ACI Convention, Orlando, Mar 27, 2022

Influence of Alkali Free Accelerators on the Early Age Properties of 3D Printable Concrete

INDIAN INSTITUTE OF TECHNOLOGY MADRAS
सिद्धिर्भवति कर्मजा

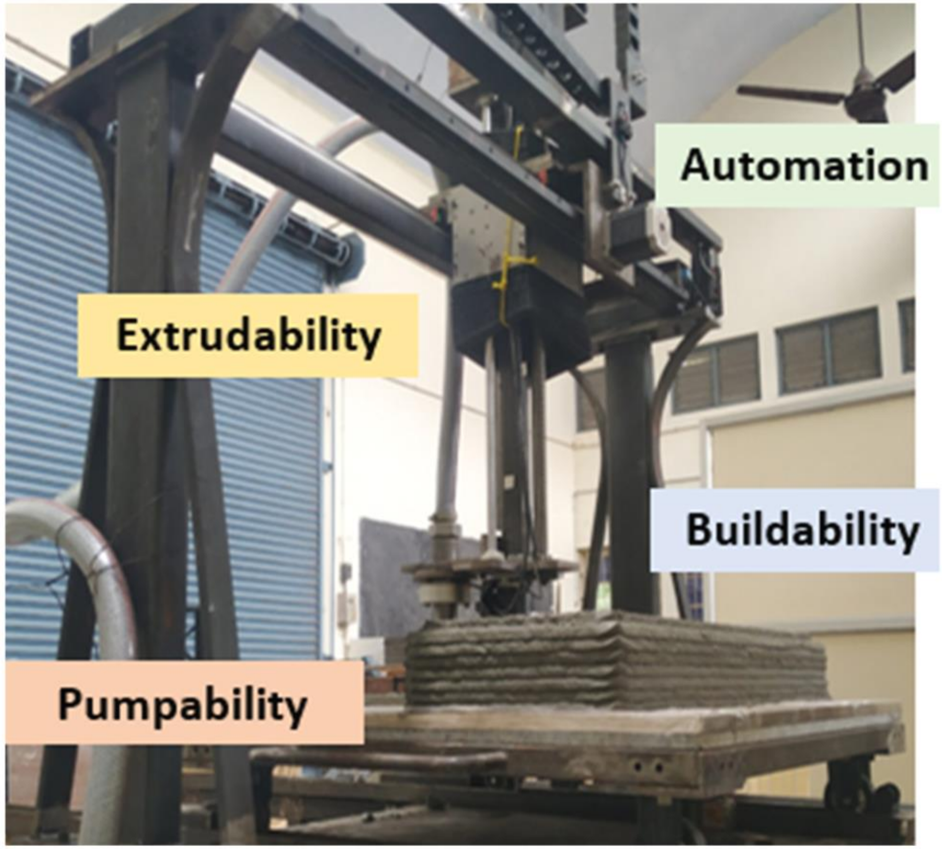
Shantanu Bhattacherjee, PhD Candidate
Manu Santhanam, Professor
With inputs from Adithya V S (Tvasta Manufacturing Solutions)

Outline

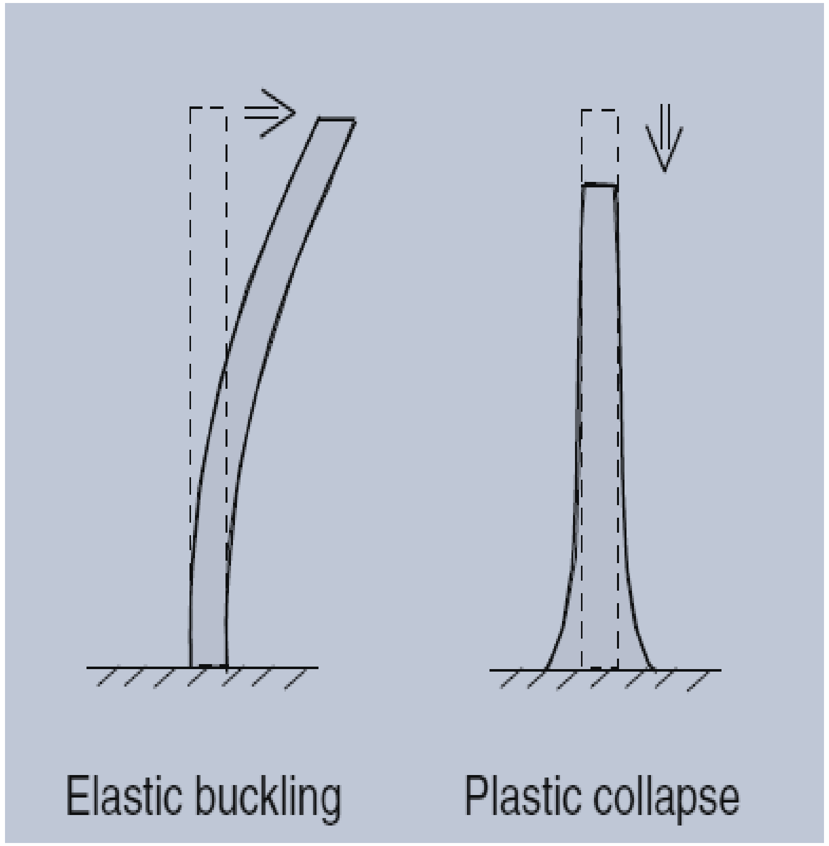
- Background and context
- Test methods for assessing buildability-related performance
- Use of alkali free accelerators – different methods of application
- Use of the squeeze flow test for evaluation
- Alternative binder for buildability
- Portfolio of 3D printed structures

Background and context

- Critical parameters for 3D printing
  - Pumpability
  - Extrudability
  - Buildability
  - Evolution of mechanical properties
  - Geometric tolerance
- Buildability
  - Relates to the retention of geometry when subsequent layers are placed
  - Forms the link between the properties governing early age behaviour and the mechanical characteristics



Failure modes of 3D printed elements



Failure modes
(Suiker 2018)

With improved buildability, both failures can be overcome to a large extent…

Buildability depends on:

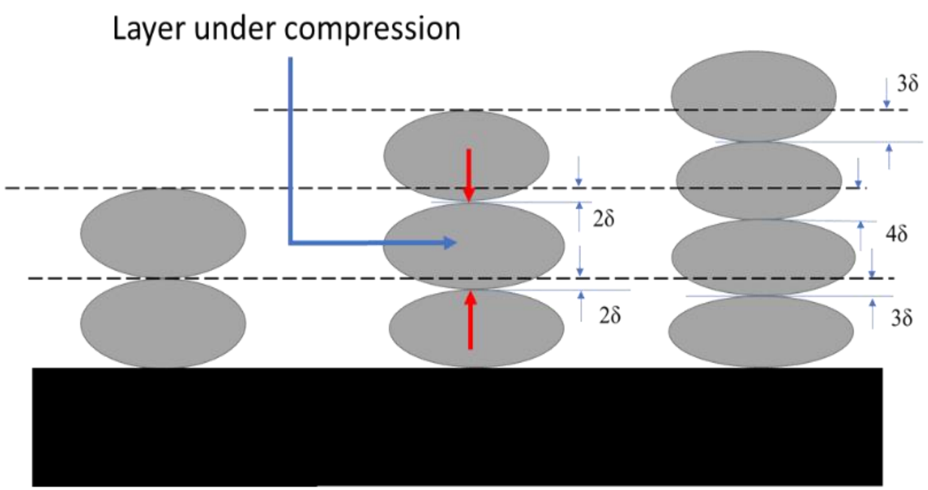
Rheological Performance

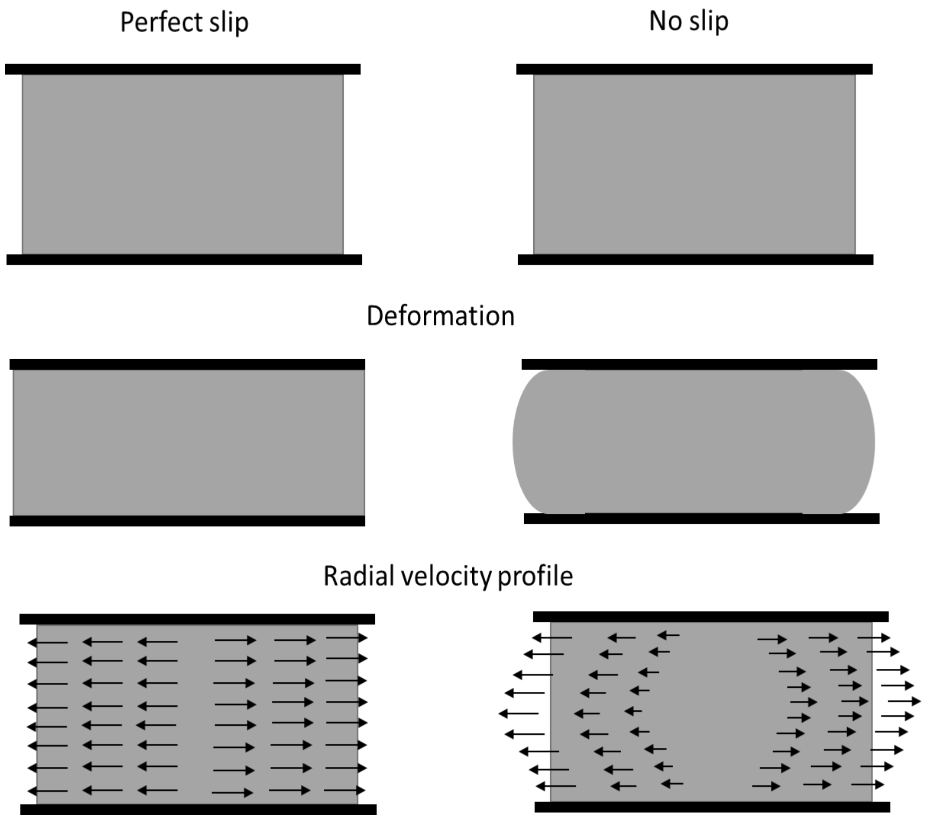
- Shear yield stress
- Recovery of original viscosity and yield stress before the deposition of next layer.
- Printing time gaps

