3D CONSTRUCTION PRINTING OF COARSE AGGREGATE CEMENTITIOUS COMPOSITE

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INSTITUTE OF **MACHINE**
AND **INDUSTRIAL DESIGN**

CONTENT

- Introduction and Motivation
- State of the Art
- Summary of Literature Review
- Aim of Doctoral Thesis
- Scientific questions and hypotheses
- Results and Discussion
- Conclusion

MOTIVATION

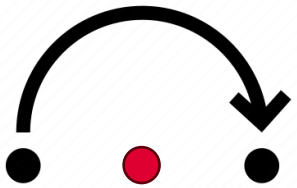
Convential Construction

Convential Construction
(FREEPIK)

Automation in Construction

Digital Fabrication
(IAAC)

Wiser Future



Actual problems/ threads

- Carbon footprint
  (in total 39%, Cement 5-10%);
  waste; HR

Efficiency doesn't meet future needs

Improvement

- Potential to decrease of carbon footprint, waste, HR

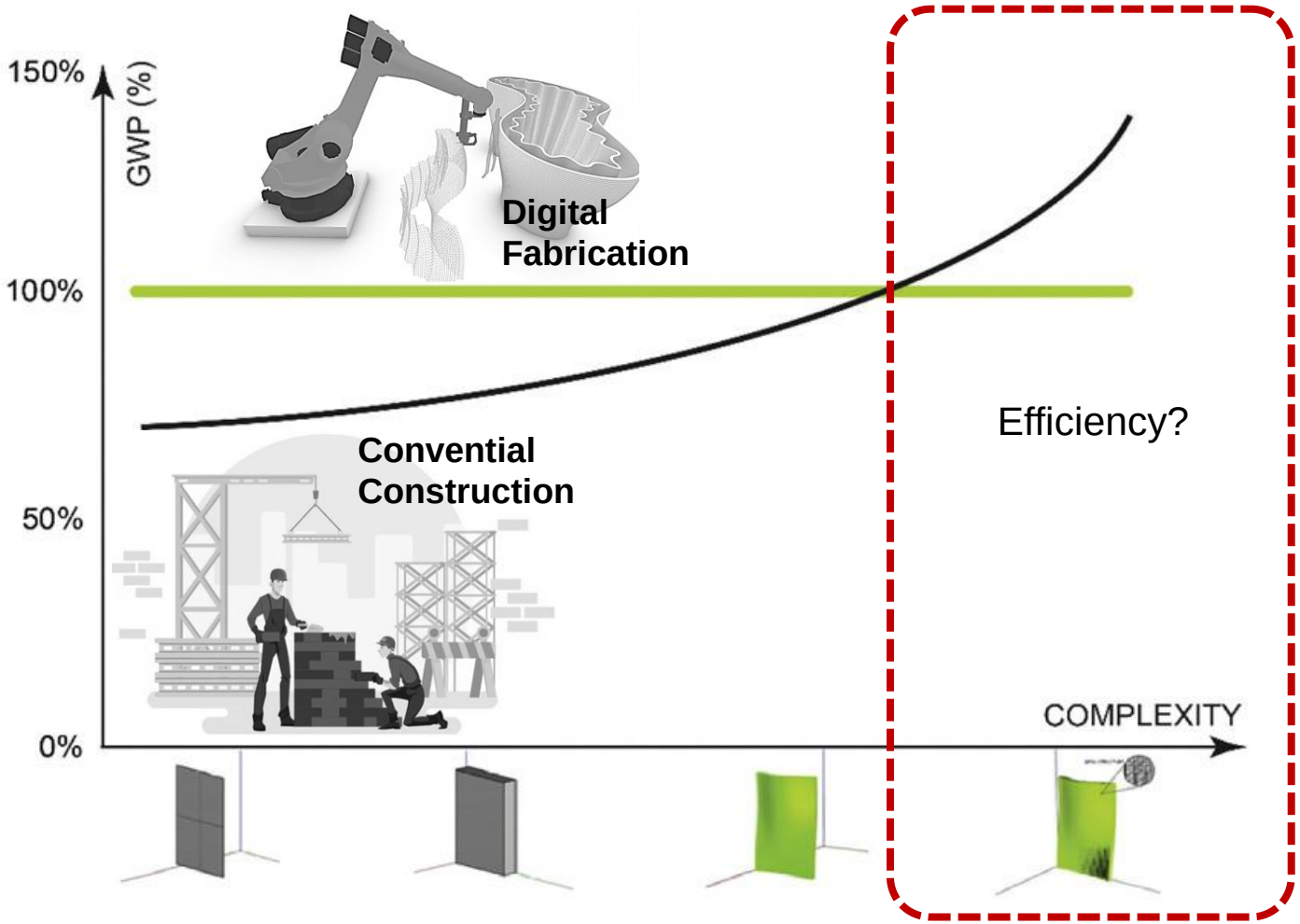
Increase efficiency (?)

