Towards a Rational Performance Based Mix-Design Approach for 3D Printable Concrete Mixes through AI Algorithms

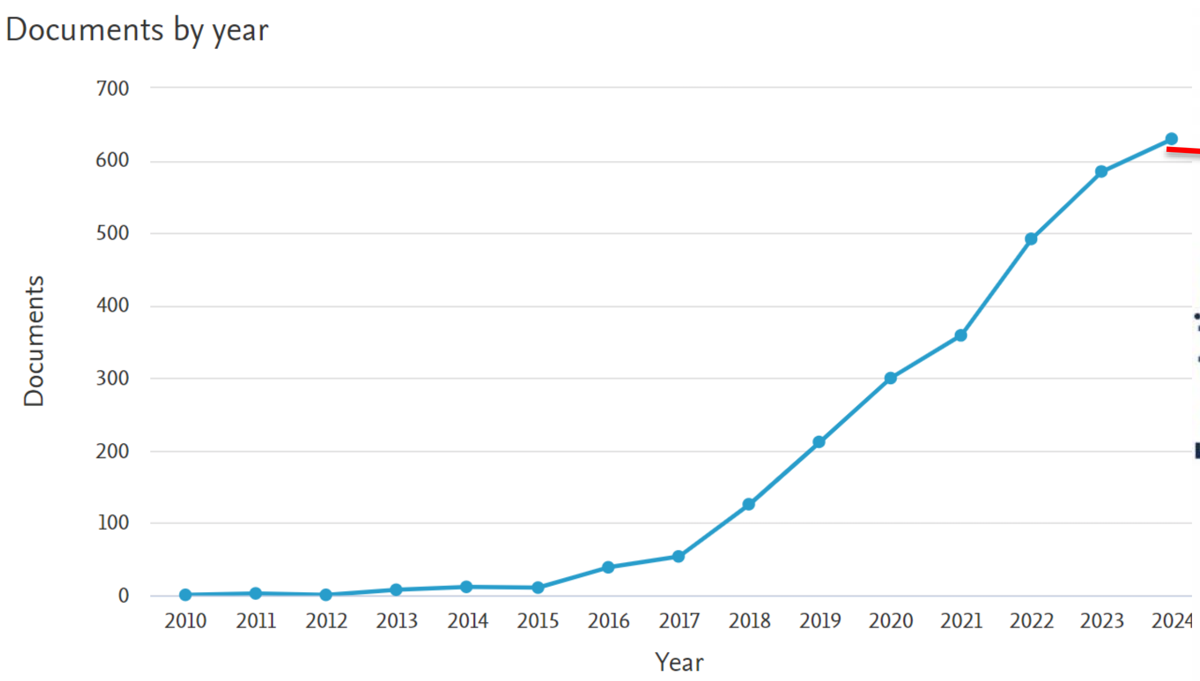
Giacomo Rizzieri, Andrea Marcucci, Francesco Soave, Massimiliano Cremonesi, Giovanni Muciaccia, Liberato Ferrara

POLITECNICO
MILANO 1863

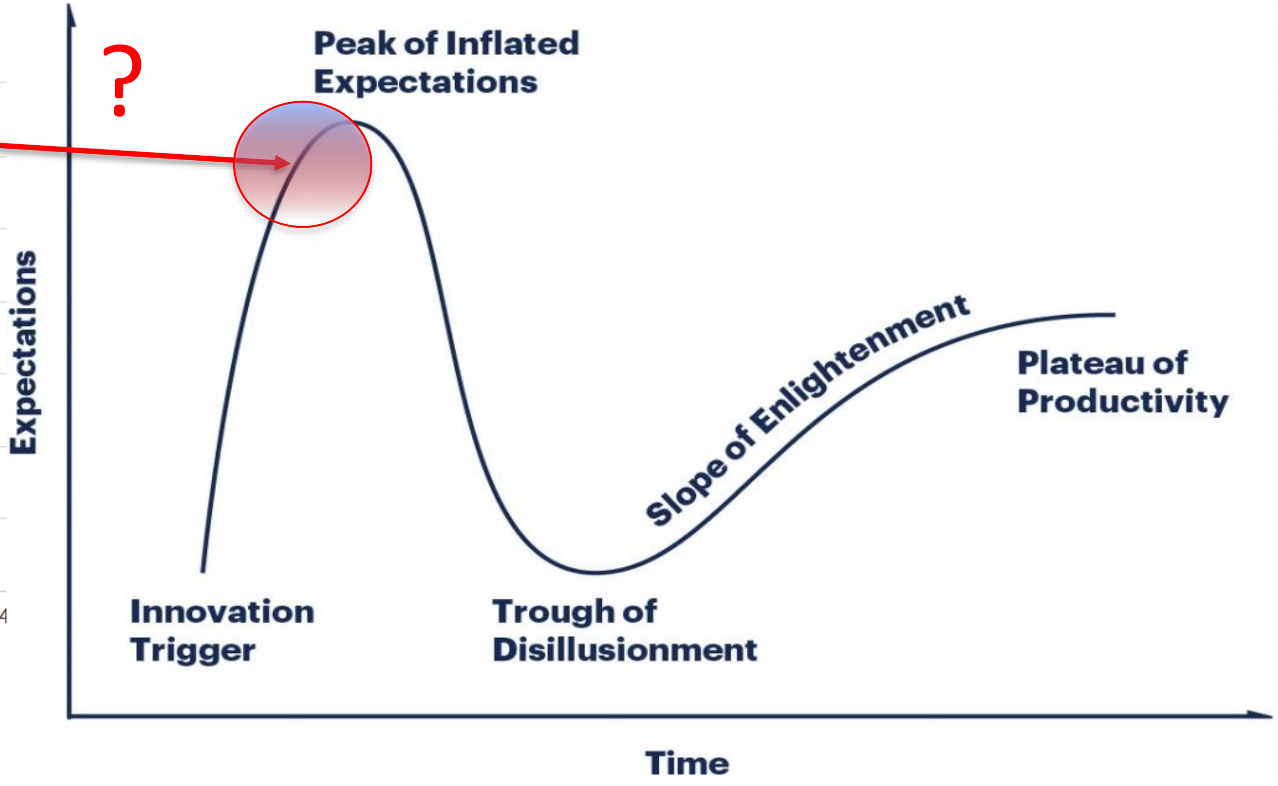
Department of Civil and Environmental Engineering
Politecnico di Milano

MUSA
MULTILAYERED URBAN SUSTAINABILITY ACTION

3D Concrete Printing: where are we?

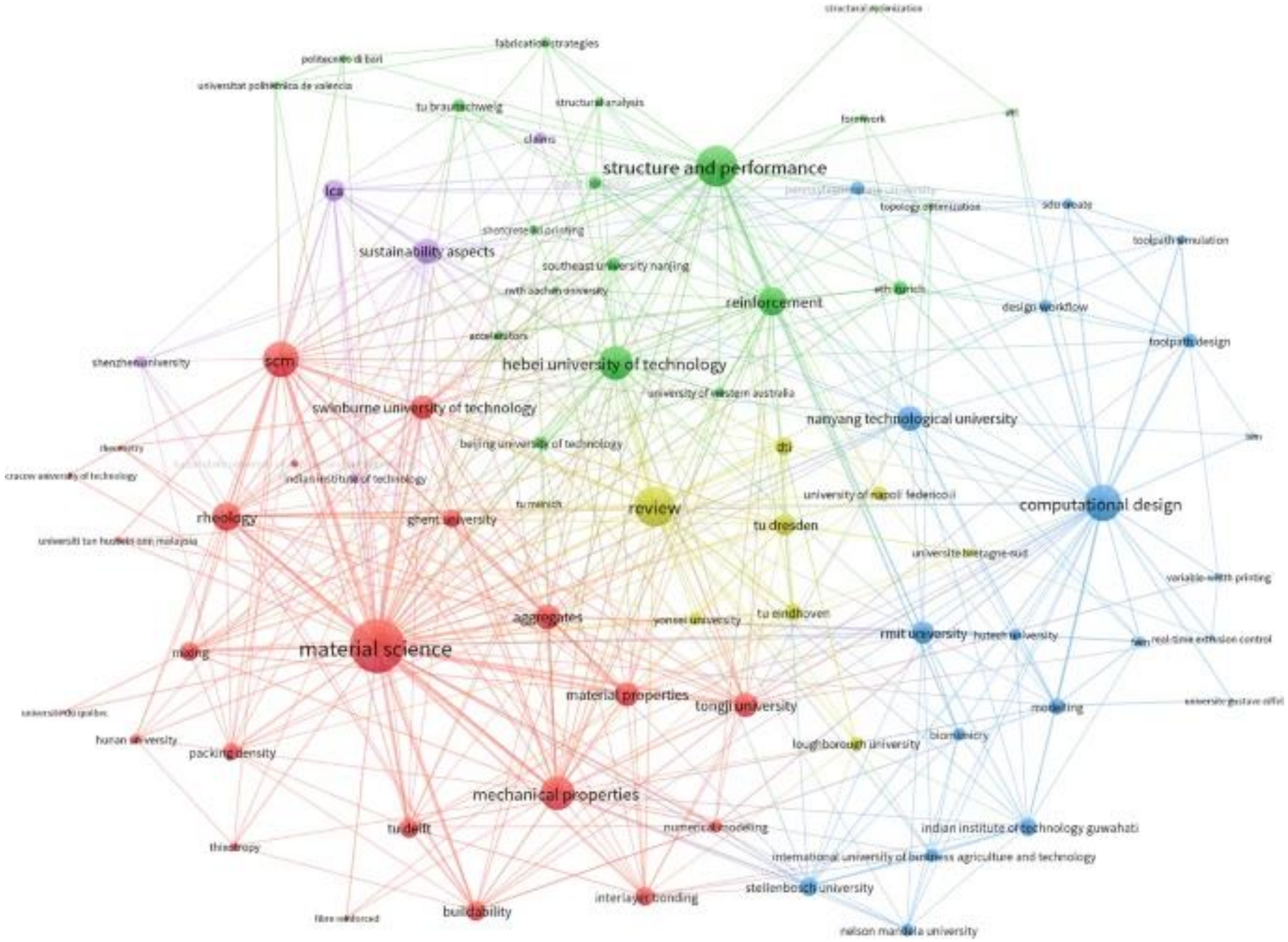


Scopus search (Sept 24th 2024) with
3D printing AND concrete
in title, abstract, keywords



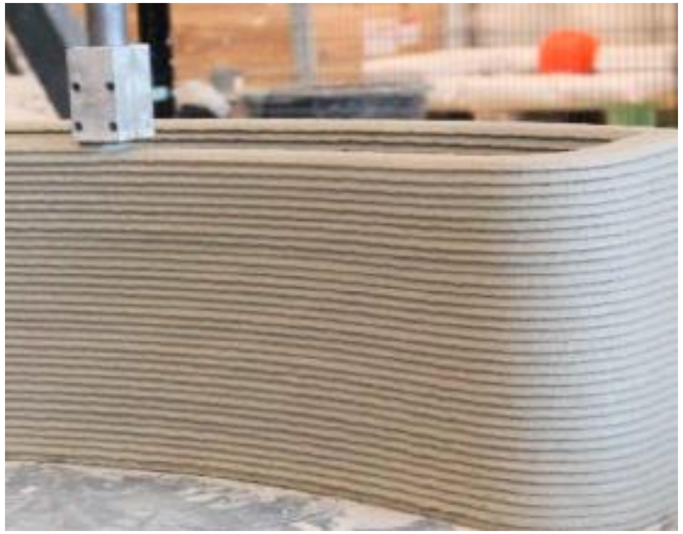
How can we transform this huge amount of «information» into a material-process&product design oriented «knowledge»?

