Practical Consideration of Concrete 3D Printing Technology in Culvert Manufacturing

Alireza Hasani

Graduate Research Assistant, Department of Civil Engineering, University of North Dakota, Grand Forks, North Dakota. alireza.hasani@und.edu

Sattar Dorafshan

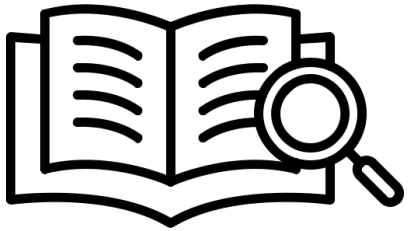
Assistant professor, Department of Civil Engineering, University of North Dakota, Grand Forks, North Dakota. sattar.dorafshan@und.edu

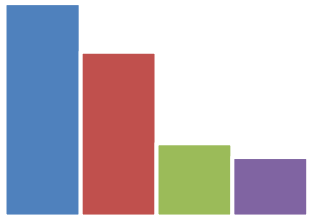
Marc Maguire

Associate professor, Durham School of Architectural Engineering & Construction, University of Nebraska Lincoln, Lincoln, Nebraska. marc.maguire@unl.edu

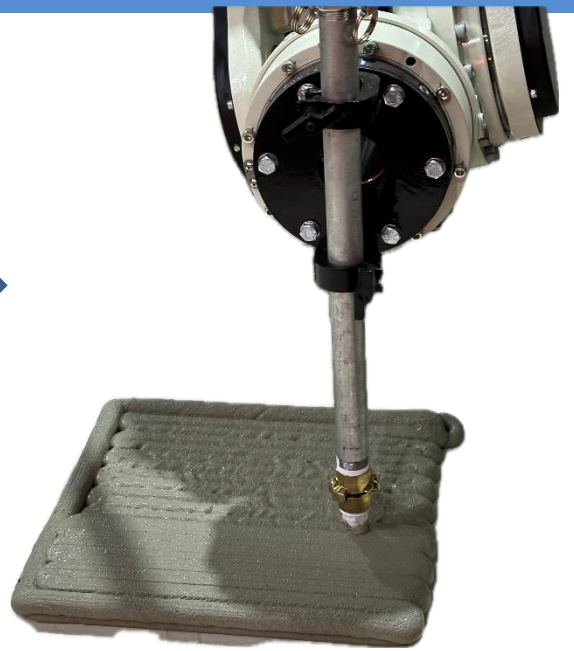
Graphical Abstract

Literature Review





Case Studies



3DCP

Buried Structures

It Works

Introduction

❑Transforming the Construction Industry?

No substantial advancements in construction industry

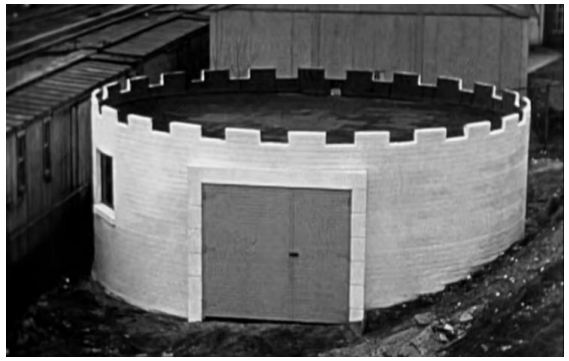
Additive Manufacturing

3D Concrete Printing (3DCP)

❑ How old is the technology?

- Urschel's wall building machine, patented in 1944






1944

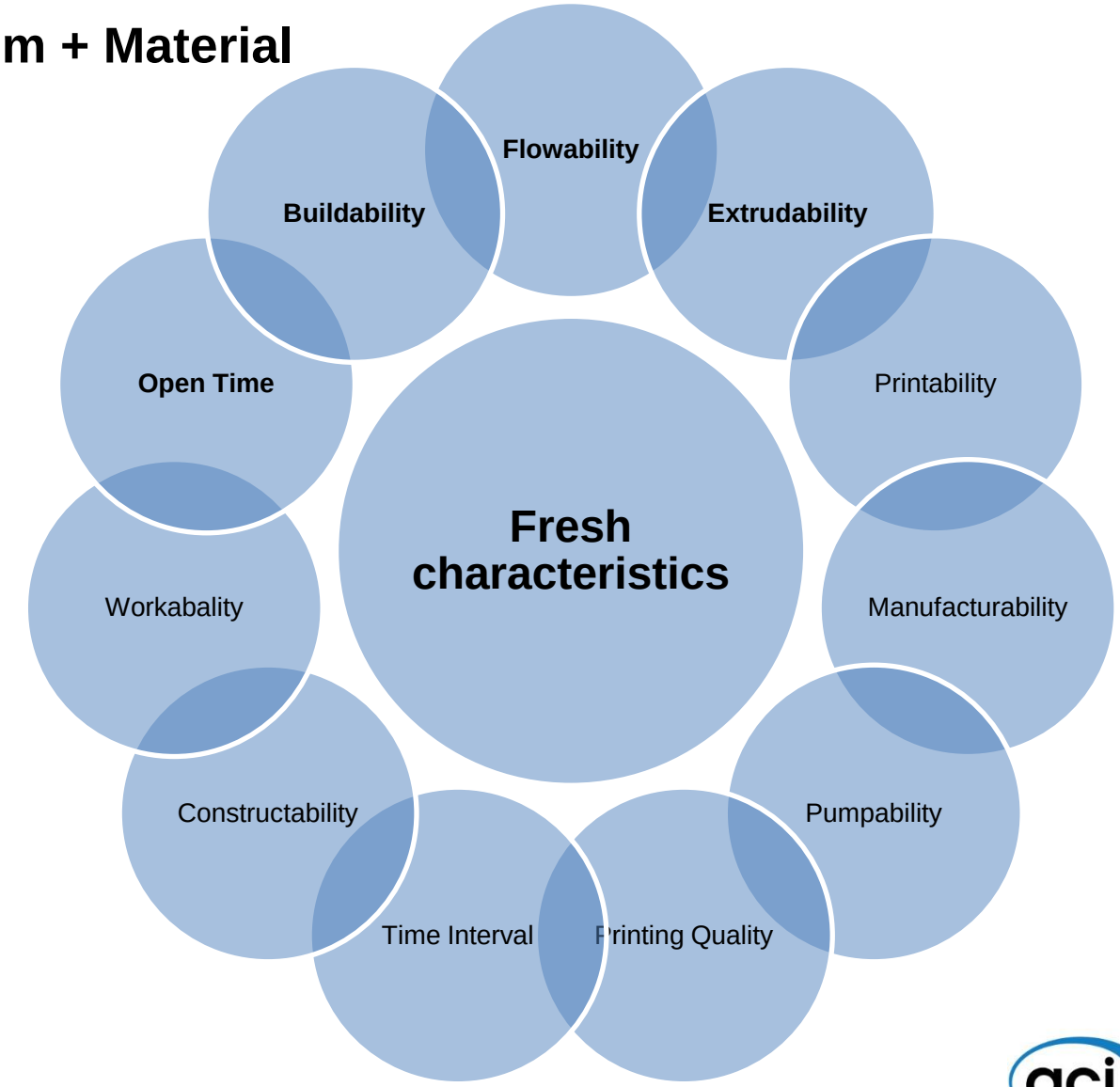
2023

❑ **Main components: System + Material**

❑ **Material Selection**

❖ Fresh characteristics

- More challenging



- Mix design:
  - w/b more important than additives.
  - More paste-like compared to typical mortar.

	w/b					s/b					
ratio	w/b< 0.2	0.2< w/b< 0.3	0.3< w/b< 0.4	0.4< w/b< 0.5	0.5< w/b	s/b< 0.5	0.5< s/b< 1.0	1.0< s/b< 1.5	1.5< s/b< 2.0	2.0< s/b< 2.5	2.5< s/b
Frequency (%)	0.3	23.3	37.5	17.7	11.2	4.3	10.8	41.5	19.8	21.2	2.4

❖ Mechanical characteristics

- Anisotropic ?

✓ Printing quality

Good printing quality

Poor printing quality

✓ Time interval: Gap time to print on another deposited filament.

- Benefits
  - Overview of 3DCP benefits compared to CIP

Total Cost	• 10 – 50 %	Construction Time	• 54 – 95 %
Workforce Need	• 50 – 80 %	Waste	• 30 – 60 %
Workforce Cost	• 45 – 60 %	Emissions	• 20 %
Material Use	• 20 – 76 %	Weight	• 0 %

