ADVANCED TRANSPORTATION INFRASTRUCTURE CENTER

Additively Construction of Civil Infrastucture

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Advanced Transportation Infrastructure Center (ATIC)

Our mission is to advance transportation infrastructure related science, technology, and education.

Our vision is to make a meaningful contribution to safety and durability of transportation infrastructure in the region through autonomy.

University of North Dakota Advanced Transportation Infrastructure Center is dedicated to augment transportation infrastructure design, construction, and maintenance through automation and cutting-edge technologies.

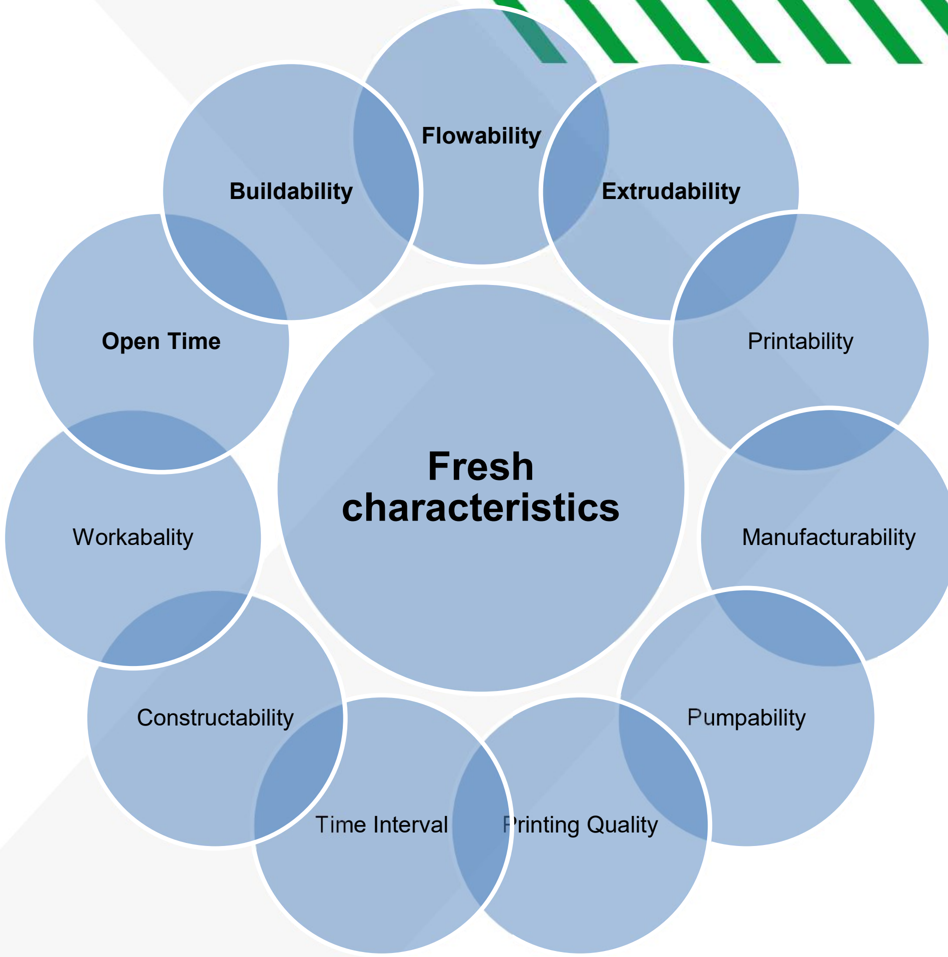
Transportation infrastructure in North Dakota plays a crucial role in national security due to the state's pivotal contributions to food and energy production. ATIC aims to address the needs of this infrastructure while supporting UND's mission of discovery and education.

Goals & Objectives

- **Establish Research Programs:** Address key challenges in Transportation Infrastructure aligned with UND's strategic plan and North Dakota's needs through basic and applied research.
- **Educate and Train the Workforce:** Provide practical, hands-on education and training opportunities for students, researchers, and professionals in the field of transportation infrastructure to meet the increasing demands of industry for a skilled workforce.

Background

- There is statewide backlog in box culvert construction
  - Workforce shortage
- Additive construction of concrete, AKA 3DCP, is one of the few alternatives
- Technology has been used for wall construction
  - Limited applications in transportation infrastructure
- Feasibility investigation for pipe
  - Code compliance without reinforcement



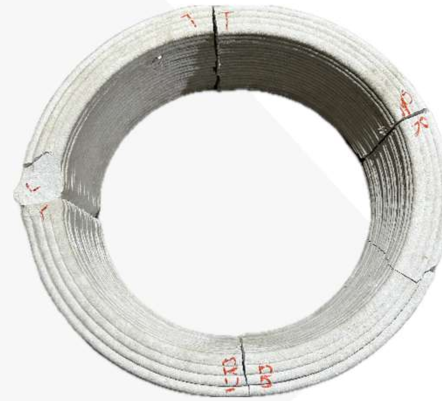
Claimed benefits of 3DCP

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

Construction

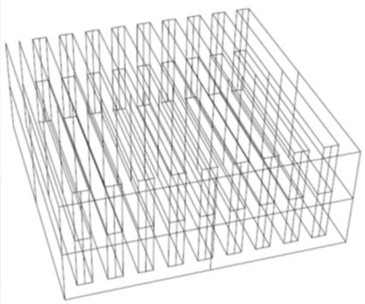
Rheology → Printing → Hardened → structural

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



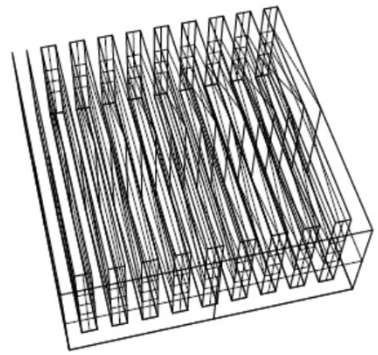
Printing process

CAD

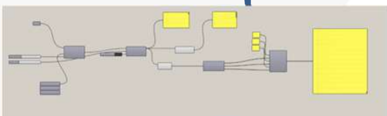


export

STL



slice



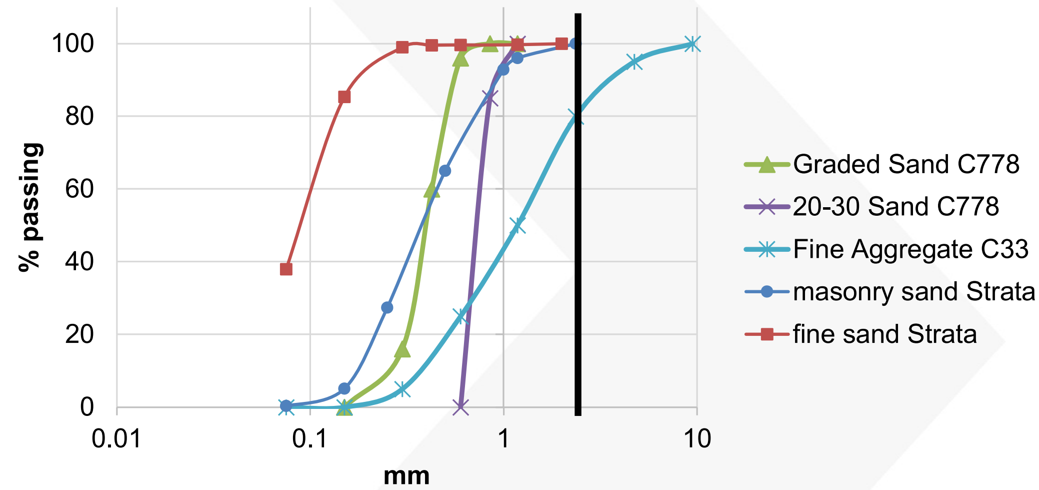
G-Code

program

print

Material

- Fine aggregates (less than 2mm)
  - Printer dependent
- Sand
- Cement
- Water
- Modifiers
  - Viscosity
  - High Range Water reducer
- Commercially available
  - Both from Europe and in US
    - De Huizenprinter Vertico (HV), Sika (very short fiber glass), Quikrete
- UND customized mix
  - Minimal or no use of modifiers



Pump system limitation

Commercial

Manufacturer	Material	Water to material ratio	Cement	Fine Sand	CUGLA Viscosmart P50 water retention agent	CSA (Accelerator)	Amorphous Silica	w/c	s/c	Short Fibers
De Huizenprinters & Vertico	Material 1 (M1)	16%	40.13%	59.07%	0.80%	-	-	0.34	1.5	No
Sika	Material 2 (M2)	16%	Not reported by the manufacturer							Yes
Quikrete	Material 3 (M3)	16%	10-30%	40-70%	-	1-5%	1-5%	-	-	No