Challenge

- Skip the repeating the past
- Higher potential to decrease of carbon footprint, waste, HR

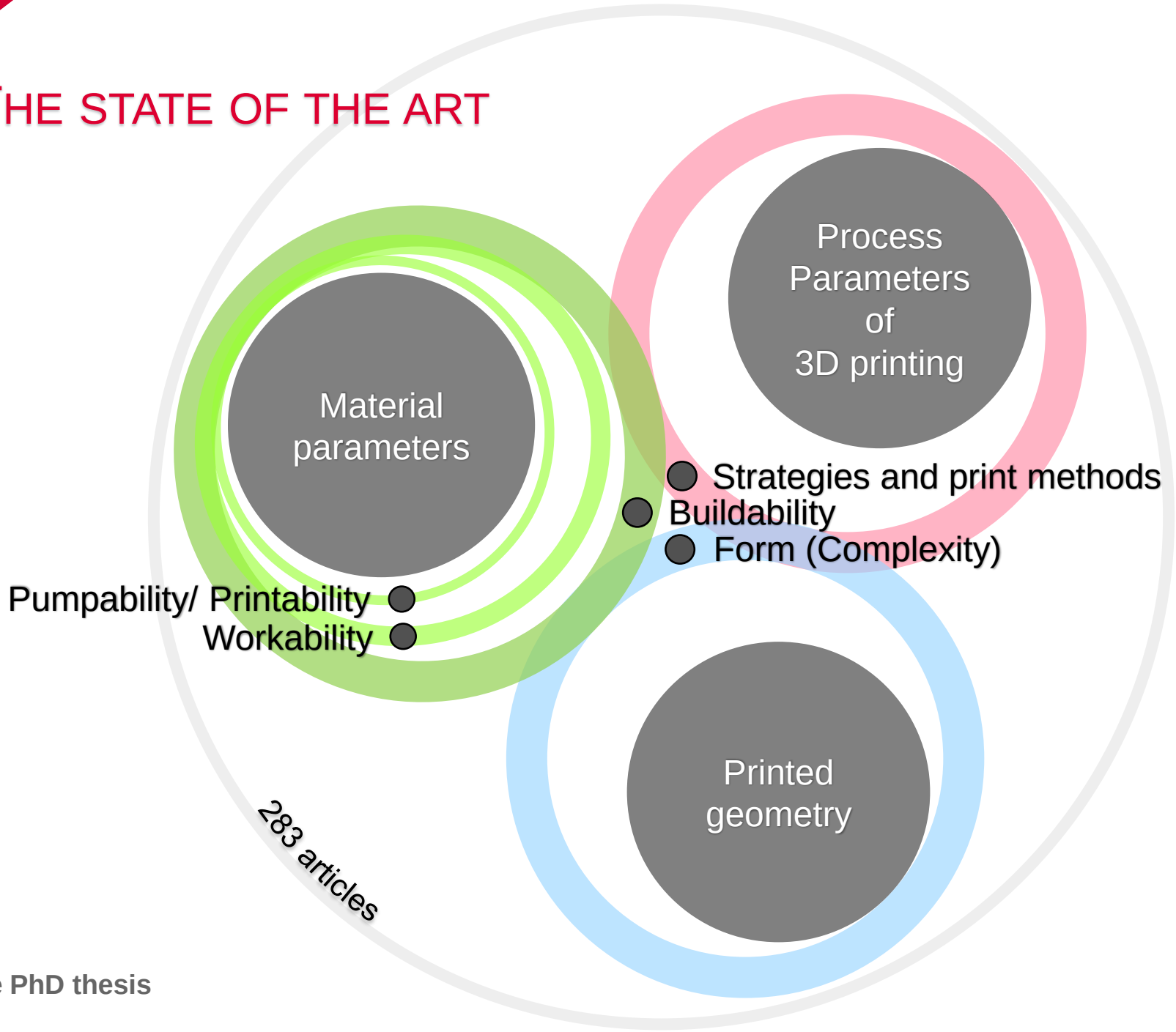
Improvement of material use for efficient 3DCP

