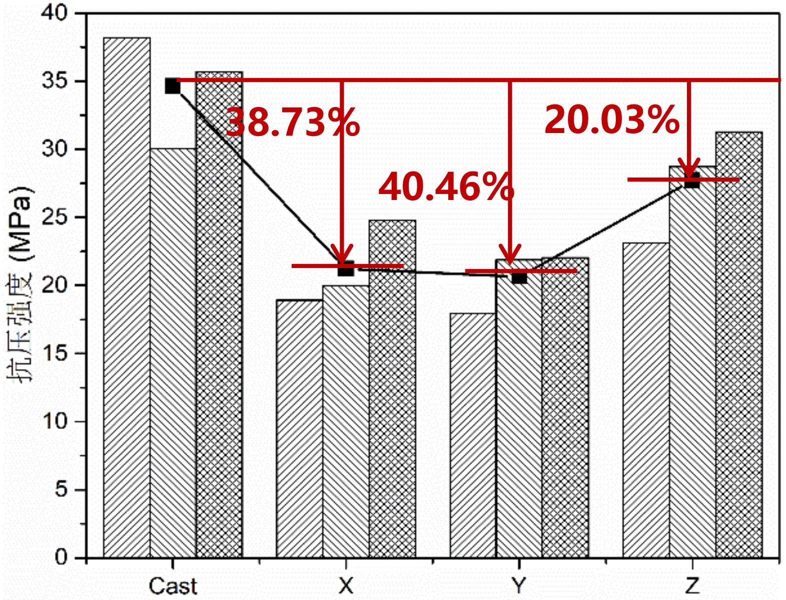


d) Vertical nozzle with 80mm scraper (VN-80S)

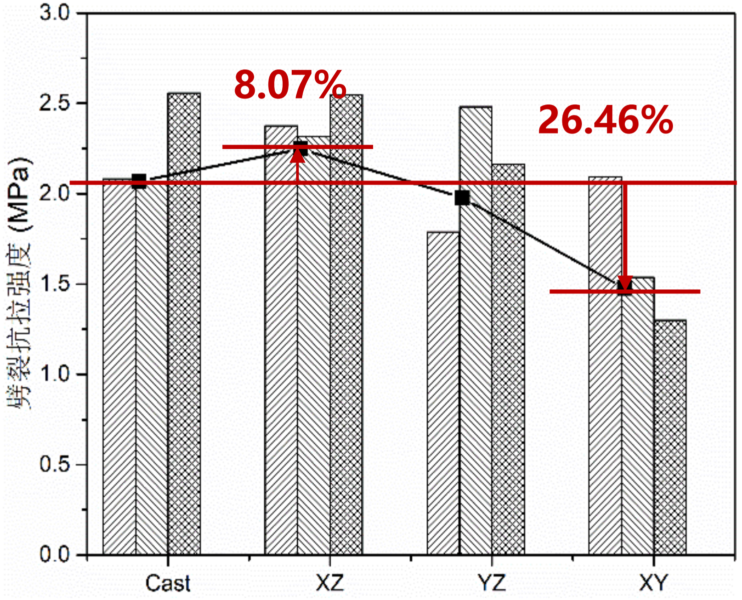
Nozzle direction and scraper could also affect buildability and anisotropy mechanical properties

3DPC with RCA – Hardened mechanical properties

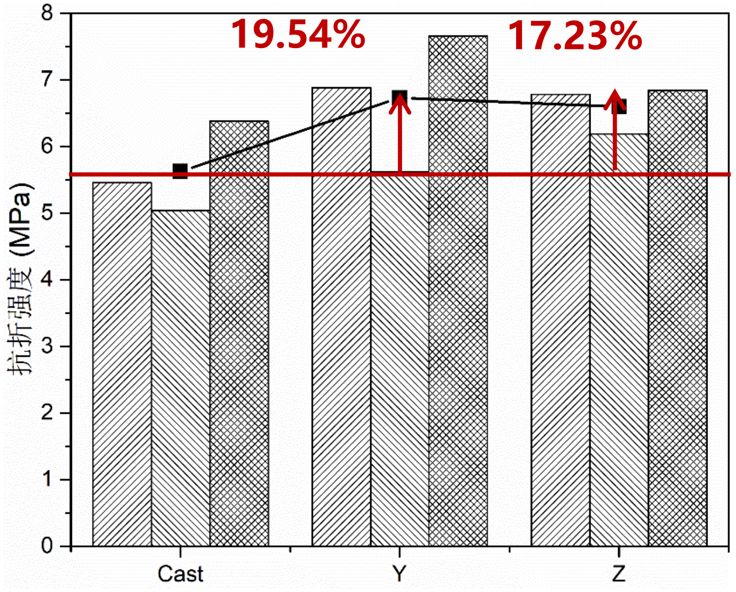
Anisotropic mechanical properties at 28d



Compressive strength

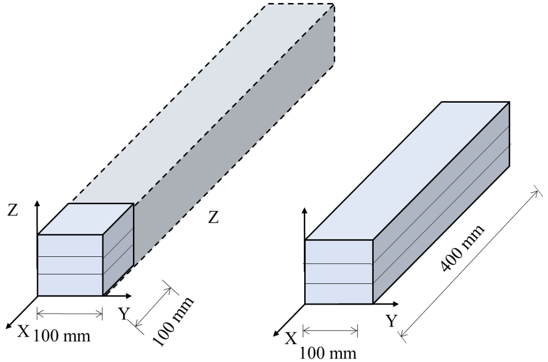


Splitting tensile strength

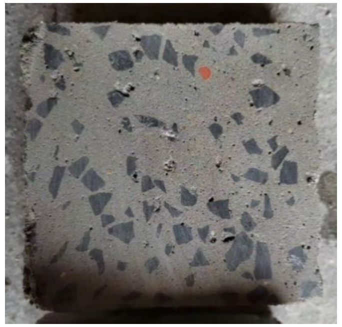


Flexural strength

Compared with the cast group, the compressive strength loss in the X-axis and Y-axis directions was significant, 38.73% and 40.46%, respectively