3DCP

Material

Early-stage Tests

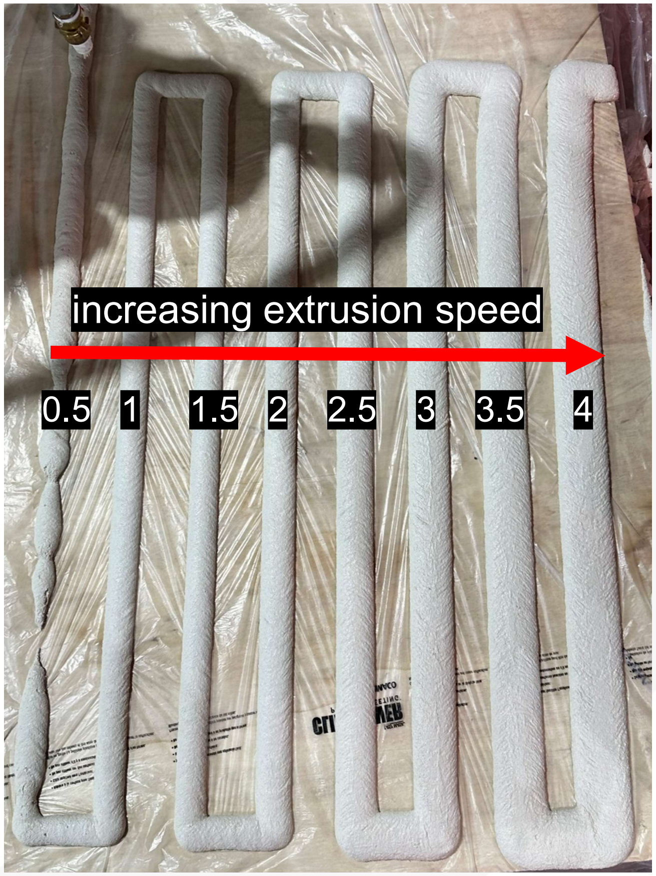
- Flow-table
- Shape retention
- Extrudability
- Buildability

Binder	Sand			Water	Additives			flow table @5min
Cement	Fine	Coarse	s/c		HRWR (% of cement)	VMA (% of cement)	UW 450 (% of cement)	
1	0.4	0.6	1	0.335-0.36	0.75	1	1	189.15

Material is Printable

Fresh properties

- Extrudability
  - Controlled both
    - Material
    - Speed or arm
    - Speed of pump



- Buildability
  - Build until you can't!

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

UND mix evaluation

Binder	Sand			Water (w/c)	Additives		Note
Cement	fine	coarse	s/c		HRWR (% of cement)	VMA (% of cement)	
500	250	250	1	90 (0.18)	0	0	Not mixed
500	250	250	1	100 (0.2)	10 (2)	0	Not mixed
500	250	250	1	100 (0.2)	10 (2)	2.5(0.5)	Not mixed VMA expired
500	0	500	1	100 (0.2)	10 (2)	0	Mixed-stiff-no retention
500	250	250	1	100 (0.2)	15 (3)	0	Mixed-stiff-no retention

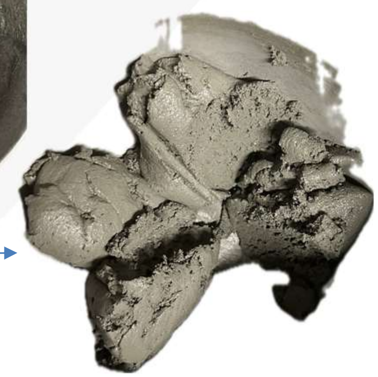




No VMA

Binder	Sand			Water (w/c)	Additives		Note
Cement	fine	coarse	s/c		HRWR (% of cement)	VMA (% of cement)	
500	250	250	1	150 (0.3)	0	0	Not mixed
500	250	250	1	200 (0.4)	0	0	too flowable
500	250	250	1	150 (0.3)	2.5 (0.5)	0	Well mixed
500	300	200	1	150 (0.3)	2.5 (0.5)	0	Well mixed- not homogenous
500	200	300	1	150 (0.3)	2.5 (0.5)	0	Well mixed- homogenous



Proposed Mix Design

Mix Id	Cement	FS	CS	s/c	w/c	HRWR (% of cement)
Mix 1	400	240	240	1.2	0.4	**0**
Mix 2	400	240	240	1.2	0.35	**0**
Mix 3	410	266.5	266.5	1.3	0.35	**0**
Mix 4 (AH)	500	200	300	1	150(0.3)	2.5 (0.5)
Mix 5 (AH)	500	200	300	1	160(0.32)	2.5 (0.5)
Mix 6 (AH)	500	200	300	1	170(0.34)	2.5 (0.5)
Mix 7	**400**	**240**	**240**	**1.2**	**0.37**	**0**

$f_c' = 4.7 ksi$

$f_c' = 6.8\ ksi$

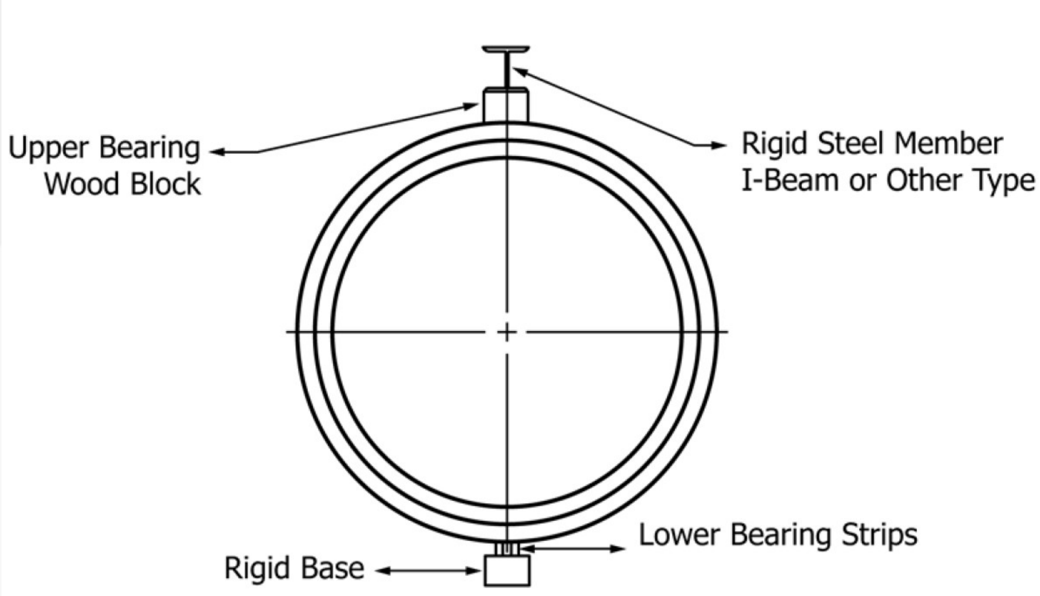
$f_c' = 9.2\ ksi$

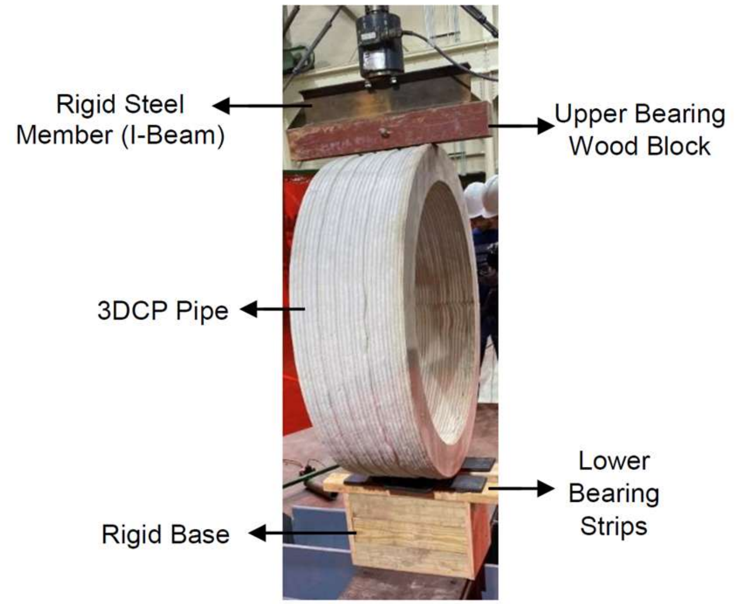
3d printing (Mix 7)

- 3d concrete printing of Mix 7 (without additives).
- Satisfied with the fresh properties results.
- Satisfied extrudability, buildability and printability.