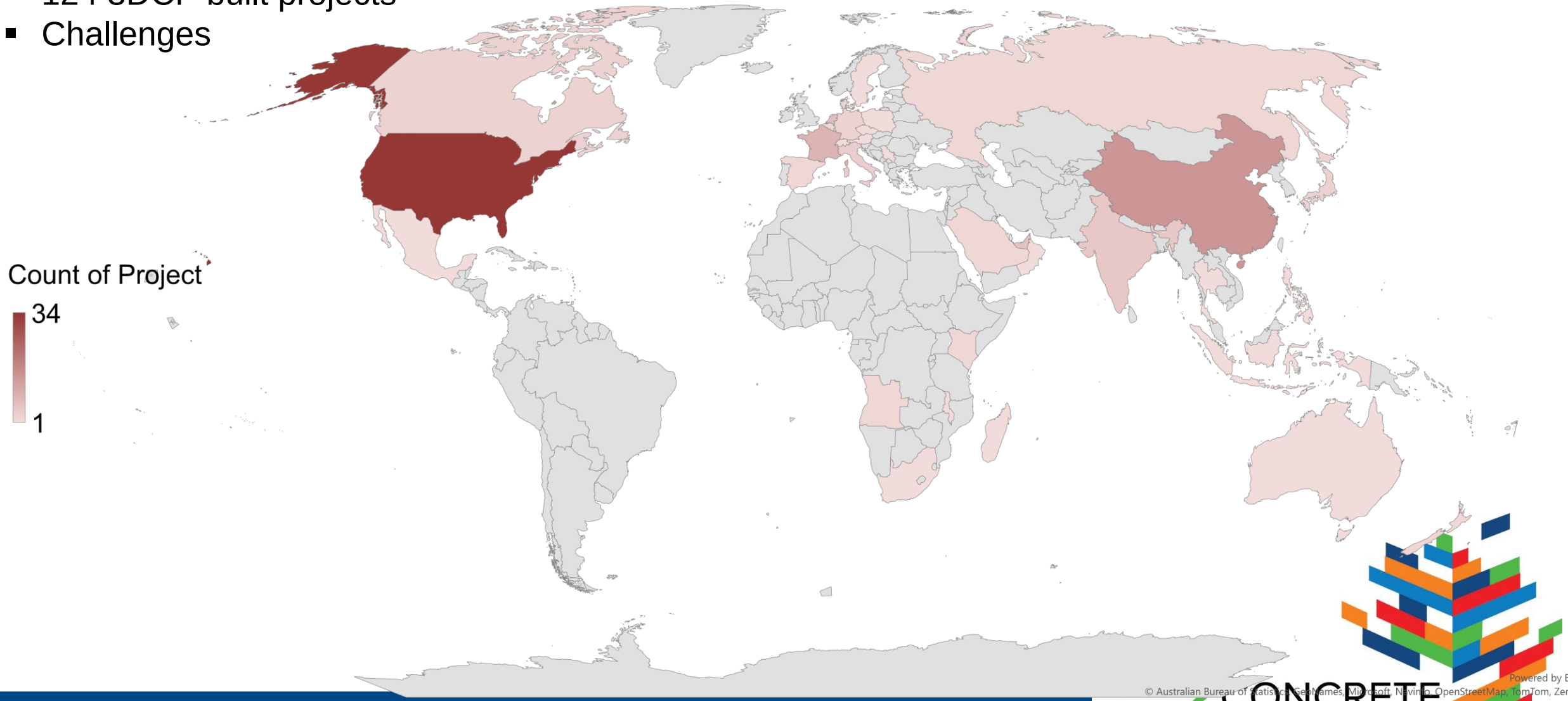
❖ Challenges

- Code compliance

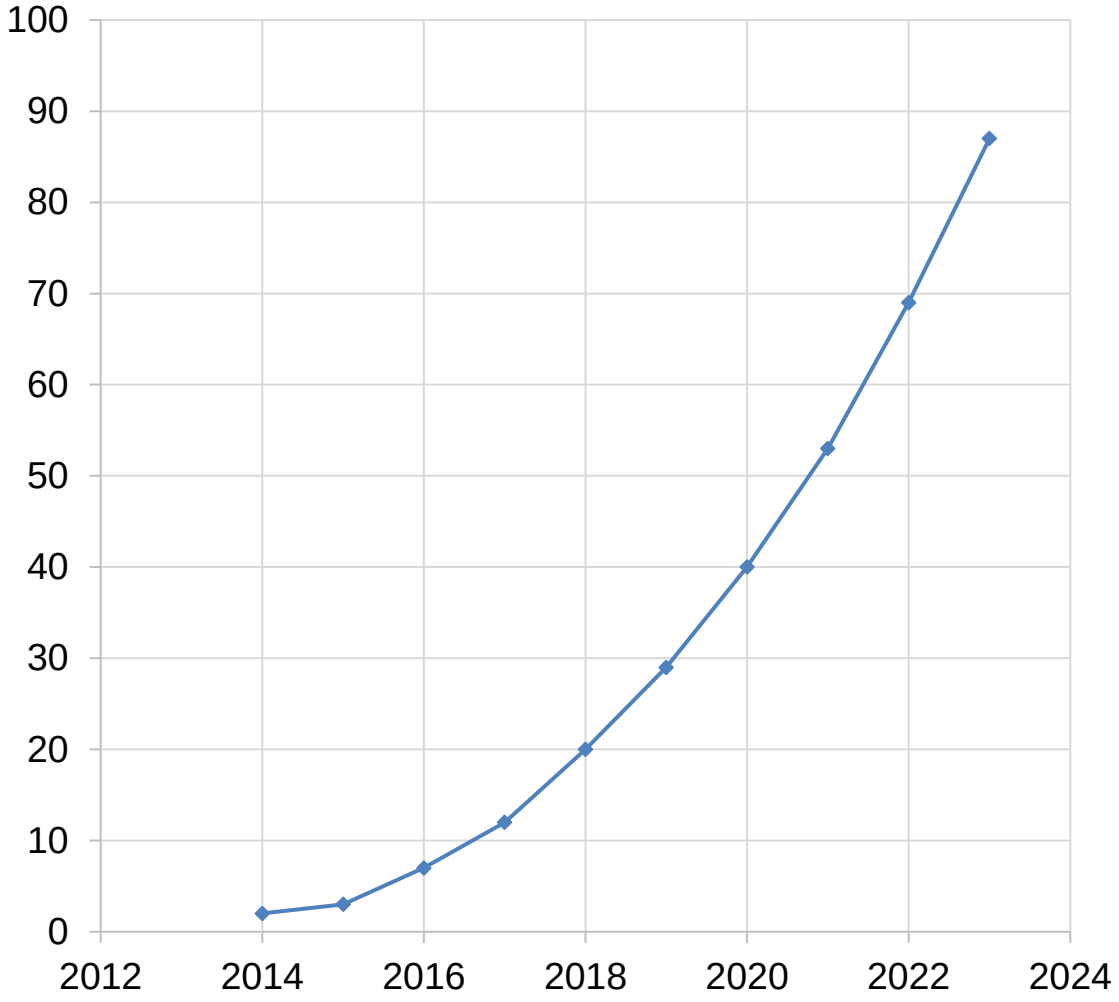
Case Studies

Takeaways

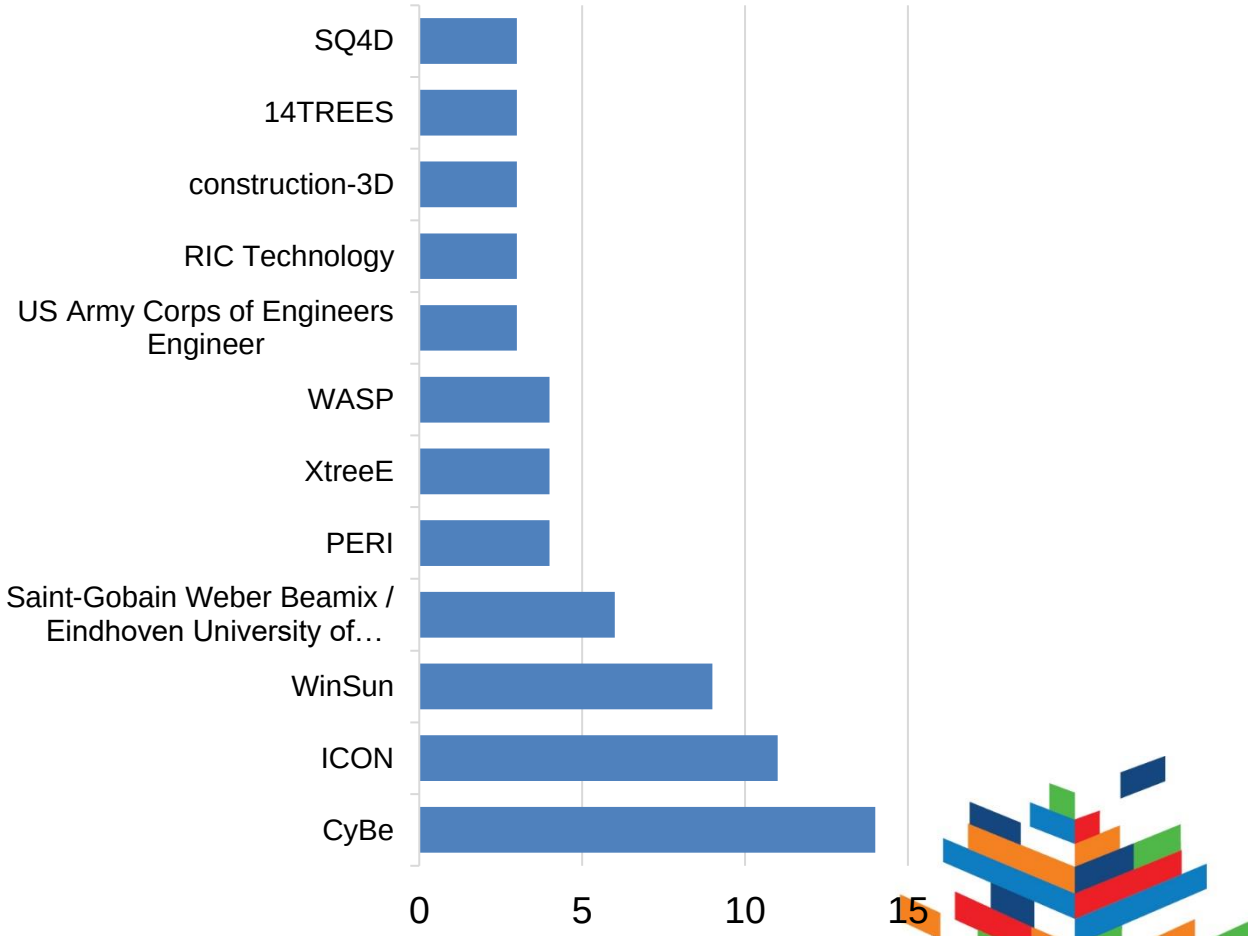
- 124 3DCP built projects
- Challenges



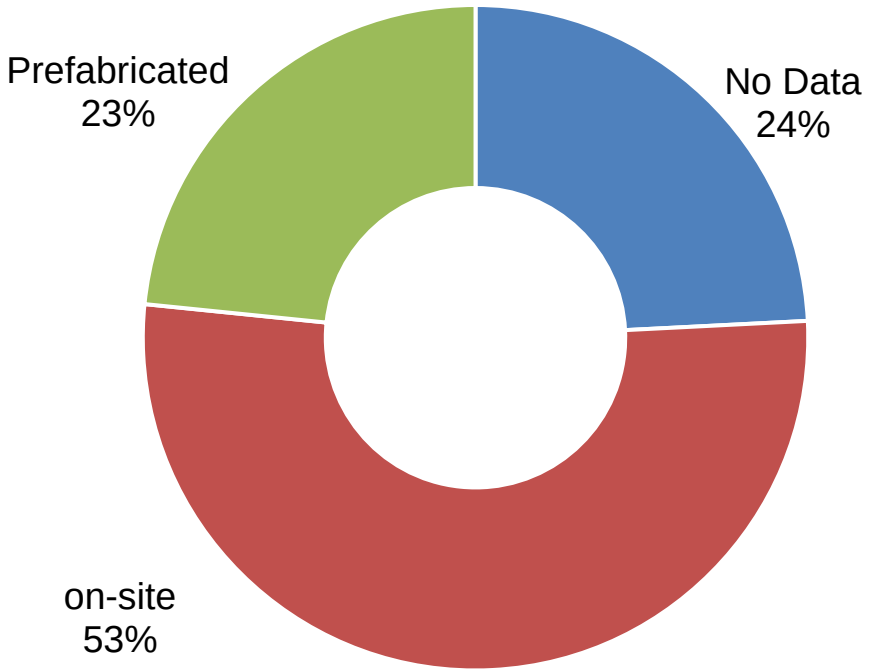
Cumulative Number of 3DCP Projects



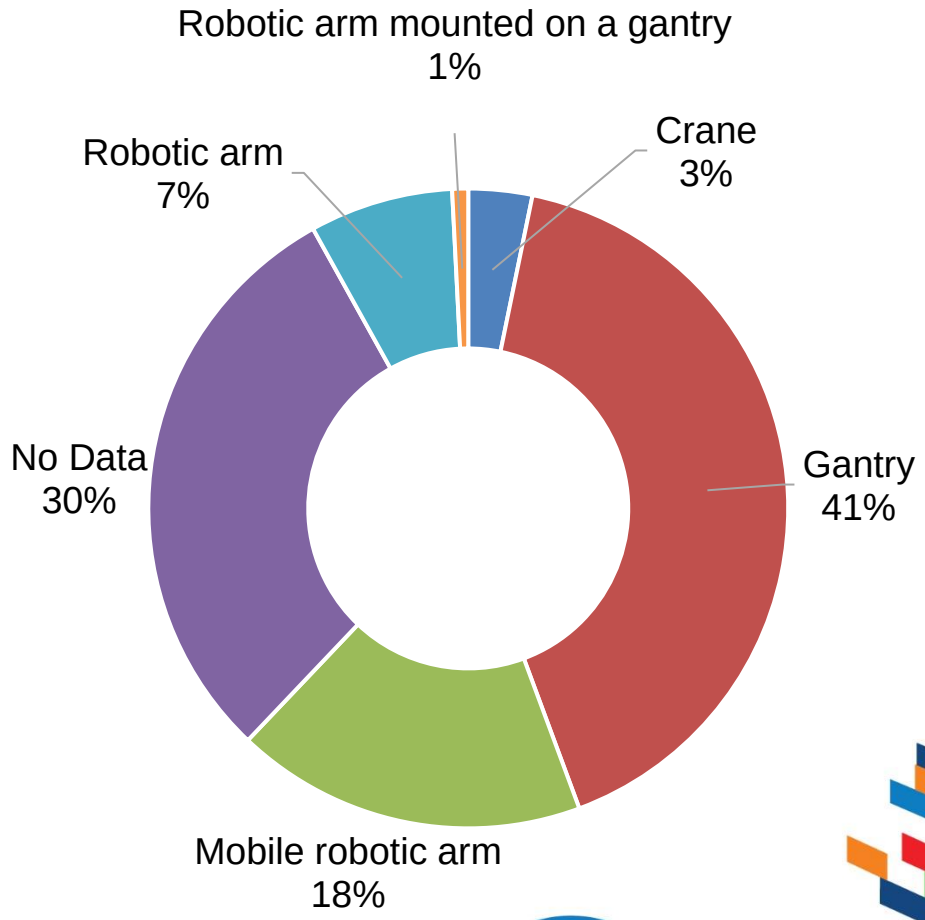
Number of projects of each company



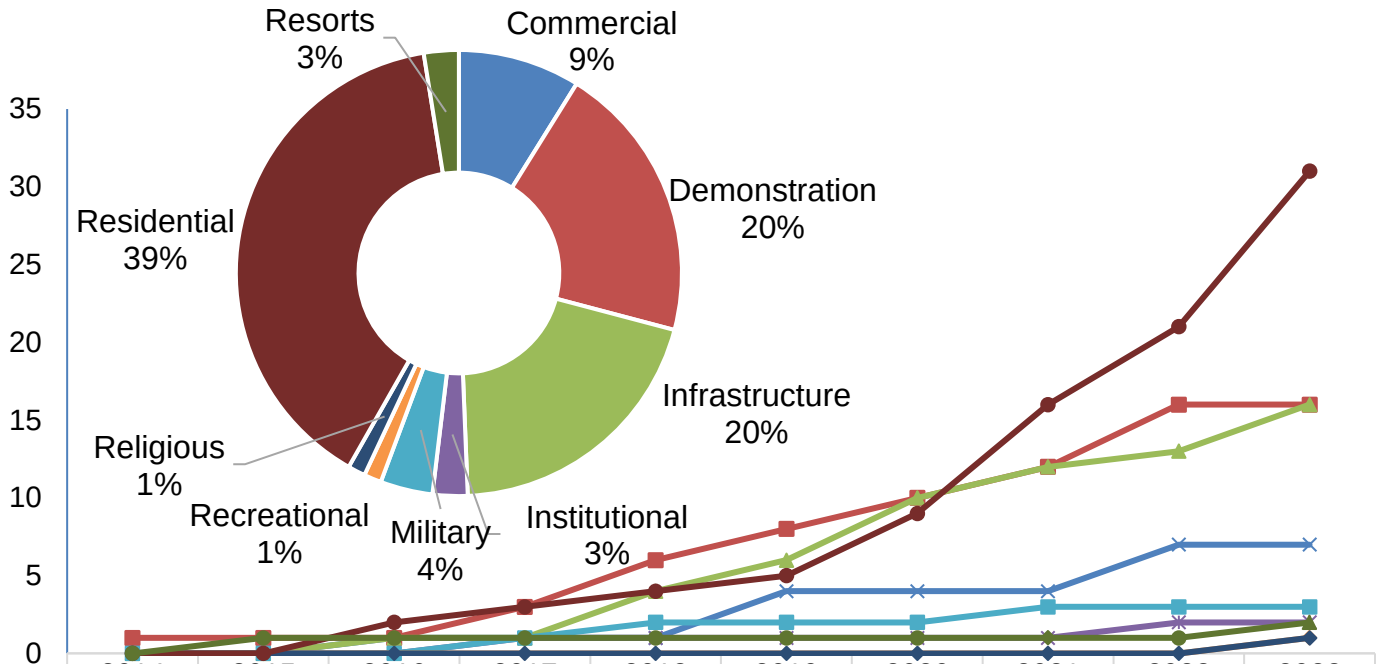
Construction Method



Printing System

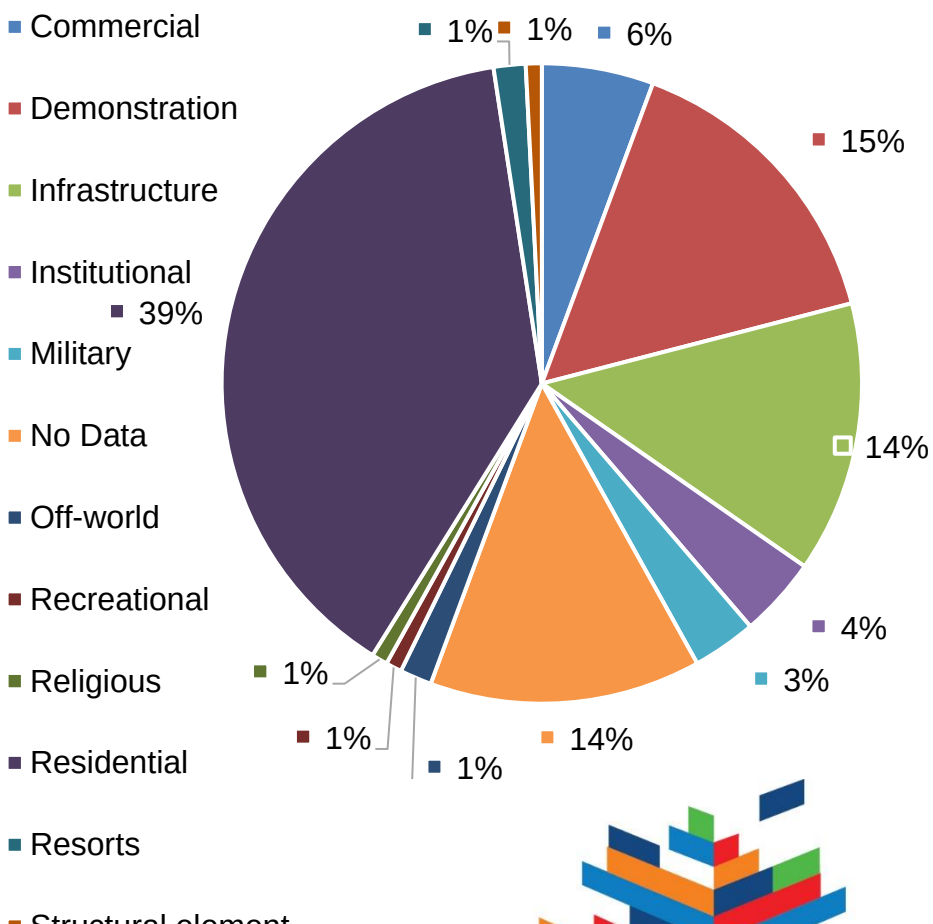


Evolution of 3DCP Projects by Structural Type Over the Years