MOTIVATION



Digital vs. Conventional manufacturing related to GWP - Global Warm Potential (G.D. Schutter et. al.)

THE STATE OF THE ART

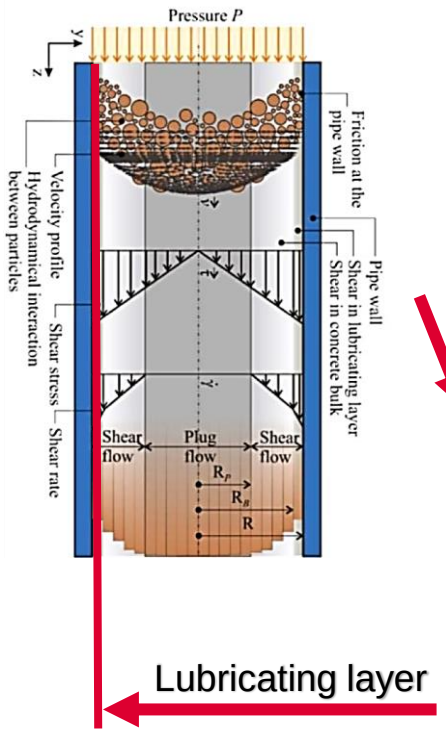


THE STATE OF THE ART

PUMPABILITY | **WORKABILITY** | **BUILDABILITY**

Secrieru, E. et. al.

- Flow characteristics
- Sliding-Pipe rheometer

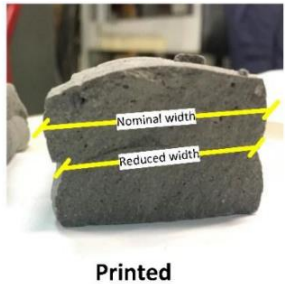


Roussel, N. et. al.; Khosnievis et. al. (2004)

- Homogeneity of layer geometry
- Nozzle geometry

Shear forces

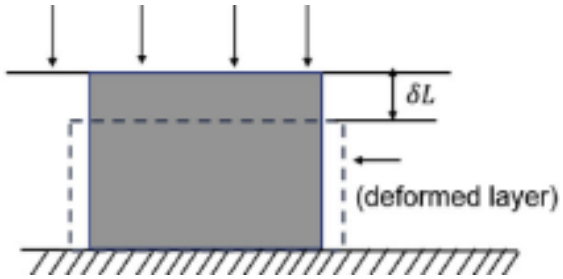
Printed circular shape

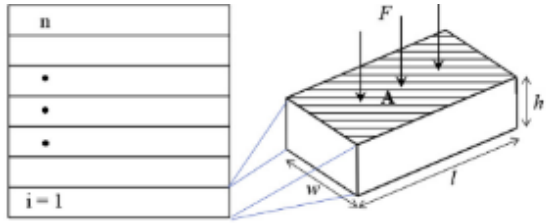


Printed rectangular shape

Shakor, P. et. al.; Panda, B. et. al.