Structural testing

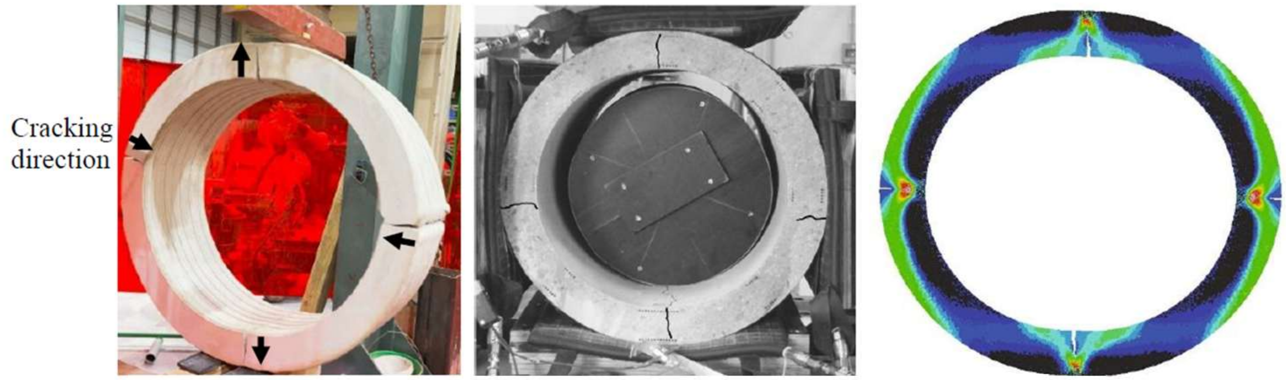
- Large scale samples
  - Varied diameter (18”-32” nominal diameter)
  - 1ft length (required length for Three-Edge Bearing test: ASTM C497)



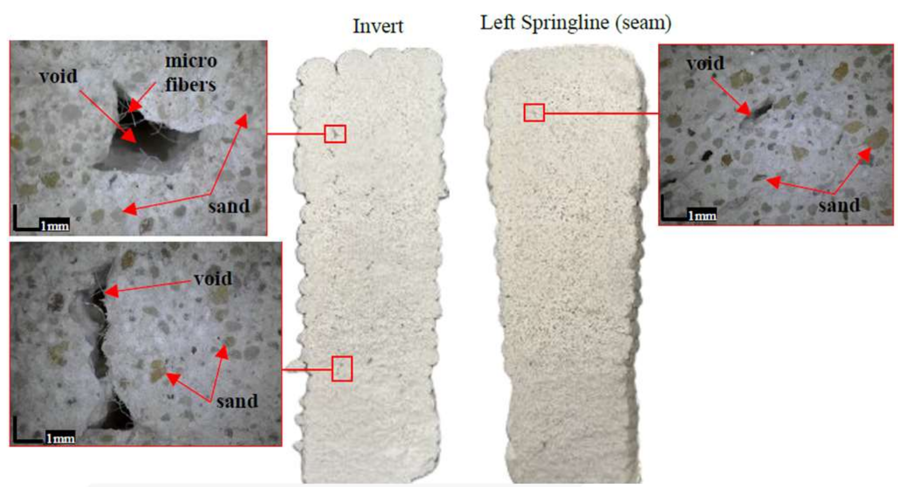


Takeaways from structural test

- Breaks similar to CIP pipes

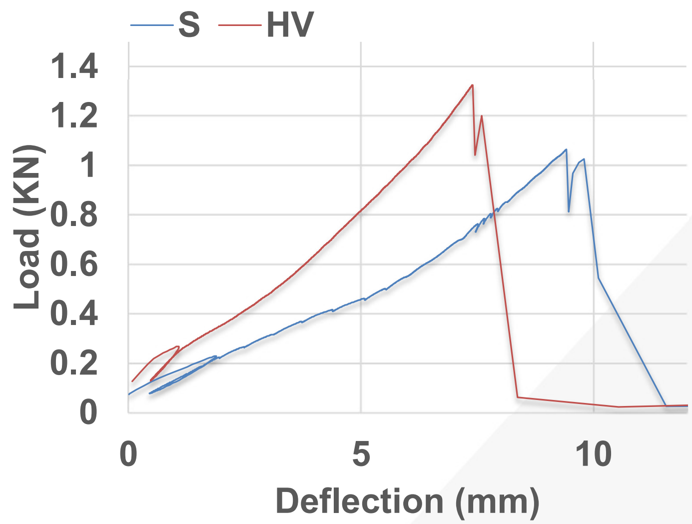


- Apparent voids (especially when fiber was introduced)