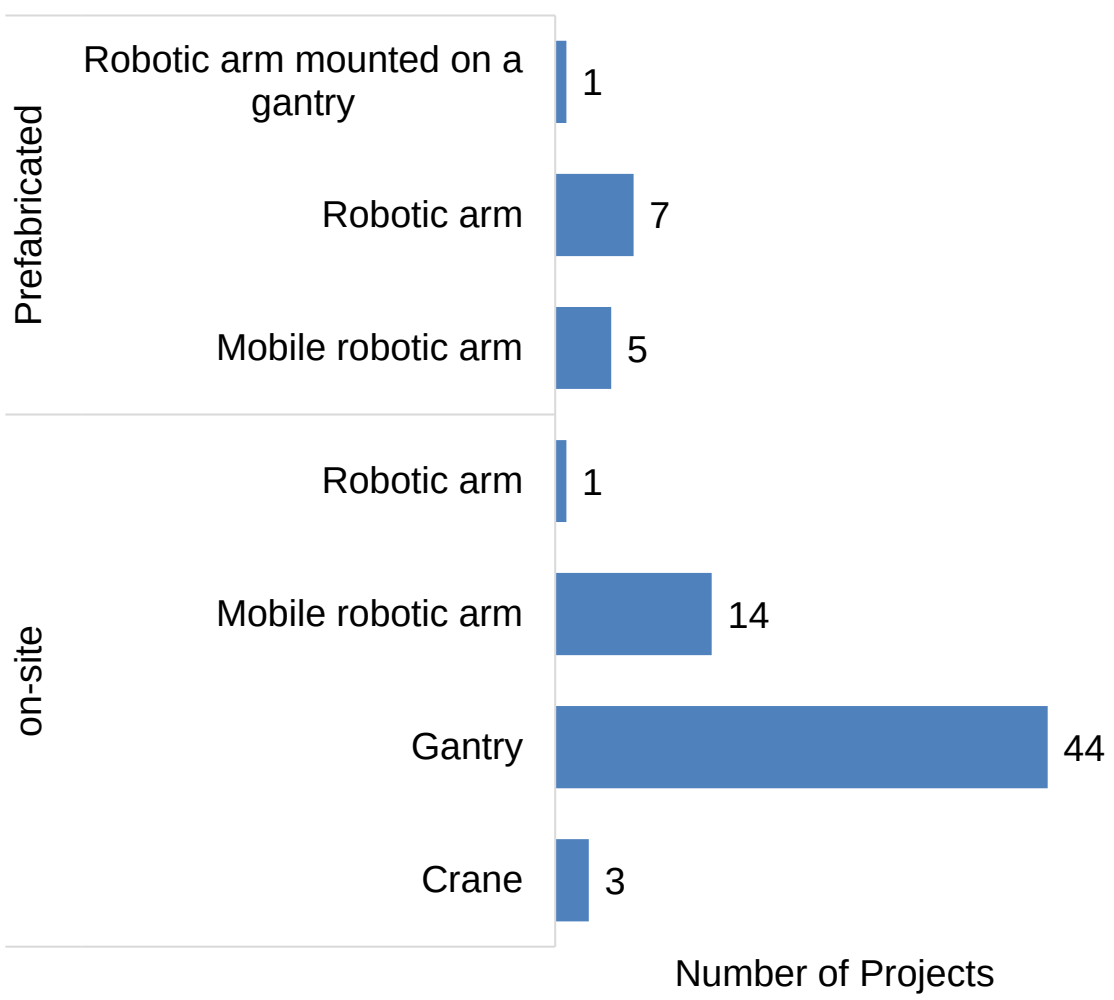


	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Commercial	0	0	1	1	1	4	4	4	7	7
Demonstration	1	1	1	3	6	8	10	12	16	16
Infrastructure	0	0	1	1	4	6	10	12	13	16
Institutional	0	0	0	1	1	1	1	1	2	2
Military	0	0	0	1	2	2	2	3	3	3
Recreational	0	0	0	0	0	0	0	0	0	1
Religious	0	0	0	0	0	0	0	0	0	1
Residential	0	0	2	3	4	5	9	16	21	31
Resorts	0	1	1	1	1	1	1	1	1	2

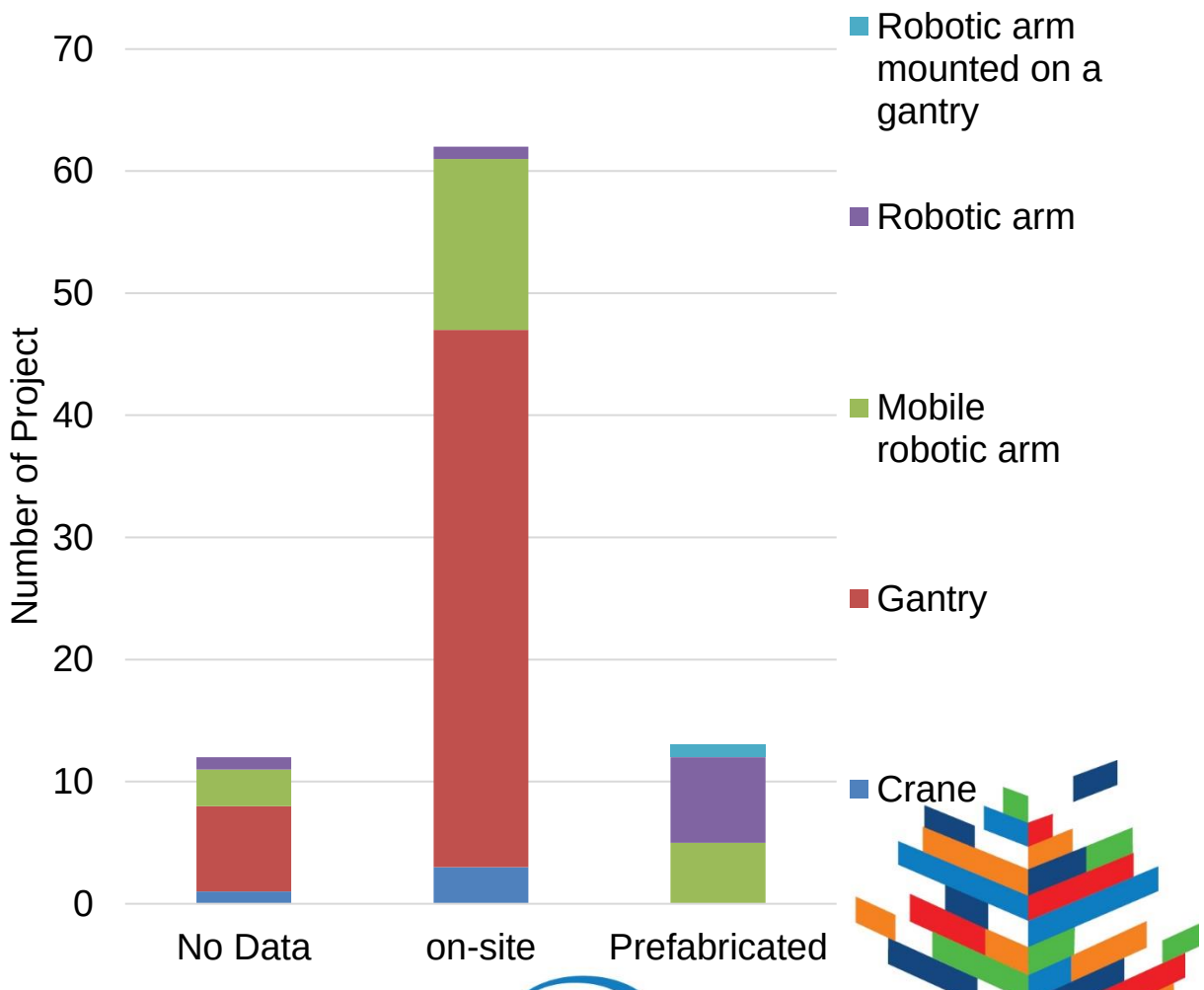
3DCP Projects by Structural Type (all data)



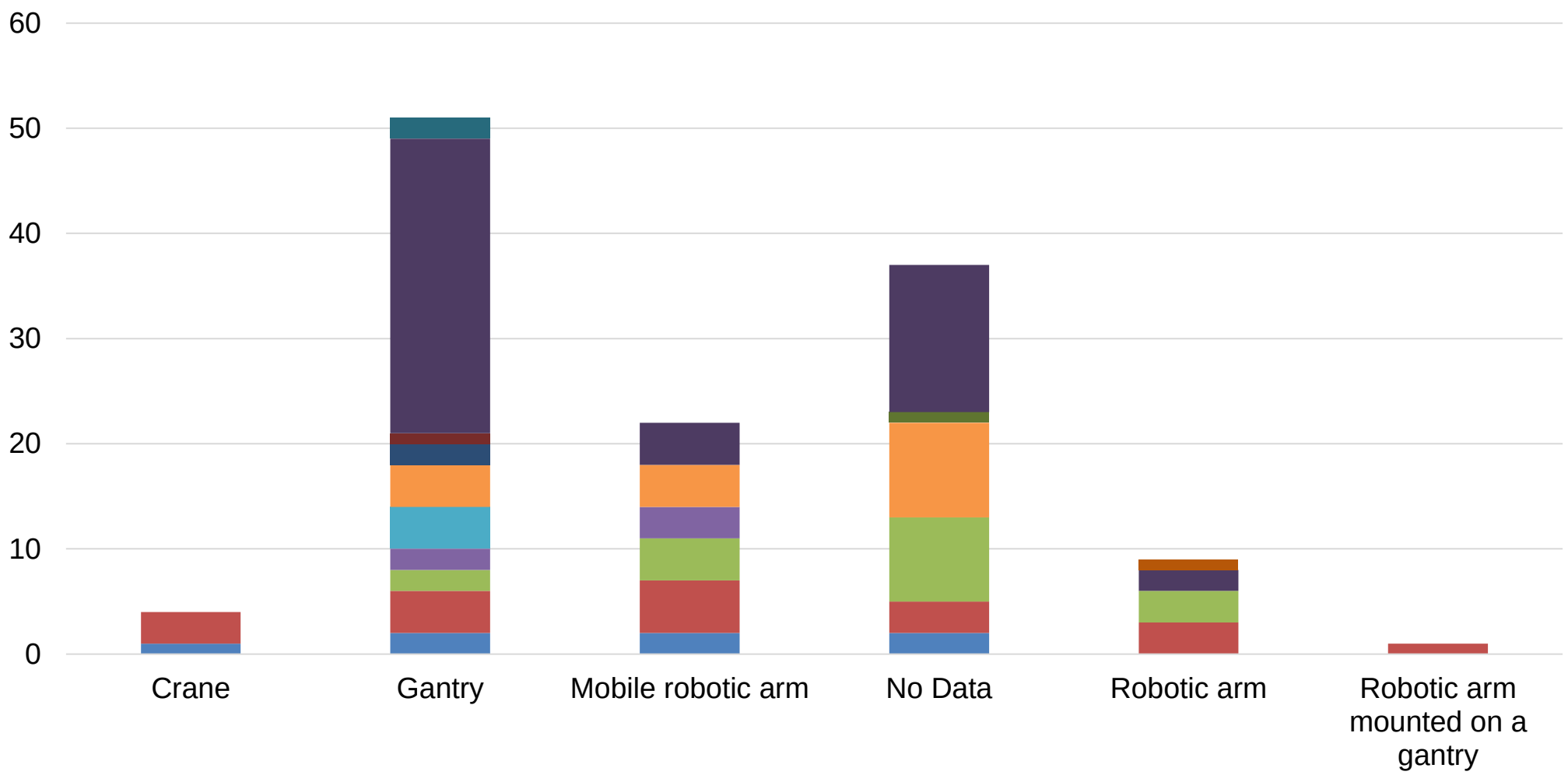
Project Count by Printing System and Construction Method



