SELECTING THE APPROPRIATE QUALITY CONTROL METHOD FOR 3D CONCRETE PRINTING: A FIRST GUIDELINE

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Contents

3D printing of a tree stump at CORAL

Introduction

Quality Control of 3DCP:

(i) ensuring the consistent quality of fresh concrete produced and delivered to the nozzle

(ii) ensuring the consistent structural build-up of printable concrete

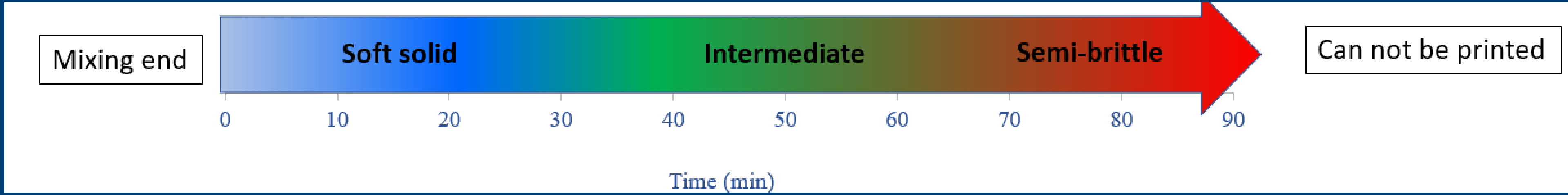
(iii) maintaining the print quality and intended geometry of extruded layers

(iv) quality assurance of hardened-printed concrete

Development of QC tools is necessary for communication between stake holders in 3DCP construction and dissemination of R& D

Structural build-up

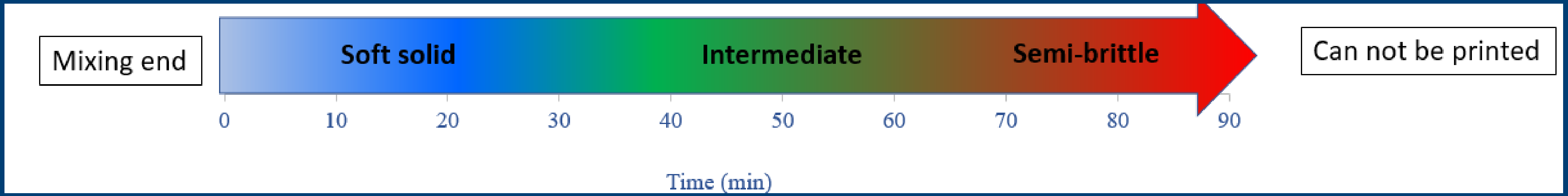
- Fresh printable concrete hardens with the time
- This transition is due to physical interaction between concrete ingredients and binder hydration



Importance:

- It governs buildability (number of printable layers) and achievable freedom of design
- Other influencing parameters: print geometry, printing process parameters, environmental factors, printer characteristics, etc.

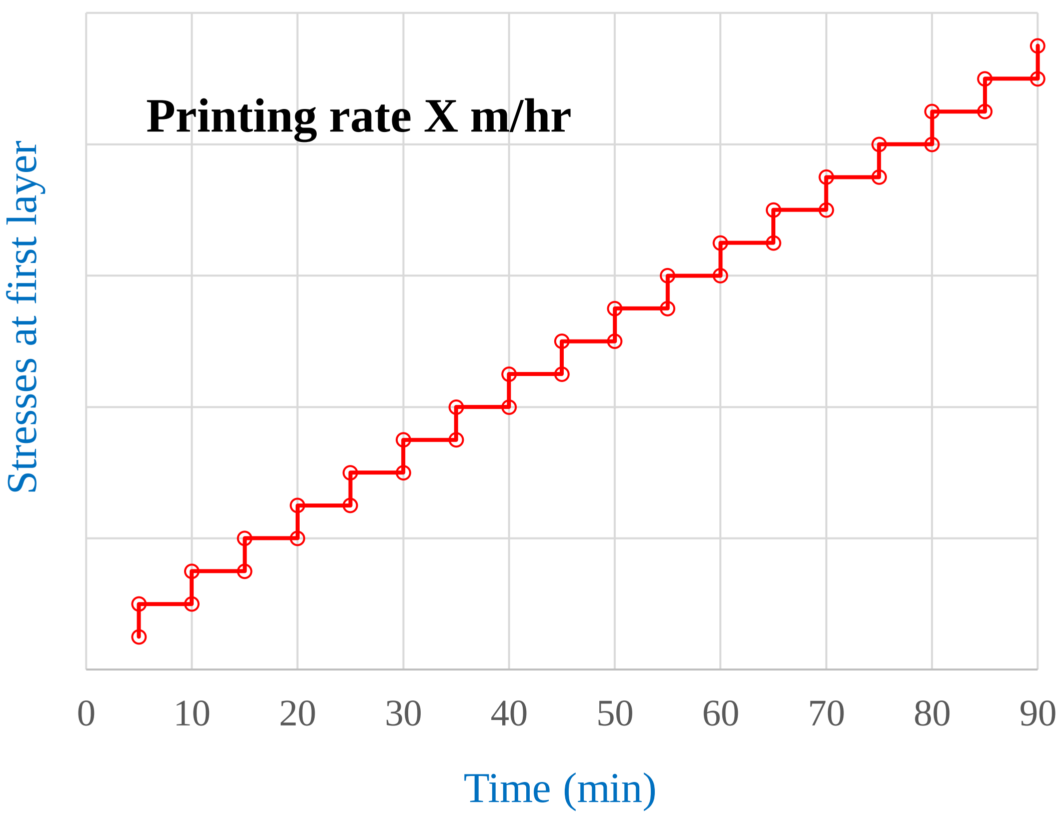
Structural build-up



- Structural build-up of concrete can be felt by touching and texture
- But these sensory evaluations are highly subjective and qualitative descriptions
- Hence structural build-up needs to be defined in terms of physical numbers and units for ensuring quality control, easy communication and transparent record keeping

Structural build-up

- Conventional concrete construction technology is more concerned with the structural build-up at the scale of hours (setting time of concrete for formwork removal)
- In 3D concrete printing technology, structural build-up needs to be assessed at the scale of minutes for deciding the vertical construction rate
- Figure (right side) illustrates the stress growth at the bottom layer due to printing of next layers.
- These stresses should not exceed the evolving intrinsic shear strength/green strength/ stiffness of bottom layers
- Hence very sensitive instruments are needed which measure the structural build-up at the resolution of minutes



Stresses growth at the first printed layer

Construction site requirements from the testing tool

- Sensitive to structural build-up
- Highly portable
- Cost effective test method
- Automated test or minimum required personnel
- Minimum material requirement for testing
- Rugged instrument
- Minimum post data processing, etc.