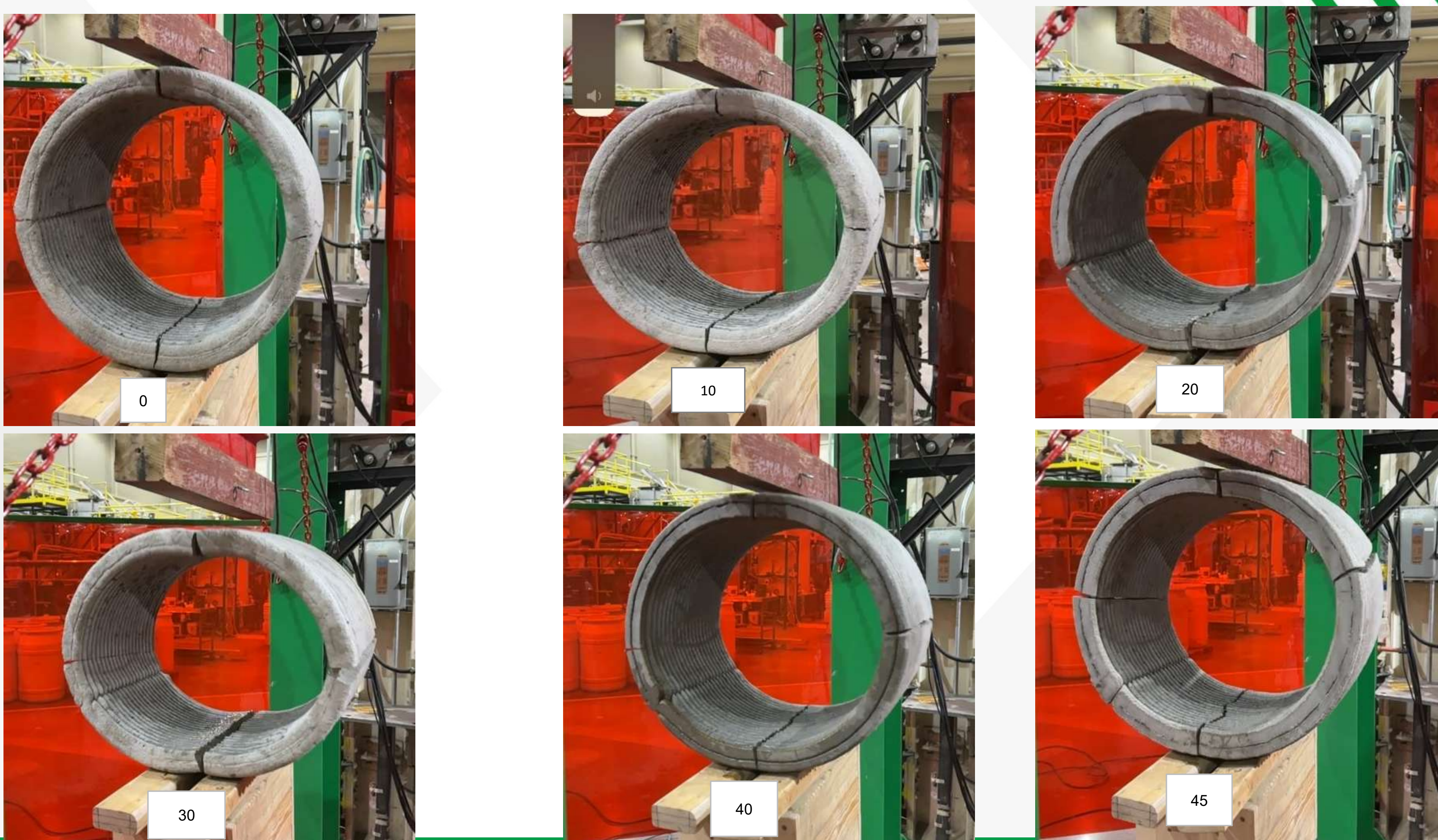


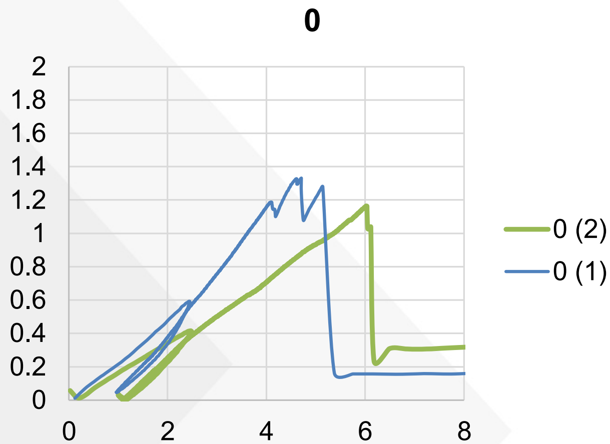
Structural properties

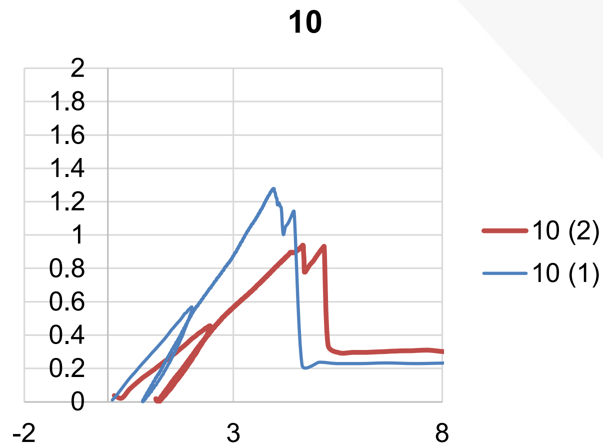
	Printed Pipes				Strength Requirements of Similar Pipes in ASTM C14			
Sample	Internal Diameter (in)	Thickness (in)	Length (in)	TEB Strength (lbf/linear ft)	Internal Diameter (in)	Thickness (in)	Minimum required TEB (lbf/linear ft)	Strength difference (% higher)
HV	33.75	5	11.75	6017	33	4.5	4875	**23**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

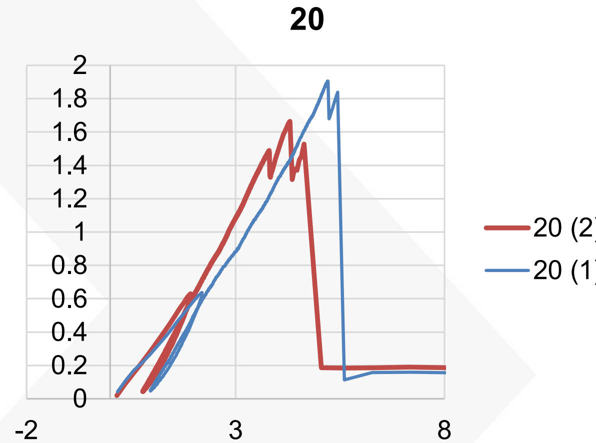


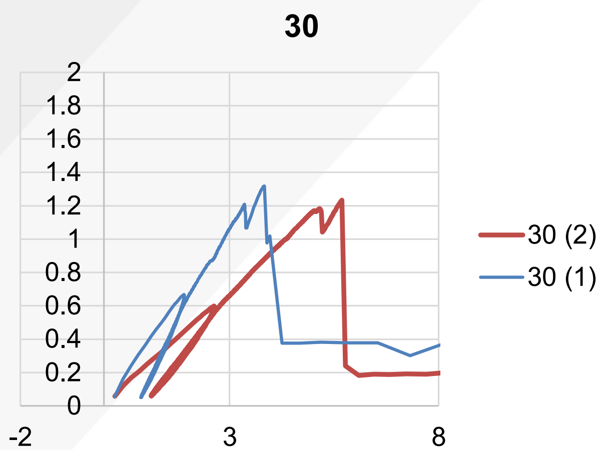
Seem section effect

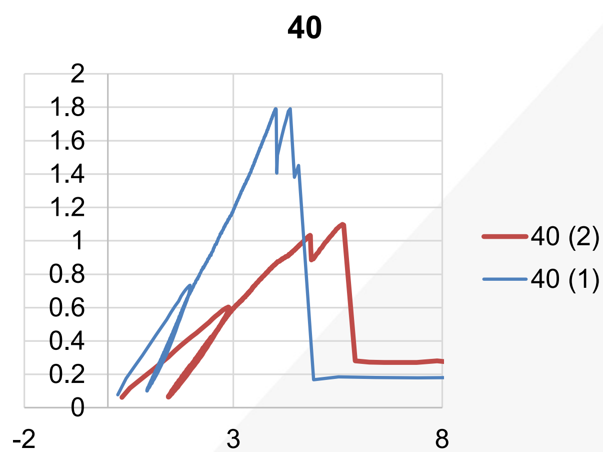


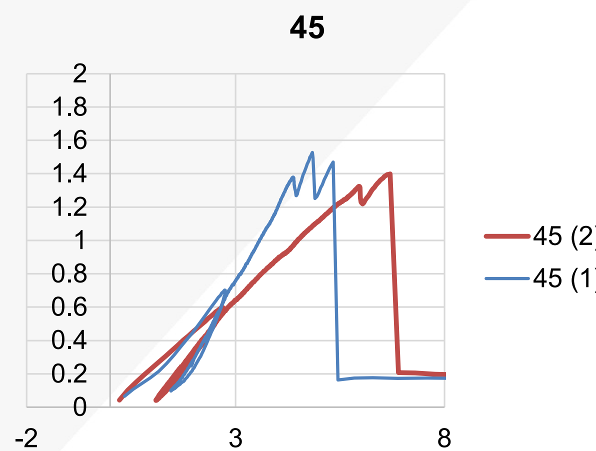

0
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
2
4
6
8
0 (2)
0 (1)


10
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-2
3
8
10 (2)
10 (1)


20
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-2
3
8
20 (2)
20 (1)

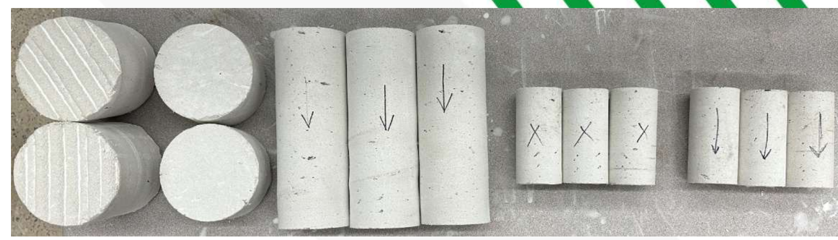

30
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-2
3
8
30 (2)
30 (1)


40
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-2
3
8
40 (2)
40 (1)


45
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-2
3
8
45 (2)
45 (1)

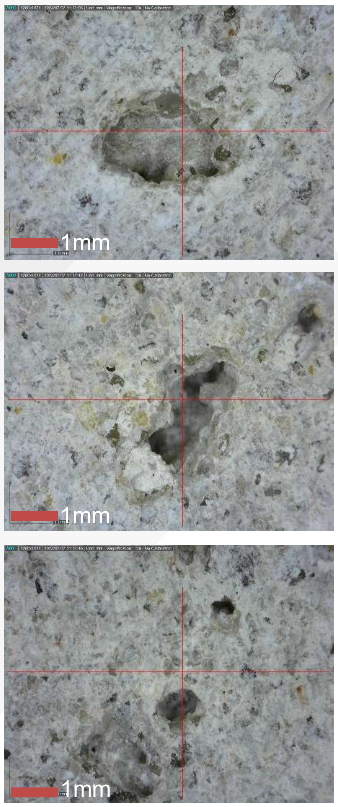
Mechanical properties

- 3DCP
  - Pipe
    - Early-stage
    - Structural
      - TEB
      - Seam
    - Mechanical (Vertico, Sika)
      - Compression: 4400 – 5200 psi
      - Tensile: 850 – 1200 psi
      - MOE: 3066 – 3440 ksi