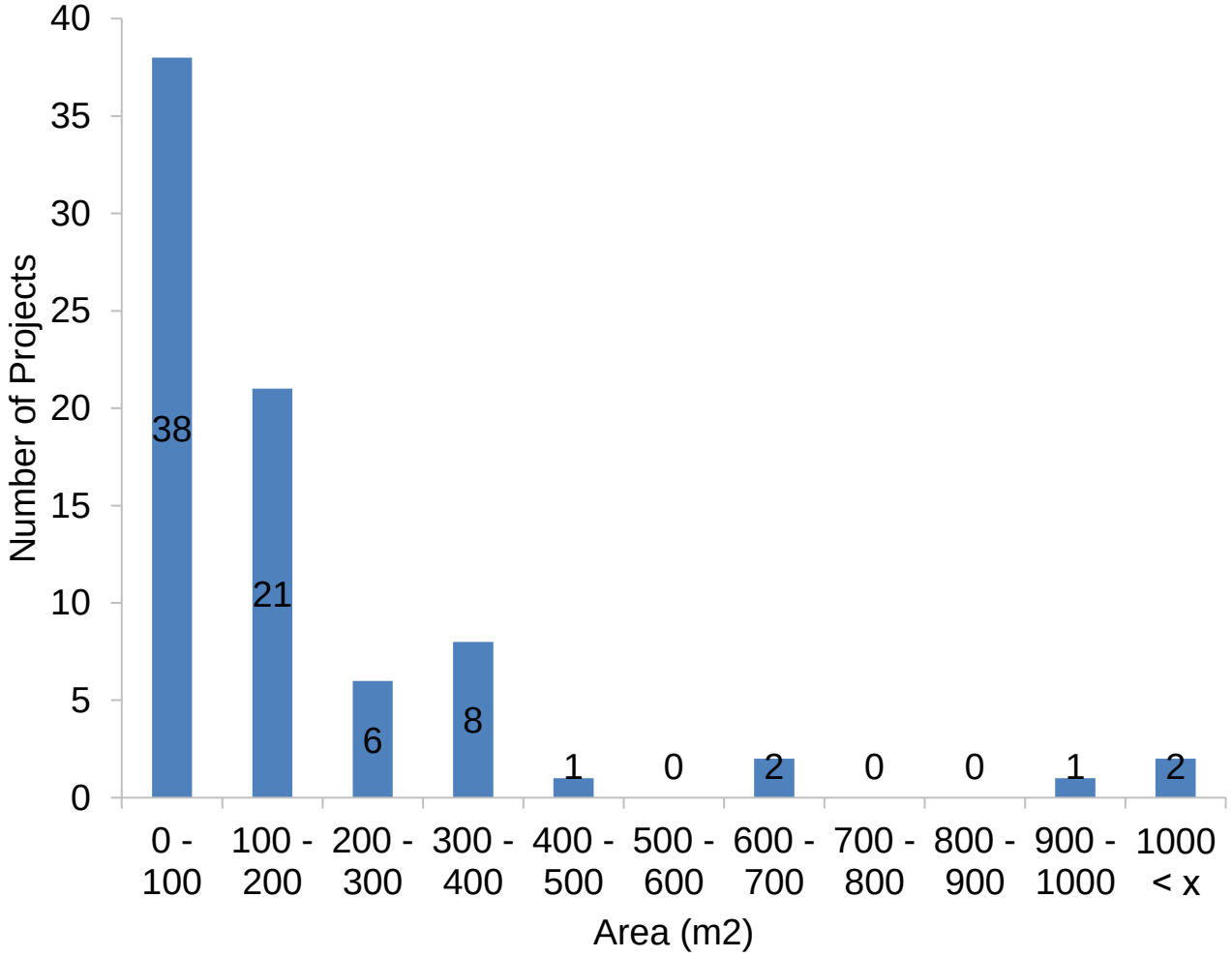
Project Count by Printing System and Construction Method (all data)



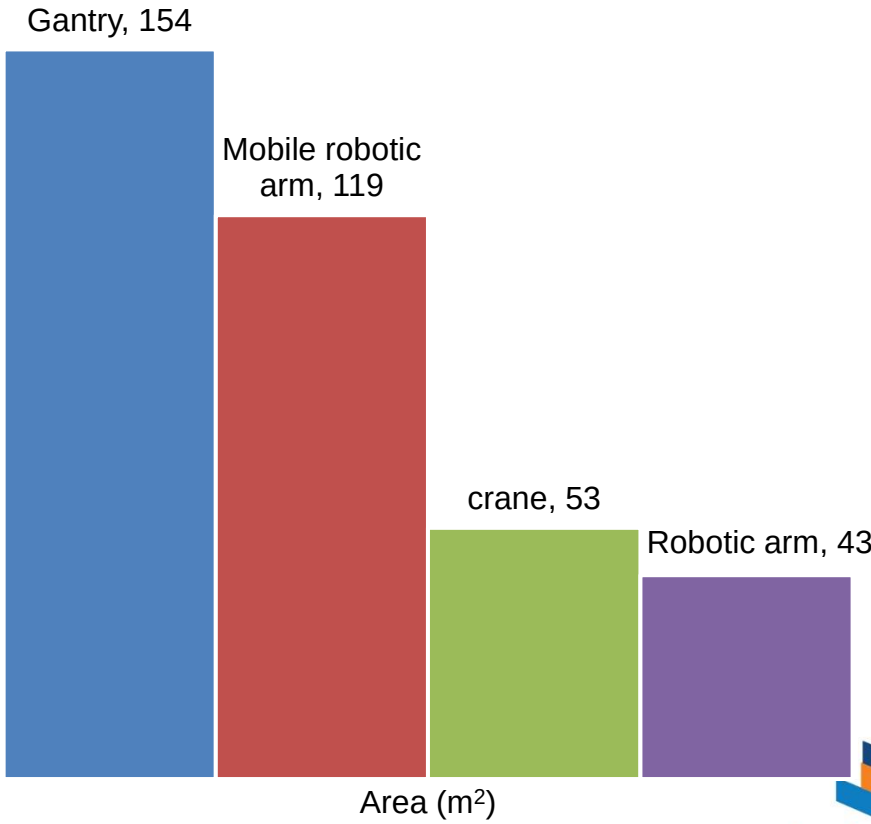
3DCP Projects by Structural Type: Distribution by Printing System



Built Area Range



Average Area Constructed by Each Printing System

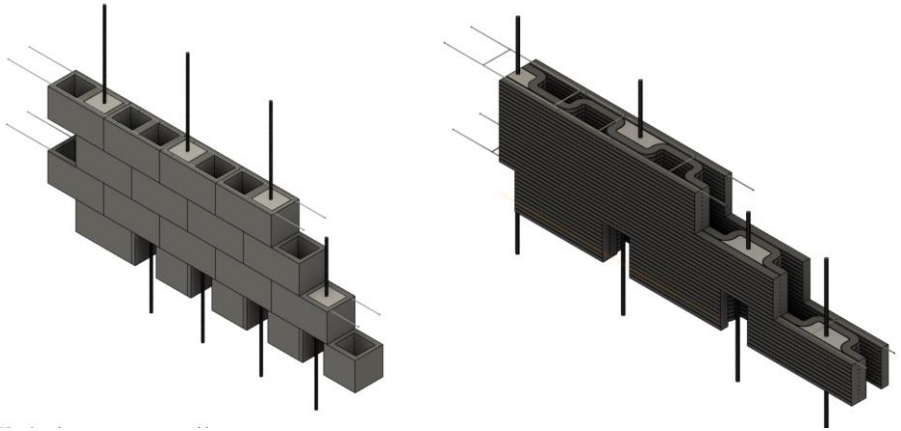


- Construction procedures:

I) load-bearing 3DCP structures (only one case)

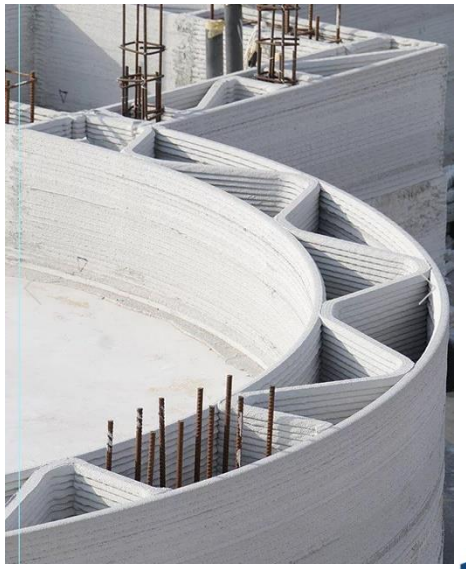
Credit: Bhooshan, S., Bhooshan, V., Dell'Endice, A. *et al.* The Striatus bridge. *Archit. Struct. Constr.* **2**, 521–543 (2022). https://doi.org/10.1007/s44150-022-00051-y

I) printed and cast structures, commonly designed based on unreinforced masonry design.



Credit: Apis Cor

II) non-load-bearing structures commonly adopted as permanent formwork for reinforced concrete.



Credit: Apis Cor

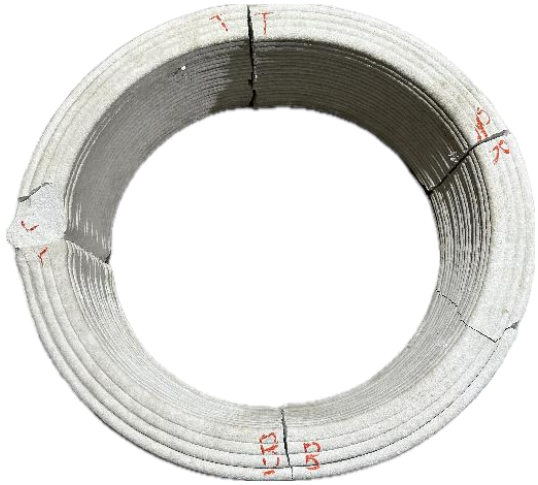
3DCP Buried Concrete Structures

Motivations

- Why 3DCP?
  - Workforce shortage in ND
- Why concrete pipes?
  - Code compatible
  - No Reinforcement

Overview

Rheology → Printing → Hardened → structural

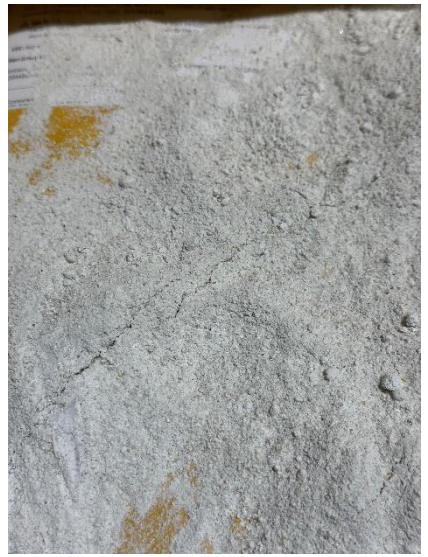


Methodology

Main components

system

material

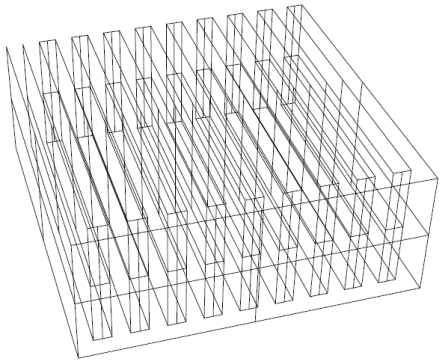


1: 6-axis robotic arm
2: Pump: 40bars, agitator, vibrator
3: Mixer

2 different materials

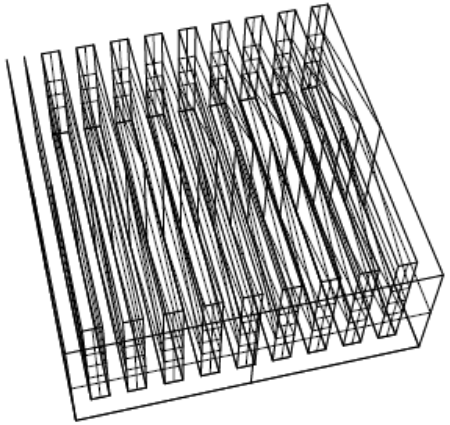
Process

CAD

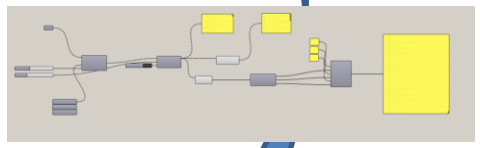


export

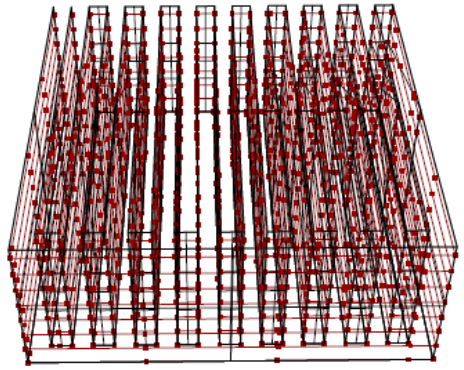
STL



slice



G-Code



program

print

- Material

Material	Water to material ratio	Portland cement CEM I 52,5 R	Industrially dried sand	CUGLA Viscosmart P50 water retention agent	Short Fibers
De Huizenprinters & Vertico (HV)	16%	40.13%	59.07%	0.80%	No fiber
Sika (S)	16%	Not Known	Not Known	Not Known	With fiber

- Printing Properties: Varied

❑ Small-scale tests

❖ Fresh characteristics

- Extrudability: Changing the extrusion rate of pump to find the optimum speed.