Experimental tests

a) Hand vane
b) Rotational rheometer
c) Uniaxial unconfined compressive strength (UUCT)
d) Squeeze flow test
e) Slow penetration test (SPT)
f) Ultrasonic pulse velocity
g) Slump
h) Flow table

Mix composition – mass proportions with respect to the binder weight.

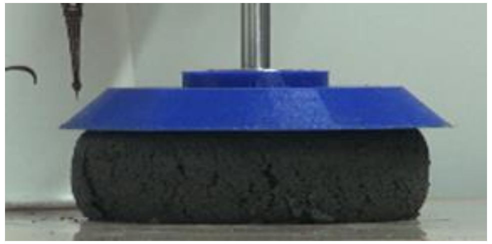
Binder[a]	Sand	Water	Water reducer
1	1.38	0.26	0.02

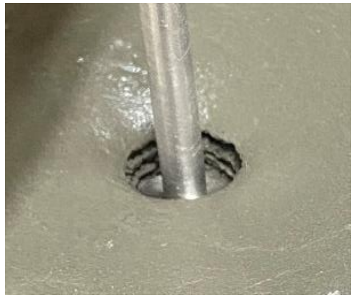
[a] OPC-I: fly ash: silica fume = 0.7 : 0.2: 0.1.


(a) Hand vane shear test

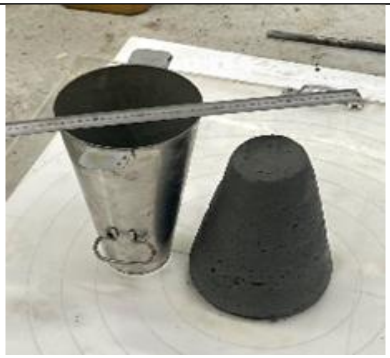

(b) Rotational rheometer test

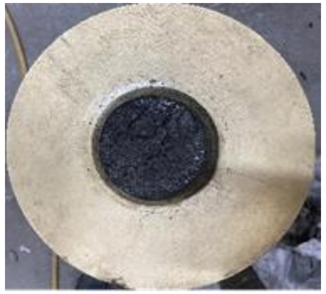

(c) UUCT


(d) Squeeze flow test


(e) SPT

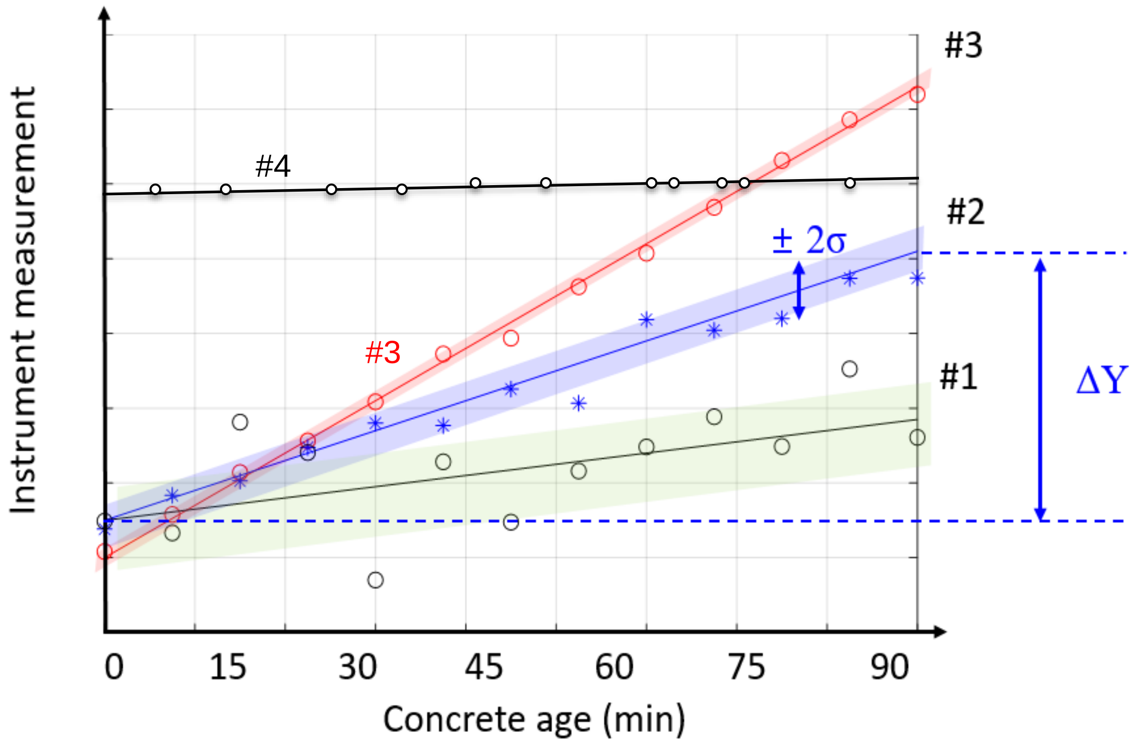

(f) UPV


(g) Slump test


(h) Flow table test

Some points to consider:

- Sensitivity (ΔY): Maximum value – minimum value
- Noise in instrument results: data fluctuation
- Coefficient of determination (R^2) measures the variation of collected data with respect to a fitting curve but it does not measure the instrument sensitivity (instrument #4 vs instrument # 2)
- Higher sensitivity is preferred from the perspective of sensor and test performance, but a simple comparison based on sensitivity is not reasonable as an instrument with high sensitivity and high noise will have poor performance
- **New performance indicator needs to be defined for evaluating the potential of candidate tests for capturing the structural build-up**