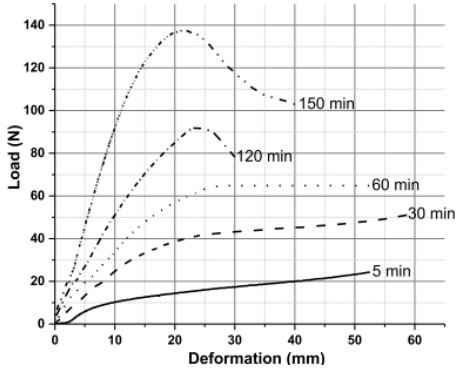
- Load bearing capacity

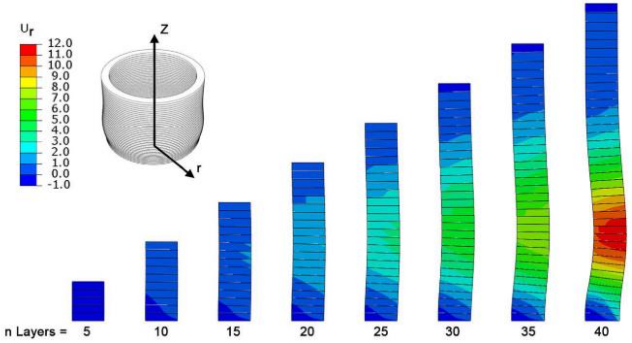




Wolfs, R.J.M. et. al.

- Elastic and plastic deformations
- Uniaxial unconfined compression test
- Failure Criterion



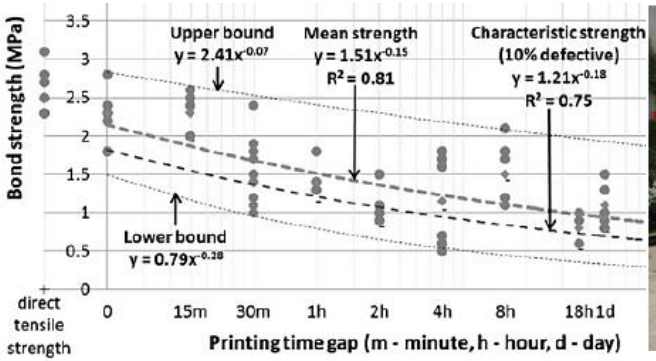


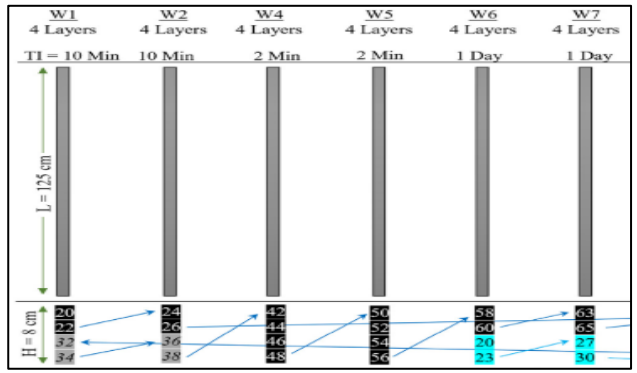
THE STATE OF THE ART

PROCESS PARAMETERS

Lee et. al.; Nerella et. al

- Weak Interlayer strength
- Print strategy

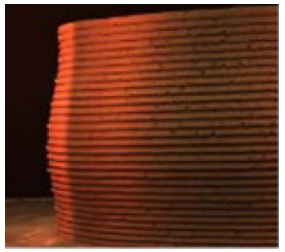


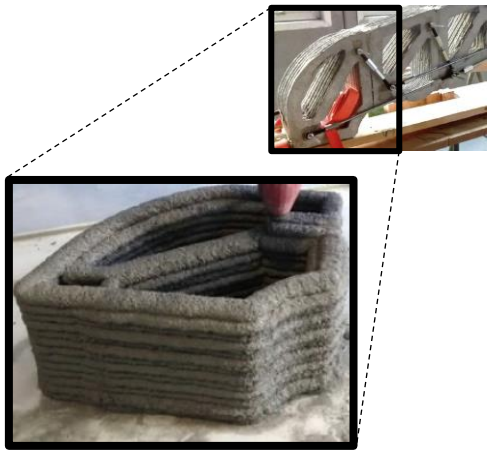


GEOMETRY FORM

Greene, G. W. et. al.; Domenico et. al.; Wolfs, R.J.M. et. al.