- Buildability: Single-layer hollow cylinder with 500mm diameter.

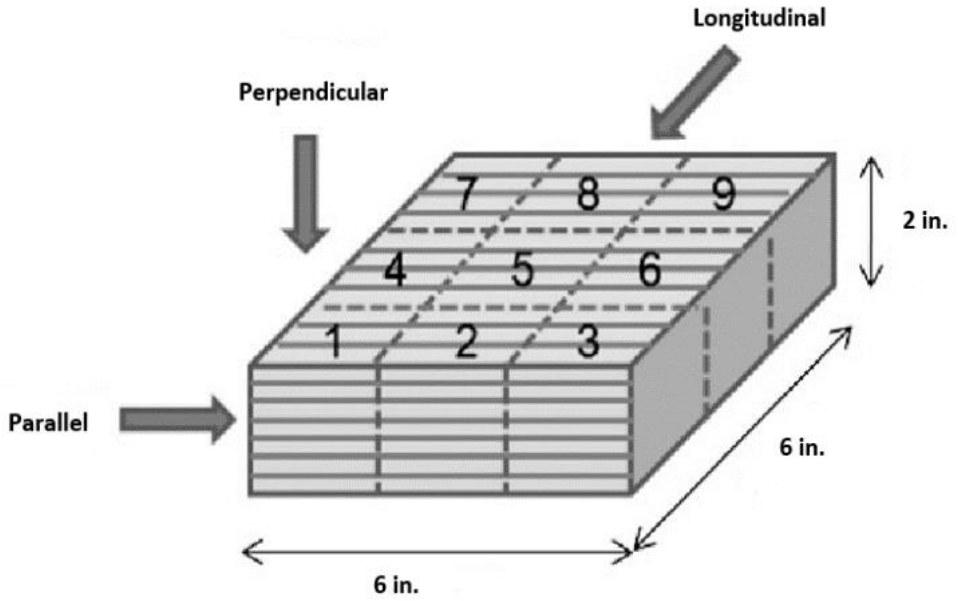
- Flow table test in time: ASTM C1437.

- Shape retention in time: Static load of 600g.

❖ Mechanical characteristics

- Compression strength ASTM C109

9 samples from10 x 8 x 4 in. slab

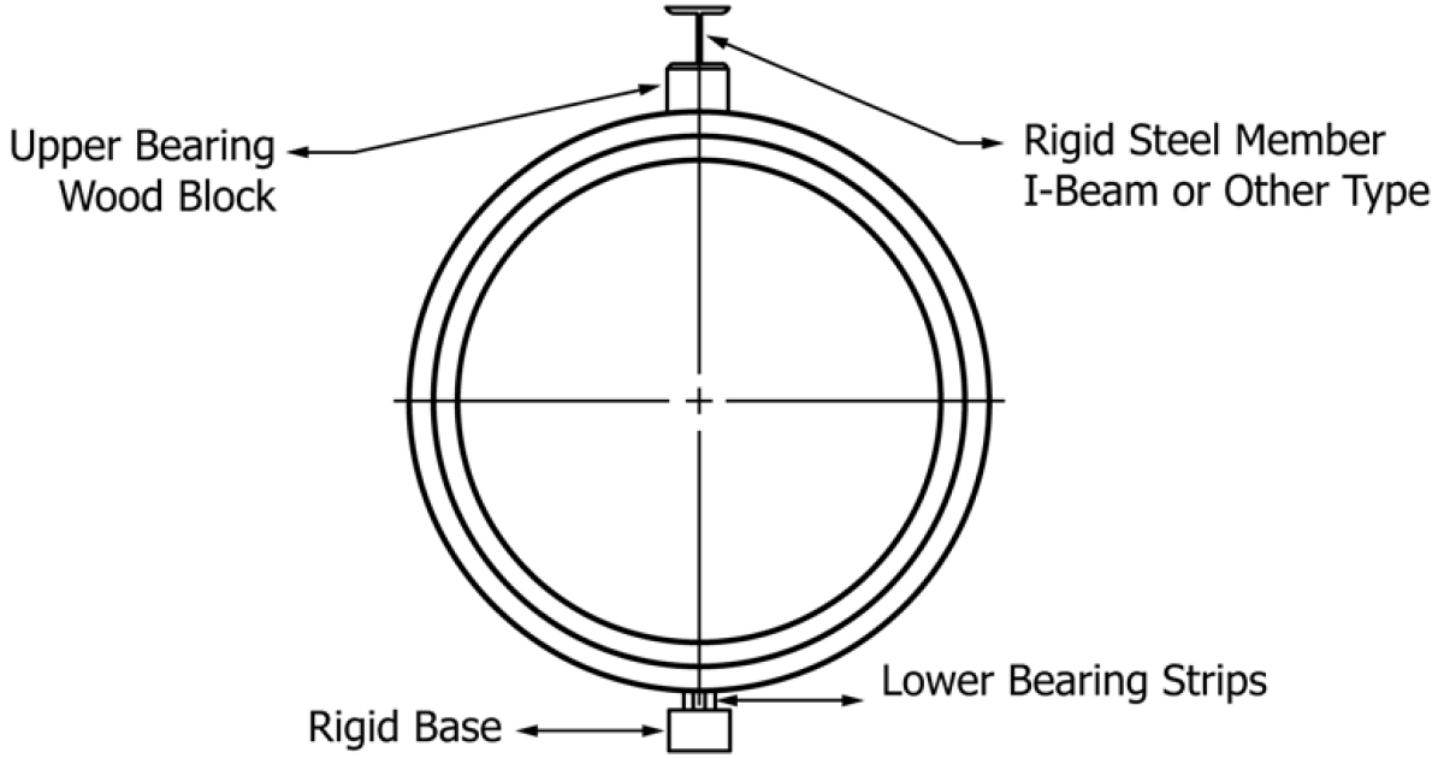


Saw cut

❖ 3D Printing

Printing Properties of concrete pipes	Height (Number of layers x height mm)	Number of layers in width	Nozzle diameter (mm)	Nozzle speed (mm/s)
HV	17x18	4	18	100
S	25x12	4	18	100

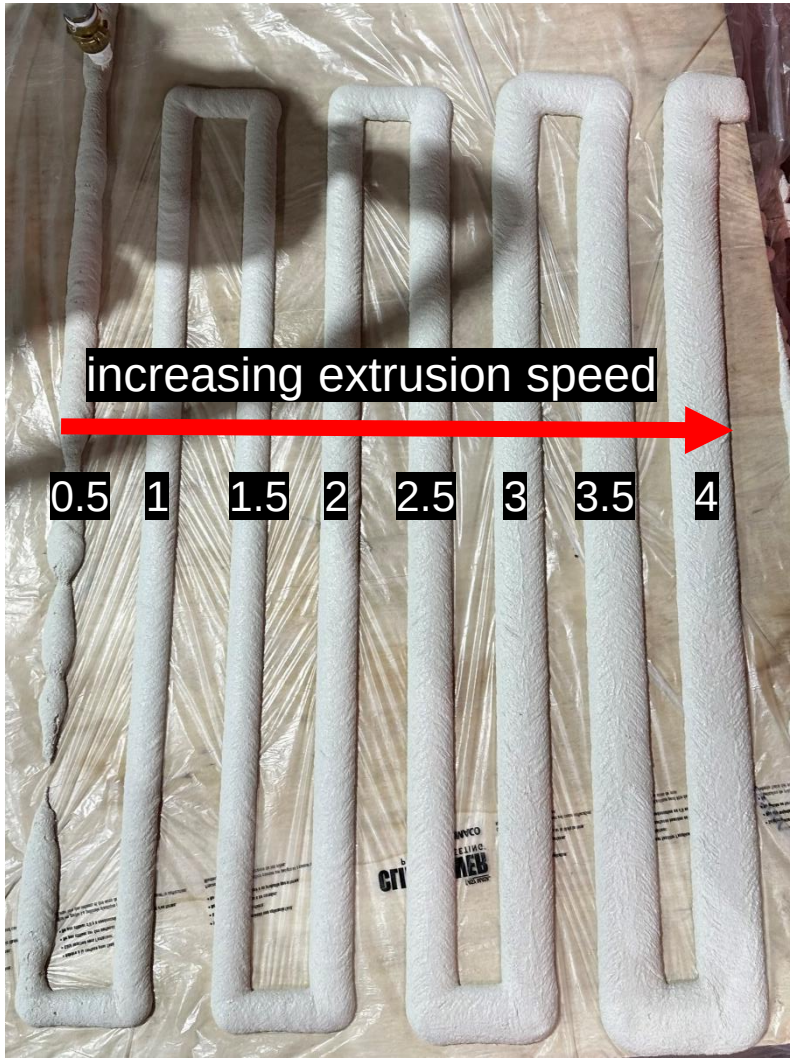
- Large-scale structural test
  - Three-Edge Bearing test: ASTM C497



Three-Edge-Bearing Test, Circular Pipe

Results

- Extrudability



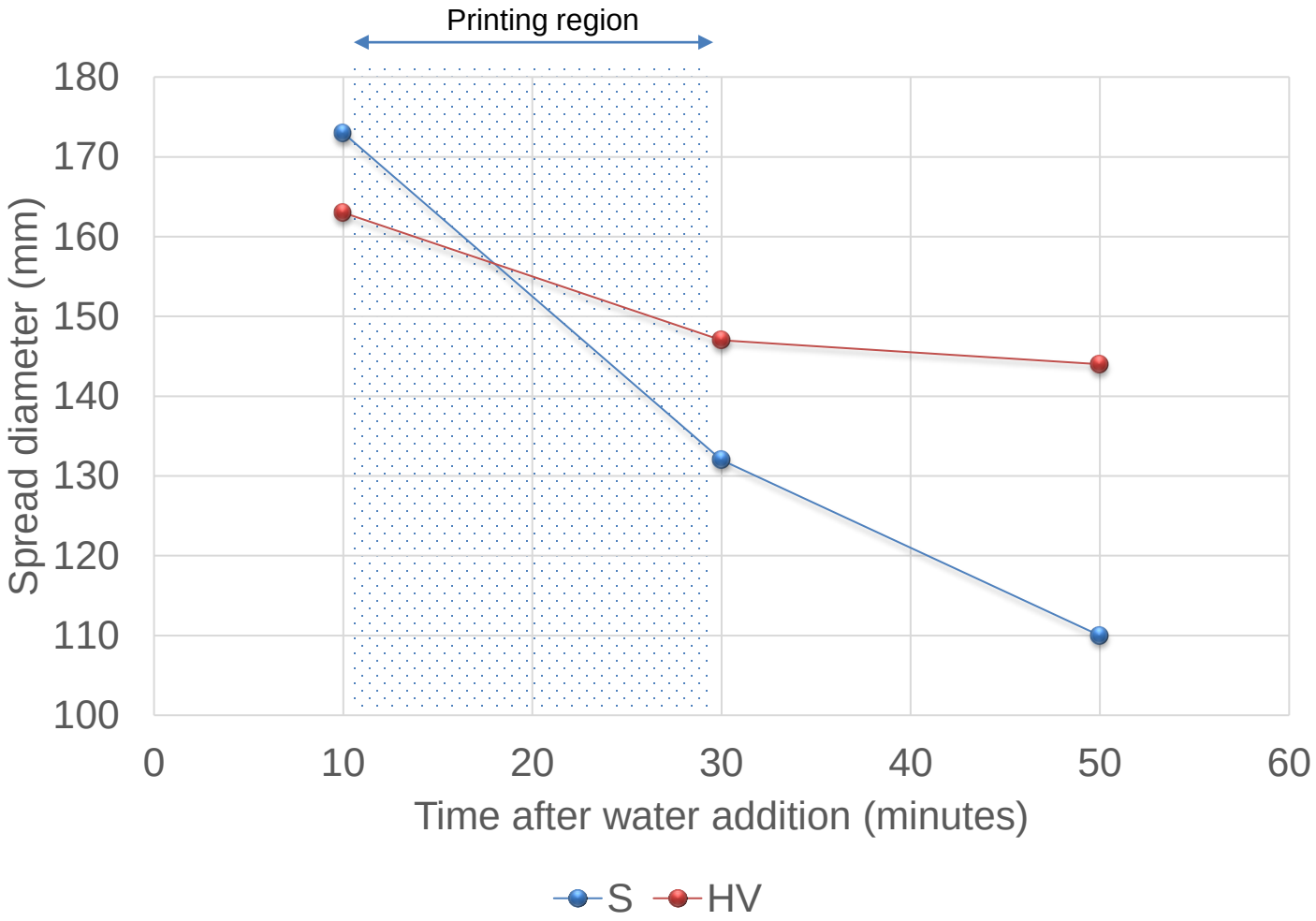
- Buildability

Buildability of a one-layer hollow cylinder with 500mm diameter	Number of layers	Nozzle height (mm)	ultimate height (mm)	Nozzle diameter (mm)	Nozzle speed (mm/s)	Open time (minutes)
HV	14	10	140	18	100	20
S	22	12	264	18	100	NA