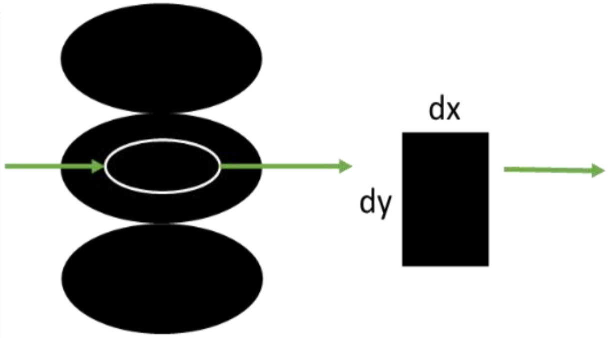
Mechanical Performance

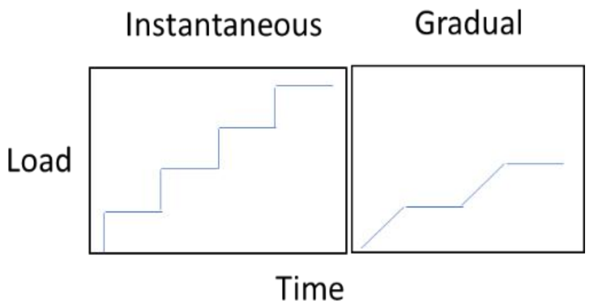
- Early age mechanical properties
- Time gap
- Compressive stress-strain behaviour with time - Transition from plastic-flow to brittle failure (elastic).

Compression of layers in 3D printing – considering yield stress fluid







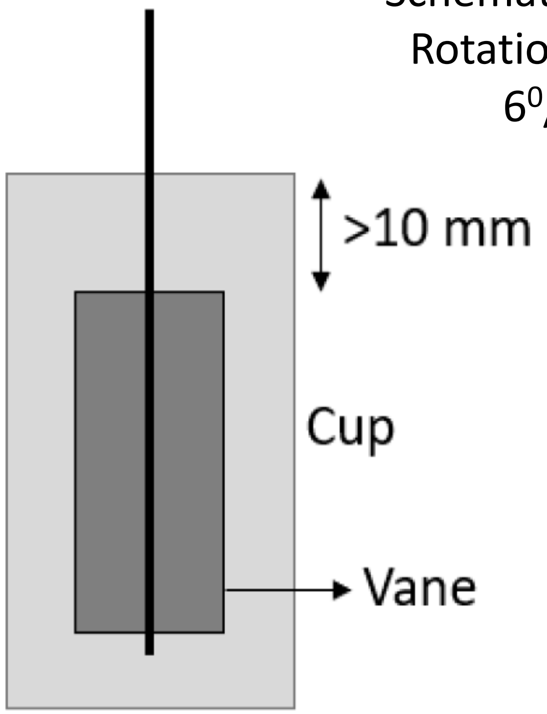


Both load profile and boundary condition are critical

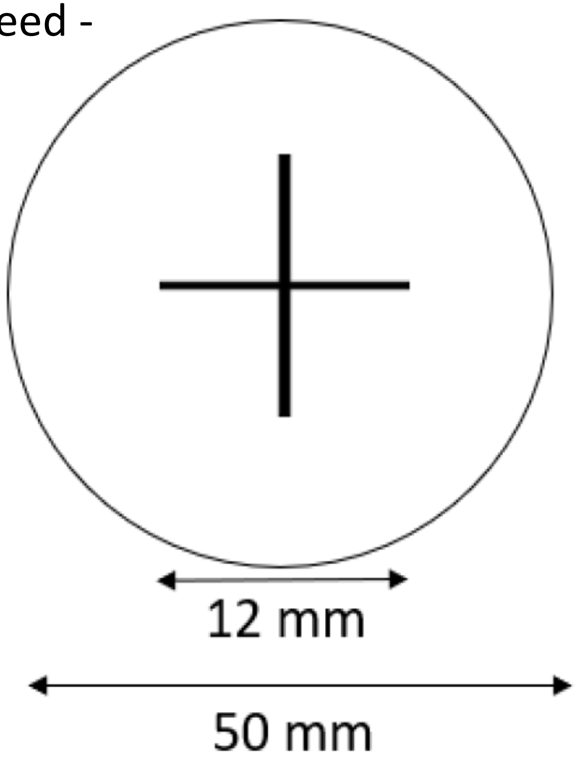
Test methods for assessment

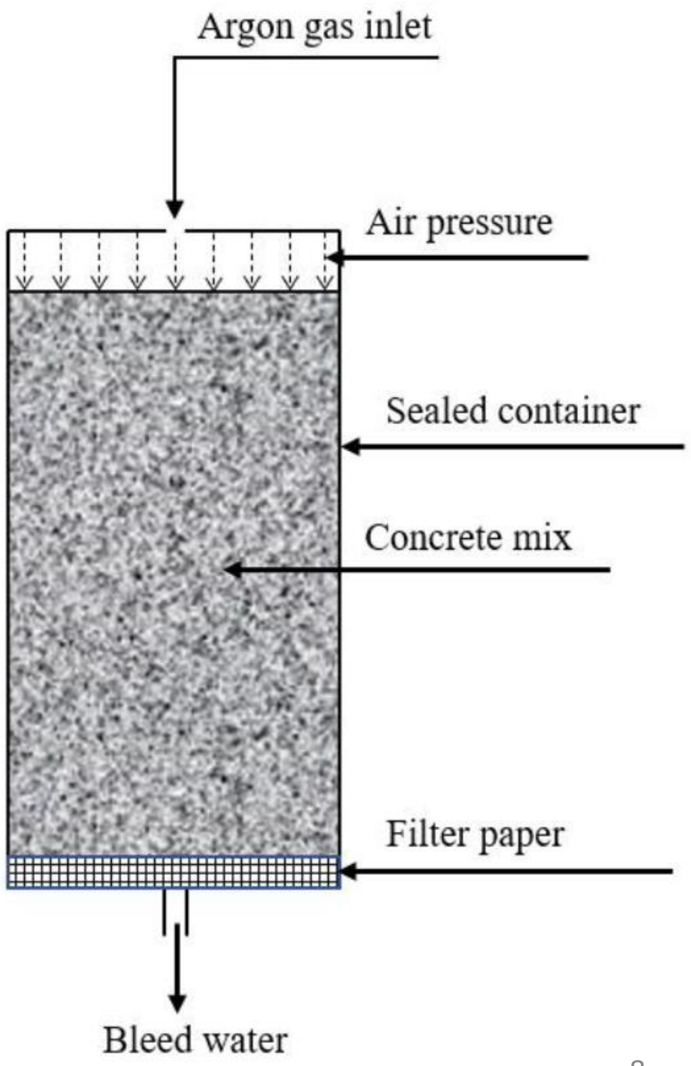
- Vane shear test for yield stress measurement
- Flow table test for workability retention
- Penetration resistance test for setting time
- Forced bleed test for resistance to phase separation
- Squeeze flow test for link between rheological and very early age mechanical characteristics
- Early and later age compressive strength