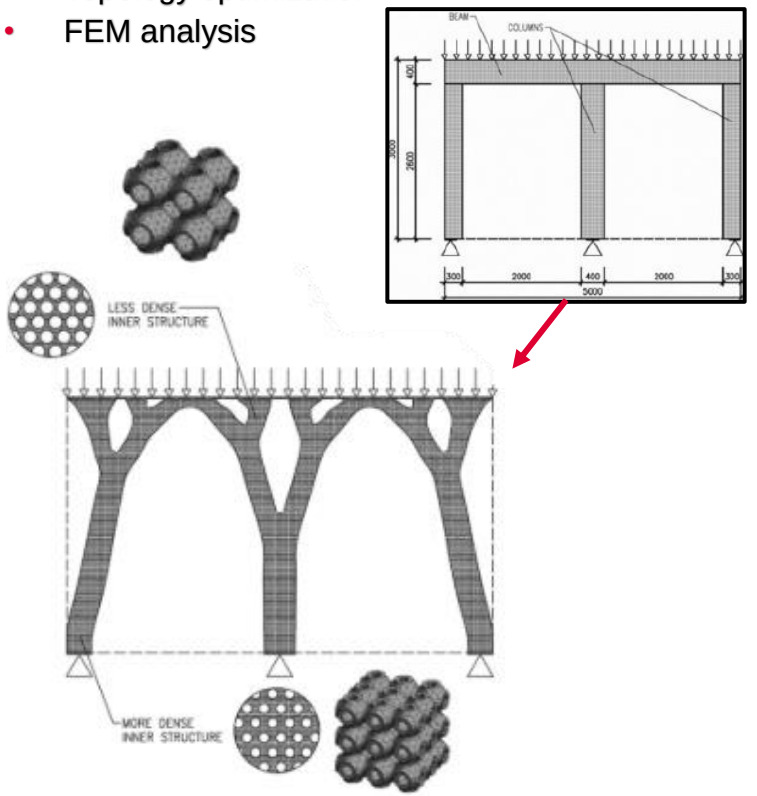
- Topology optimization
- FEM analysis





Yarimitsu, S. K. et. al.; Podroužek, J. et. al.

- Design and evaluation
- Topology optimization
- FEM analysis



SUMMARY OF LITERATURE REVIEW

Material Parameters

Pumpability/ Printability
- Lubricating layer formation

Workability
- *Adhesion of layers*

Buildability
- *Failure modes*

Process Parameter
- *Print track geometry*
- *Print velocity*

Printed Geometry
- *Kind of geometry*
- *Pre-print Analysis*

GENERAL CONCLUSION

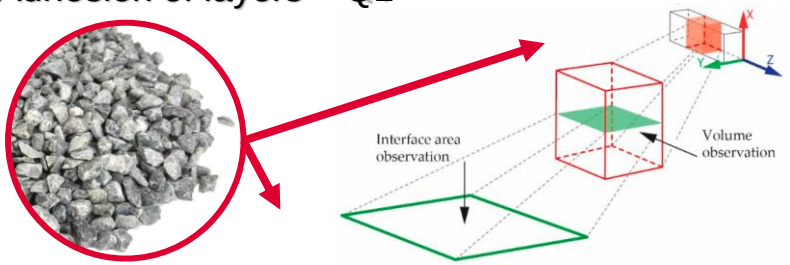
ONLY MORTARS

WHITE SPOT

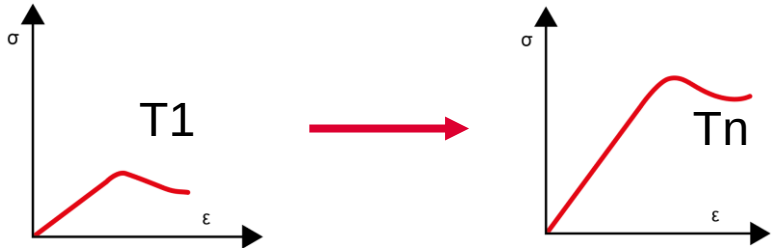
REAL CONCRETE

How does it behave in 3DCP?