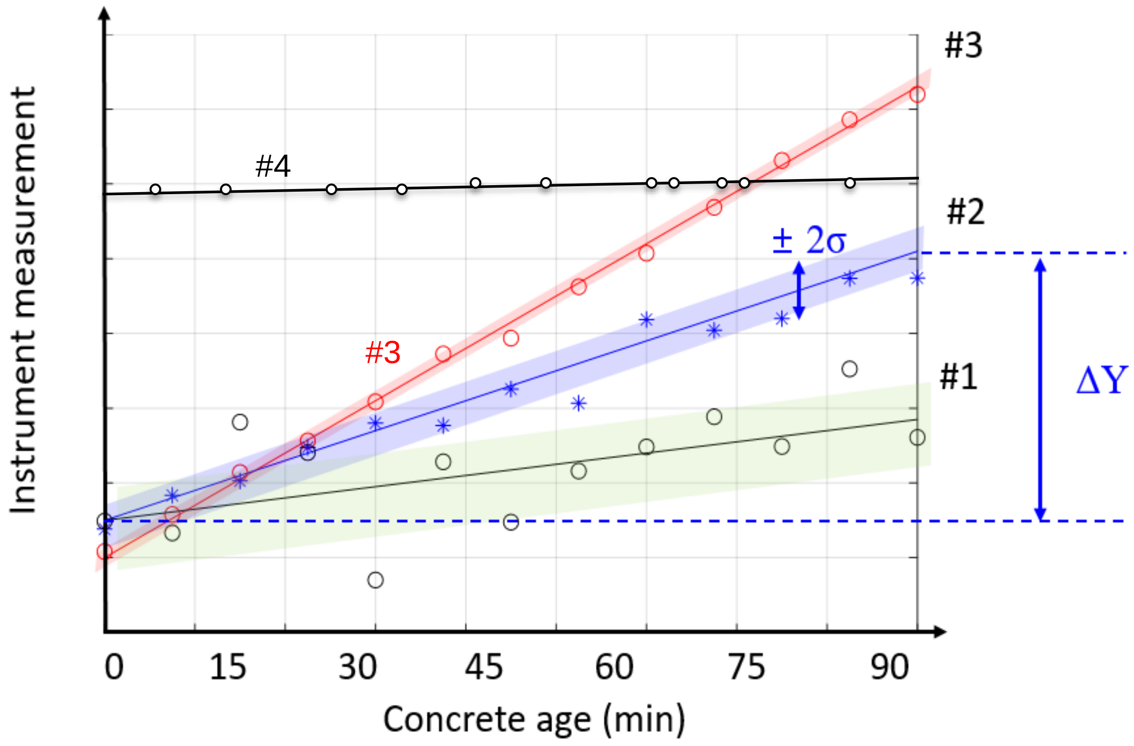
Response of four instruments (#1, #2, #3 and #4) to the structural buildup

Some points to consider:

For a more accurate and confident determination of the concrete quality at a certain instant, the instrument output should be consistent, and the amount of deviation in the measurement results should be minimized while the sensitivity should be maximized.

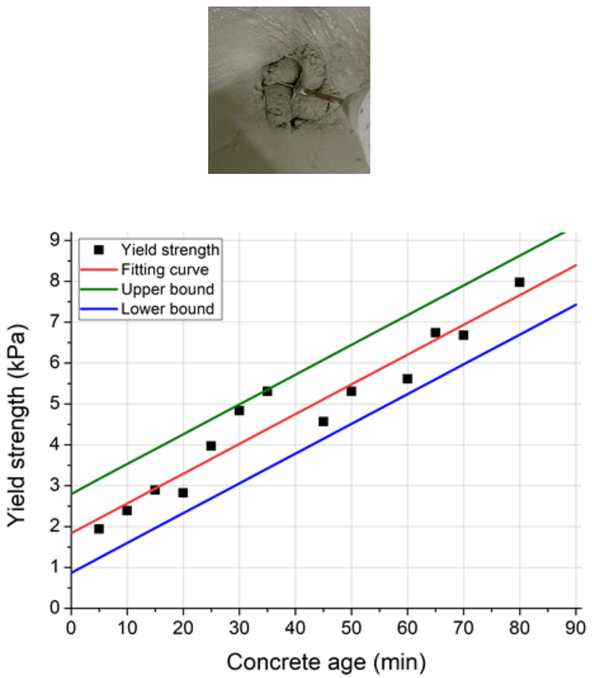
$$\text{Performance index} = \frac{\text{Sensitivity}}{2 * \text{standard deviation}} = \frac{\text{Maximum value} - \text{Minimum value}}{2 * \text{standard deviation}}$$