3D Concrete Printing: where are we?

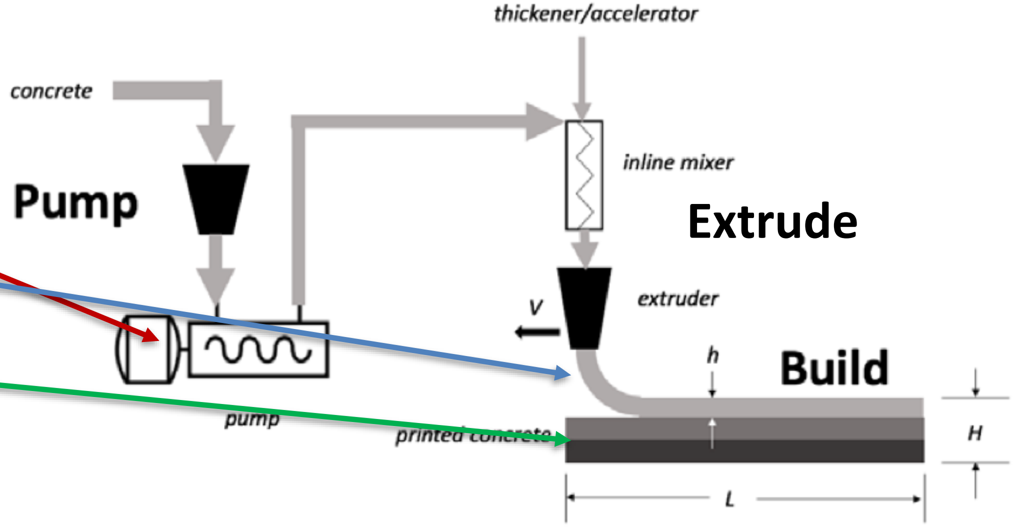


How does 3D concrete printing work?

Mixing → Pumping → Extruding → Building



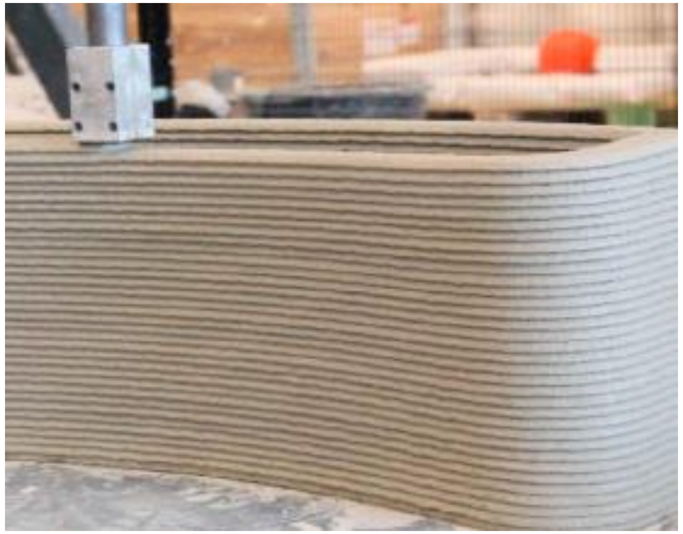
- **Pumpability:** Rheological yield strength
- **Extrudability:** Early age tensile strength
- **Buildability:** Early age shear and compressive strength

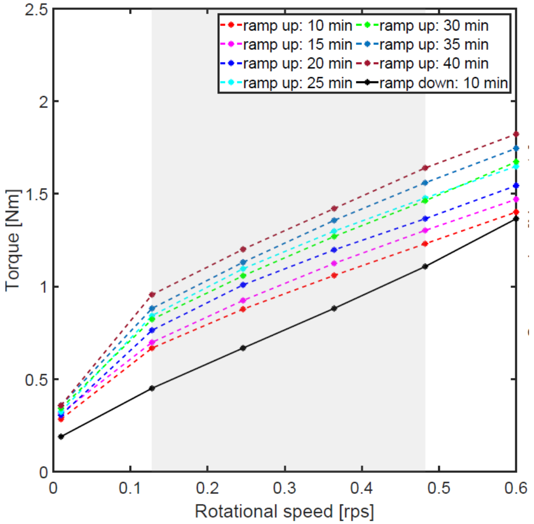


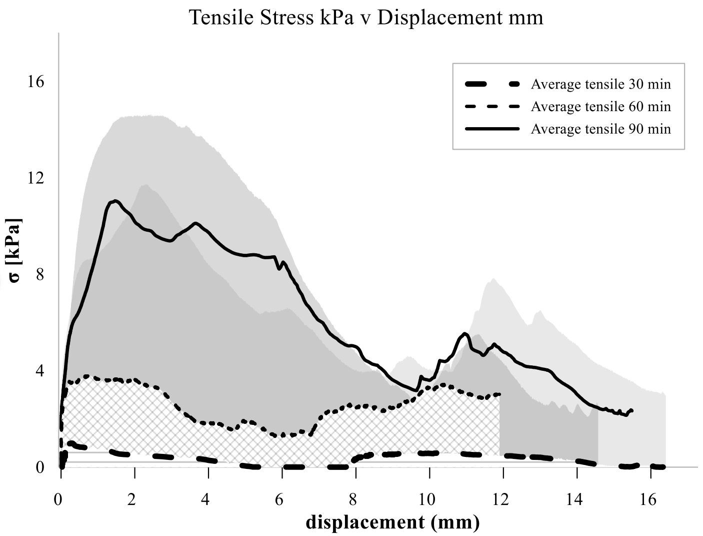
How does 3D concrete printing work?

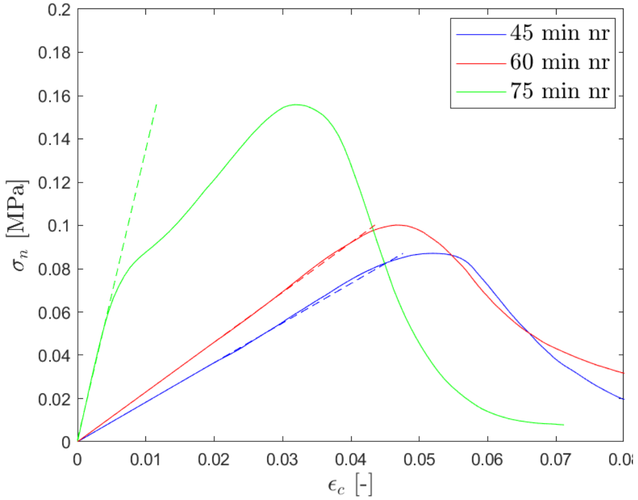
Mixing → Pumping → Extruding → Building

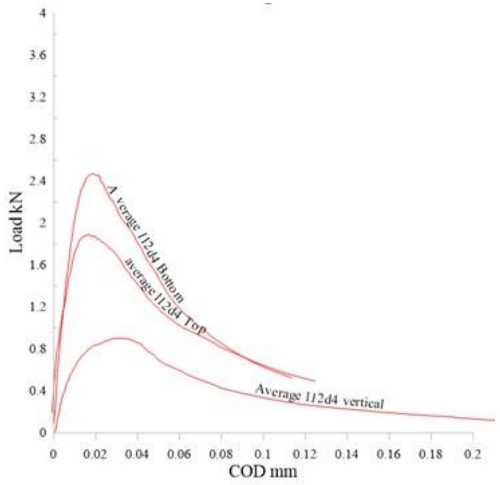
Mixing → Pumping → Extruding → Building



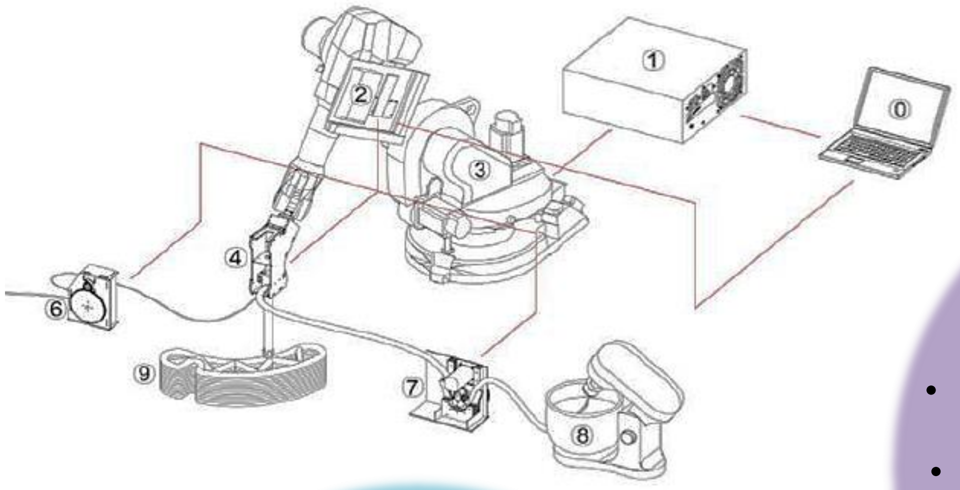








Material – process – product design



Materials

- Binders
- Admixtures
- Aggregates
- Mix design
- Rheology
- Mechanical properties

Structure

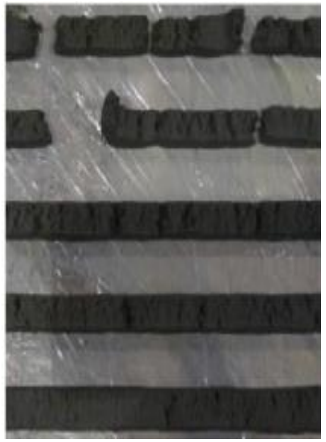
- Material ortotropy
- Reinforcement integration
- Durability and maintenance
- Topology optimization
- Sustainability

Process

- Printing velocity
- Extrusion velocity
- Toolpath
- Nozzle size
- Nozzle head height

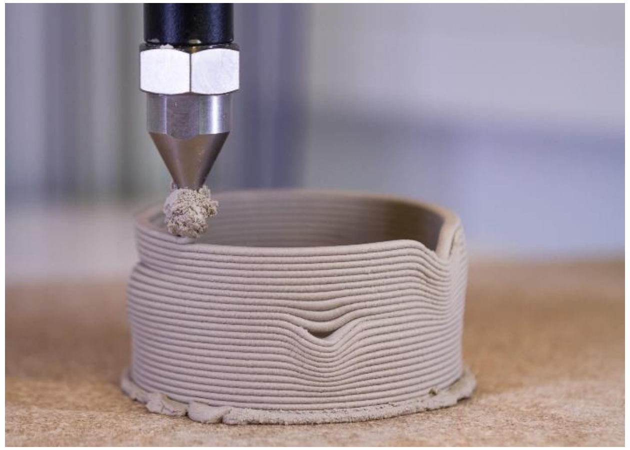
3D Concrete Printing: material-process-product design

At the scale of the filament:



Filament tearing
Ramyar et al. (2022)

Uneven layer's height
TechnoMagazine



Under-extrusion

Over-extrusion

At the scale of the object:

Elastic buckling
R. J. M. Wolf (2019)

Plastic collapse
Concre3DLab Ghent

Plastic shrinkage cracking

Weak bonds and cold joints

Solutions and beyond

1) The trial-and-error approach

- Relying on the experience of the workers
- Huge amount of time and resources

2) Experimental test

- Time-consuming
- Not considering the process

3) Numerical simulations

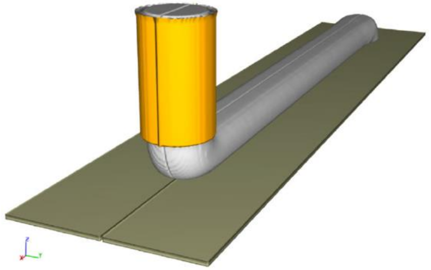
- Quantitative outputs
- Softwares are under development)
- Accuracy is related to experimental test

4) Online monitoring through sensors and digital twins

- Accurate results and online correction of the printing/material parameters
- Under development

1)

2)



3)

4)

Solutions and beyond

IDEA

To develop a tool to help control the extrusion process and to develop new 3D printable mixes.