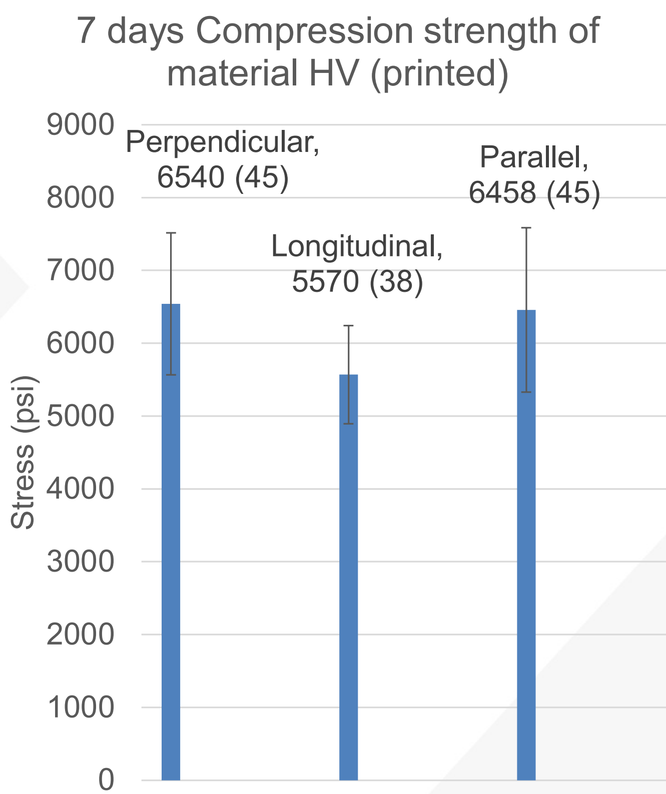


Mechanical properties

HV



Parallel



S

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

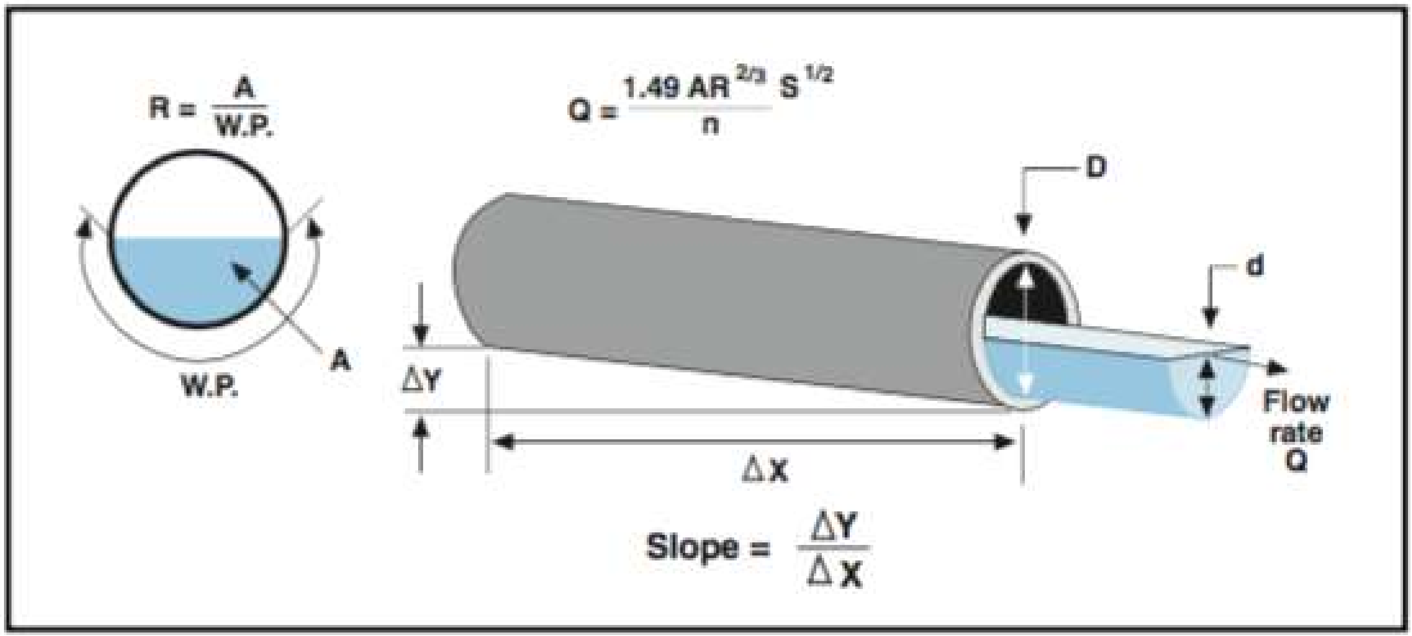
Hydraulic

- Manning Roughness Coefficient

$$Q = VA = (\frac{1.49}{n})AR^{\frac{2}{3}}S^{\frac{1}{2}}$$

Q = Flow Rate, (ft^3/s)
v = Velocity, (ft/s)
A = Flow Area, (ft^2)

n = Manning's Roughness Coefficient
R = Hydraulic Radius, (ft)
S = Channel Slope, (ft/ft)



Relative roughness

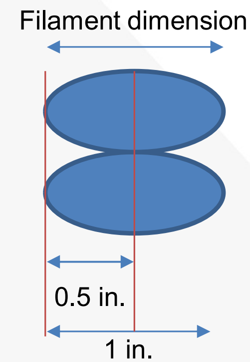
$$x = \frac{\varepsilon}{D}$$

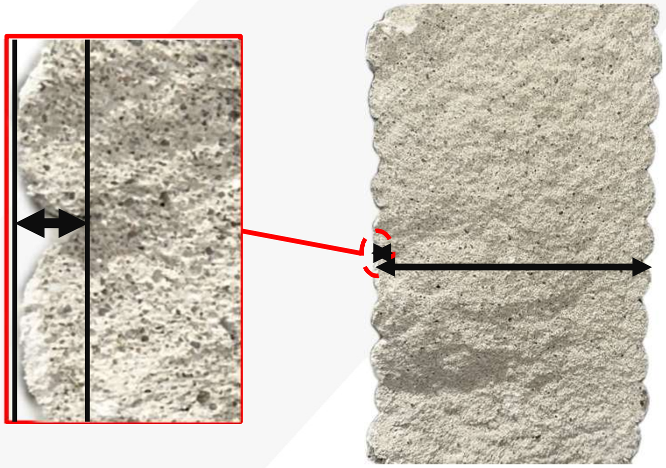
- ε → average height of surface irregularities
- D → pipe diameter

I: Considering half of the size of the filament as the roughness:

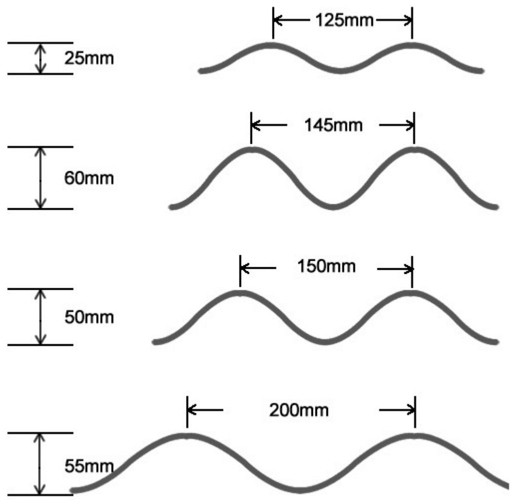
Filament size of 1 in. and Pipe diameter of 33 in.

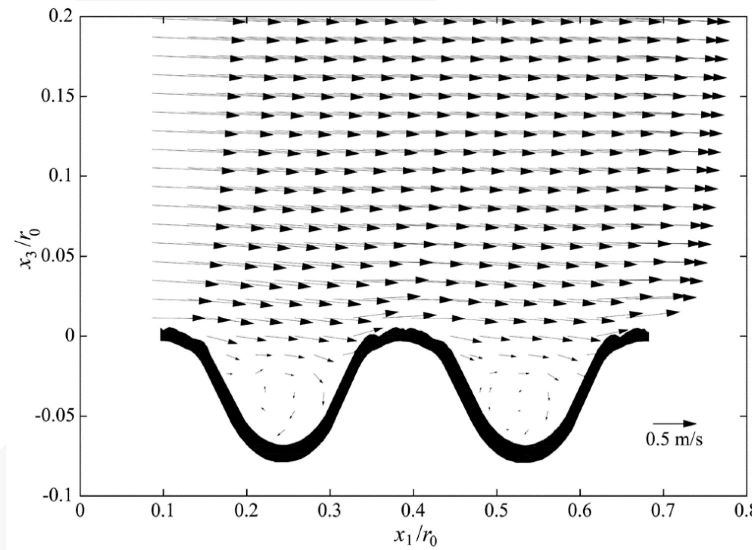
Relative Roughness $= \frac{0.5}{33} = 0.015$