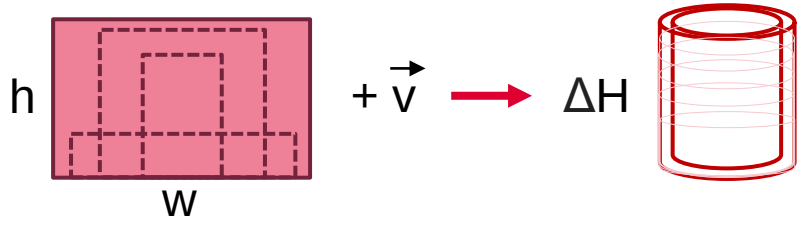
- Adhesion of layers – Q1



- Fresh mixture behaviour developement – Q2



- Limits of Process Parameters – Q3



THE MAIN GOAL OF DOCTORAL THESIS

The benefit of thesis

- Clarify the behaviour of cementitious composites with a coarse aggregate fraction of 8 mm for additive manufacturing.

The benefit of thesis

- Achieve full potential of concrete material
- Bring generalised material description
- Reduction of waste => CO_2 emission

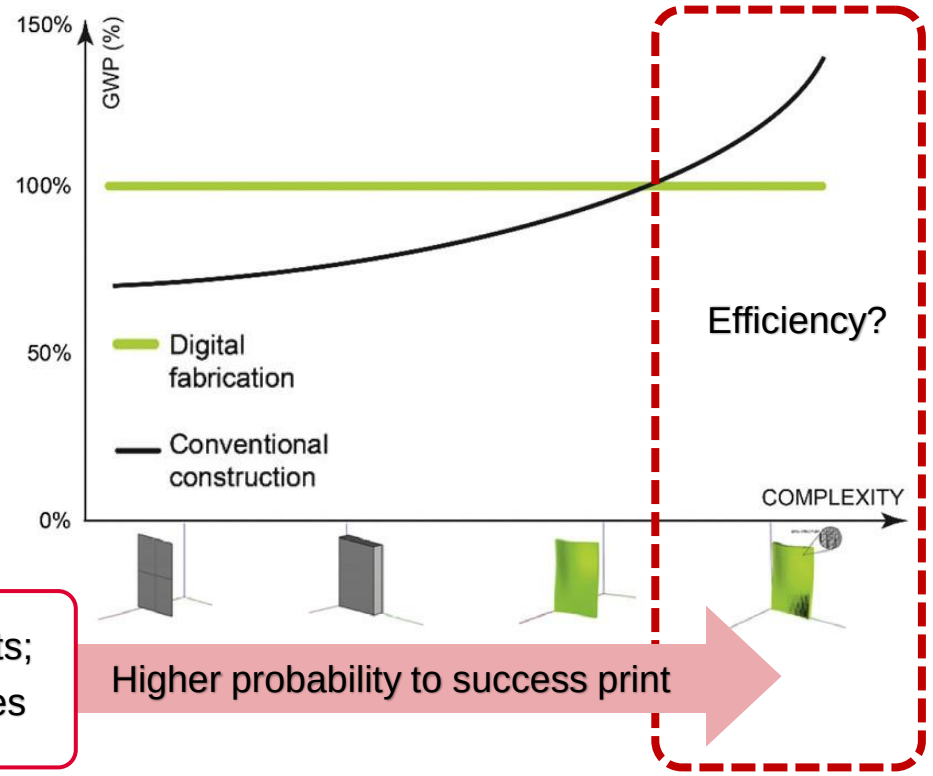
Application potential ?

Material behaviour prediction

Print prediction; reduction of experiments; reduction of waste and human resources

Higher probability to success print

Digital vs. Convential manufacturing related to environmental impact – GWP (G.D. Schutter et. al.)