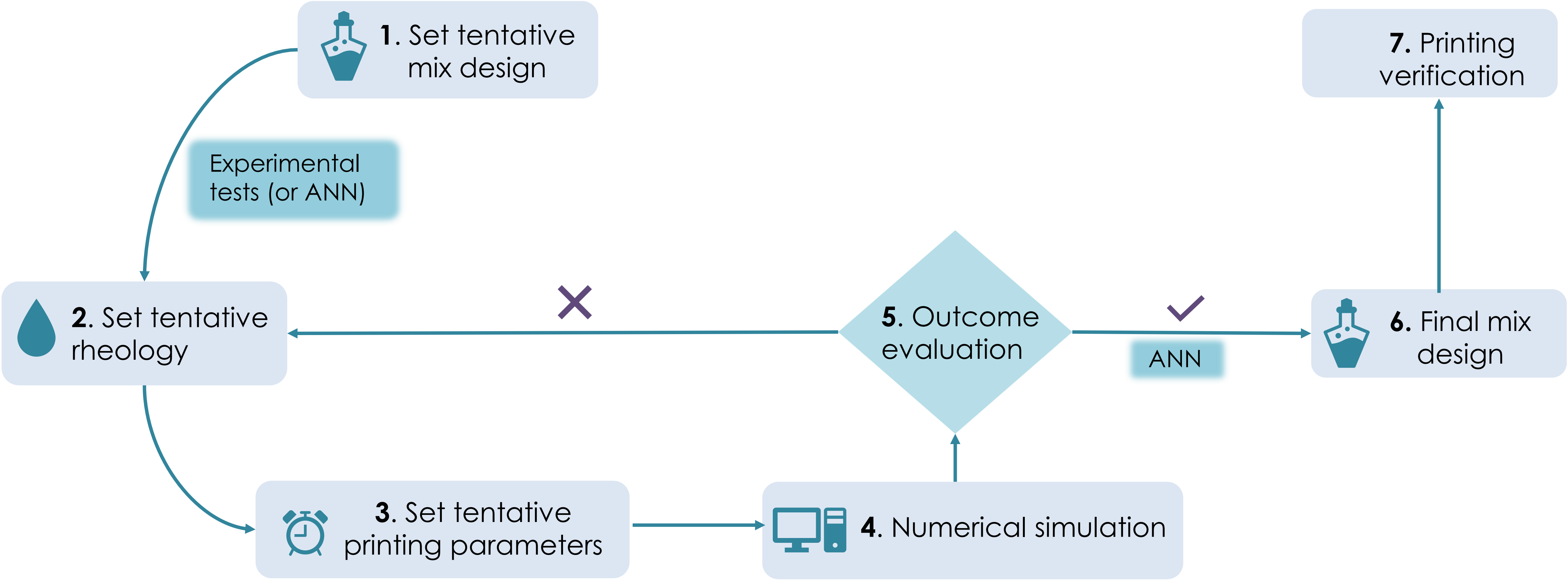
WHY?

- Increase reliability and geometrical accuracy of the printed objects.
- Optimize the process while ensuring good layer quality.
- Develop of new and more sustainable mixes.

HOW?

Combining in a single framework experimental tests, numerical simulation and AI techniques.

Proposed material & process design tool

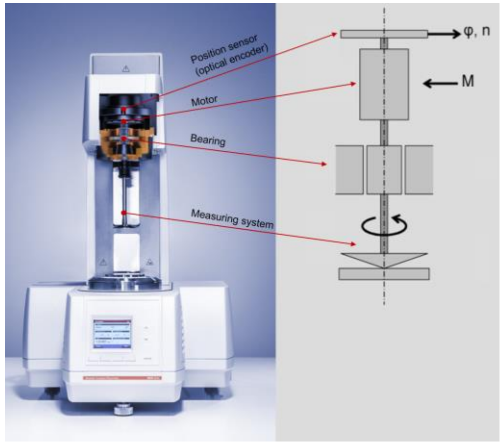


Proposed tool: Flow Table Test

1. Set tentative mix design → **2.** Set tentative rheology

Experimental tests (or ANN)

① Rheometer



A. P. Wiki, "Rheological measurements The rheometer

Prediction of τ_0, τ_d and μ_p applicable only in laboratory settings. Time consuming and hardly suitable for zero slump mixes

② Slump Test

Google images

Prediction of τ_0 with an upper limit for stiff mixes with zero slump (3D print mix). Fast and easier but does not discriminate beyond a certain yield stress

③ Flow Table Test

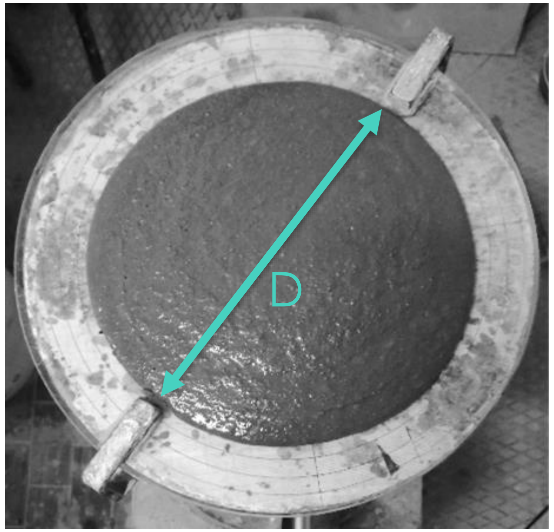
Proposed apparatus for the determination of τ_0 aimed at addressing the limitations of the Slump Test. Fast and easier

Proposed tool: Flow Table Test

Reference 3DPC mixes

Mix	Cement mortars		
	A	B	C
CEM type	CEM I	CEM I	CEM I
Cement (%)	100	100	100
Agg. Max size (mm)	2.00	2.00	2.00
Microsilica (%)	/	/	/
Fly Ash (%)	/	/	/
w/b	0.40	0.40	0.33
a/b	0.82	1.03	1.25
Sp (%)	0.20	0	0.20
Rheometer Test			
Time (min)	10	15	15
τ_0 (Pa)	80	300	658
μ (Pa·s)	10	15	15

Reading Diameter



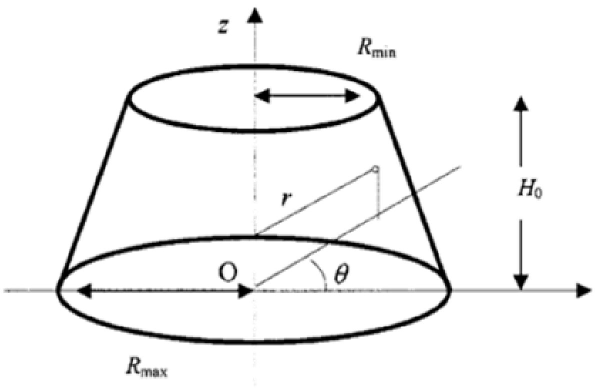
- F. Soave, G. Muciaccia, and L. Ferrara, **An indirect methodology for evaluating the rheological properties of a digitally fabricated concrete incorporating corrosion inhibitors** *RILEM Spring Convention 2024 -Milan, April 10 –12, 2024*
- F. Soave, G. Muciaccia, and , L. Ferrara. **A Simplified Method for Evaluating 3DP Concrete Rheology with Digital Image Processing Technology of Flow Table test results.** *Italian Concrete Conference (ICC2024) – Florence, June 19 –21, 2024*

Proposed tool: Flow Table Test

Static yield strengths prediction

Roussel's formulation

$$\begin{cases} \dfrac{\partial p}{\partial r} = \dfrac{\partial \tau}{\partial z} \\ \dfrac{\partial p}{\partial z} = -\rho g \end{cases} \qquad \tau = \frac{225\, \rho\, g\, V^2}{128\, \pi^2 R_d^5}$$

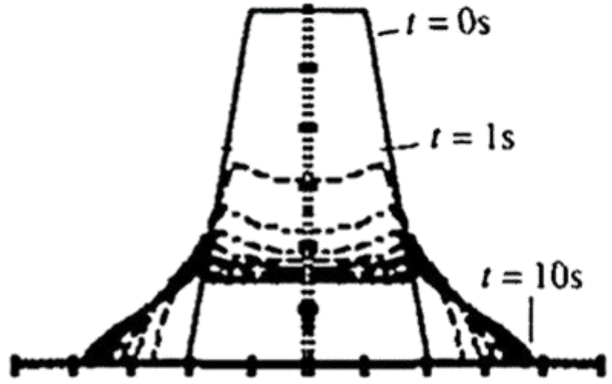


- $\rho\ [kg/m^3]$ is the concrete density,
- $g\ [m/s^2]$ is the gravitational acceleration
- $V\ [m^3]$ is the volume cone
- $R_d\ [mm]$ is the spreading radius at drop d
- $D_d\ [mm]$ is the spreading diameter at drop d

Characteristic length of the contact surface is much larger than the characteristic length of the fluid depth (H << 2R)

Kurokawa's formulations

$$\tau = \frac{1}{\sqrt{3}}\sigma_v = \frac{1}{\sqrt{3}}\frac{P_g}{A_{spread}} = \frac{1}{\sqrt{3}}\frac{\rho\, g\, V}{A_{spread}} = \frac{\rho\, g\, V}{100\sqrt{3}\pi R_t^2} \cdot 10^8 = \frac{\rho\, g\, V}{25\sqrt{3}\pi D_d^2} 10^8$$



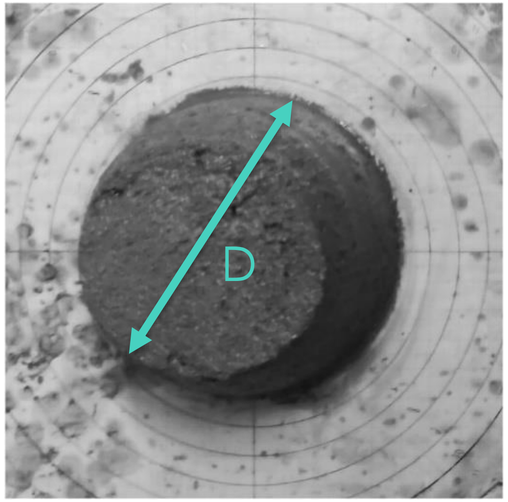
The material maintains a truncated cone shape after the slump, utilizing the Von Mises plasticity criterion (H >>2R)

- F. Soave, G. Muciaccia, and L. Ferrara, **An indirect methodology for evaluating the rheological properties of a digitally fabricated concrete incorporating corrosion inhibitors** *RILEM Spring Convention 2024 -Milan, April 10 –12, 2024*
- F. Soave, G. Muciaccia, and , L. Ferrara. **A Simplified Method for Evaluating 3DP Concrete Rheology with Digital Image Processing Technology of Flow Table test results.** *Italian Concrete Conference (ICC2024) – Florence, June 19 –21, 2024*