Vane shear and forced bleed tests

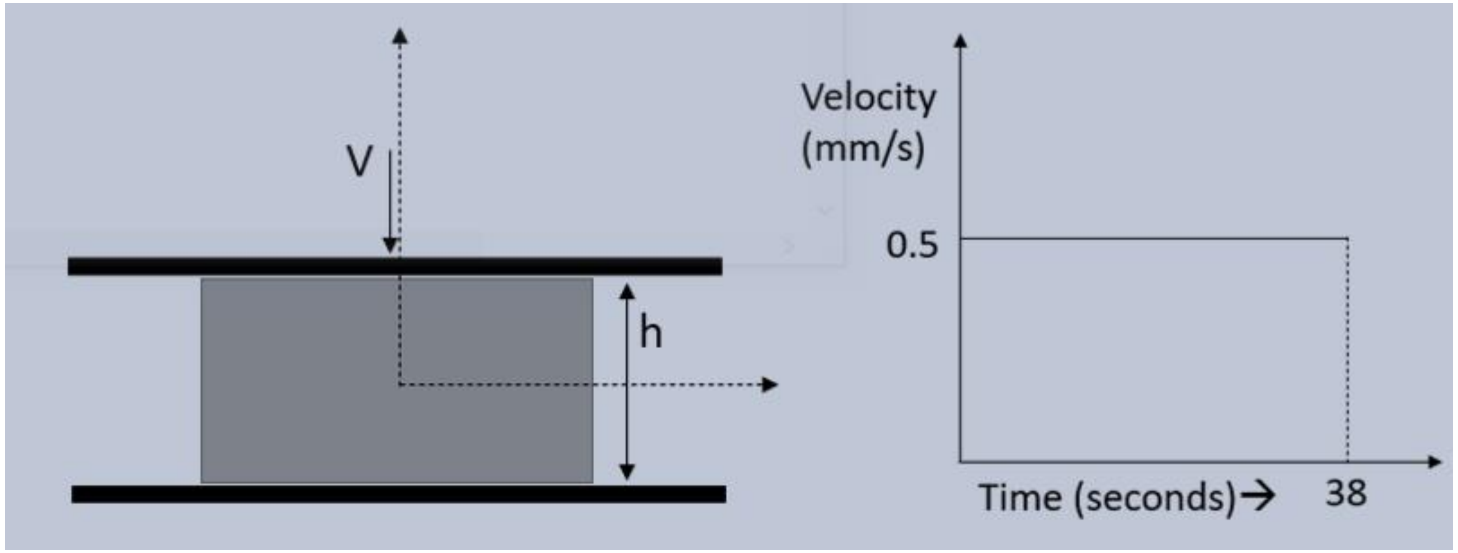


Schematic diagram
Rotation speed - 6^0/min





Squeeze flow test

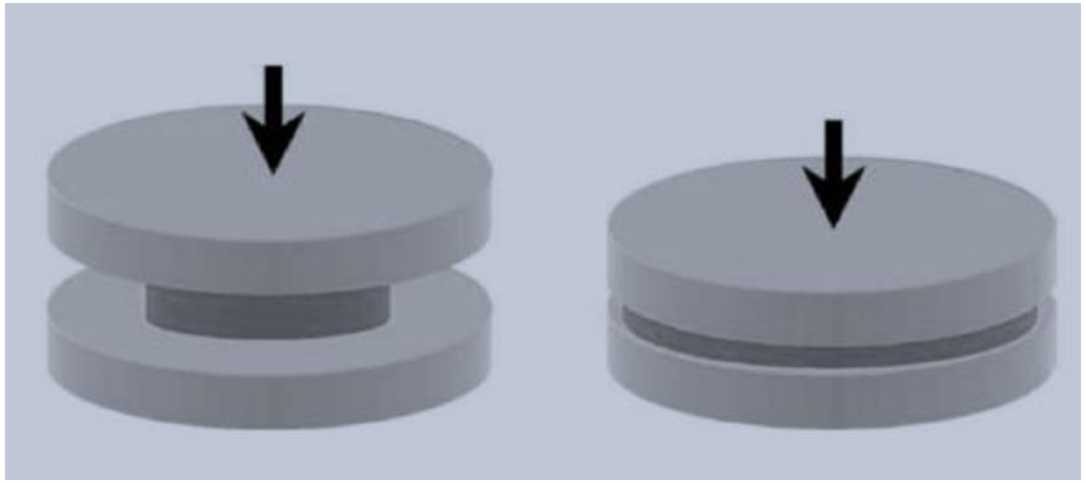


$$True\ strain = ln\,(1 - \varepsilon)$$

$$True\ stress = \sigma_0\,(1 - \varepsilon)$$

$$\sigma_{zz} = -p_0 - \sqrt{3}\tau_y + 3\eta(\sqrt{3}|\dot{\varepsilon}|)\dot{\varepsilon}$$

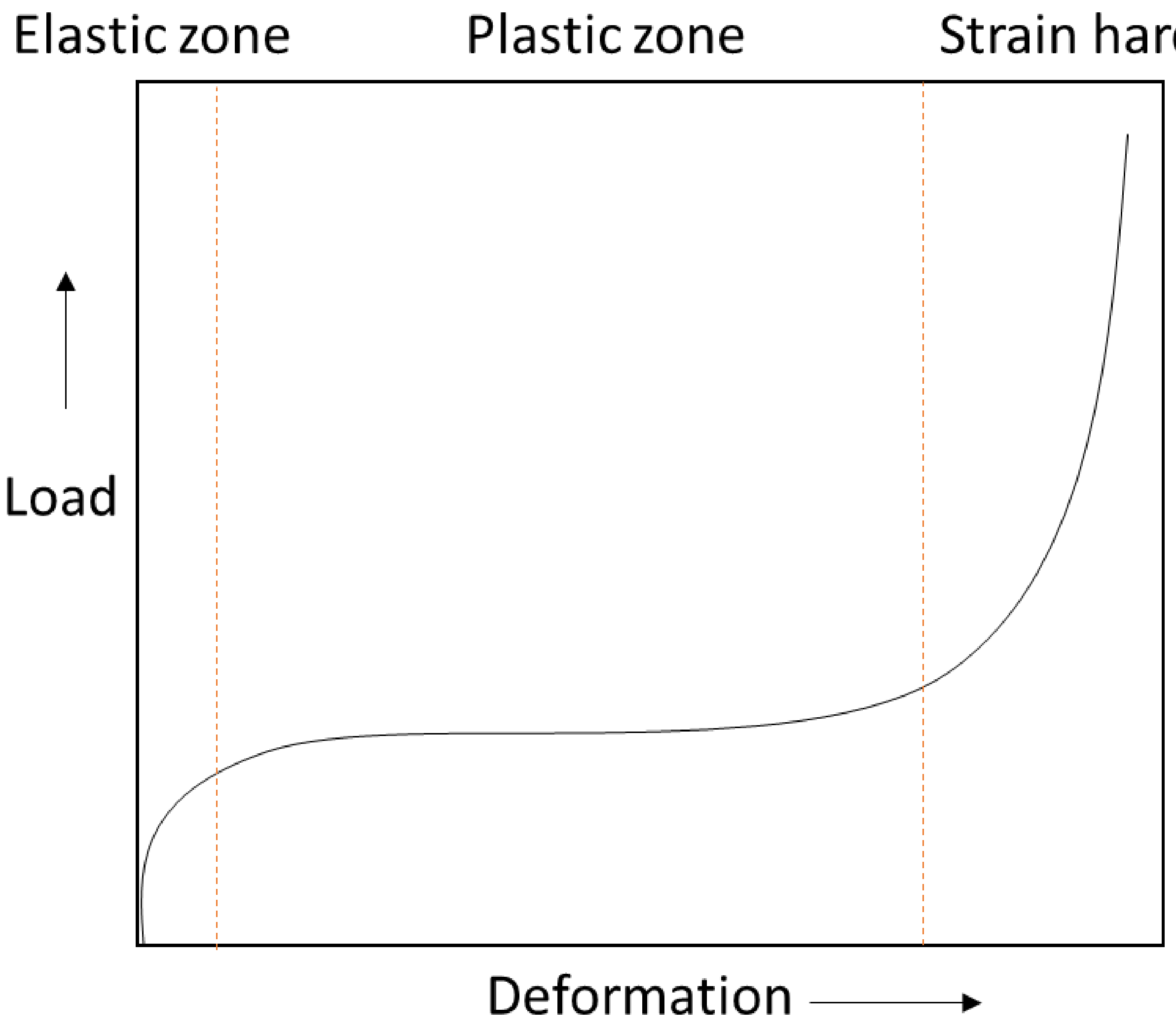
- Constant volume

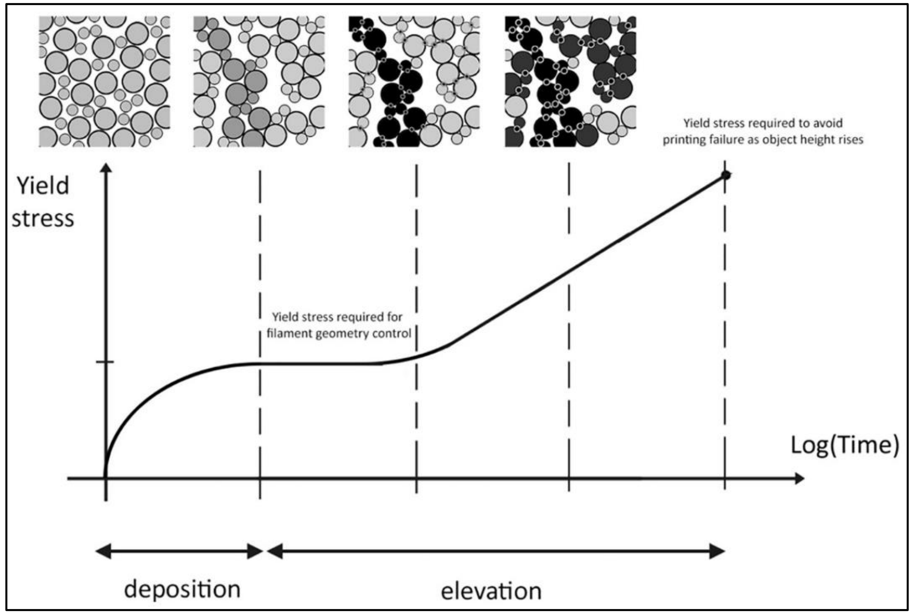


P_0 – Ambient pressure
τ_y – Yield stress of the material in simple shear
η – Shear viscosity
$\dot{\varepsilon}$ – Compression rate