Design tables for corrugated pipes

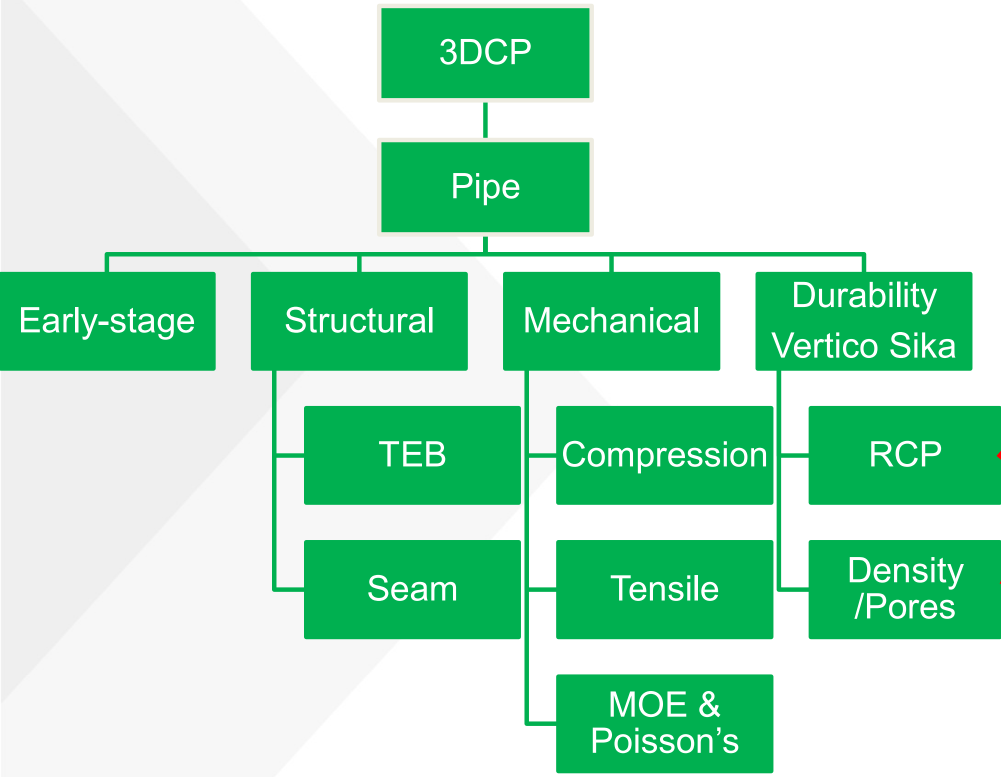


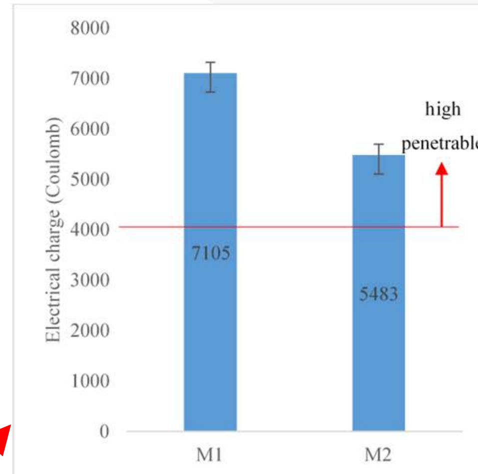


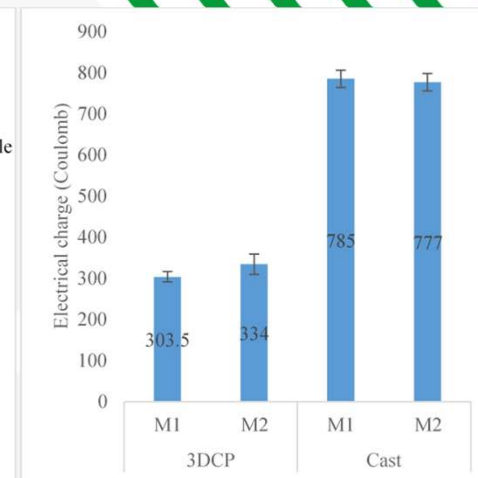
$$0.23 > n_{3DCP} > 0.13$$

Somewhere between reinforced concrete and corrugated metal pipes

Durability

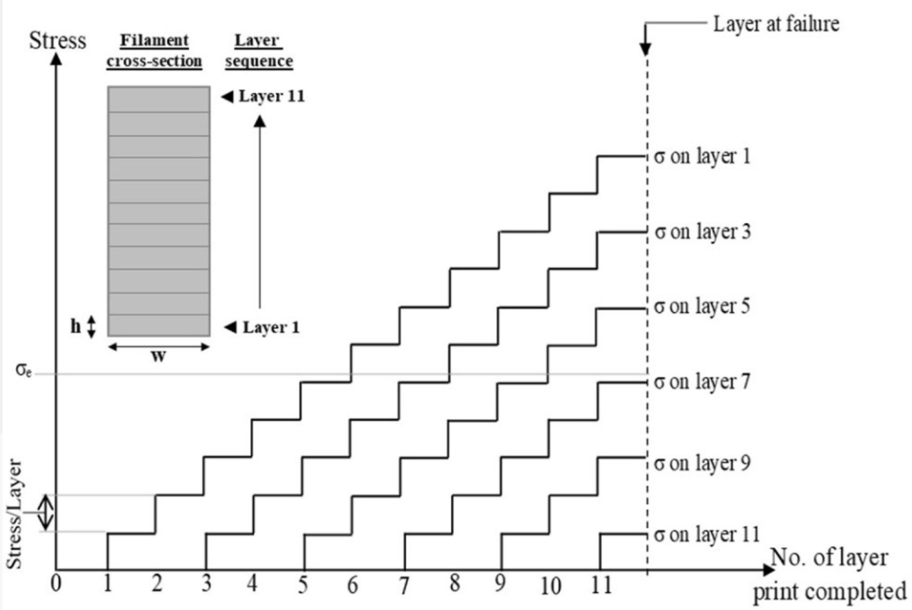




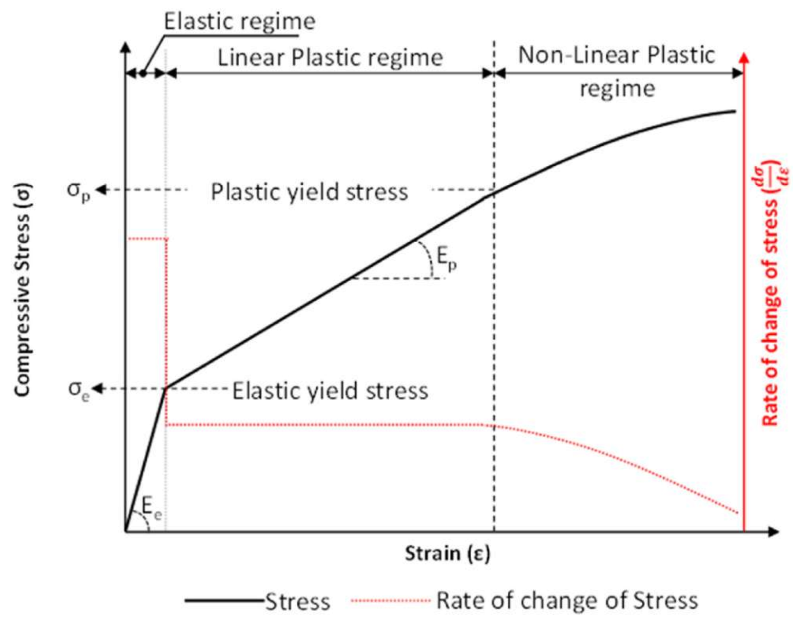


Specimens		ASTM C497	ASTM C642						
		Absorption (%)	Absorption after immersion (%)	Absorption after immersion and boiling (%)	Bulk density, dry (g/cm^3)	Bulk density after immersion (g/cm3)	Bulk density after immersion and boiling (g/cm3)	Apparent density (g/cm3)	Volume of permeable pore space (voids %)
3DCP Core	M1	11.55	10.68	11.55	1.96	2.17	2.18	2.53	22.62
	M2	11.90	11.21	11.90	1.94	2.16	2.17	2.53	23.12
Mold-Cast	M1	13.38	9.79	13.38	1.92	2.10	2.17	2.58	25.63
	M2	13.80	9.83	13.80	1.90	2.09	2.16	2.58	26.22
Difference between average of mold-cast and core specimens		1.87	-1.13	1.87	-0.04	-0.07	-0.01	0.05	3.05

Tolerance

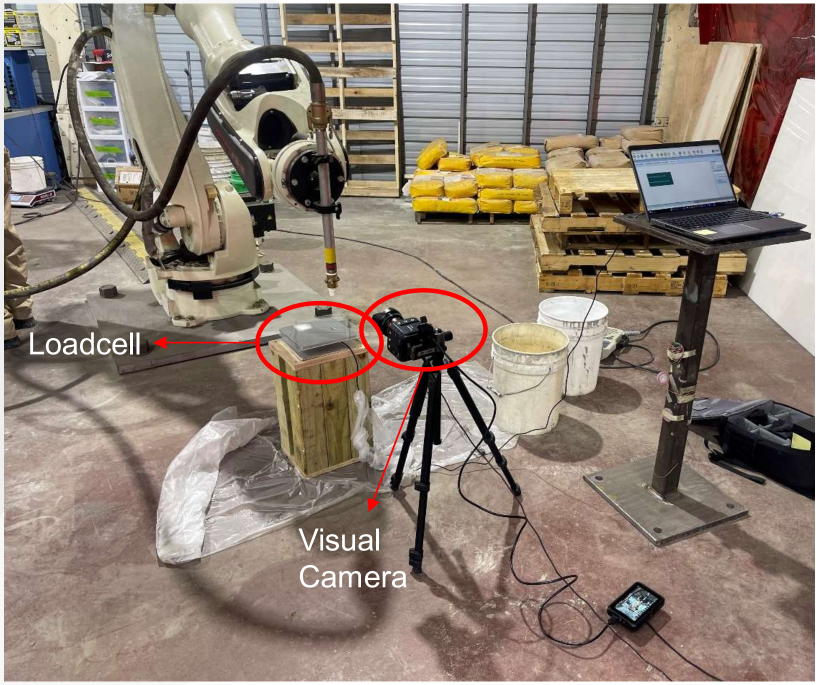


Stress
Filament cross-section
Layer sequence
Layer 11
Layer 1
Layer at failure
σ on layer 1
σ on layer 3
σ on layer 5
σ on layer 7
σ on layer 9
σ on layer 11
h
w
σ_e
Stress/Layer
0 1 2 3 4 5 6 7 8 9 10 11
No. of layer print completed