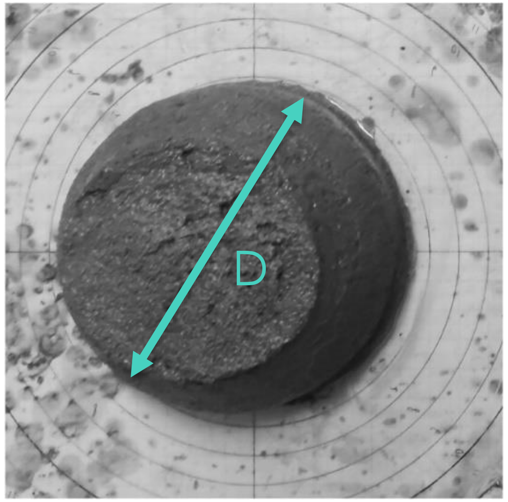
Proposed tool: Flow Table Test

Procedure

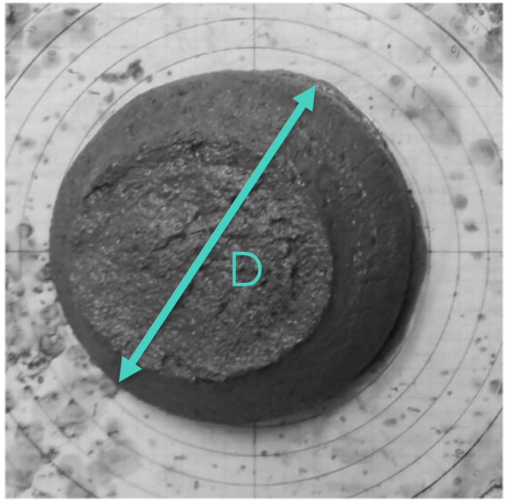
Drop 0



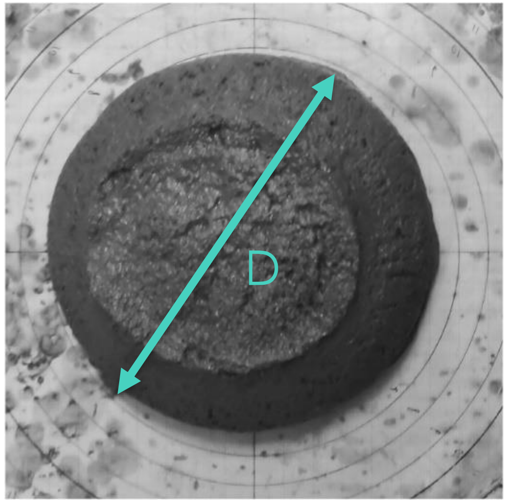
Drop 5



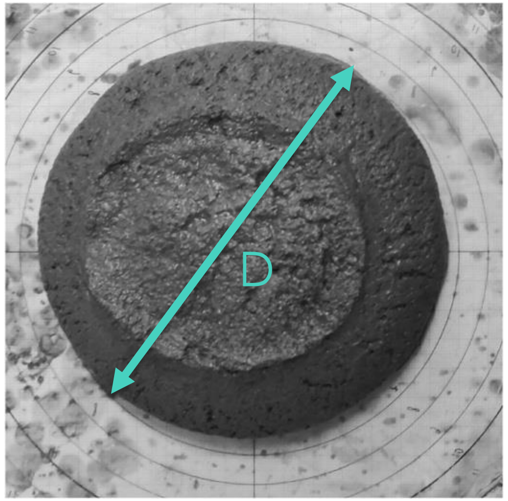
Drop 10



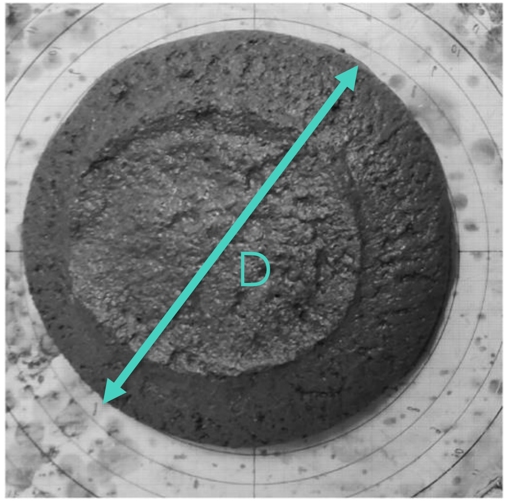
Drop 15



Drop 20

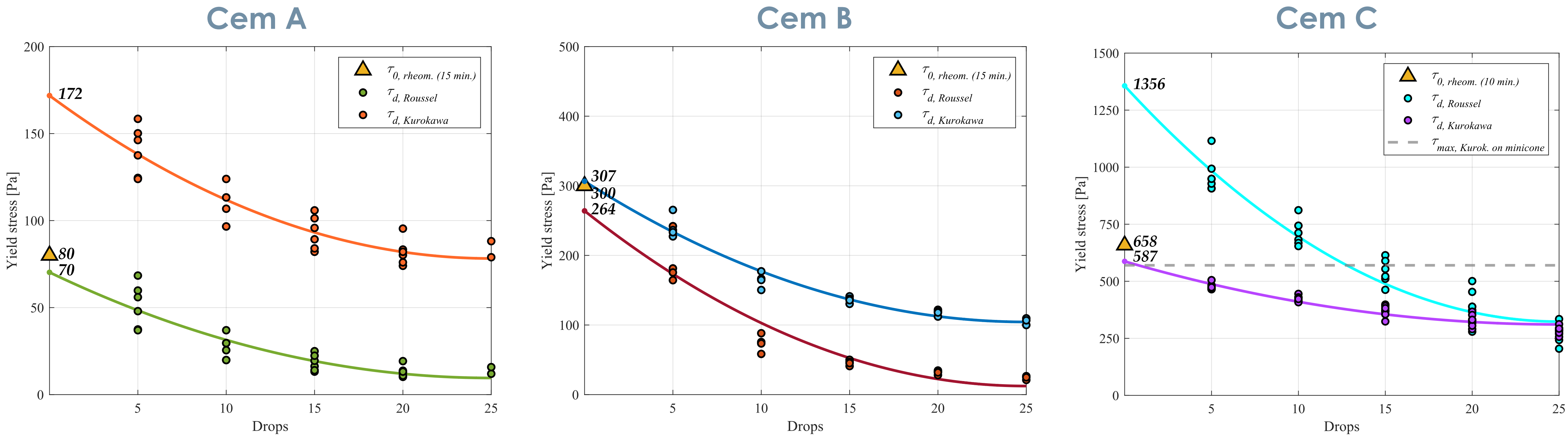


Drop 25



Test Validation

Mix	$\tau_{0,Rheom}$ (Pa)	$\tau_{0,Roussel}$ (Pa)	$\tau_{0,Kurokawa}$ (Pa)	Error (%)
Cem A	80	70	172	-12.5
Cem B	300	264	307	2.3
Cem C	658	1456	587	-10.8



Limit formulation Roussel to 300 Pa above proposed to use Kurokawa

- F. Soave, G. Muciaccia, and L. Ferrara, **An indirect methodology for evaluating the rheological properties of a digitally fabricated concrete incorporating corrosion inhibitors** *RILEM Spring Convention 2024 -Milan, April 10 –12, 2024*
- F. Soave, G. Muciaccia, and , L. Ferrara. **A Simplified Method for Evaluating 3DP Concrete Rheology with Digital Image Processing Technology of Flow Table test results.** *Italian Concrete Conference (ICC2024) – Florence, June 19 –21, 2024*

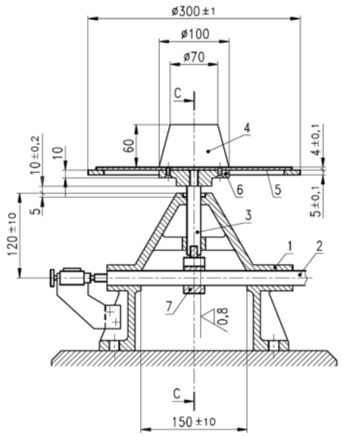
Proposed tool: Flow Table Test

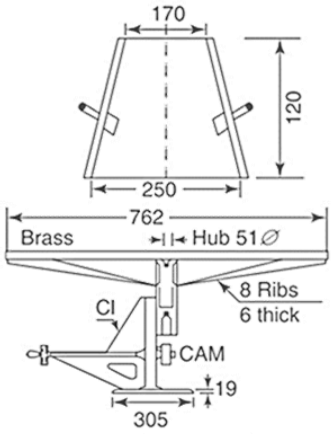
Correlation limit

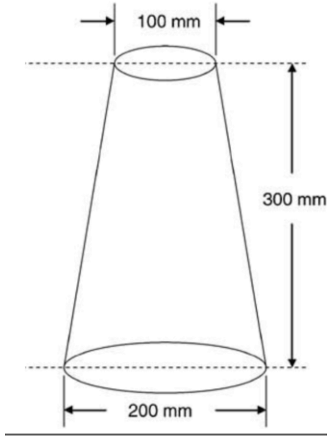
Cone	Mortar cone (flow table test)	Concrete cone (flow table test)	Abrams cone
Diameter inf. (cm)	10	25	20
Diameter sup. (cm)	7	17	10
Height (cm)	6	12.9	30
Volume cone (cm3)	344	4206.59	5497.78
$\tau = \frac{\rho\, g\, V}{25\sqrt{3}\pi D_d^2} 10^8$ Limit Kurokawa's formulations (Pa)	1521.77	2692.76	12146.34
$\tau = \frac{225\, \rho\, g\, V^2}{128\pi^2 R_d^5}$ Limit Roussel's formulations (Pa)	570.57	1200.07	2270.68

Density→2300 (Kg/m3)

Gravity→9.807 (m/s2)



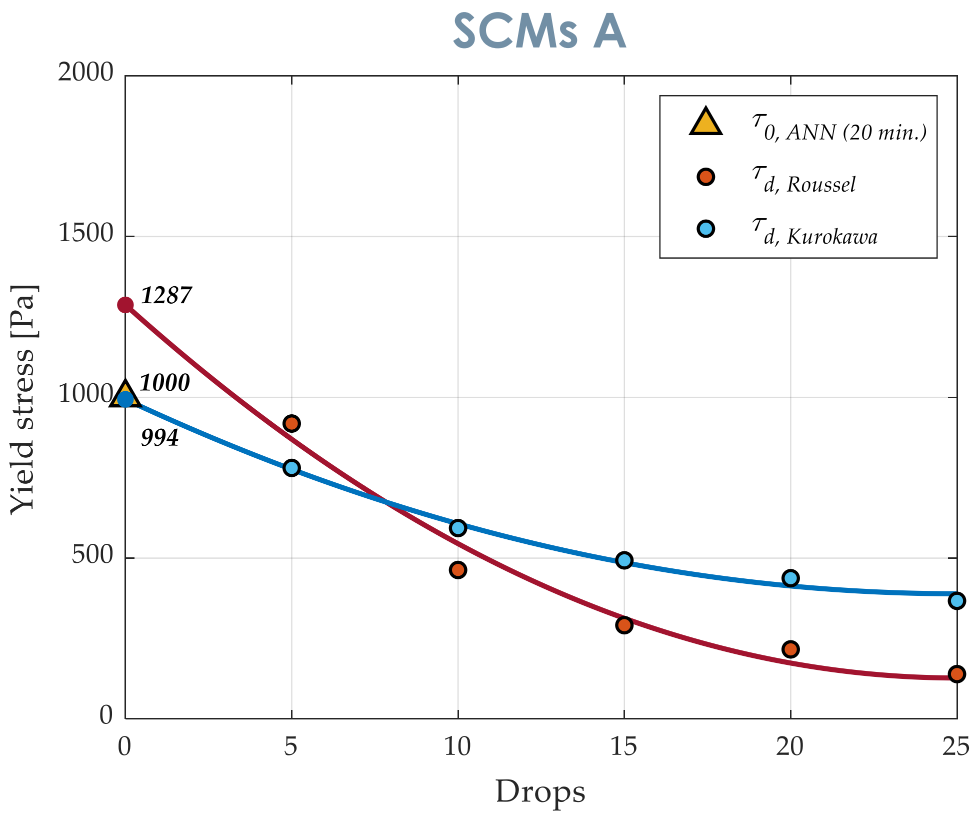




Proposed tool: Flow Table Test

Concrete cone setup

Mix	Cement mortars			SCMs mortars
	A	B	C	A
CEM type	CEM I	CEM I	CEM I	CEM I
Cement (%)	100	100	100	100
Agg. Max size (mm)	2.00	2.00	2.00	75
Microsilica (%)	/	/	/	5
Fly Ash (%)	/	/	/	65
w/b	0.40	0.40	0.33	0.33
a/b	0.82	1.03	1.25	1.00
Sp (%)	0.20	0	0.20	0.25
Time (min)	10	15	15	20
τ_0 (Pa)	80	300	658	1000