Engmann et al. 2005

Behaviour in the squeeze flow test





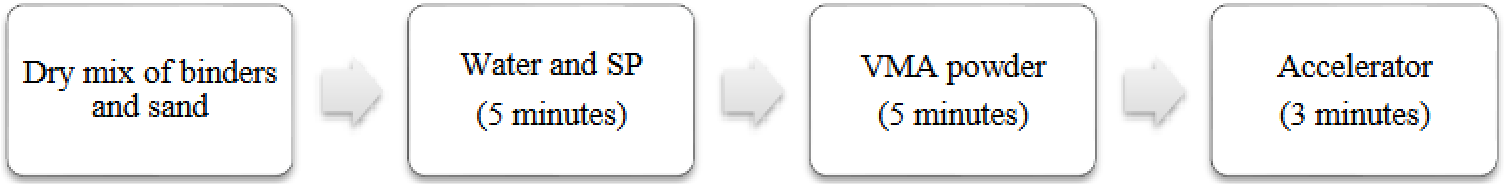
Yield stress vs log Time with microscopic structure evolution
(Wangler et al. 2019)

Measures to improve buildability

- Faster hardening cements
  - CSA binders
  - Rapid hardening cements
  - Limestone calcined clay cement
- Use of accelerating admixtures
  - Admixed
  - Added at the nozzle
  - Sprayed
- Increasing amount and size of aggregate

Study on alkali free accelerators

- Mix design
  - Cement : Fly Ash (Type F) = 0.8:0.2
  - Quartz sand (max size 2 mm) = 1.5
  - Water to cementitious materials ratio = 0.32
  - PCE based superplasticizer and HPMC VMA
  - Alkali-free aluminium sulphate-based accelerator – aluminium sulfate octadecahydrate (50 - 100%) and diethanolamine (2.5 – 10%)
- Mixing sequence



Flow table results

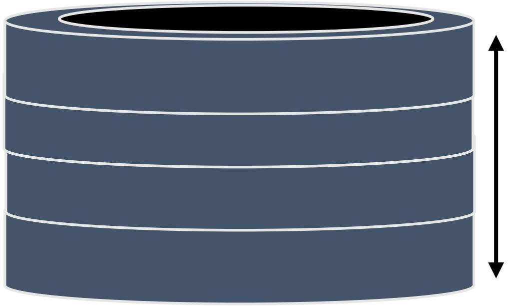
Mix	Time after mixing	Spread (%)	Reduction in spread with respect to initial flow (%)	Remarks
Control mix (No accelerator)	Initial	80±3	16.25	Workable
	After 30 mins	67±2		Workable
Mix with 1% accelerator	Initial	55±3	18.18	Workable
	After 30 mins	45±1		Workable
Mix with 2% accelerator	Initial	50±2	44	Workable
	After 30 mins	28±2		Very Stiff
Mix with 3% accelerator	Initial	40±2	62.5	Stiff
	After 30 mins	15±1		Very stiff

Vane shear results

Accelerator (%) by weight of the binder	Yield stress at 5 minutes (kPa)	Yield stress at 30 minutes (kPa)	Slope (considering linear rate) (kPa/min)
0 (Control mix)	1.75 ± 0.1	2.3 ± 0.1	0.022
1	2.5 ± 0.2	3.3 ± 0.35	0.032
2	2.7 ± 0.5	4.23 ± 0.45	0.061

Considering the pump can extrude a mix with static shear yield stress of around 2.5 kPa (Rahul et al. 2019):

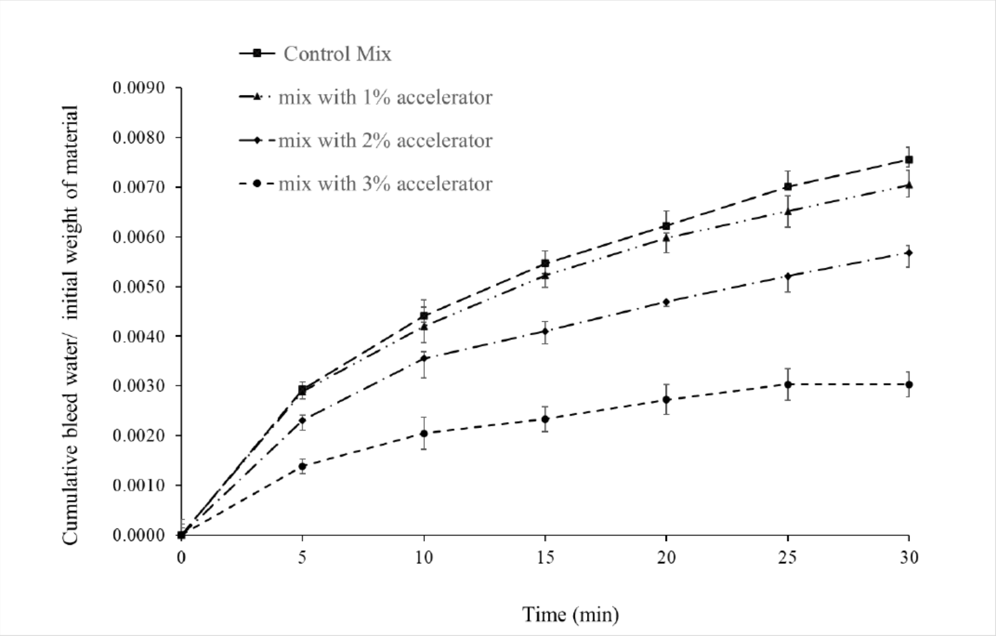
- Mix with 2% accelerator might not get extruded properly.
- 2% accelerator cannot be added at the mixer
- Printable open time will be critical for accelerated mixes.

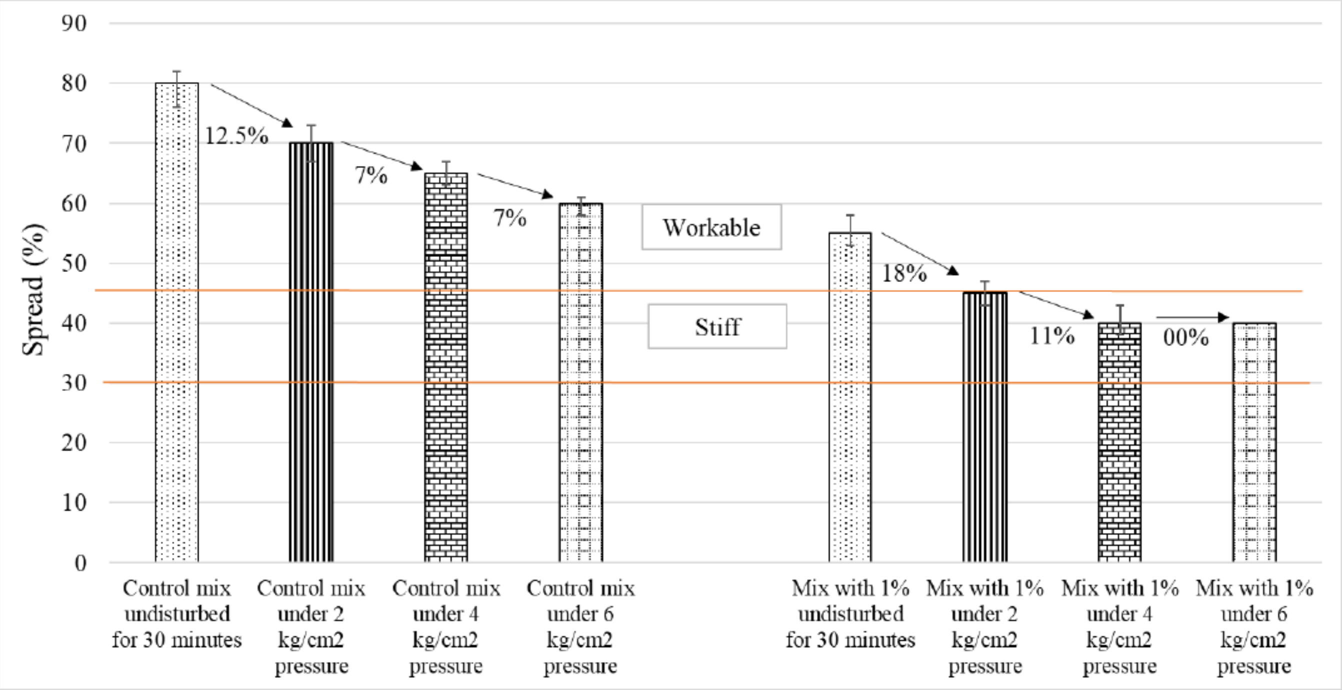


$$\tau = \frac{\rho g h}{\sqrt{3}}$$

- Considering it takes 30 minutes to print 300 mm height cylinder.
- Shear stress at bottom will be 3.95 kPa.
- Which is more than the static yield stress of mix with 1% accelerator.