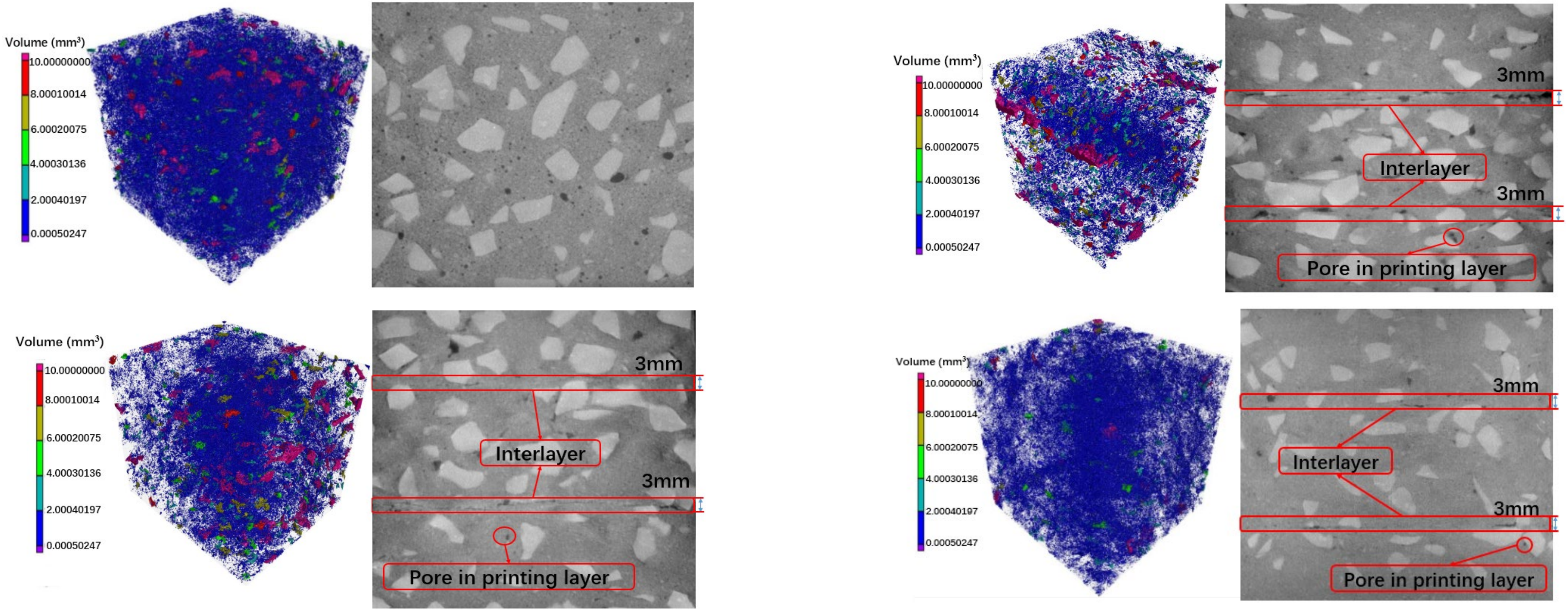
28-day sample



Sample features

3DPC with RCA – Microstructure

Characteristics of pore structure by X-CT



Interlayer and pore structure distribution characteristics of each group of 3DPC specimens

Scraper could reduce porosity of 3DPC and longer scraper performs better
Scraper could reduce the interlayer porosity of 3DPC
Scraper could reduce the percentage of large size pores (>10 mm^3)

3DPC with RCA

Secondary mixing of ready-mix concrete

Ready-mix concrete

Concrete mixing plant

Secondary mixing materials

Secondary mixing container

3D printed concrete

Construction site

Preparation process

Concrete preparation

Transportation

Secondary mixing

Secondary transfer

Concrete printing

scientific issues

Moderate yield stress, low plastic viscosity and thixotropy, low rheology changes with time

Rheological regulation

High yield stress, plastic viscosity and thixotropy, moderate open time

The method uses small coarse aggregate concrete as the basic material and does not require significant adjustments to existing concrete preparation, facilitating the promotion of high-volume applications of 3DPC

3DPC with RCA – Engineering application

- A 6-story apartment house with a total floor area of 3596 m^2 has been completed in Hebei Province, using 3D-printed recycled coarse aggregate concrete in conjunction with the large-scale columnar printer, multifunctional print head and wall leveling system.

Outline

1. Background
2. 3DPC with Recycled Powder
3. 3DPC with Recycled Fine Aggregate
4. 3DPC with Recycled Coarse Aggregate
5. Conclusion

Conclusion

- The incorporation of recycled powder can enhance the printability of 3DPC and can partially replace the gelling material to highlight the low carbon property of 3DPC.
- The high water absorption of recycled fine aggregates can enhance the buildability of the ink, which can be scientifically regulated to reduce its negative impact on the shrinkage performance of the ink.
- The use of recycled coarse aggregates enhances 3DPC printability and optimizes performance through the application of admixtures and nozzle scrapers to achieve mechanical properties that meet engineering applications.

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Thank you for your comments!

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