Increasing the volume increases the upper limit of the formulations

- F. Soave, G. Muciaccia, and L. Ferrara, **An indirect methodology for evaluating the rheological properties of a digitally fabricated concrete incorporating corrosion inhibitors** *RILEM Spring Convention 2024 -Milan, April 10 –12, 2024*
- F. Soave, G. Muciaccia, and , L. Ferrara. **A Simplified Method for Evaluating 3DP Concrete Rheology with Digital Image Processing Technology of Flow Table test results.** *Italian Concrete Conference (ICC2024) – Florence, June 19 –21, 2024*

Proposed tool: numerical model

2. Set tentative rheology → **3**. Set tentative printing parameters

Material parameters: $\rho = 2100\ kg/m^3$ $\mu = 7.5\ Pa \cdot s$ $\tau_0 = 630\ Pa$

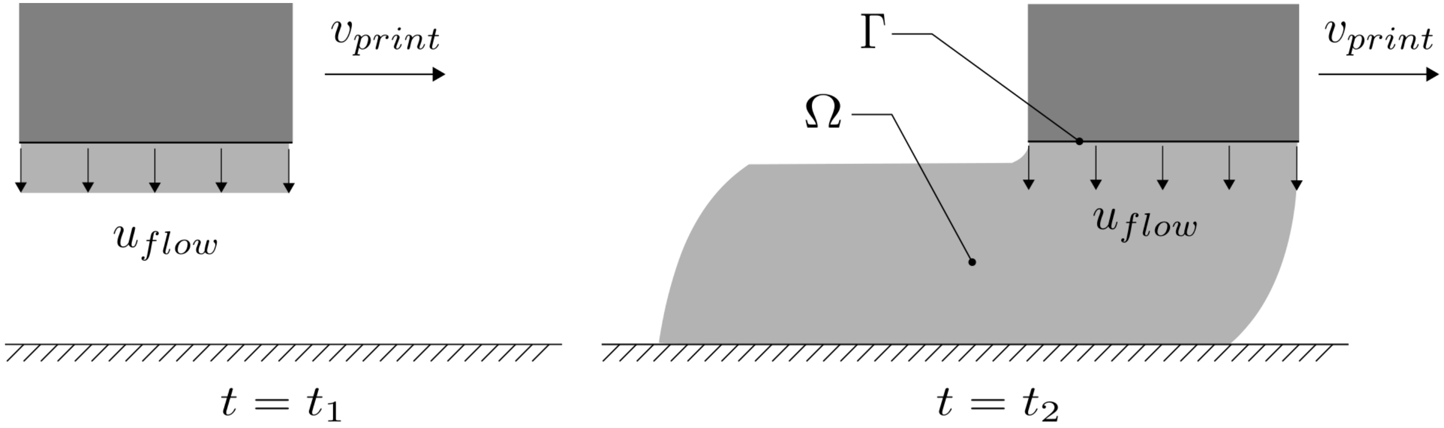
Printing parameters

$v_{flow} = 33.6\ mm/s$

$v_{print} = 30\ mm/s$

$d_{nozzle} = 25\ mm$

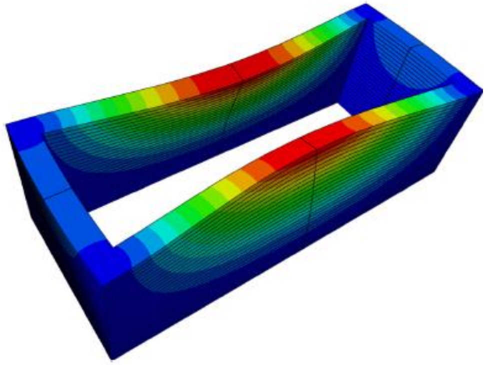
$h_{nozzle} = 12.5\ mm$



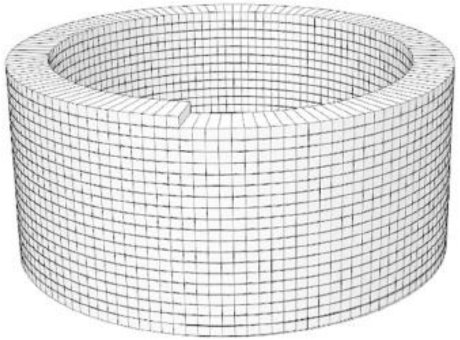
Proposed tool: numerical model

3. Set tentative printing parameters → **4.** Numerical simulation

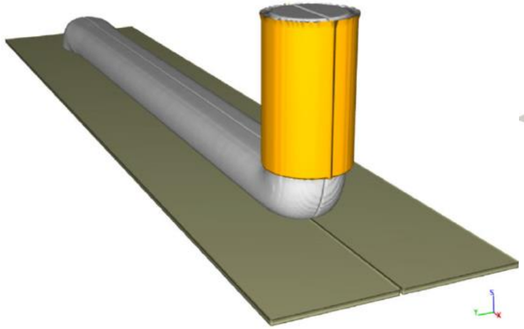
Numerical models for 3D Concrete Printing (3DCP) are still being developed:



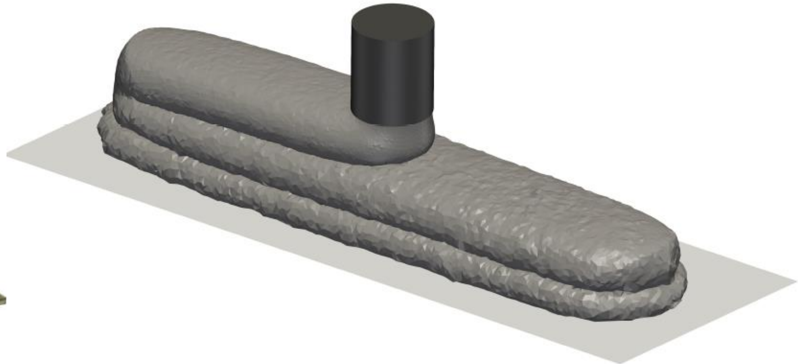
R. Wolfs et al. (2019)



T. Ooms et al. (2021)



R. Comminal et al. (2020)



G. Rizzieri et al. (2023)

at the scale of the object

at the scale of the filament

Proposed tool: numerical model

Navier-Stokes equations

Balance of linear momentum

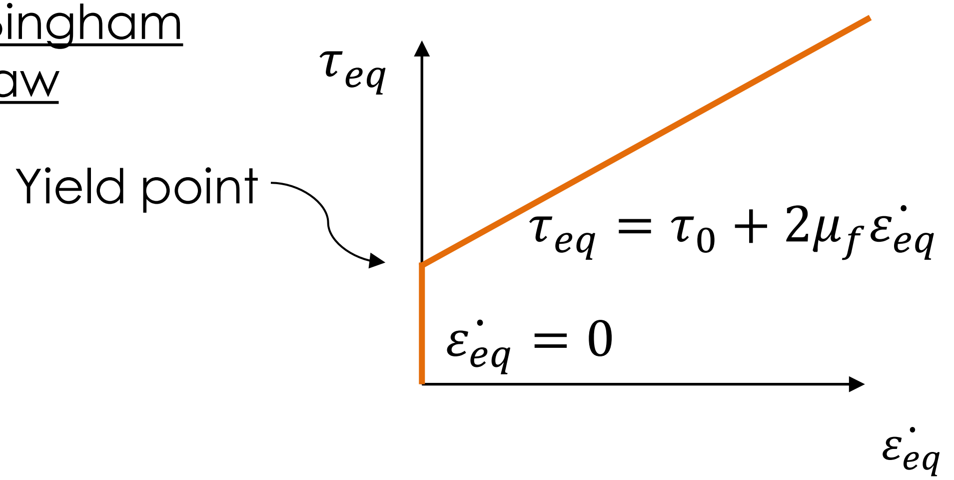
$$\nabla_{\boldsymbol{x}} \cdot \boldsymbol{\sigma} + \rho \boldsymbol{b} = \rho \left(\left.\frac{\partial \boldsymbol{u}}{\partial t}\right|_{\boldsymbol{X}} + (\boldsymbol{c} \cdot \nabla_{\boldsymbol{x}})\boldsymbol{u} \right) \quad \text{in } \Omega_t \times [0, T]$$

Balance of mass

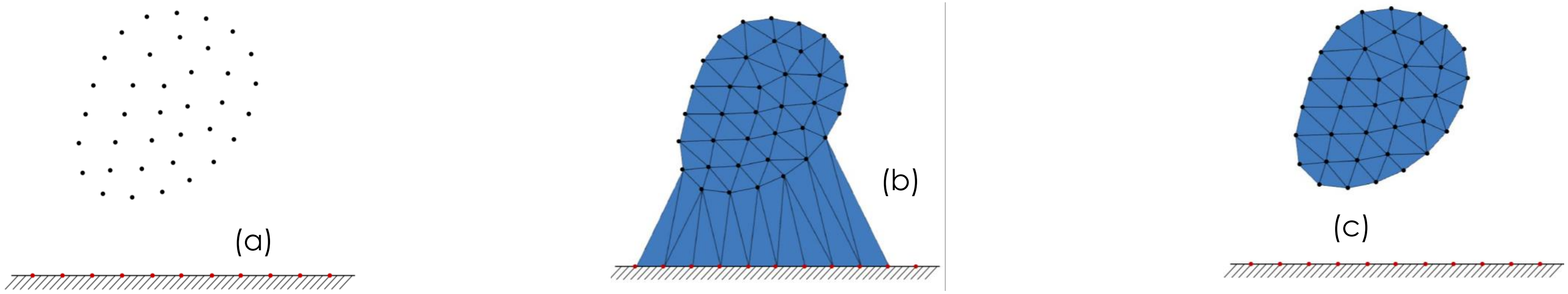
$$\left(\left.\frac{\partial p}{\partial t}\right|_{\boldsymbol{X}} + \boldsymbol{c} \cdot \nabla_{\boldsymbol{x}} p \right) + K \nabla_{\boldsymbol{x}} \cdot \boldsymbol{u} = 0 \quad \text{in } \Omega_t \times [0, T]$$

Rheological/constitutive law

Bingham law



Particle Finite Element Method



Remove the previous mesh, obtaining a set of points.