HV

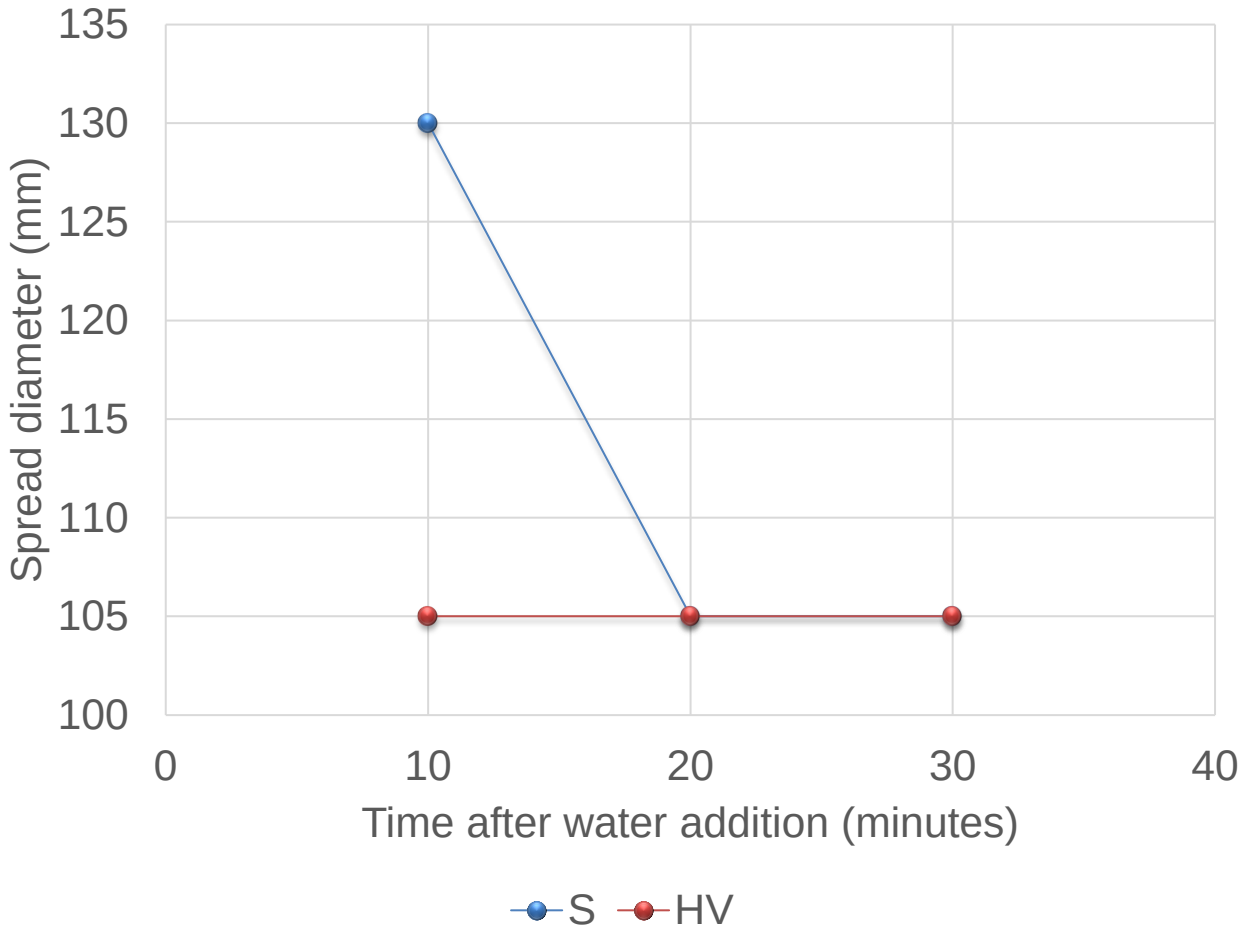
S

- Flow table test

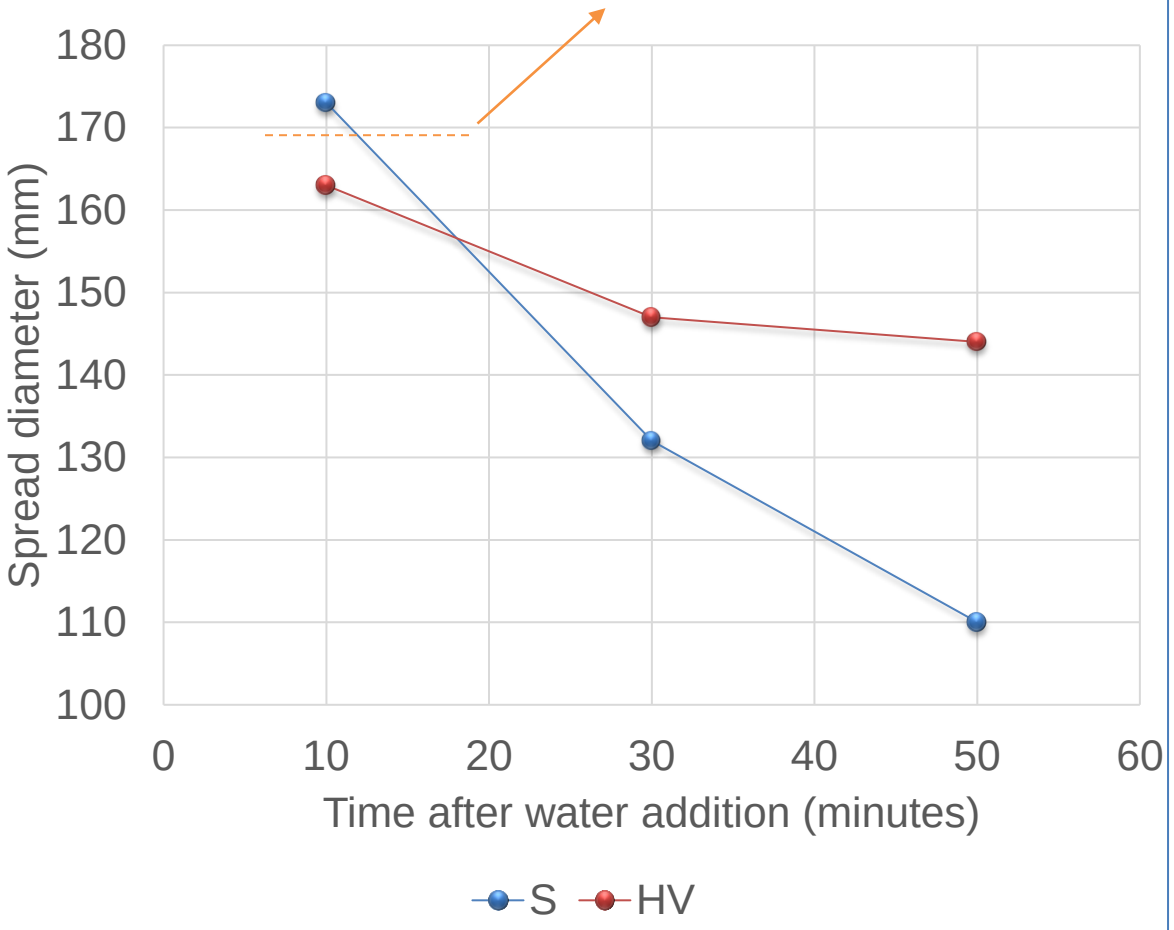


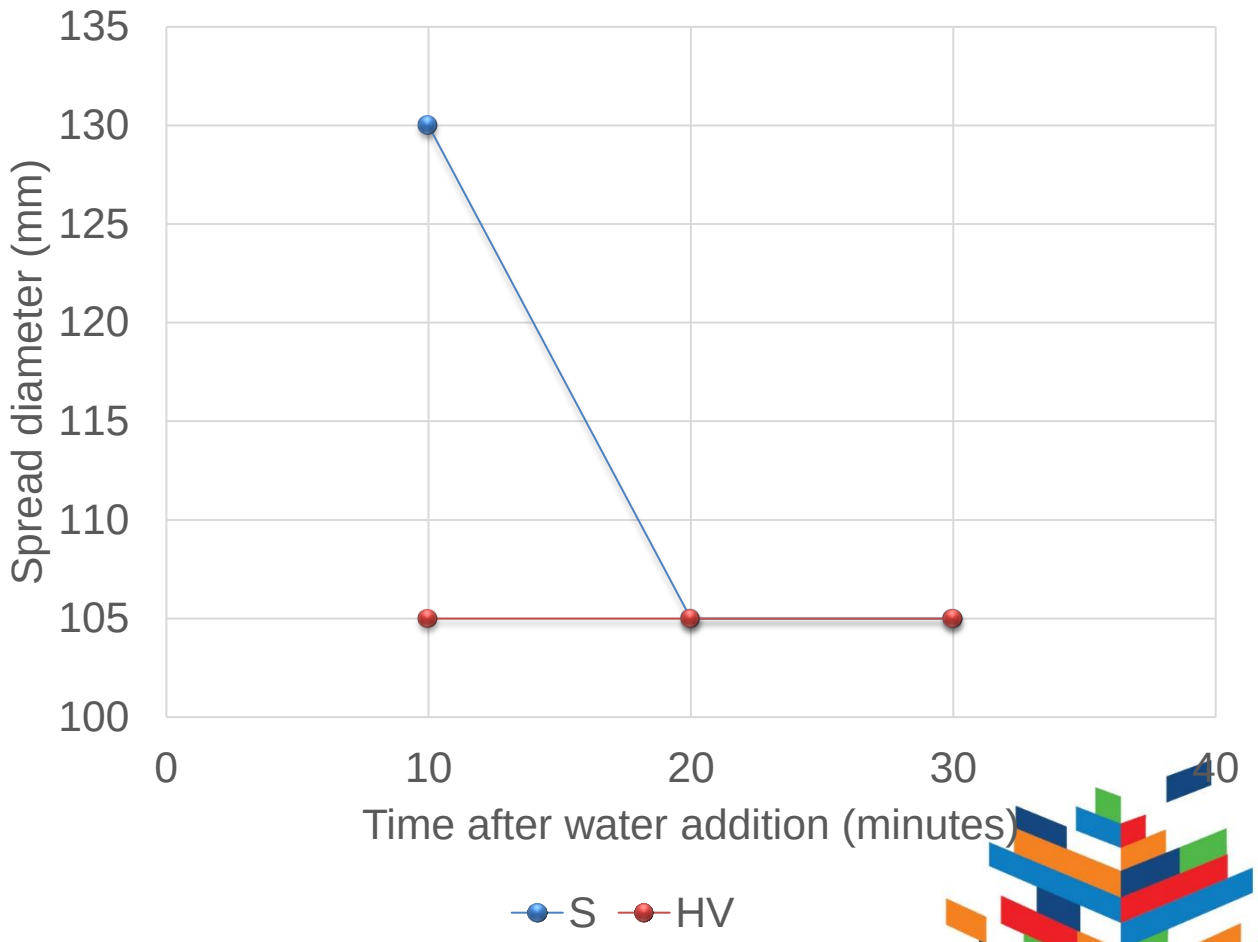
Demolded samples for flow table test at 50 minutes

- Shape retention test



Did not see any shape deformation using 600g with flowability lower than certain number