$$= \frac{\Delta Y}{2\sigma}$$

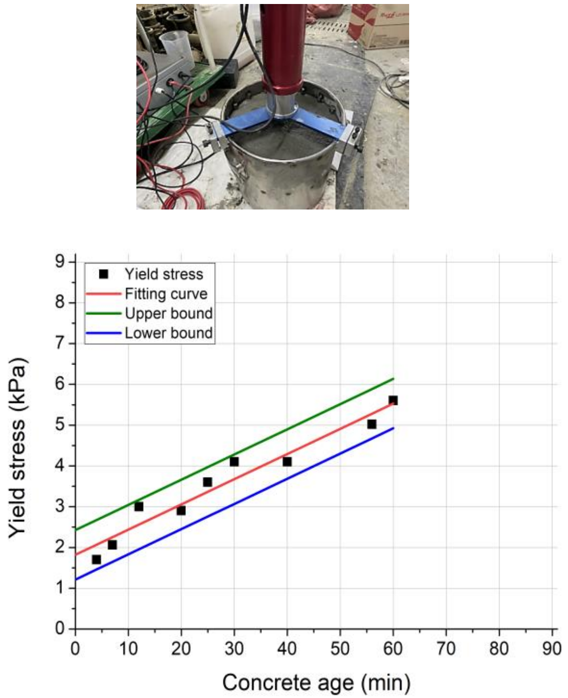


Response of four instruments (#1, #2, #3 and #4) to the structural buildup

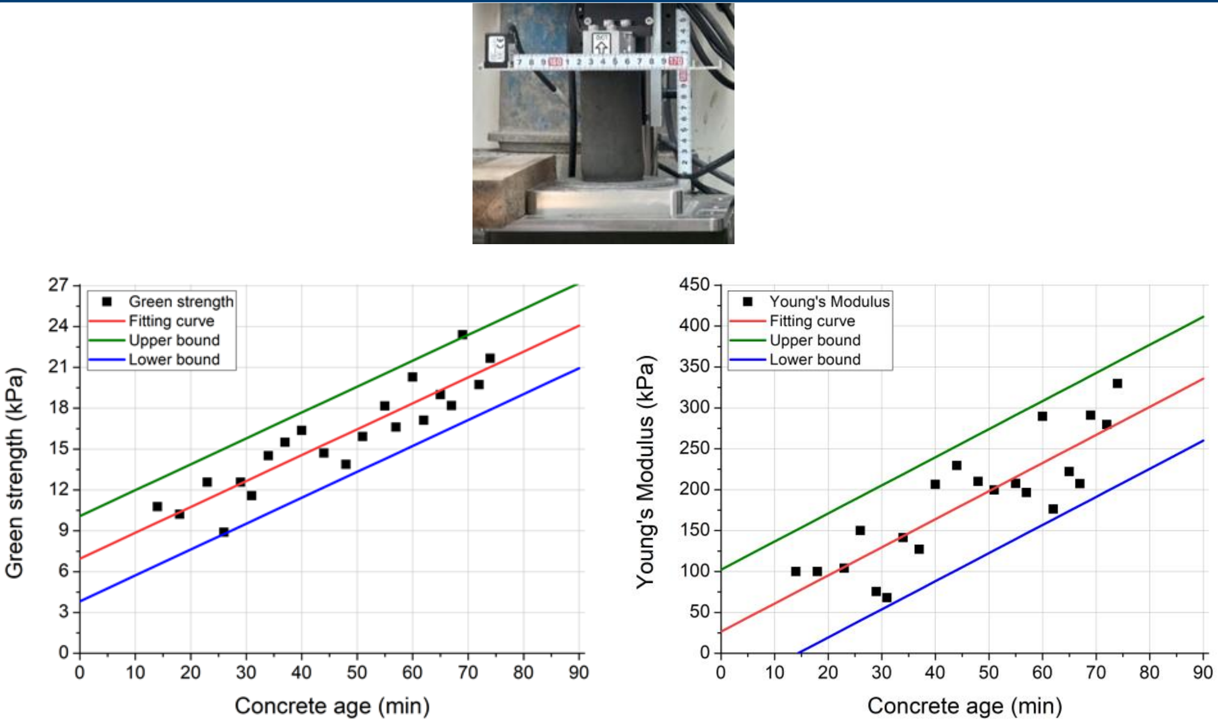
Experimental results



Hand vane shear test

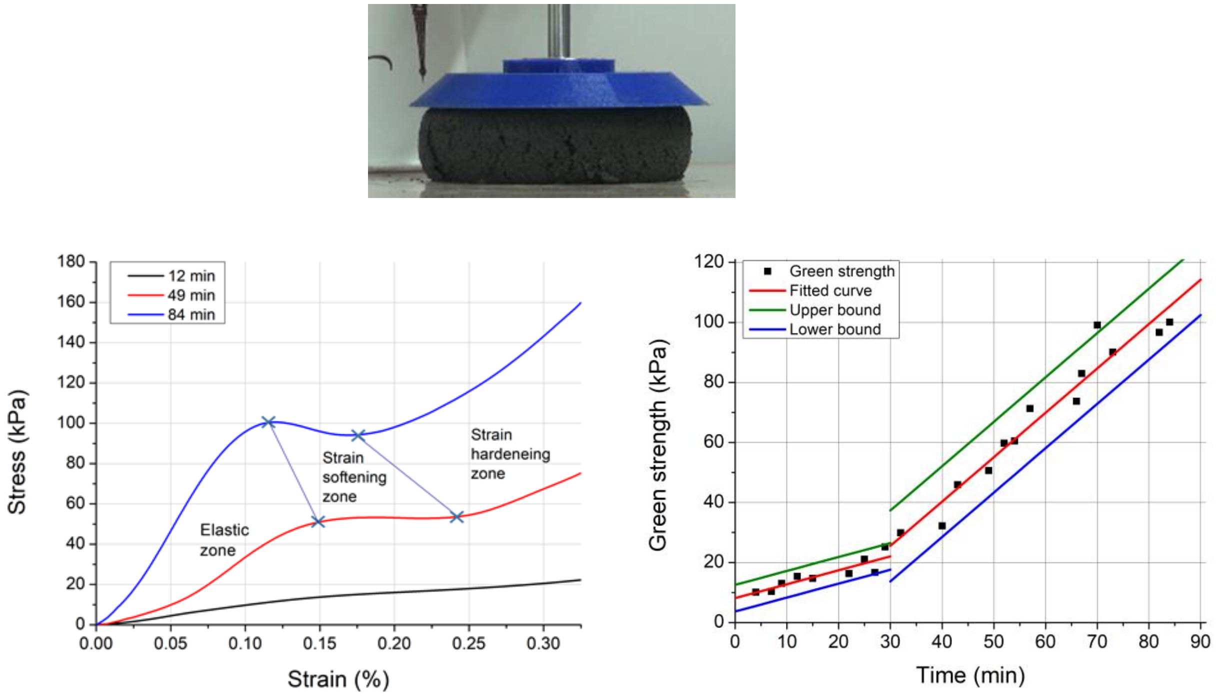


(b) Rotational rheometer test

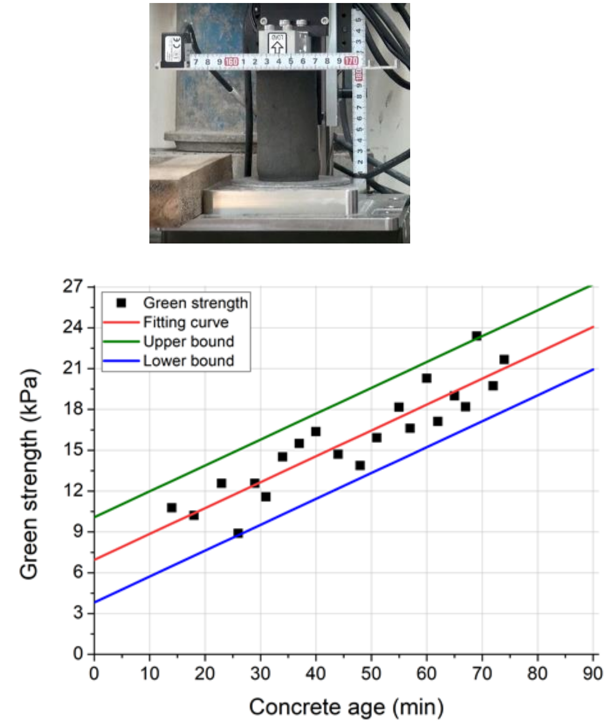


(c) UUCT

Experimental results

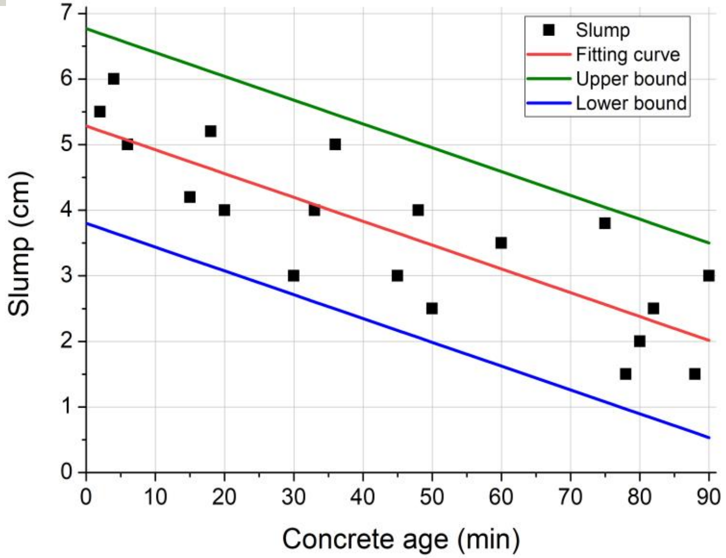


Squeeze flow test

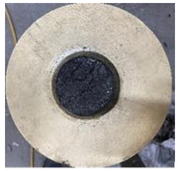


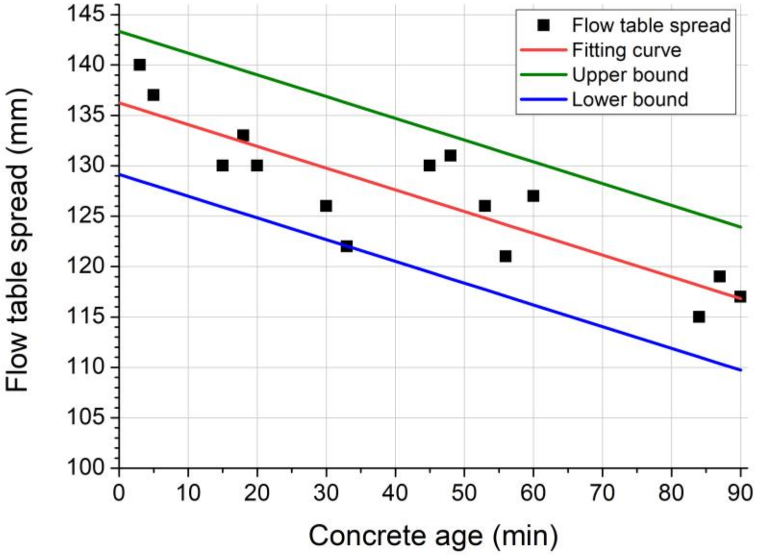
(c) UUCT

Experimental results



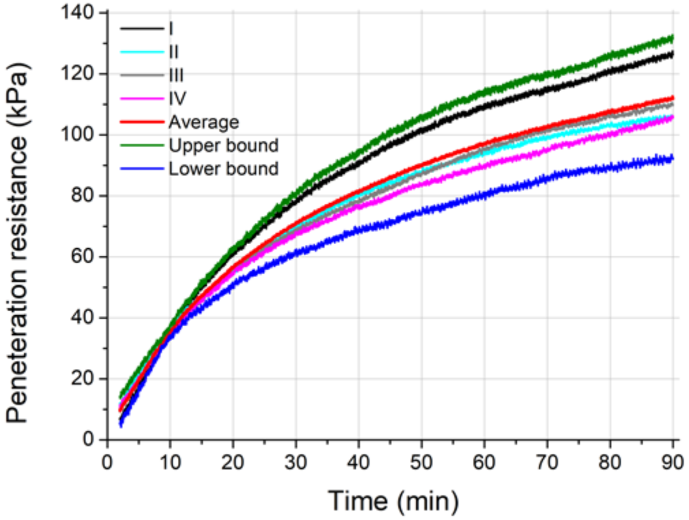
Slump test



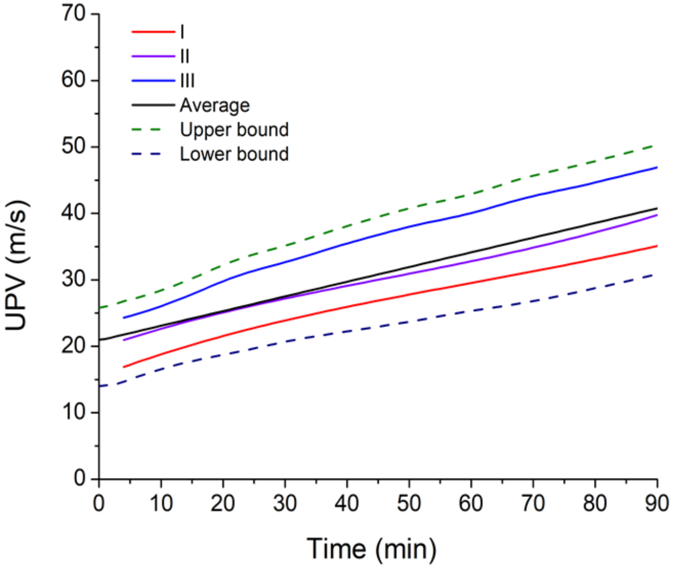


Flow table test

Experimental results



Slow penetration test



UPV test

Experimental results

Fitting models for the test methods.

Characterization method	Equation
Hand vane test – yield stress (kPa)	$\tau_H = 0.073t + 1.838, R^2 = 0.93$
Rotational rheometer – yield stress (kPa)	$\tau_R = 0.062t + 1.82, R^2 = 0.94$
UUCT – compressive strength (kPa)	$f_{UUCT} = 0.190t + 6.95, R^2 = 0.84$
UUCT – stiffness/Young's modulus (kPa)	$E_{UUCT} = 3.436t + 26.55, R^2 = 0.74$
Squeeze flow test – compressive strength/green strength (kPa)	$f_{SQ} = 0.465t + 8.119, R^2 = 0.79, t < 30$
	$f_{SQ} = 1.479t - 18.842, R^2 = 0.94, t > 30$
Slow penetration test – yield stress (kPa)	$\tau_{SPT} = 32.428\ln(x) - 36.713, R^2 = 0.98, t > 4$
Ultrasonic pulse velocity (m/s)	$V = 0.22t + 20.87, R^2 = 0.99$
Slump test – yield stress (kPa)	$\tau_S = 0.007t + 2.46, R^2 = 0.68$
Flow table test – yield stress (kPa)	$\tau_F = 0.014t + 0.85, R^2 = 0.75$