Forced bleed results (and flow after forced bleed)

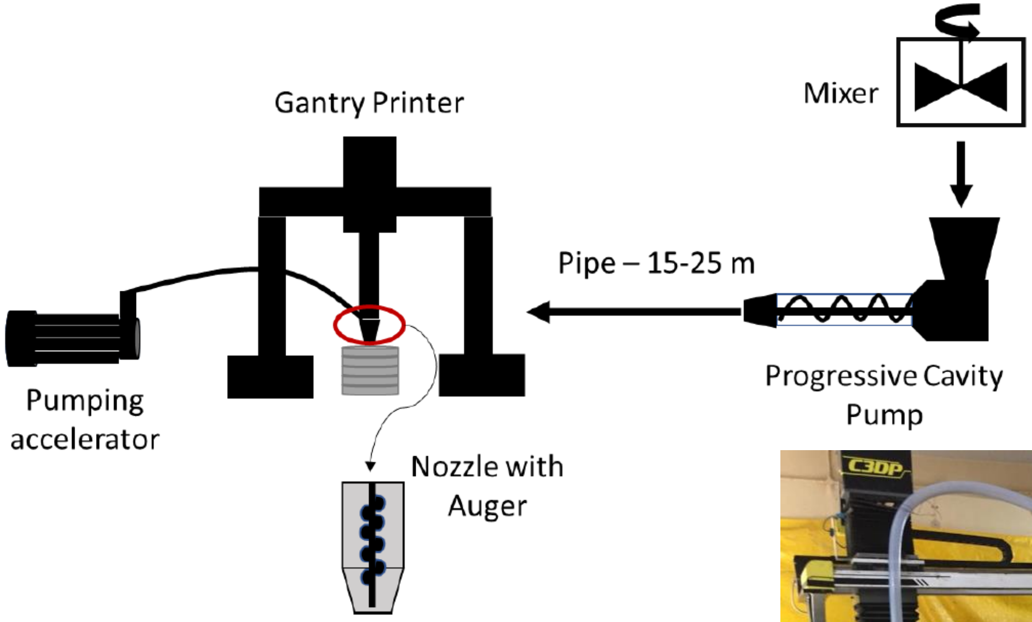


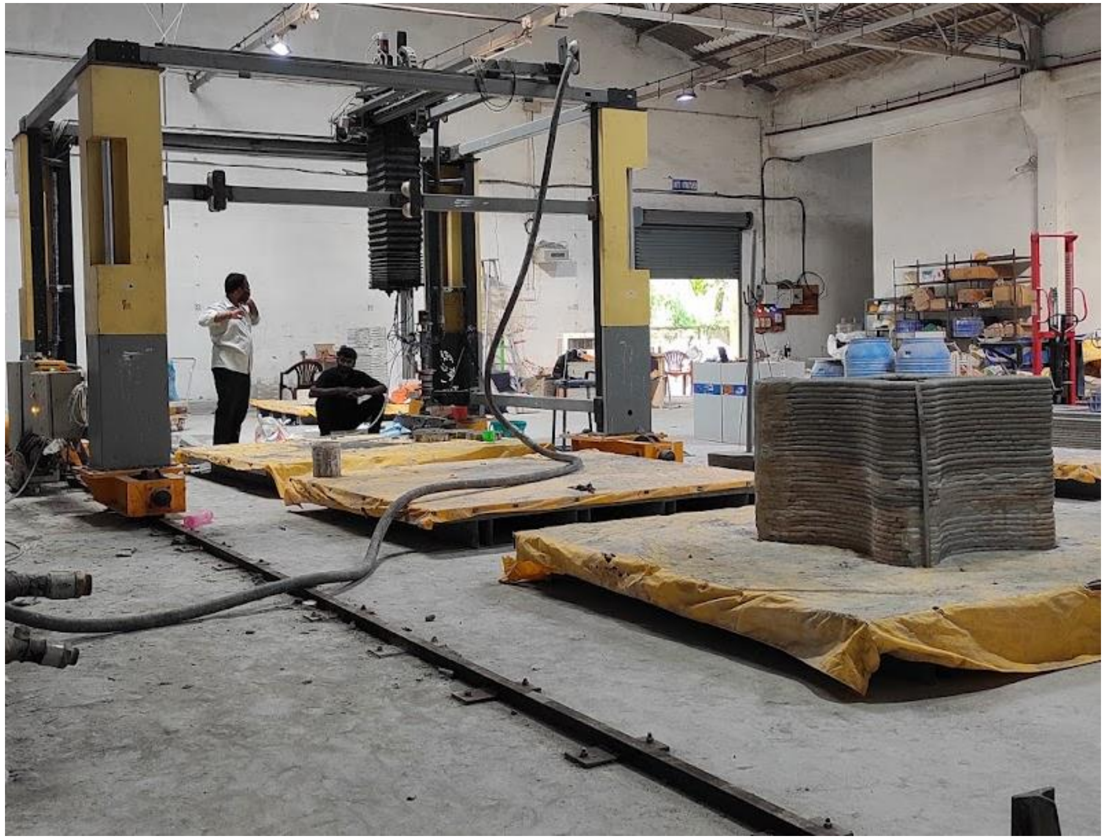


Compressive strength

Accelerator dosage (%)	1-day Compressive strength (MPa)	28-day Compressive strength (MPa)
	Lab	Lab
0	8.4 ± 0.2	32.7 ± 2.9
1	9.8 ± 0.37	33.1 ± 3.2
2	10.41 ± 0.46	37.4 ± 1.0

Print trials



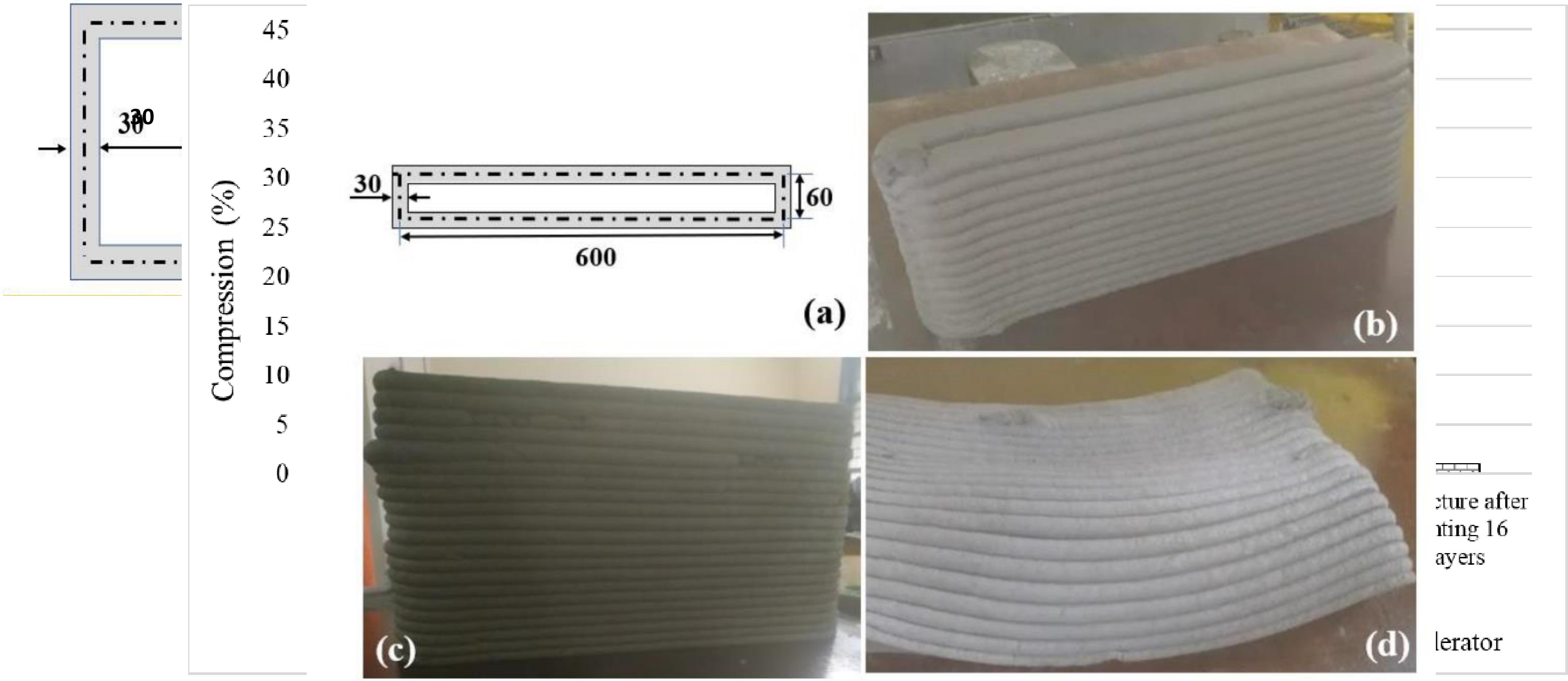


Print trials – vane shear and comp. strength

Accelerator dosage (%)	Time after mixing (mins)	Vane shear initial static yield strength (kPa)	28-day Compressive strength (MPa)
		print trials	print trials
0	5	1.73 ± 0.20	30.0 ± 1.5
	30	2.10 ± 0.35	
1	5	2.30 ± 0.32	31.2 ± 2.0
	30	2.93 ± 0.49	
1.5	5	2.80 ± 0.37	33.6 ± 1.0
	30	4.20 ± 0.49	

Note: The behaviour of mix with 1.5% accelerator dosage in the print trials is validated against 2% accelerator dosage in the lab studies.