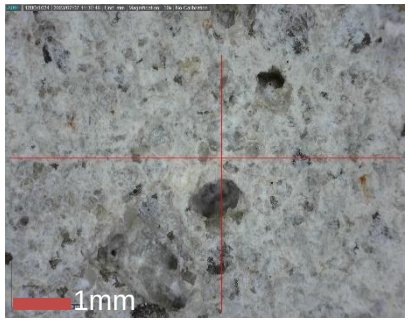
- Compression strength

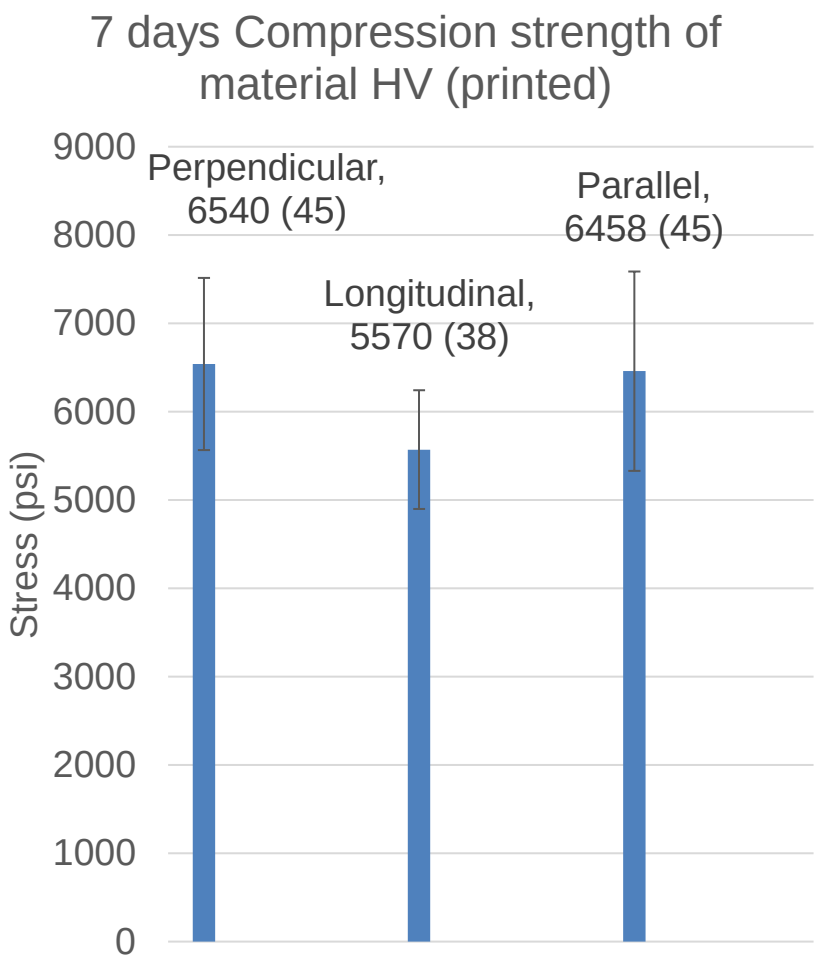
HV

Perpendicular

Longitudinal

Parallel



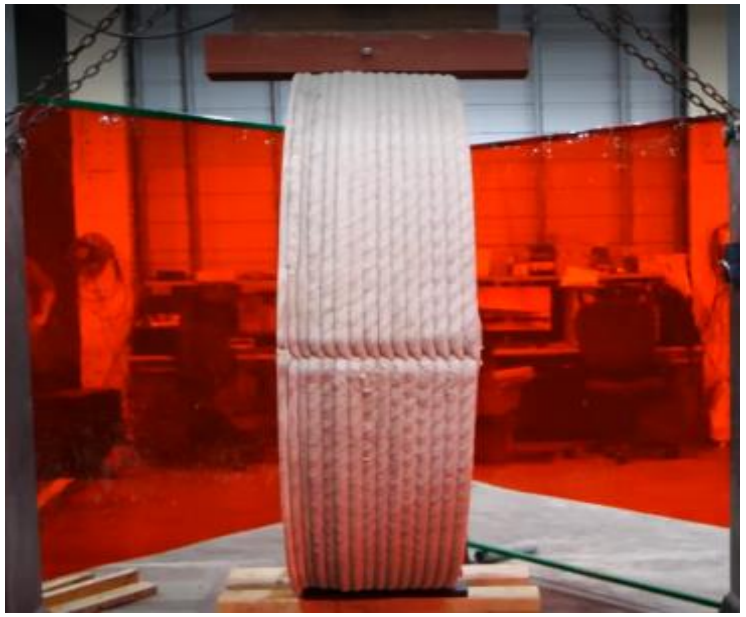


S

Reported 7 days compressive strength [psi (MPa)]
5800 (40)

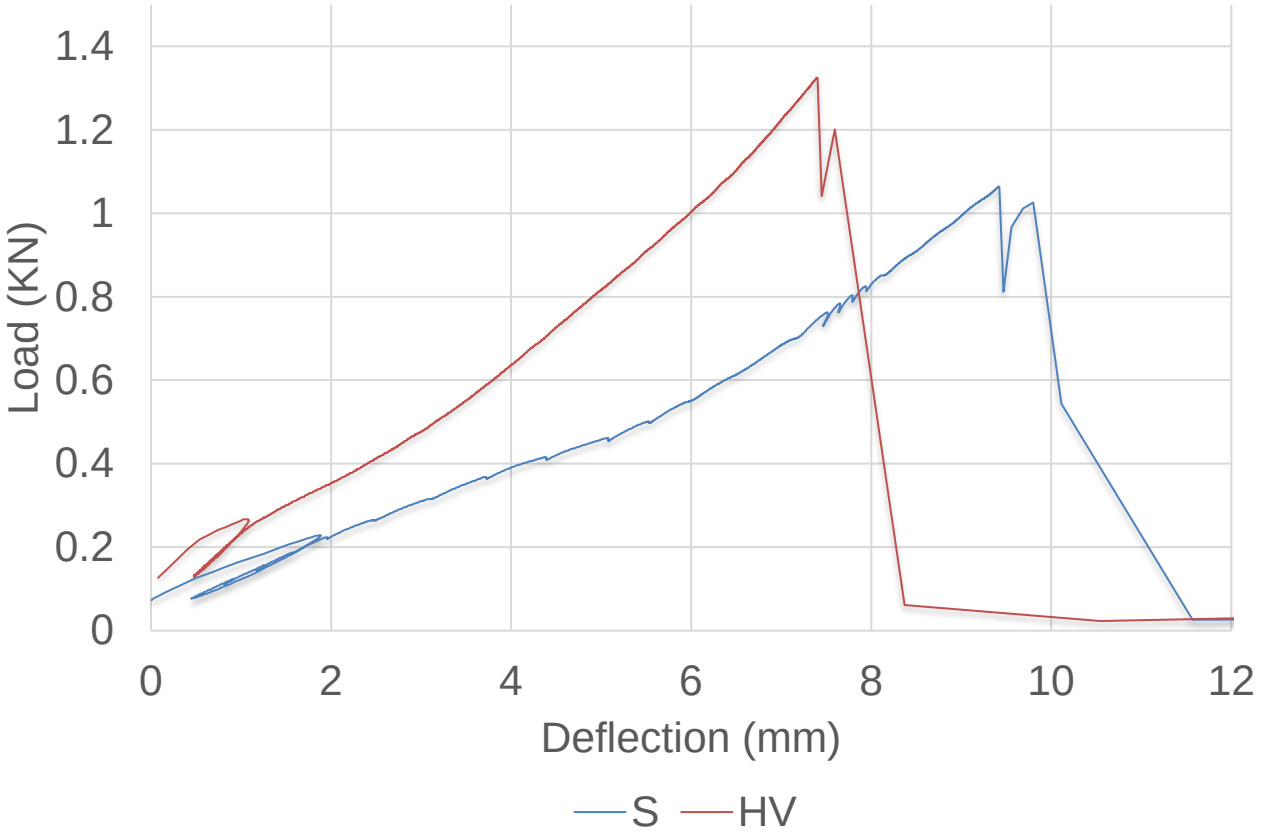
	Printed Pipes				Strength Requirements of Similar Pipes in ASTM C14			
Sample	Internal Diameter (in)	Thickness (in)	Length (in)	TEB Strength (lbf/linear ft)	Internal Diameter (in)	Thickness (in)	Minimum required TEB (lbf/linear ft)	Strength difference (% higher)
HV	33.75	5	11.75	6017	33	4.5	4875	23
S	32.5	3.9	12.25	4470	33	3.75	3150	42