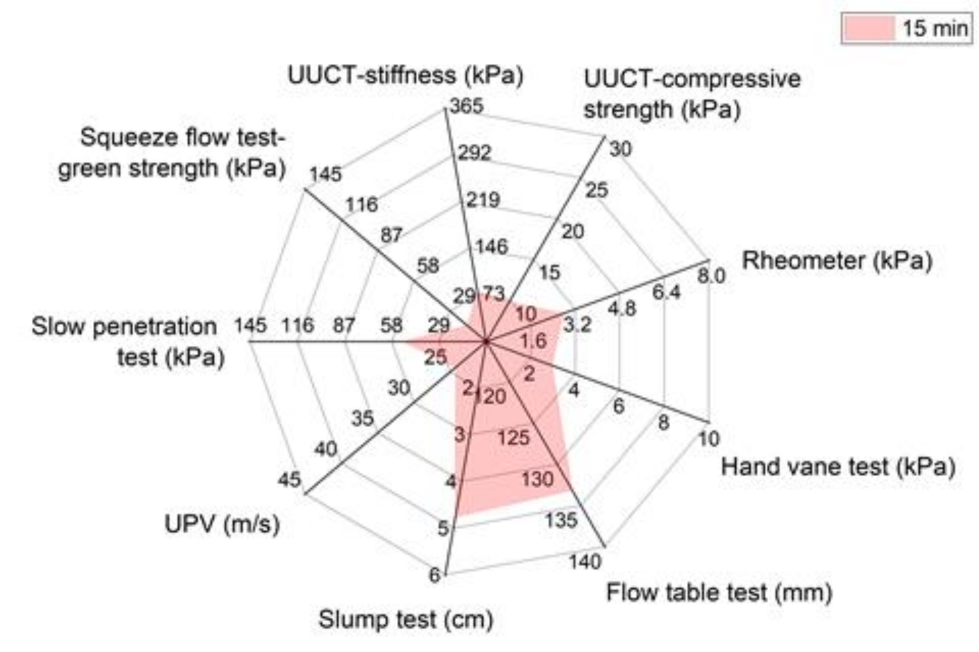
Here, t represents the time,
Coefficient of t represents the structuration build-up by the corresponding instrument

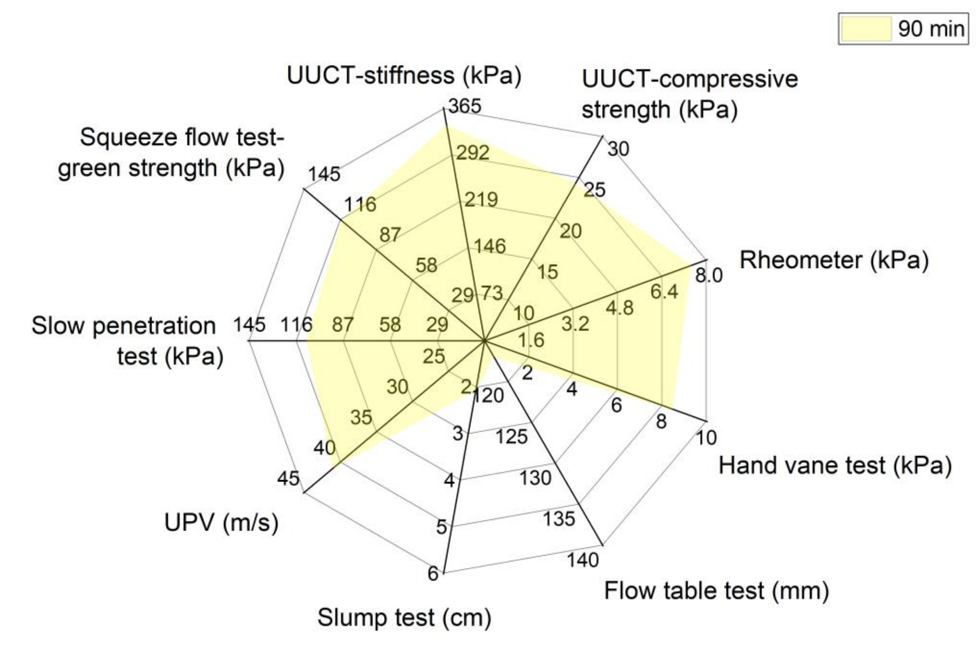
Experimental results

$$\text{Performance index} = \frac{\text{Sensitivity}}{2 * \text{standard deviation}} = \frac{\text{Maximum value} - \text{Minimum value}}{2 * \text{standard deviation}} = \frac{\Delta Y}{2\sigma}$$

Instrument	Performance index
Squeeze flow test-green strength (kPa)	11.35
Slow penetration test (kPa)	8.45
Hand vane test (kPa)	6.79
Rheometer (kPa)	6.11
UUCT-green strength (kPa)	5.49
UUCT-stiffness (kPa)	4.08
Flow table (mm)	2.7
Slump test (cm)	2.2
UPV (m/s)	2.06