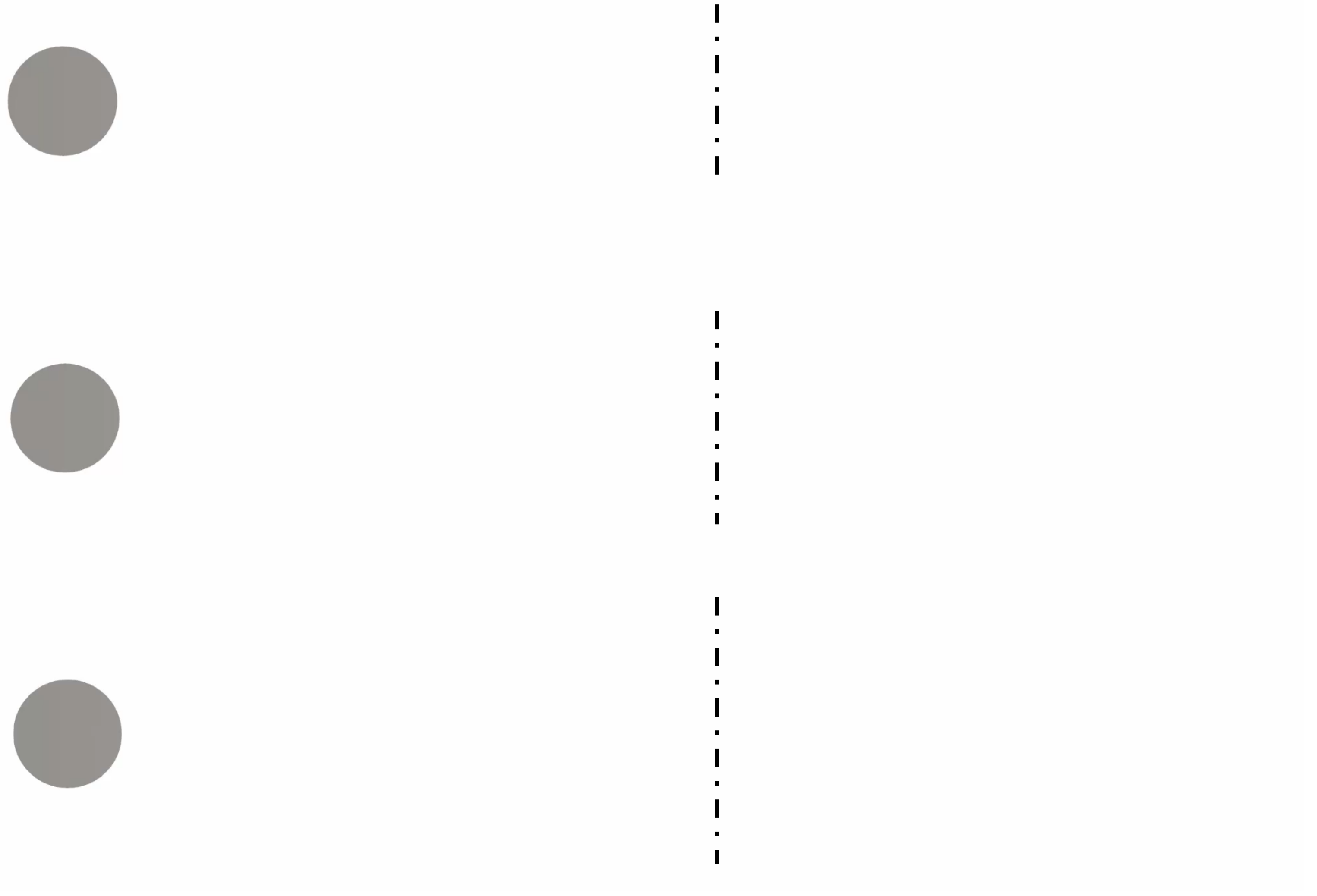
Delaunay triangulation is performed.

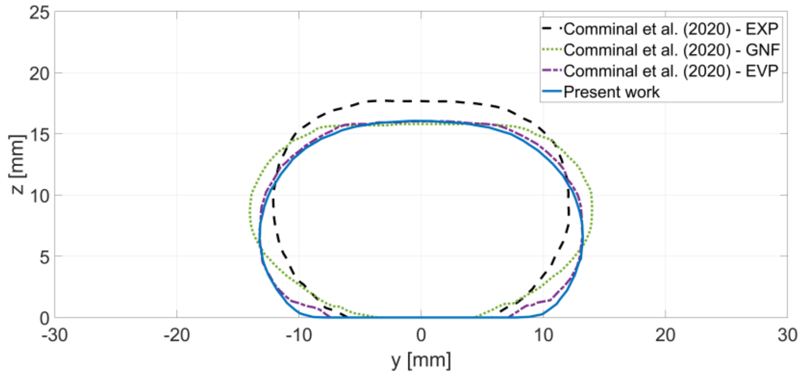
The alpha-shape method removes overly distorted elements.

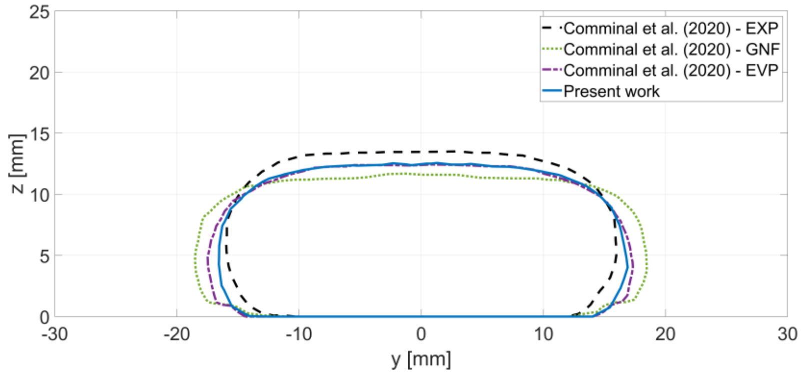
❖ G. Rizzieri, L. Ferrara, and M. Cremonesi. **Numerical simulation of theextrusion and layer deposition processes in 3D concrete printing with the Particle Finite Element Method.** *Comput Mech, 73, 277–295 (2024)*. DOI: 10.1007/s00466-023-02367-y.

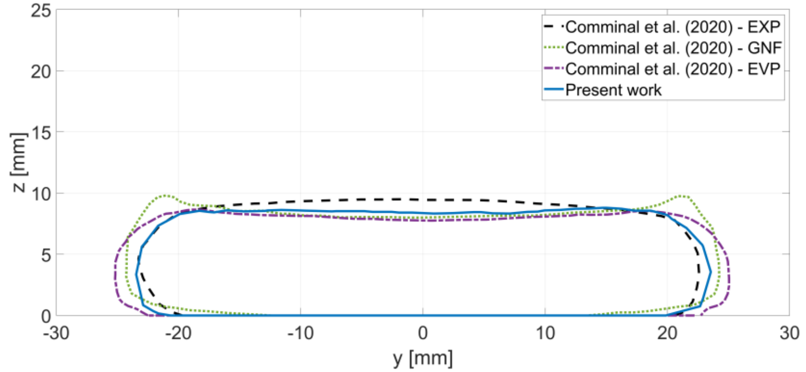
Proposed tool: numerical model

Code validation



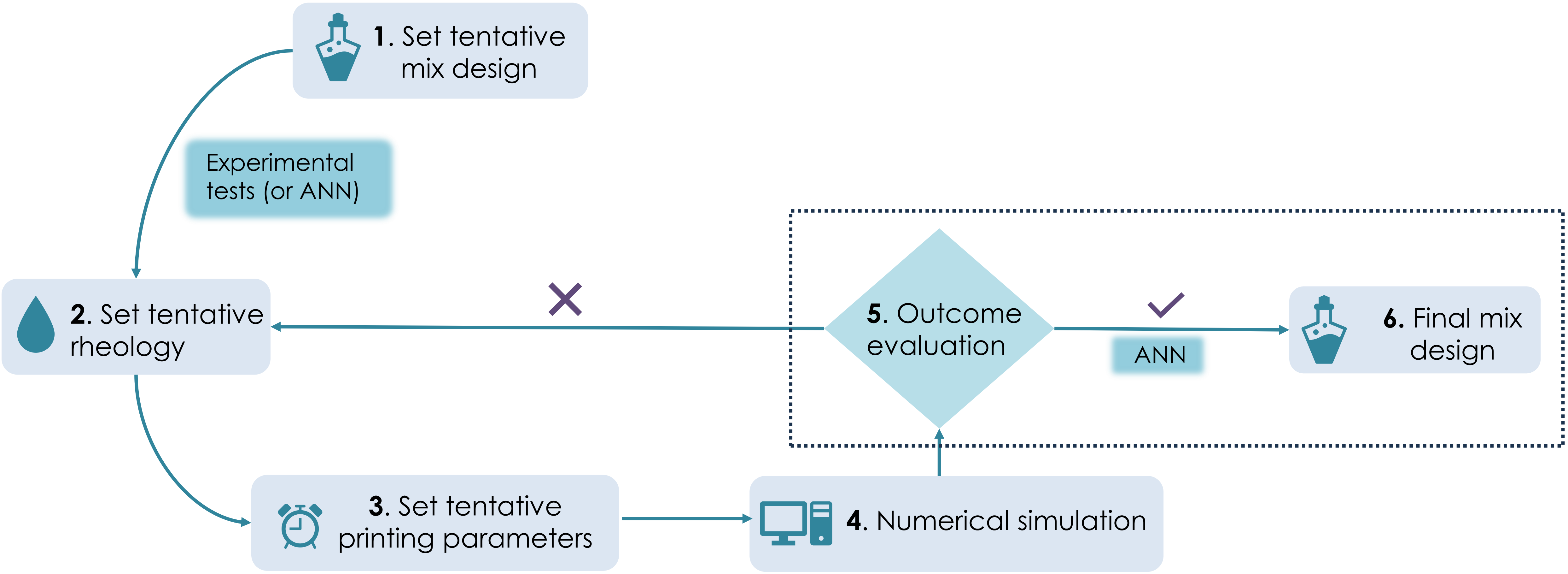






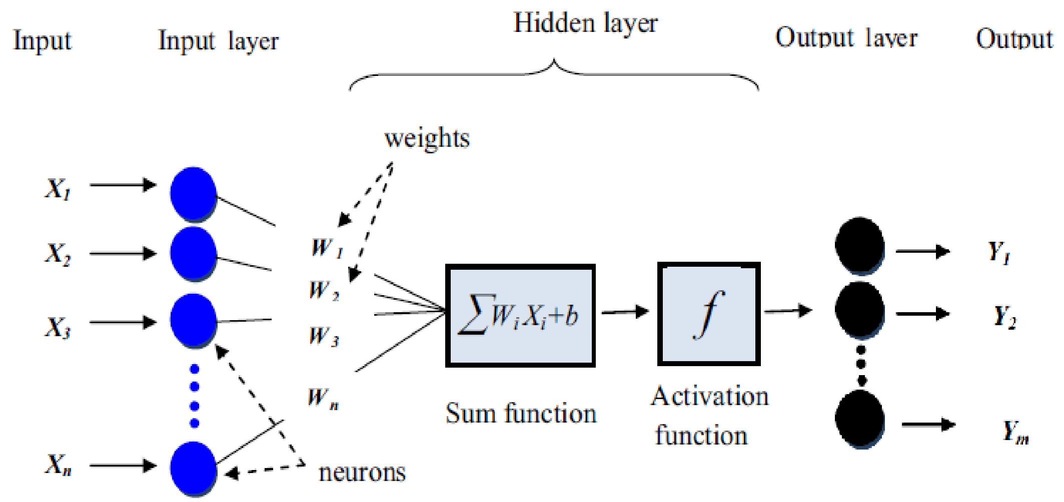
❖ G. Rizzieri, L. Ferrara, and M. Cremonesi. **Numerical simulation of the extrusion and layer deposition processes in 3D concrete printing with the Particle Finite Element Method.** *Comput Mech, 73, 277–295 (2024)*. DOI: 10.1007/s00466-023-02367-y.