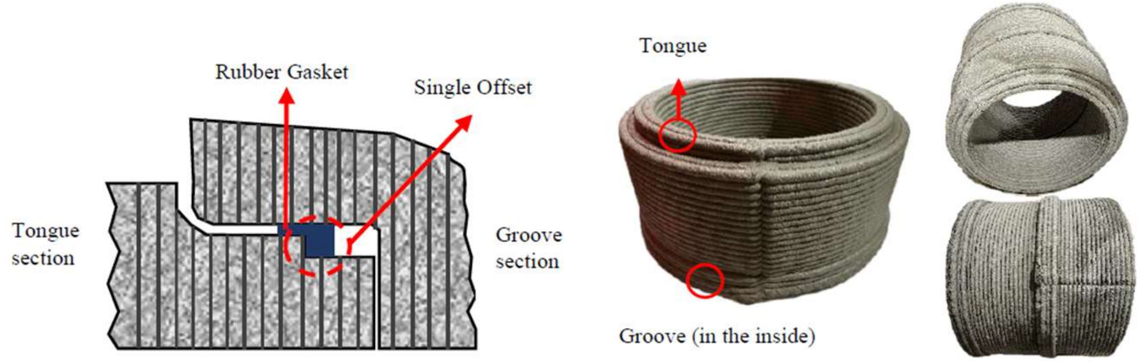
Elastic regime
Linear Plastic regime
Non-Linear Plastic regime
σ_p
Plastic yield stress
E_p
σ_e
Elastic yield stress
E_e
Compressive Stress (σ)
Rate of change of stress $\left(\frac{d\sigma}{d\varepsilon}\right)$
Strain (ε)
Stress
Rate of change of Stress

Quality control (during construction)



Connections

- Print tongue and groove



- Use of sealant and ties

Tongue and groove

Dried printed base with a layer of plastic and mold oil

Pipe Joints Types Illustrated

We have tried something similar to the top 2 without the tapers or offsets.

Confined

Single Offset

The bottom one is what was referred to as a “highway” joint. Notice no bell, just a flat outer surface.

Tongue And Groove

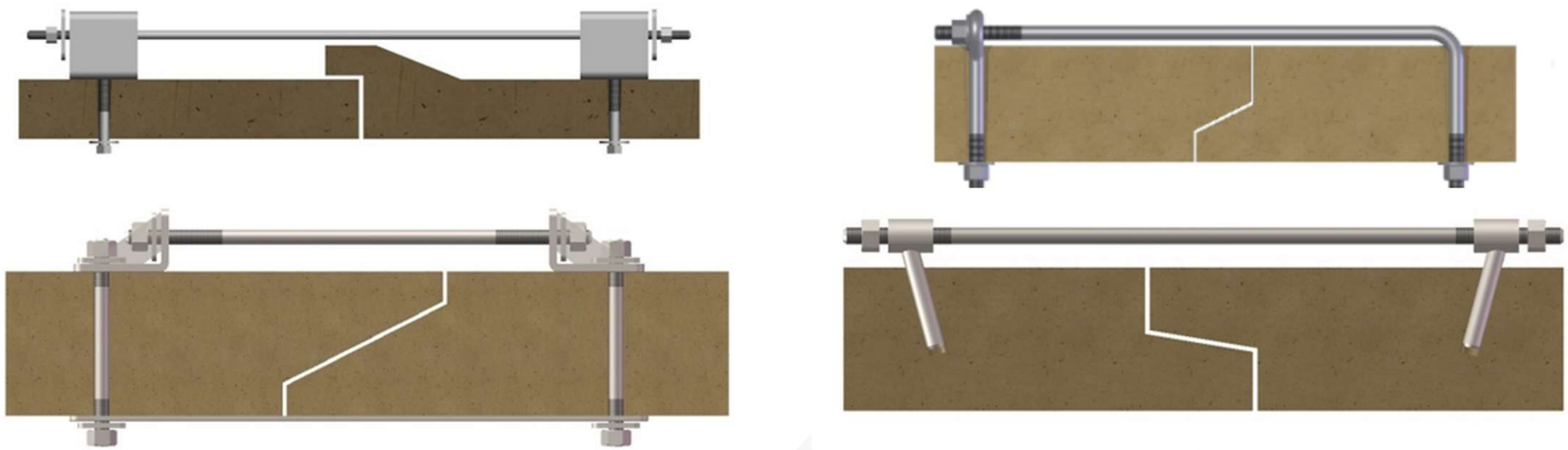
Photo from Rinker’s website: https://www.rinkerpipe.com/a-complete-guide-to-reinforced-concrete-pipe/

Connection

- Pipe Ties

(Not different than conventional precast)

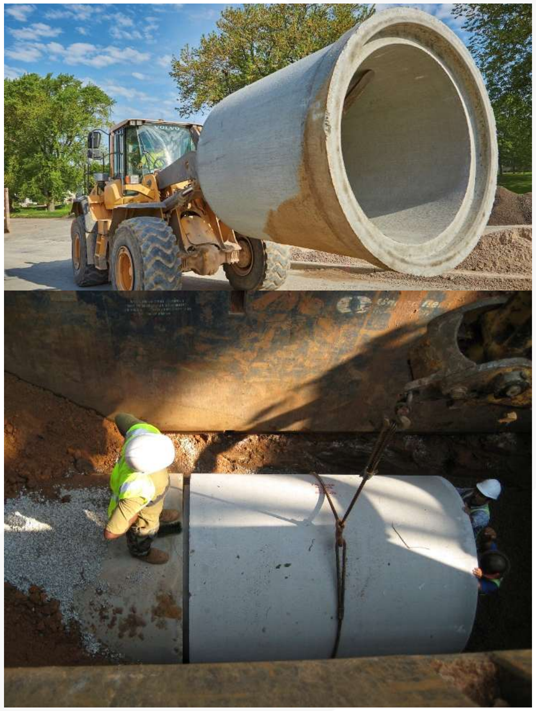
Readily available for purchasing



Transportation

- Using Hooks

Simple Methods



Limitation

- Reinforcement placement
- Lack of standard
    - – NIST

PROJECTS/PROGRAMS

Additive Manufacturing with Cement-based Materials

Summary

Additive Manufacturing (AM) with concrete, also known as 3-D Concrete Printing (3DCP) and more recently Additive Construction (AC) with concrete, is an emerging and rapidly evolving technology in the construction industry. This approach to concrete construction has the potential to change the way cementitious materials are used to create infrastructure components. Automating the placement of concrete materials may improve construction efficiency by eliminating the need to erect formwork, improve infrastructure durability by providing precise control of concrete formulations, and improve construction safety by removing humans from hazardous working environments. Rapid construction enabled by 3DCP techniques can provide shelter to communities affected by natural disasters, build with local materials in hostile environments (e.g., military and mining applications), build taller wind turbine towers to access higher energy winds, and repair concrete in areas which are hard to access with conventional construction equipment. The concrete design and engineering community lacks sufficient knowledge about the performance of 3DCP structures subjected to designed loading scenarios to properly design 3DCP structures for a given application. The role of the printing process in determining the failure mode and a detailed understanding of the relationship between the 3DCP structure's constituent material properties and structural response are critical to developing performance-based standards and guidelines for 3-D printing construction techniques. Developing this knowledge base and coupling it to measurements of concrete materials in the 3DCP process would mark a significant step toward revolutionizing concrete construction.