SCIENTIFIC QUESTIONS AND HYPOTHESES

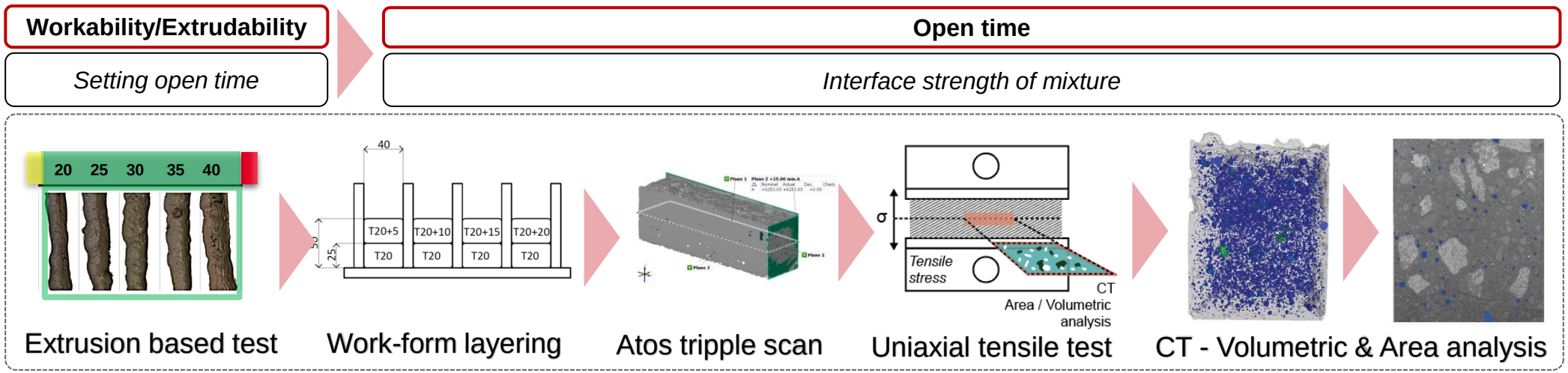
Scientific question Q1:

How do aggregate size fraction (8mm), affect the adhesion of the layer with dependance to mix freshness, and layered time?

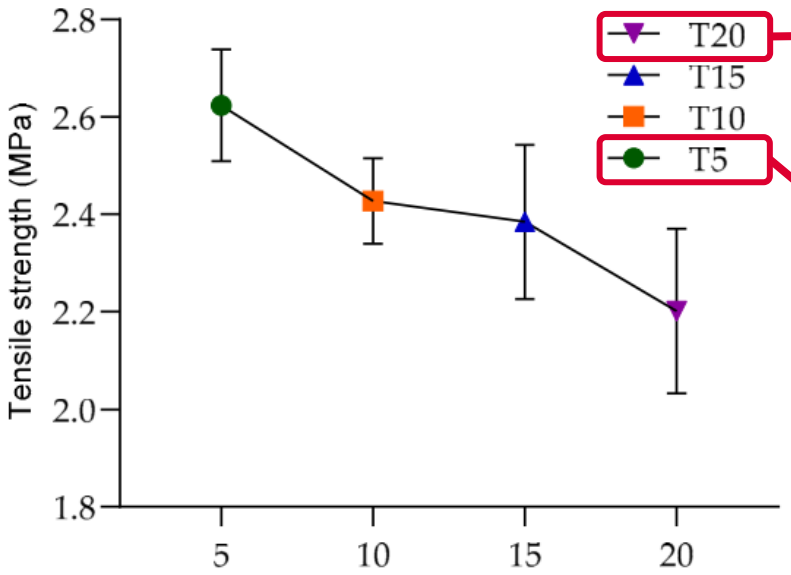
Hypotheses:

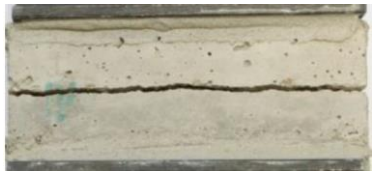
With large time delay, increase number of pores would be observed at the interface area close to the coarse aggregate grains. That causes lower interlayer strength.