Print trials – accelerator added in the mix

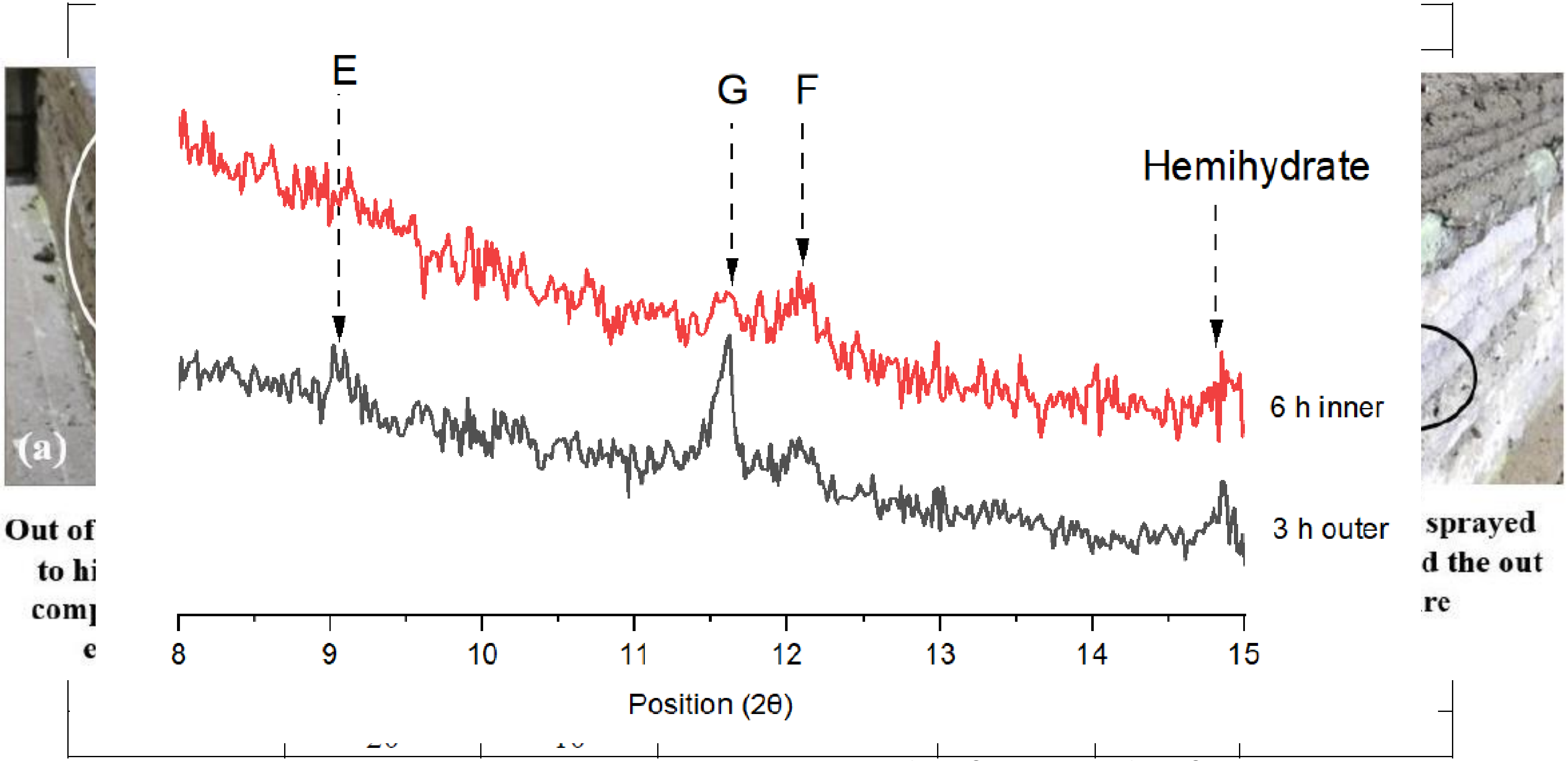


mixer

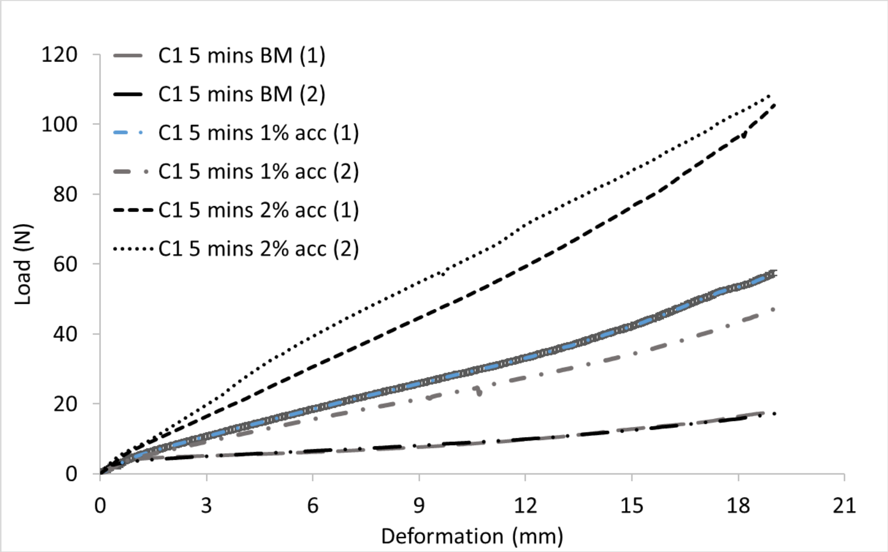
Print trials – addition at the nozzle

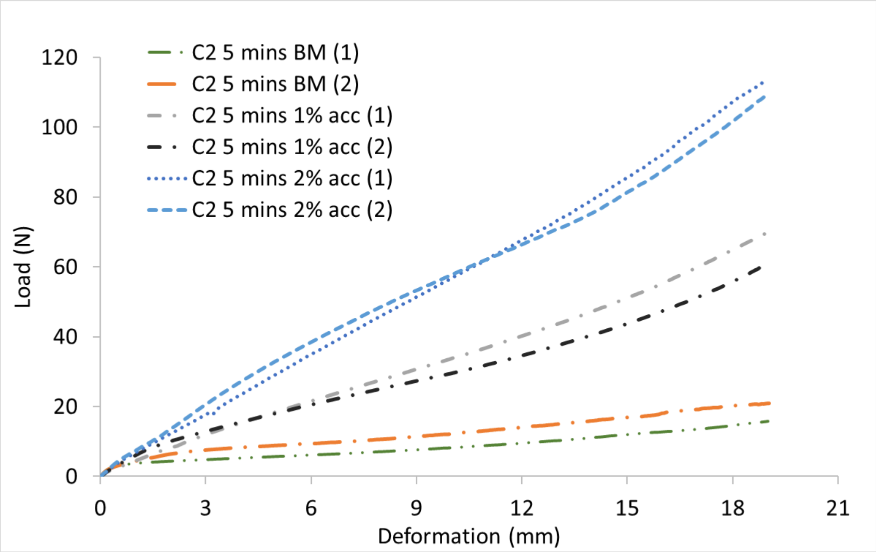
Buildability assessment

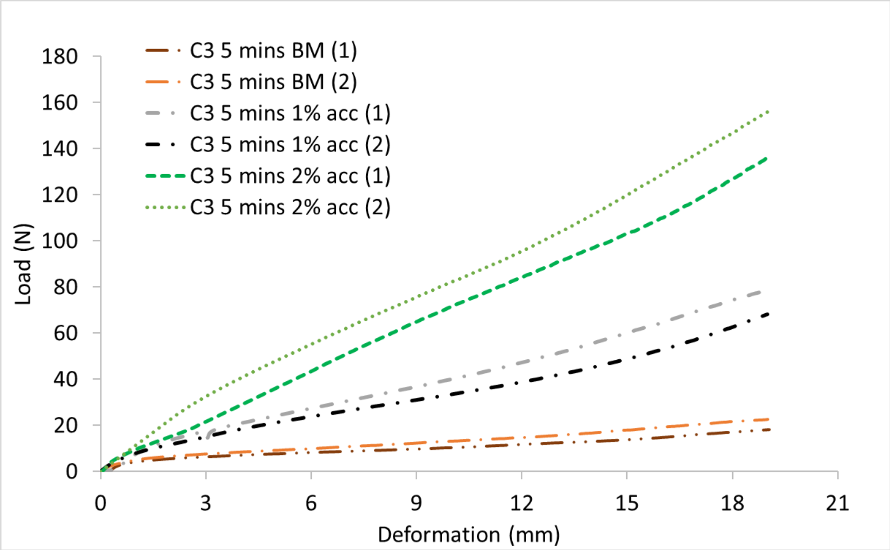
Print trials – accelerator sprayed on surface post-printing