Proposed tool: artificial neural network



Artificial Neural Network (ANN) – structure

Artificial neural network generic structure:

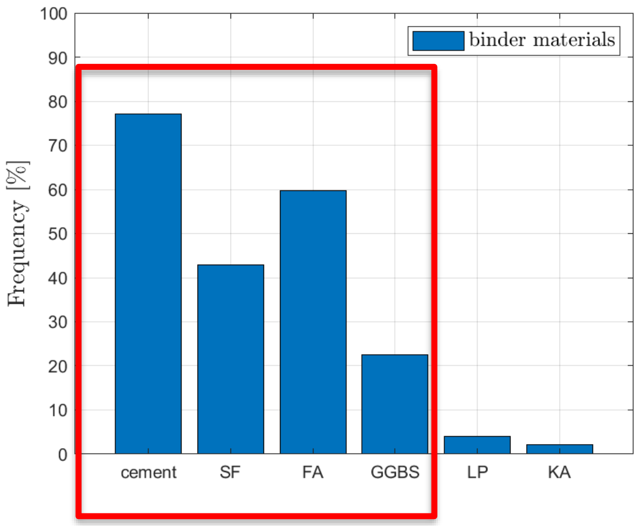


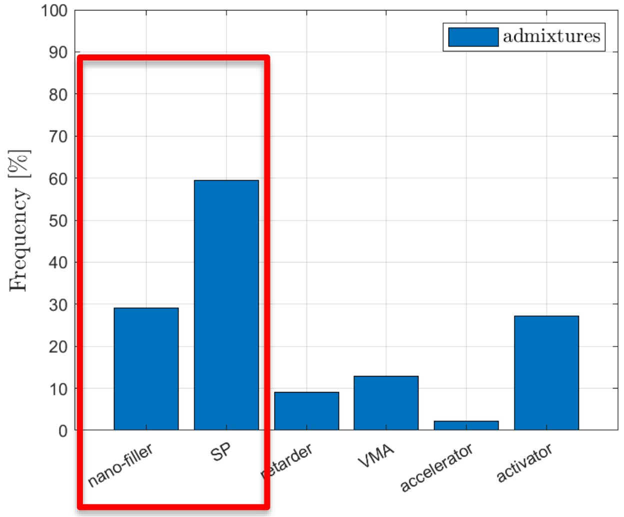
10 significant input selected:

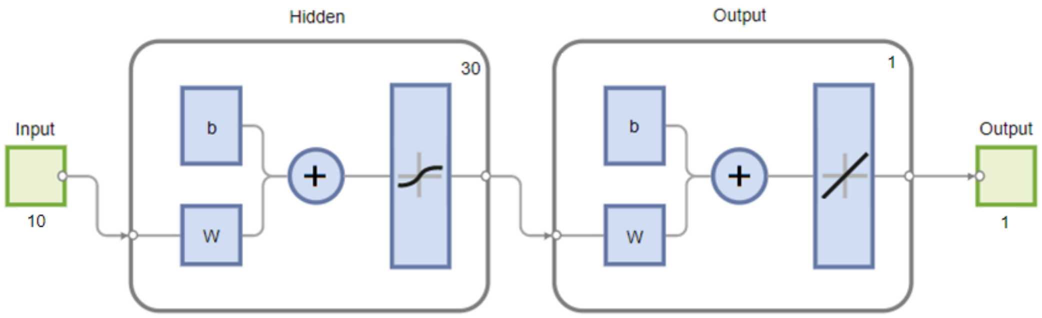
- time from mixing
- aggr. max size
- water/binder
- aggregates/binder
- cement content
- Silica fume content
- fly ash content
- GGBS content
- nano-filler content
- superplasticizer content

SCMs (fly ash content, GGBS content)

additives (nano-filler content, superplasticizer content)







STATIC YIELD STRESS

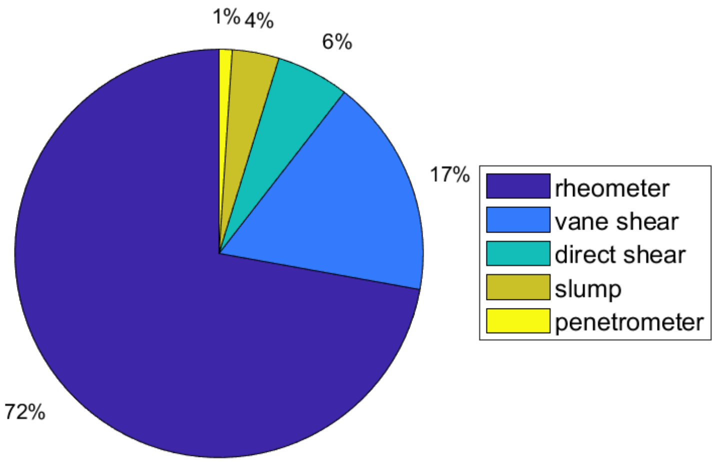
Artificial Neural Network (ANN) – data filtering

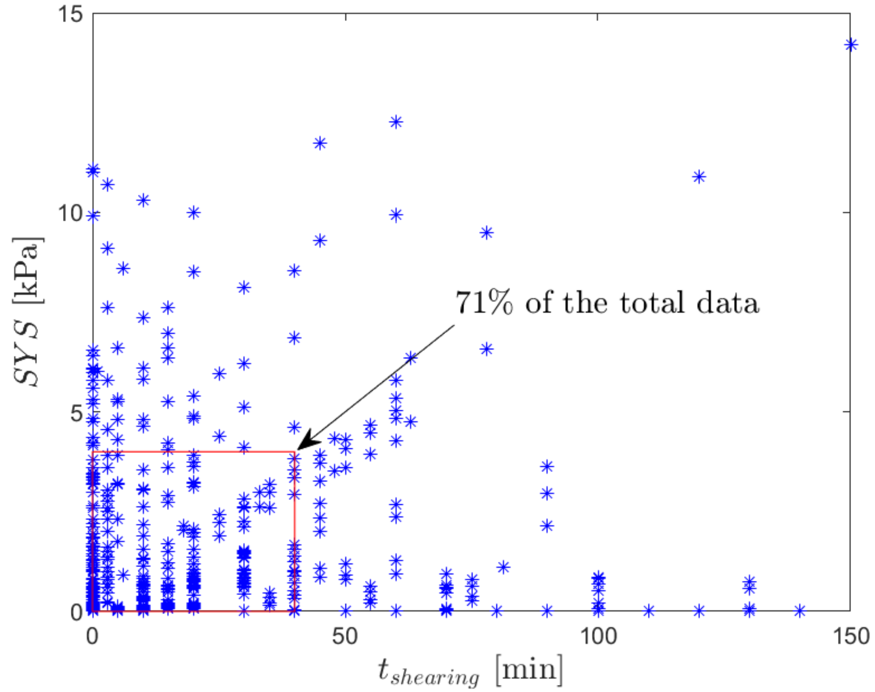
485 — Excluding records related to discarded inputs