ORGANIZATIONS

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Infrastructure Materials Group

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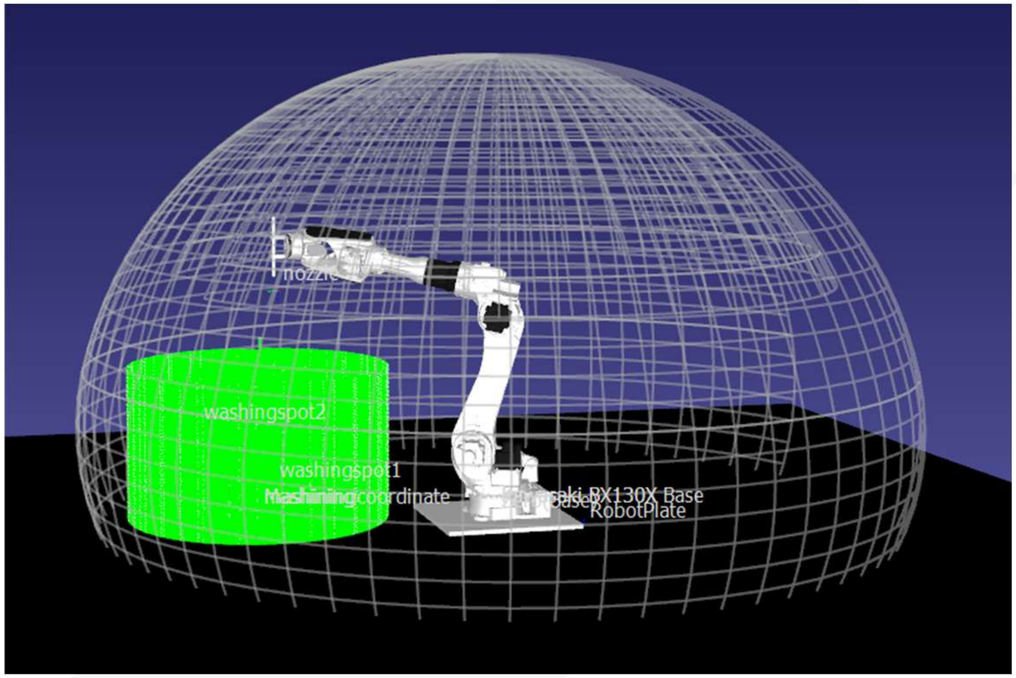
PROJECT STATUS

ONGOING

Printing system limitation

$d = 36\ in, t = 4\ ¾\ in\ \ h = 4\ ft$



Main Takeaways

- Unreinforced 3DCP pipes meet AASHTO strength and roughness requirement
- Manning and roughness can be controlled by the printing system
- Continuous longitudinal seam section orientation affected structural properties during TEB
- 3DCP pipe segments can be successfully connected with printed tongue and grove
- No additive mixes can be printed
- Both strength and deflection varied between identical pipes
  - Appropriate factors of safety must be developed

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3DCP-PF and PPC Composite Action

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Why Box Culverts?

- Box culverts are:
  - Widely used in transportation infrastructure
  - Repetitive, formwork-intensive structures
  - Labor- and time-consuming to construct

- Conventional construction challenges:
  - Complex formwork assembly
  - High labor cost
  - Limited geometric flexibility

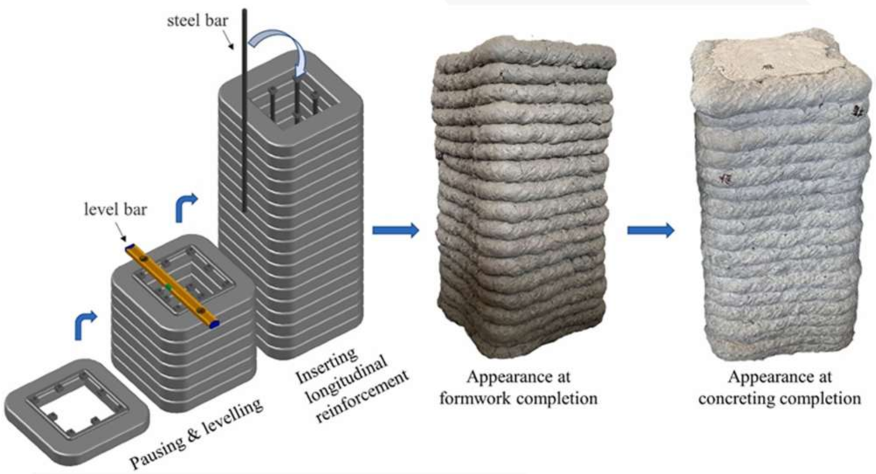
Opportunity for 3DCP Formworks

- Permanent formwork eliminates removal
- Enables modular and optimized cross-sections
- Potential structural contribution from printed shell
- (composite action)
- Faster construction

(3x4ft formwork)

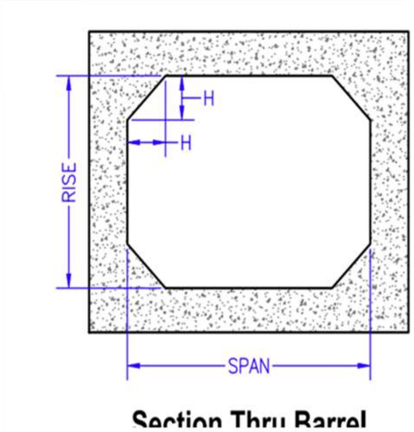
Reinforcement Techniques in 3DCP (Overview)

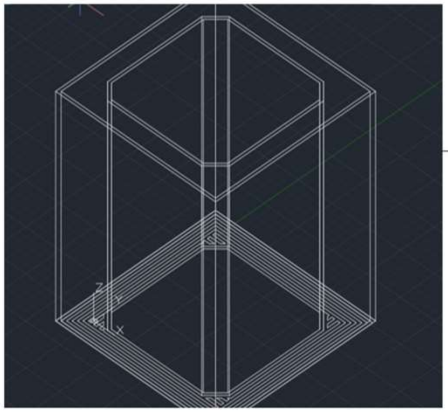
- Conventional steel bars inserted post-printing
- Embedded reinforcement during printing
- Mesh or cage placement inside printed shells
- Fiber-reinforced printable concrete
- Mechanical interlock features



Methodology

- 3D Concrete Printed 3x4 box culvert formwork
- Mesh reinforcement installed after printing
- Testing Protocols: Splitting tensile tests, bond strength tests, and full-scale Beam Tests.





Reinforcement Design

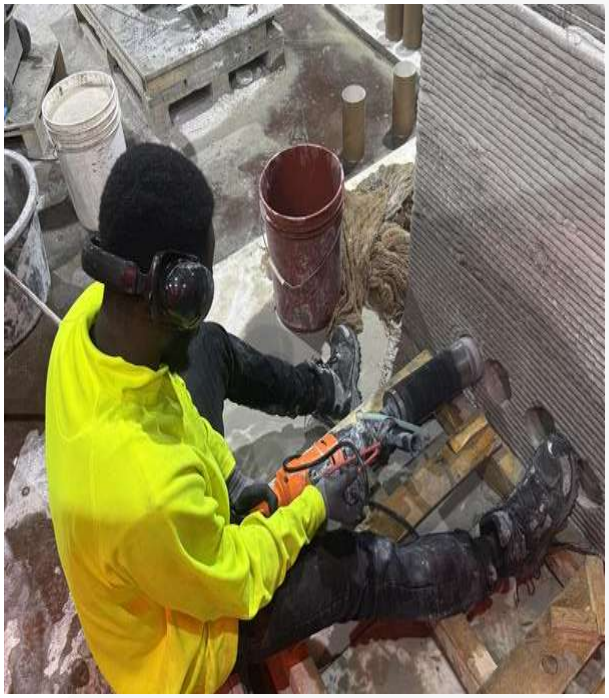
Assembling rebars (4in spacing)

Final Rebar

Placing the rebar cage in the formwork

Testing of samples

- 7-day compressive strength
- 7-day Tensile strength
- Visual/dimensional inspection vs ASTM C1577



Results -7 days Compressive strength Test

Sample	3DCP (psi)	PPC(psi)	3DCP + PPC (psi)
TEST 1	6251	5442	4108
TEST 2	6467	5802	3368
TEST 3	6122	5494	3336
	6280	5579.333333	3604

Results -7 days Splitting Tensile strength Test

sample	3DCP(psi)	PPC(psi)	3DCP + PPC (psi)
TEST 1	288	436	230
TEST 2	351	329	271
TEST 3	330	324	257
	323	363	252.66

Failure Modes

3DCP-PF

PPC

3DCP-PF and PPC

Observations from Compressive Failure

- Compressive stress did not propagate through the full height of the specimen
- Failure was localized near the top region, while the lower portion remained largely intact
- No full-height splitting cracks observed, indicating non-uniform stress distribution

Limitations

- Reinforcement Integration
- Coring and Penetrations Through Embedded Reinforcement
- Buildability and Material Constraints
- Composite Action Uncertainty
- Construction Tolerances and Quality Control