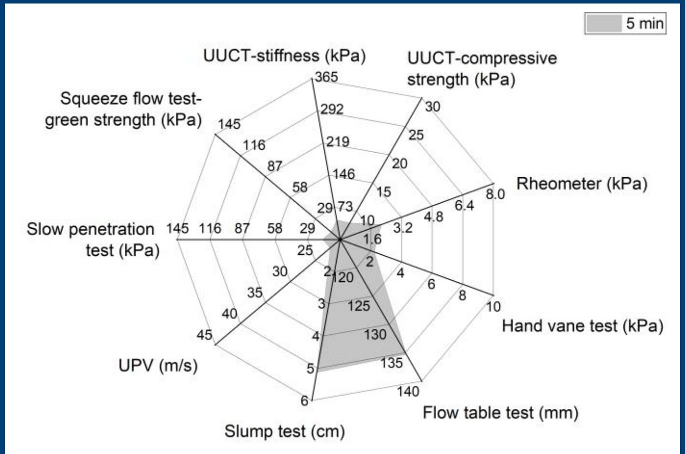
Nomogram for quality control

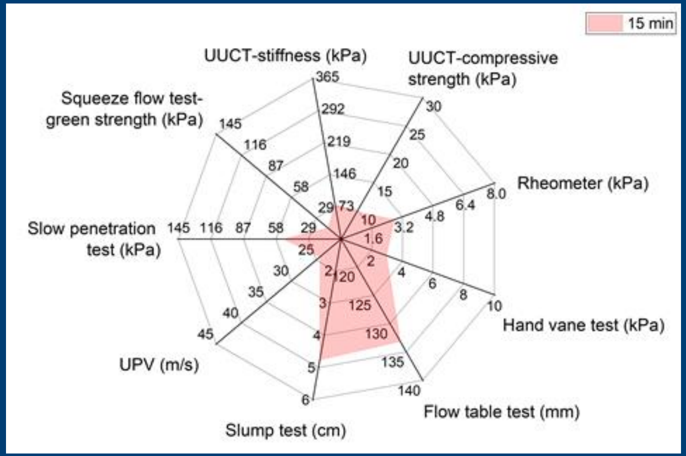


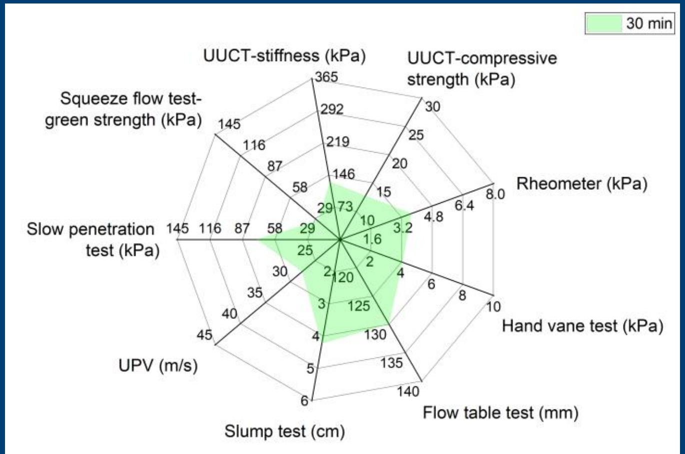


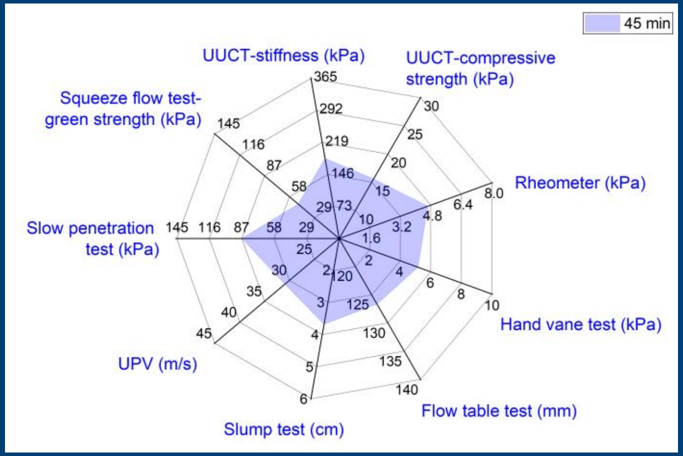
- Nomogram can supplement the premix technical sheet for customers.
- Customers can use it to verify premix performance and quality.
- Site Engineers can use nomograms to ensure specified rheological performance in concrete production.

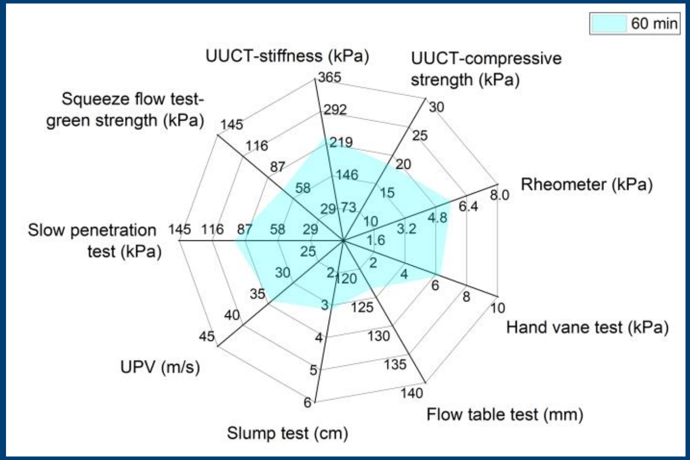
Nomogram for quality control

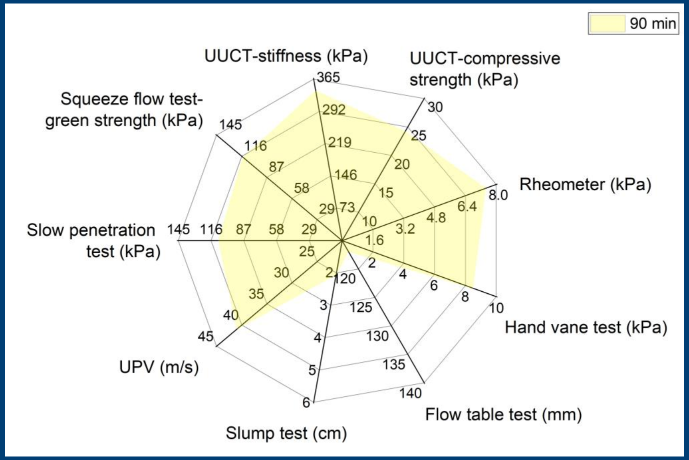












Summary

Test name	Sensitivity/Performance index	Portability	Price	Required personnel	Material for one test specimen	Ruggedness	Category of test nature
Hand vane	Good	Handy	Economical	1	2.5 liters	Torque sensor-low, Torque wrench meter-good	Offline, discrete
Rheometer	Good	Inconvenient	Expensive	1	20 liters (dependent on rheometer type)	Average	Offline, discrete
UUCT	Good	Inconvenient	Expensive	1-2	0.2 liter	Good	Offline, discrete
Squeeze flow test	Better	Inconvenient	Expensive	1-2	0.1 liter	Good	Offline, discrete
Slow penetration test	Better	Inconvenient	Expensive	1	0.9 liter	Good	Offline, continuous
UPV	Poor	Average	Expensive	1	0.1 liter	Transducers (low)	Offline, continuous
Slump mold	Poor	Handy	Economical	2	6 liters	Better	Offline, discrete
Flow table test	Poor	Handy	Economical	1	0.3 liter	Better	Offline, discrete