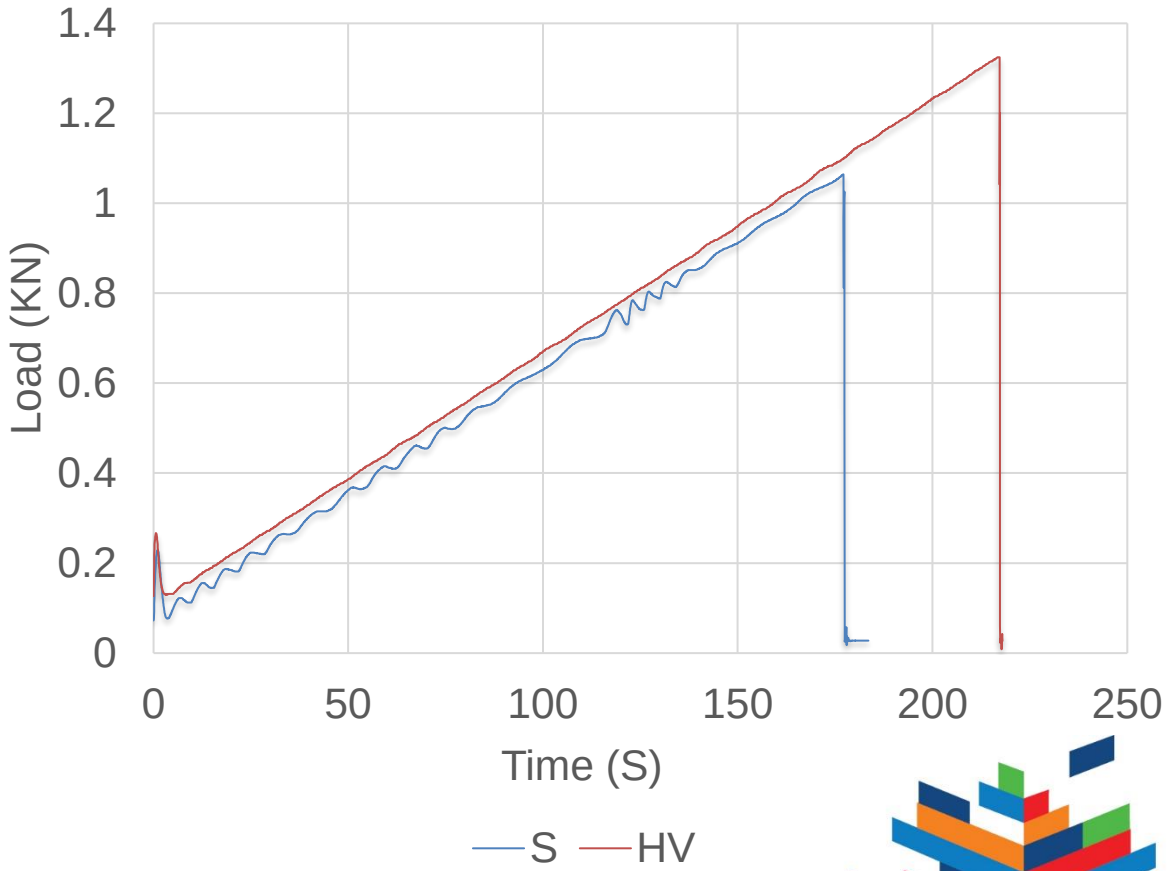
HV



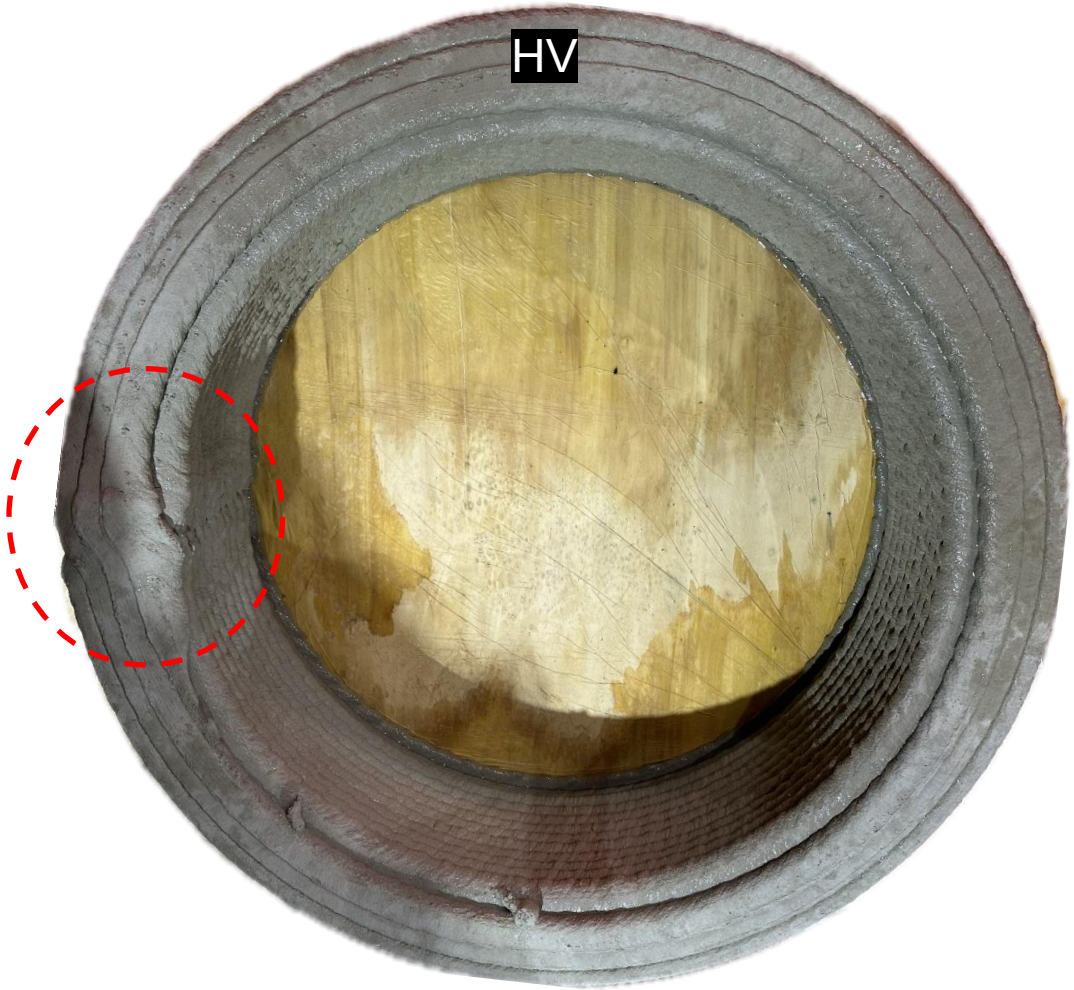
S

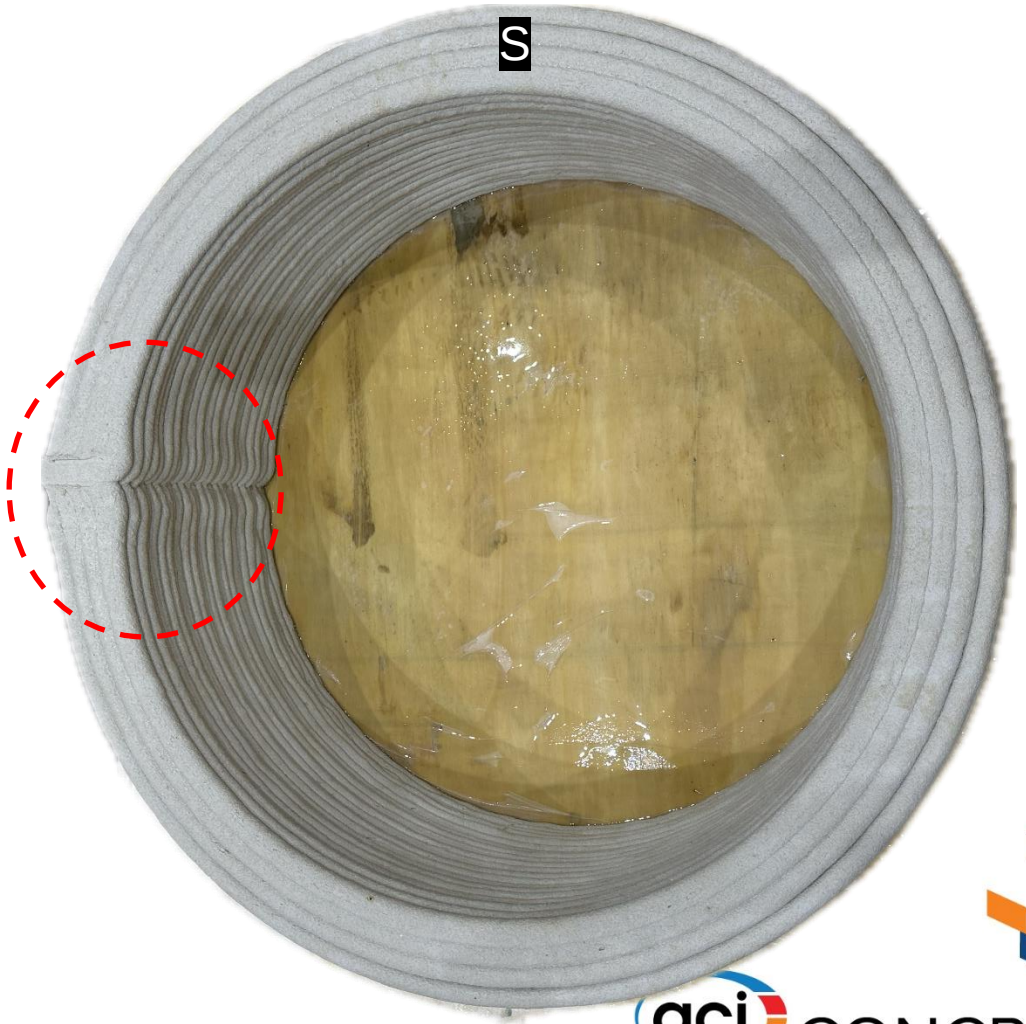
- Structural tests





- Potential weakness at the intersections of layers (seam section)





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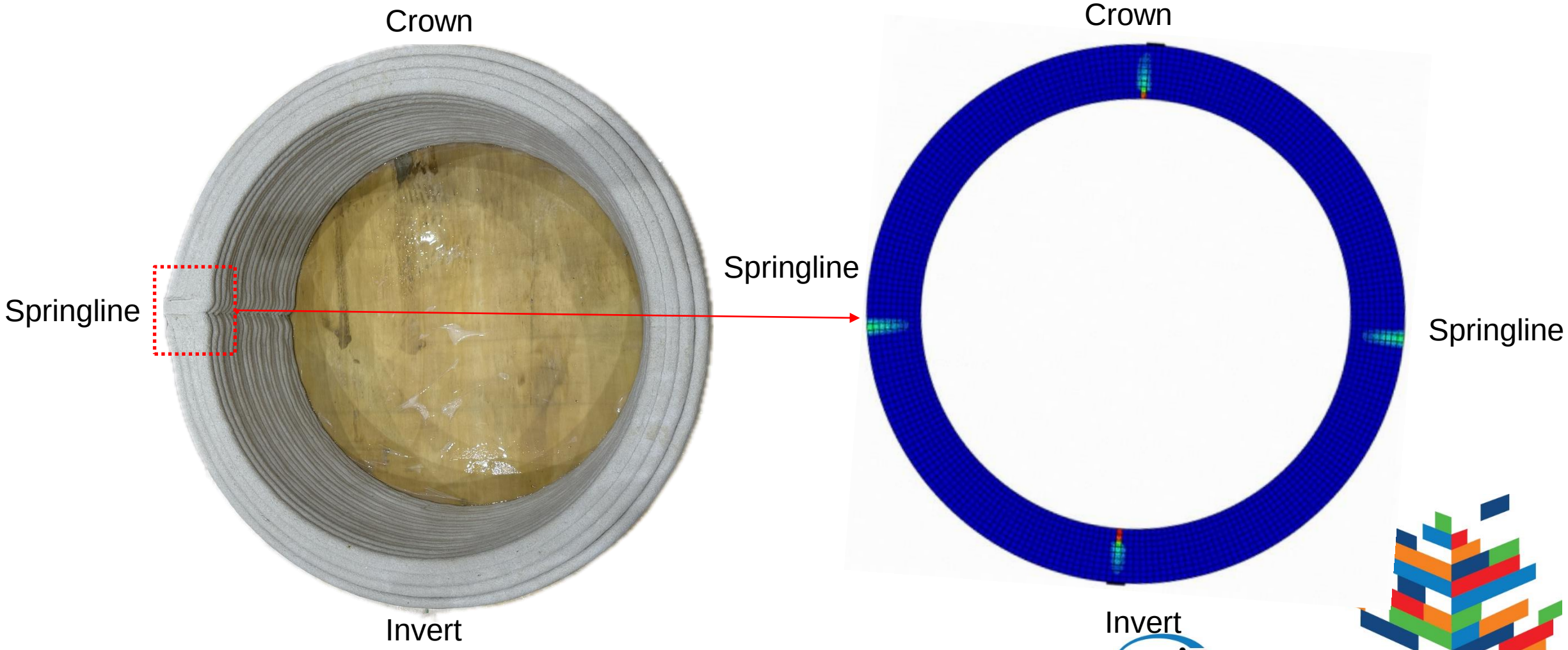
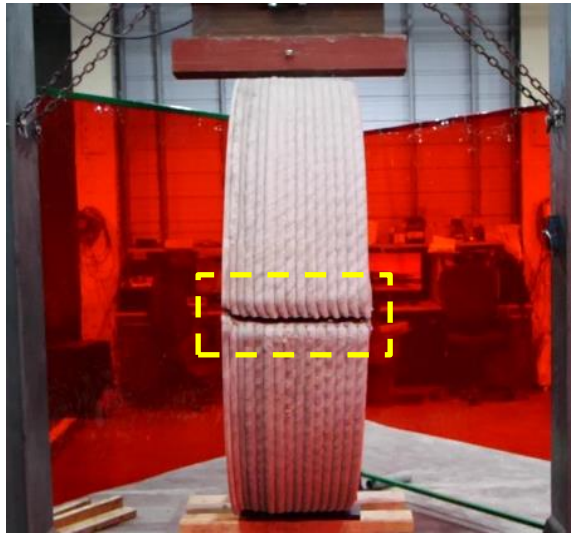
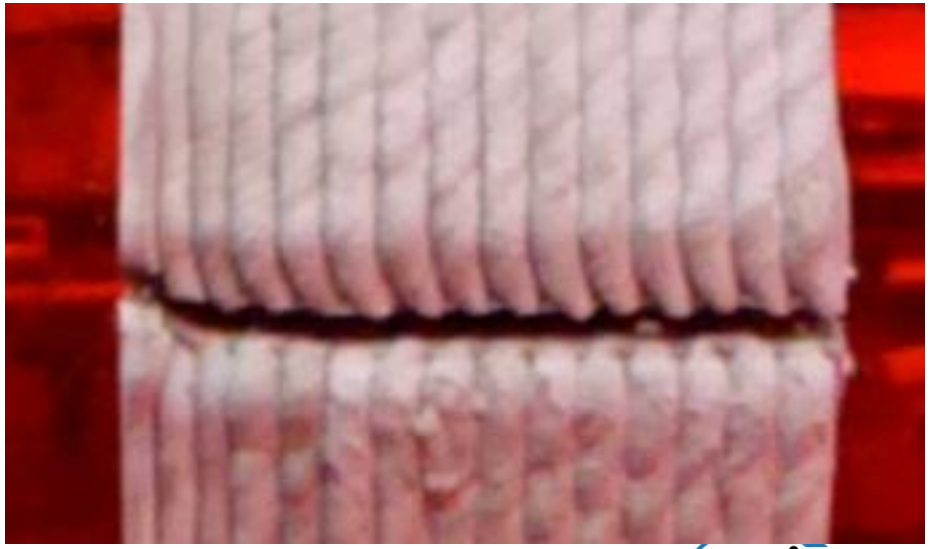


- Crack propagation and failure behavior

S

HV



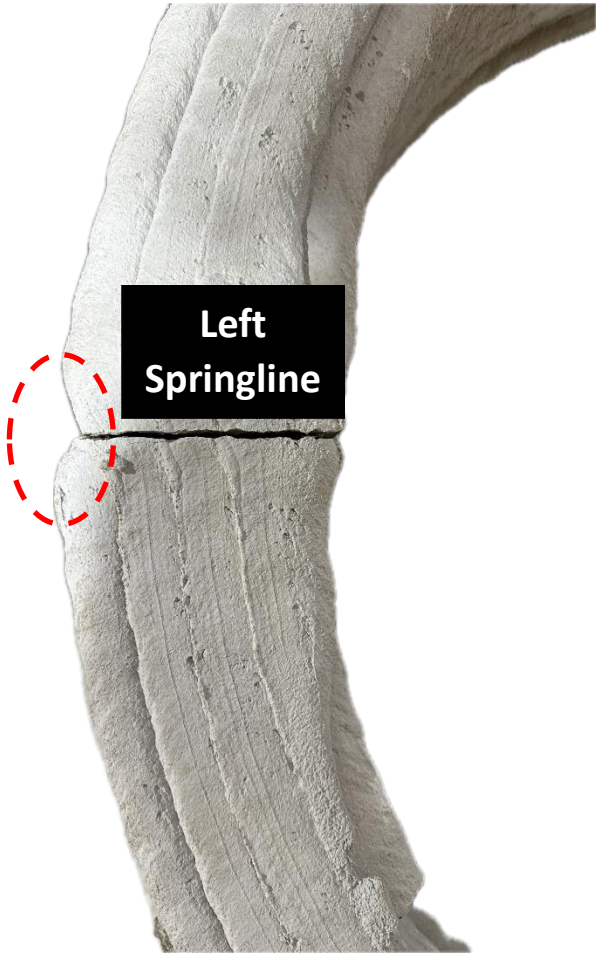


No observable voids at seam section

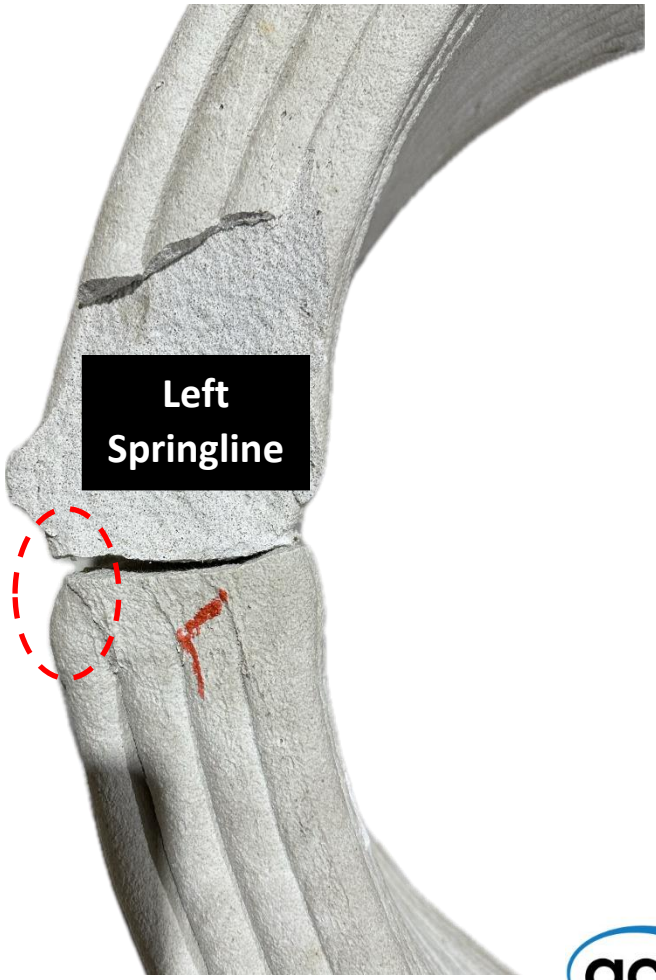
HV

S

HV



S



HV

VS.

S

VS.

	Invert	Left Springline (seam)	Crown	Right Springline
HV				
S				

Conclusion

- Case studies: Categorized 3DCP built projects / On-site 3DCP of residential building using gantry.
- Lower flowability or workability (S) resulted in higher buildability but less printing quality (more voids).
- Rheological properties will affect printing and consequently hardened and structural performance.

- Flexibility increased by using short fibers. However, pipe failure are still brittle.
- Seam section is not as weak as expected. It can influence the pipe failure, but only when seam section is aligned with the anticipated cracking region most probably due to decrease in effective width.
- Strength of pipes exceeded the required ASTM strength.

Acknowledgement

Advisor: Dr. Dorafshan

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NDDOT, CEM at UND

Thank You

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TRANSPORTATION TECHNOLOGY RESEARCH INSTITUTE

Alireza Hasani

alireza.hasani@und.edu

Look forward to engaging with you during the convention!