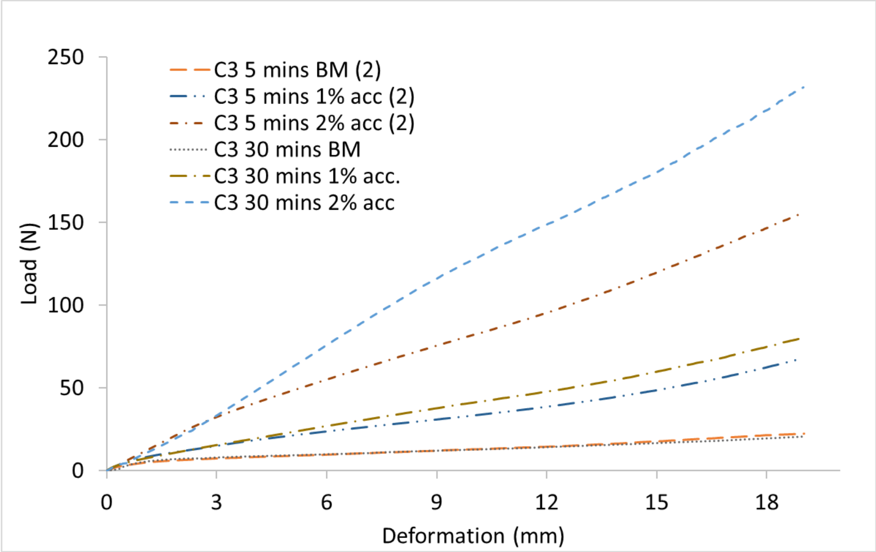


Squeeze flow test





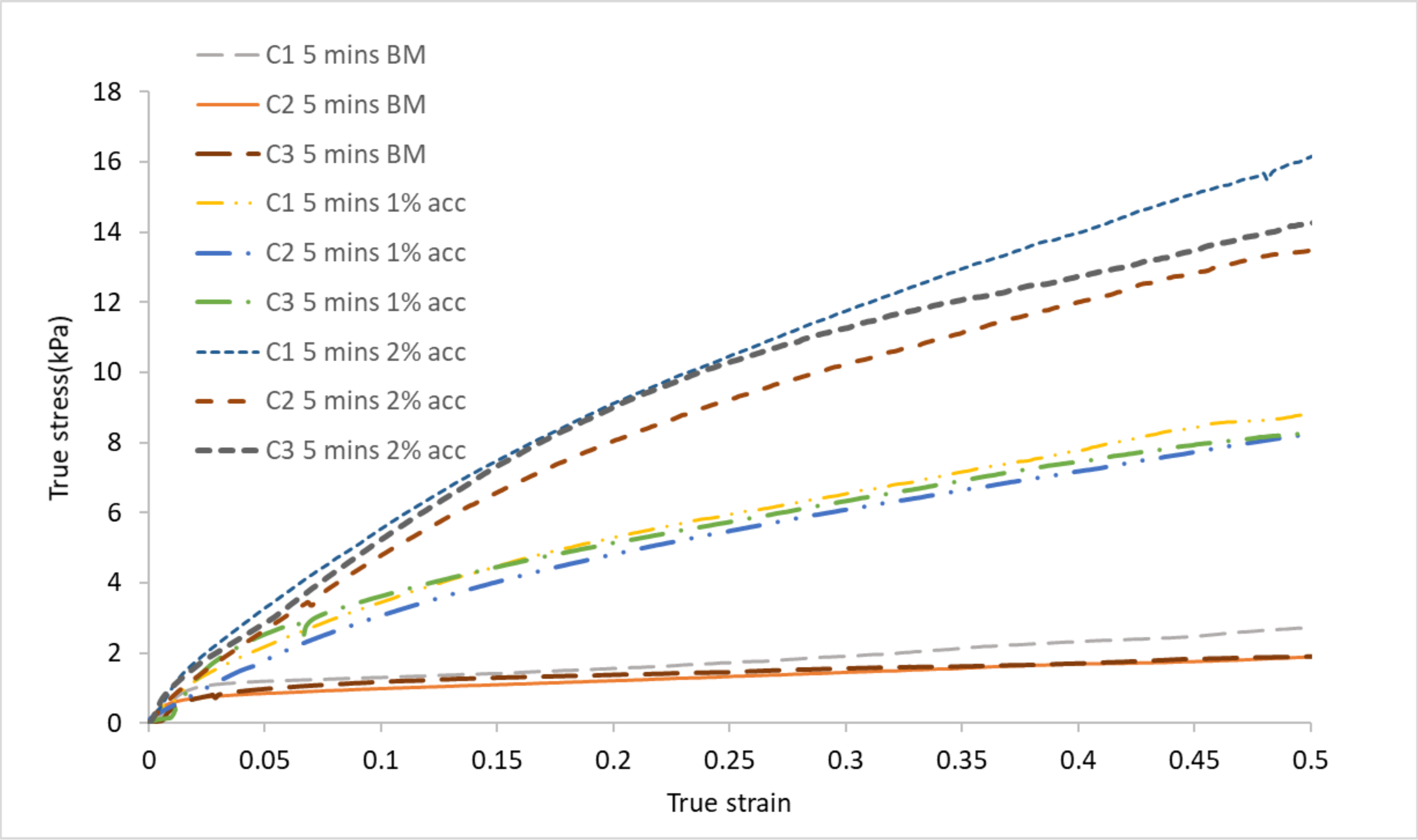




Different aspect ratio

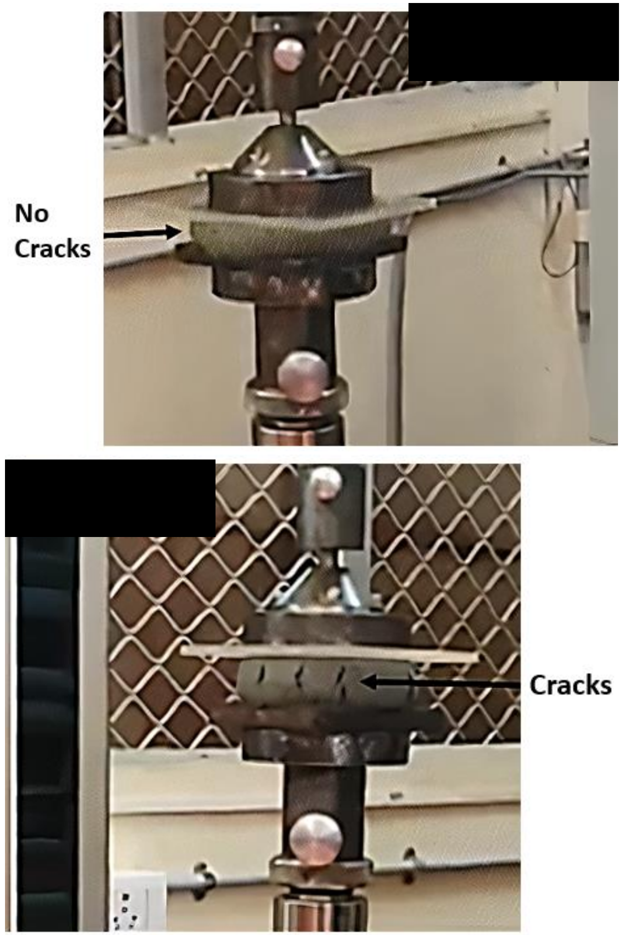
- C1 – 0.68
- C2 – 0.6
- C3 – 0.55

Squeeze flow – stress-strain curve



True stress vs strain

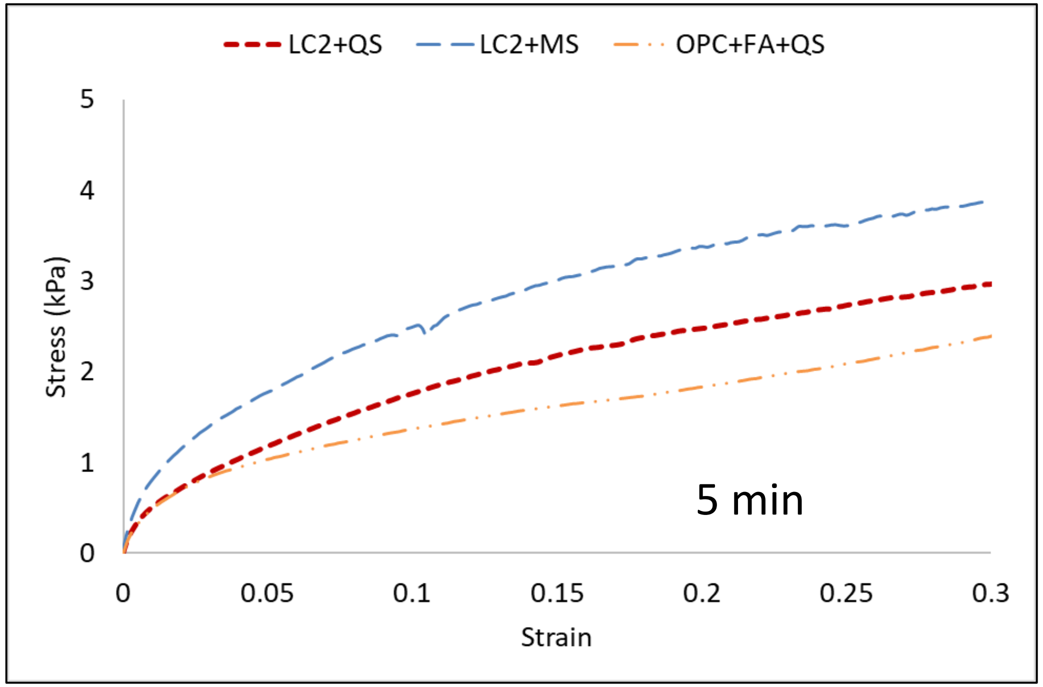
Plastic flow hardening observed with accelerators

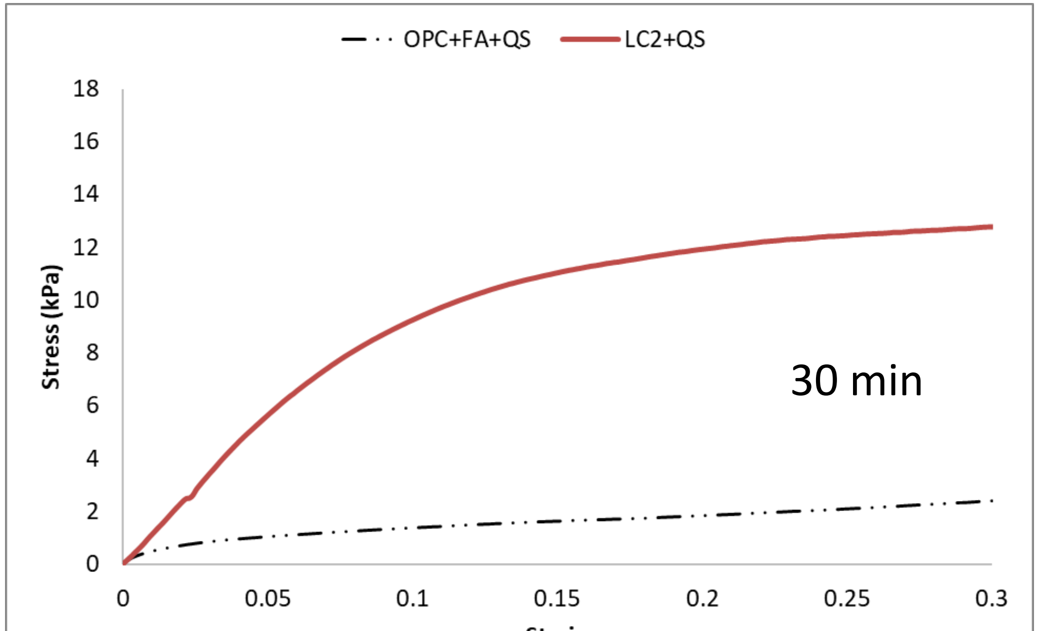


Cracking due to high stiffness

Use of limestone calcined clay cement

- Binder with 50% OPC, 30% calcined clay (with ~ 60% kaolinite), and 15% limestone, 5% gypsum
- Undergoes faster structural build up compared to mixes with plain cement – results from squeeze flow test presented below





LC2 – increase of aggregate-binder ratio

1.1 m high cylinder – aggregate/binder = 1.5

1 m high cylinder – aggregate/binder = 2.33

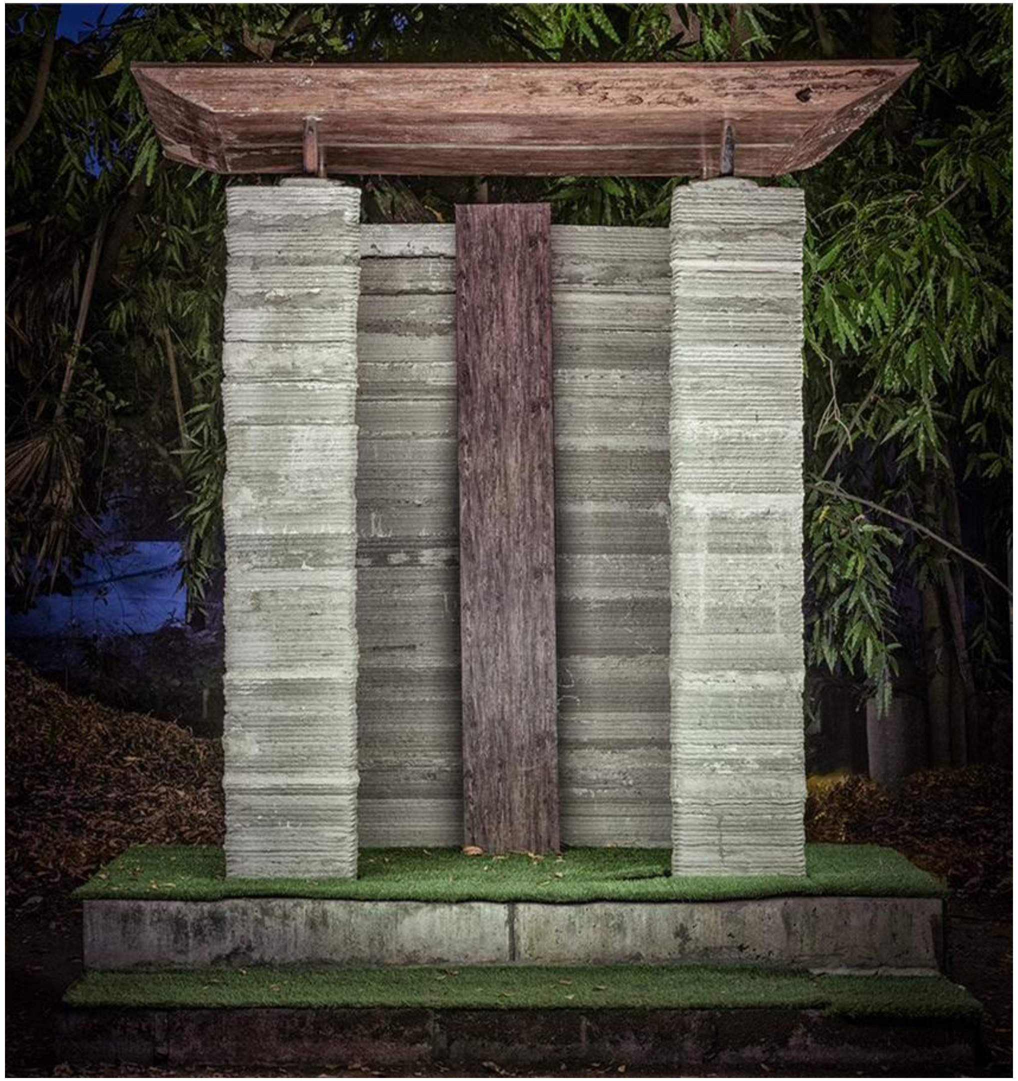
1 m high cylinder – aggregate/binder = 3

Conclusions

- The layer compression during printing plays a critical role in governing buildability of a structure
- Addition of accelerator helps in increasing the buildability of the printed structures – different methods to include accelerator possible
- Squeeze flow test is promising with respect to evaluation of early age characteristics of 3D printable systems
- In addition to the yield stress, plastic flow hardening on addition of accelerator is considered to control the buildability of the mix

Portfolio of 3D printed structures

tvasta



IMPRINT: IITM & Tvasta’s first 3D structure

India’s first 3D printed house at IIT Madras campus

Total 460 sqft area – sponsored by Habitat for Humanity

Doffing Units at Govt. Hospital – sponsored by St Gobain

Sanitary blocks at Indian Air Force, Jaisalmer

INDIAN INSTITUTE OF TECHNOLOGY MADRAS · सिद्धिर्भवति कर्मजा ·

tvasta

INDIAN INSTITUTE OF TECHNOLOGY MADRAS
सिद्धिर्भवति कर्मजा

tvasta

Guest House at Indian Air Force, Chiloda (Gandhinagar)

tvasta

tvasta

Thank you!