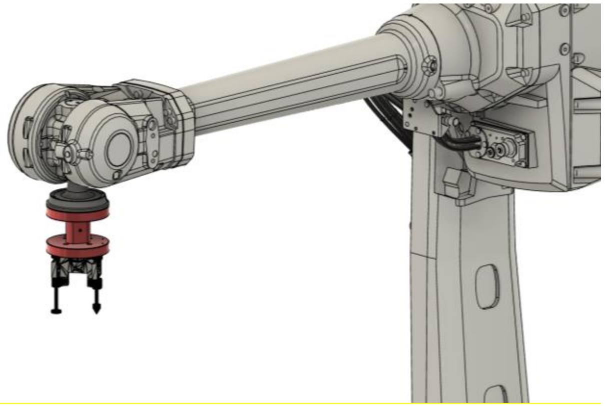
Additional details

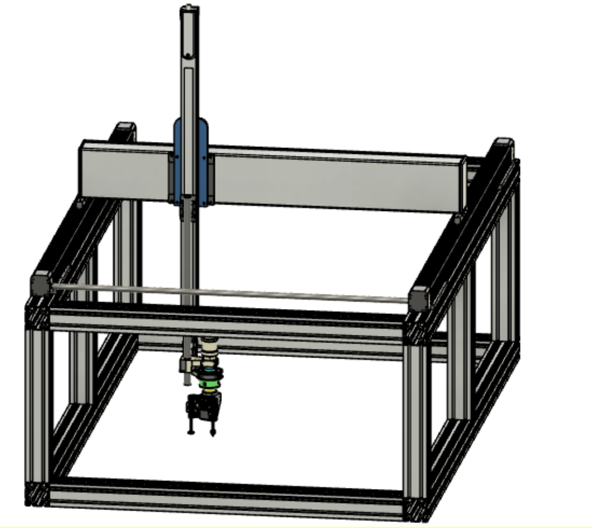
Research paper: Recommendations for quality control in industrial 3D concrete printing construction with mono-component concrete: A critical evaluation of ten test methods and the introduction of the performance index. Developments in the Built Environment, 2023

Limitations of current tests

- Manual
- Concrete used in these tests does not represent the real-3D printed concrete layers
- None of single of these instruments can capture all the important rheological properties: shear stress, green strength, stiffness

A new development





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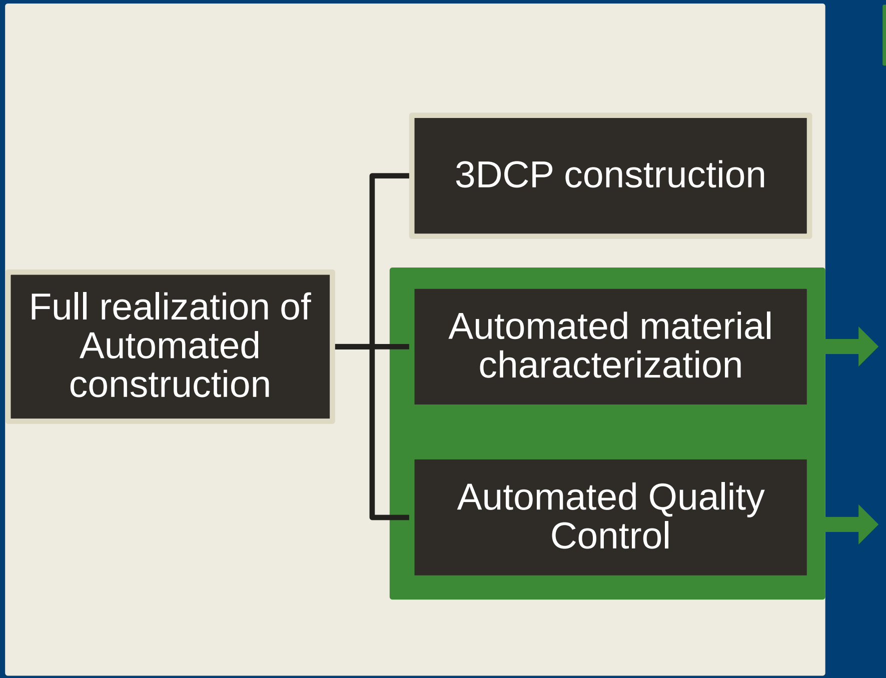
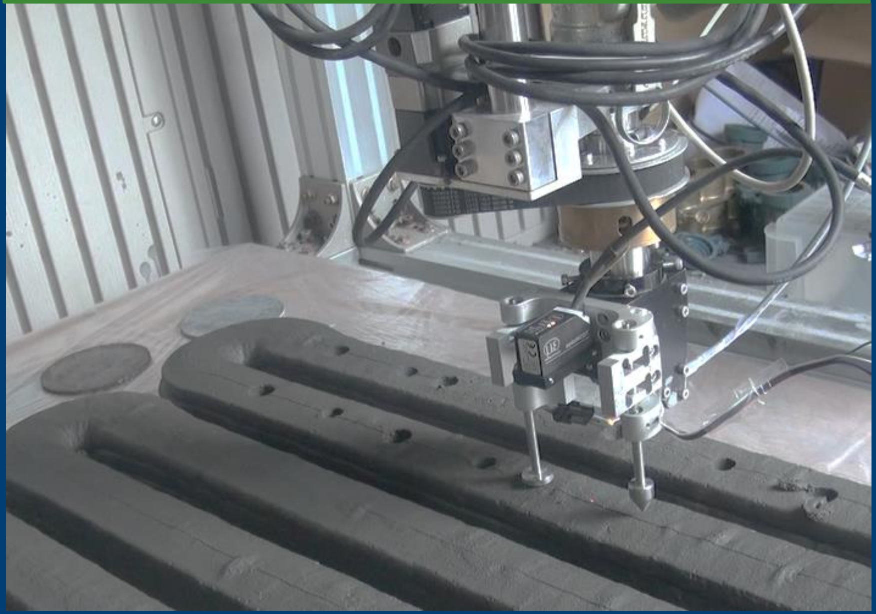
Limitations of current tests

Towards Full Automation in 3D Concrete Printing Construction: Development of an Automated and Inline Test Method for In-situ Assessment of Structural Build-up and Quality of Concrete, Developments in Built Environment (under review)

Atta Ur Rehman, Ik-Gyeom Kim, Jung-Hoon Kim*



Automated testing of 3DCP



Acknowledgement

Supervisor: Prof. Jung-Hoon Kim

Funding: National Research Foundation (NRF) Korea under Grant No. NRF-2021R1A2C2013522 and 2021R1I1A1A01050267

Q & A

Thank you