434 — Measures taken with rheometers and shear vane tests

304 — Measures until 40 minutes from last shearing phase and SYS < 4kPa

Final set of measures

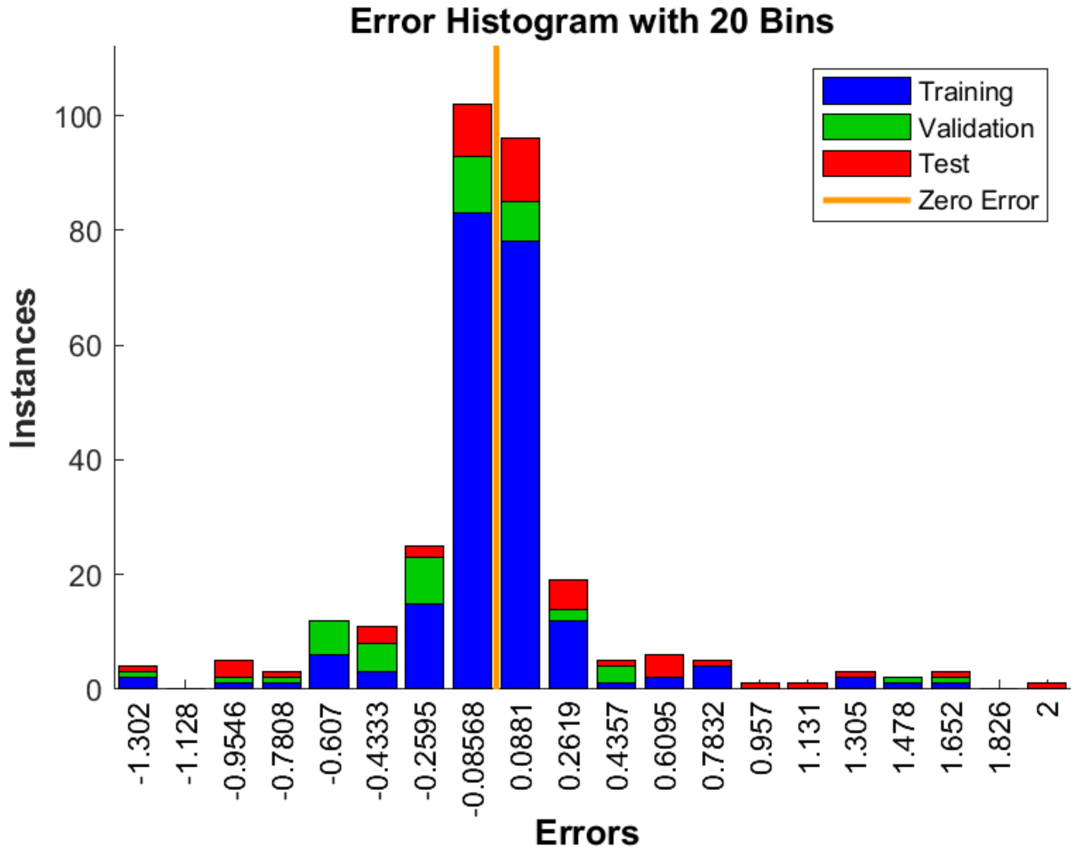




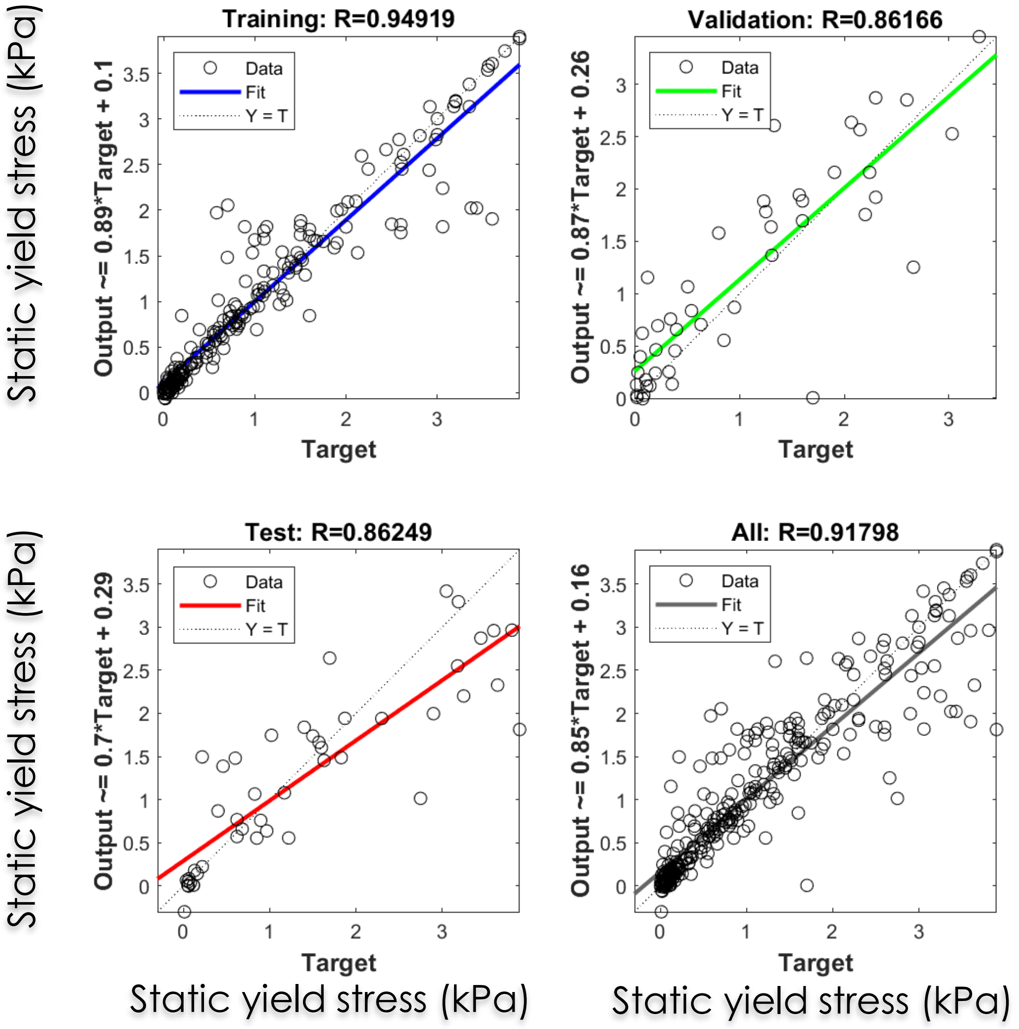
Artificial Neural Network (ANN) – results

NETWORK PERFORMANCE

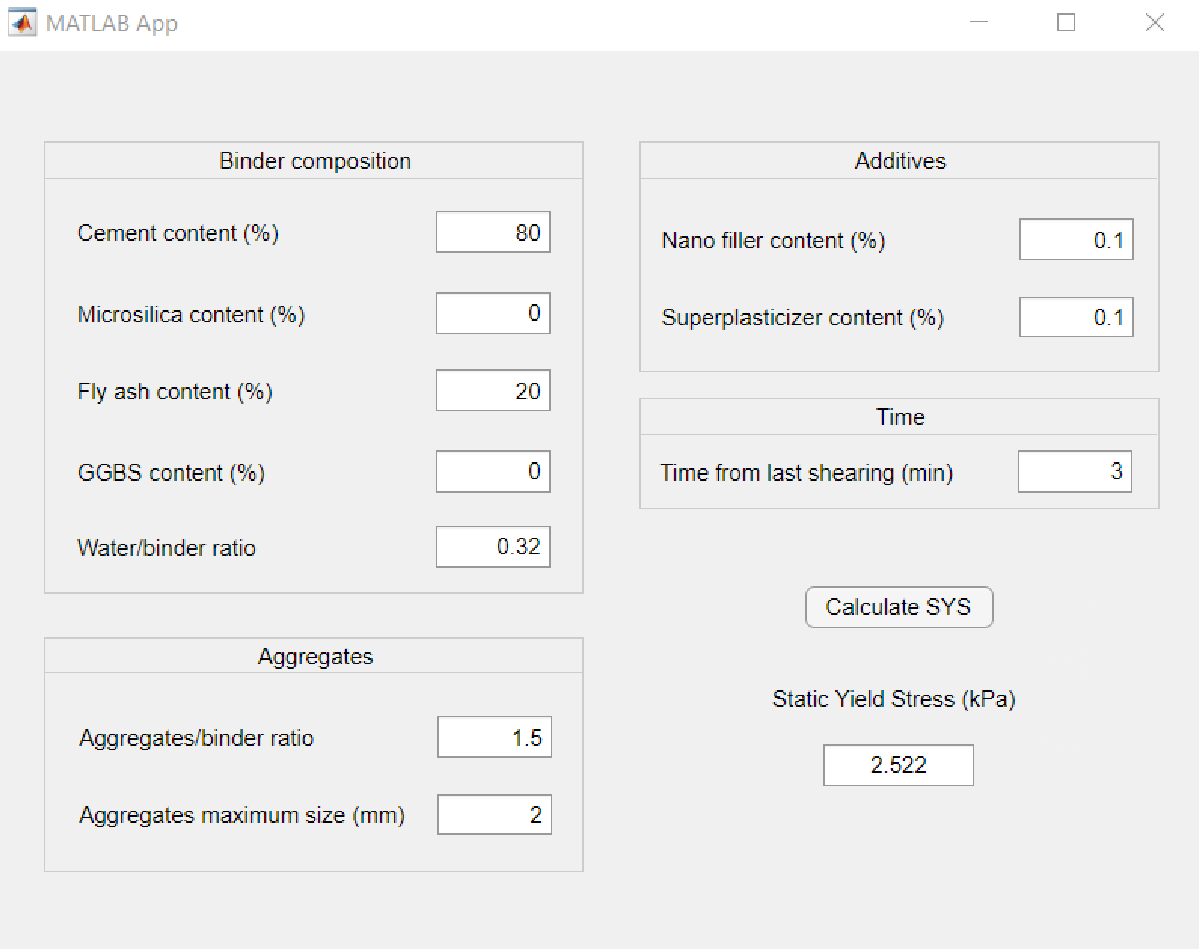
Mean Squared Error



Regression values



Artificial Neural Network (ANN) – results



Parameter	Test 1	Test 2	Test 3	Test 4	Test 5
Aggr. max size (mm)	2.00	0.65	2.00	0	1.00
Water/binder ratio	0.32	0.35	0.42	0.35	0.35
Aggr./binder ratio	1.50	0.75	1.02	0	1.00
Cement (%)	80	70	0	70	0
Microsilica (%)	0	5	8	5	0
Fly ash (%)	20	25	78	25	50
GGBS (%)	0	0	14	0	50
Nano filler (%)	0.10	0.50	0	0.25	0
SP (%)	0.10	0.30	0	0	0
Time from shearing (min)	3	15	0	20	20
Static y. s. measured (kPa)	2.600	0.660	0.380	0.200	1.570
Static y. s. predicted (kPa)	2.522	0.760	0.459	0.196	1.899
Error (%)	3.0	15.2	20.9	1.7	21.0

Flow Table Test

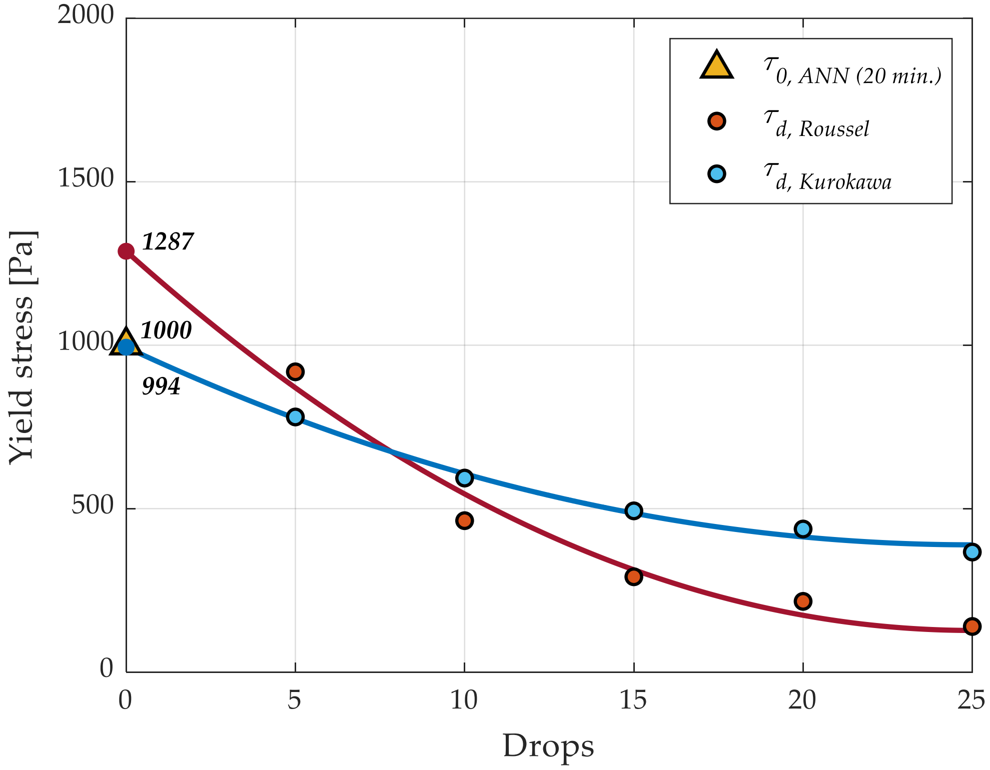
Prediction capability is very limited, as also the number of data is

OVERFITTING

In order to build a more efficient predicting network, data must be more or number of inputs must be lower.

3DCP validation: “AI” designed mix

Mix	SCMs mortar
CEM type	CEM I
Cement (%)	100
Agg. Max size (mm)	75
Microsilica (%)	5
Fly Ash (%)	65
w/b	0.33
a/b	1.00
Sp (%)	0.25
Time (min)	20
ANN τ_s (Pa)	1 000



3DCP validation: “AI” designed mix

Preliminary conclusions

- This study has provided a contribution to materials and process 3D concrete printing design aiming at optimization and control of the extrusion process by developing 3D printable mixes tailored to specific printing parameters.

- The methodology combines three core techniques: **Experimental Testing**, **Numerical Analysis**, and an **Artificial Neural Network (ANN).**

  - Flow Table Test: Enables rapid determination and control of the rheological properties of various mixes, including those generated by the ANN.

  - Numerical Model: Defines stability domains for different mixes with varying rheological properties, based on printing input parameters.

  - Artificial Neural Network: Utilizes its database to generate mixes that meet the rheological properties defined by the numerical analysis.

- While the results are promising, further refinement is needed across all three techniques to achieve a fully closed and optimized system with more reliable outcomes.

POLITECNICO
MILANO 1863

DEPARTMENT OF CIVIL AND
ENVIRONMENTAL ENGINEERING

MUSA
MULTILAYERED URBAN SUSTAINABILITY ACTION

The project MUSA – Multilayered Urban Sustainability Action – project, funded by the European Union – NextGenerationEU, under the National Recovery and Resilience Plan (NRRP) Mission 4 Component 2 Investment Line 1.5: Strengthening of research structures and creation of R&D "innovation ecosystems", set up of "territorial leaders in R&D".

Te MUSA Tech

Thank you
for your attention!