Workflow and methods:



RESULTS AND DISCUSSION





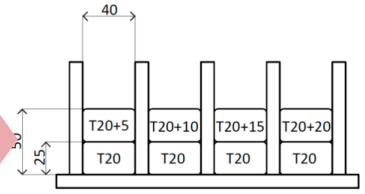
- Single crack plane

- Multiple crack planes

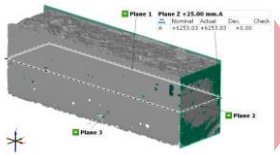
Coarse aggregate penetration

Methods

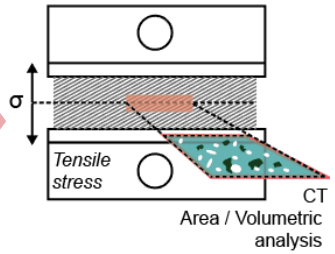
Extrusion based test



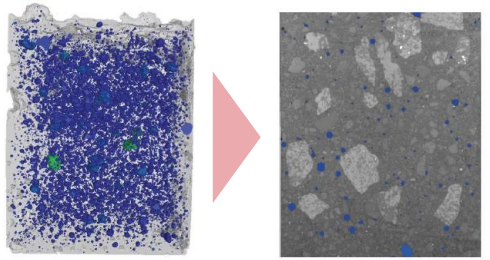
Work-form layering



Atos tripple scan

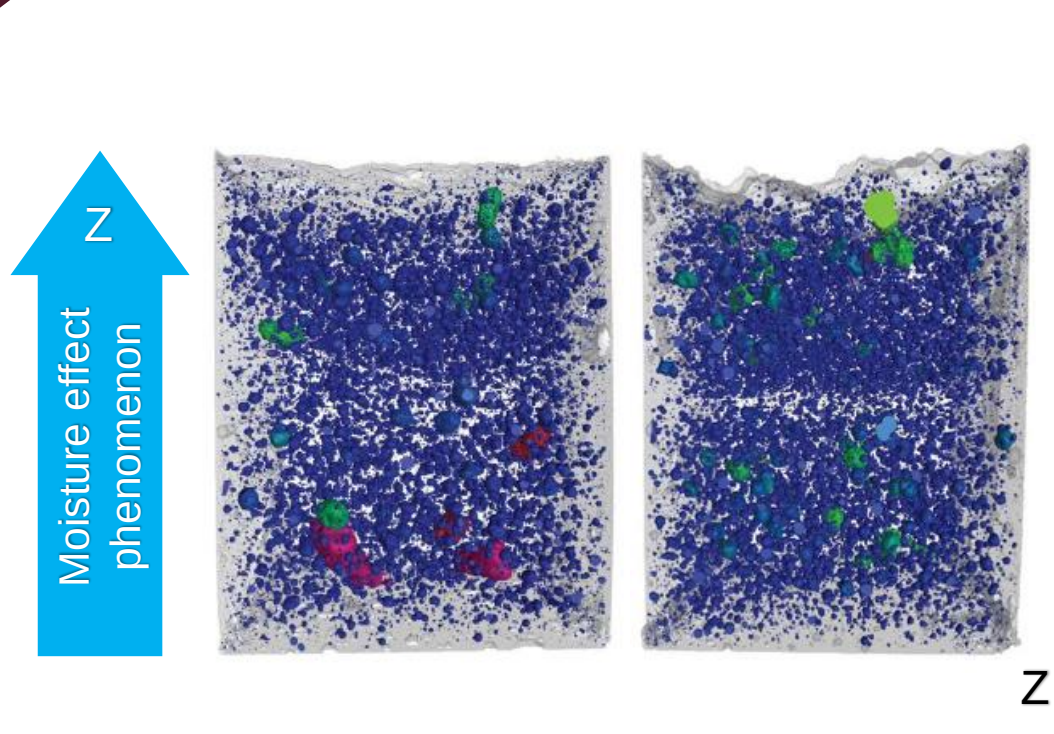


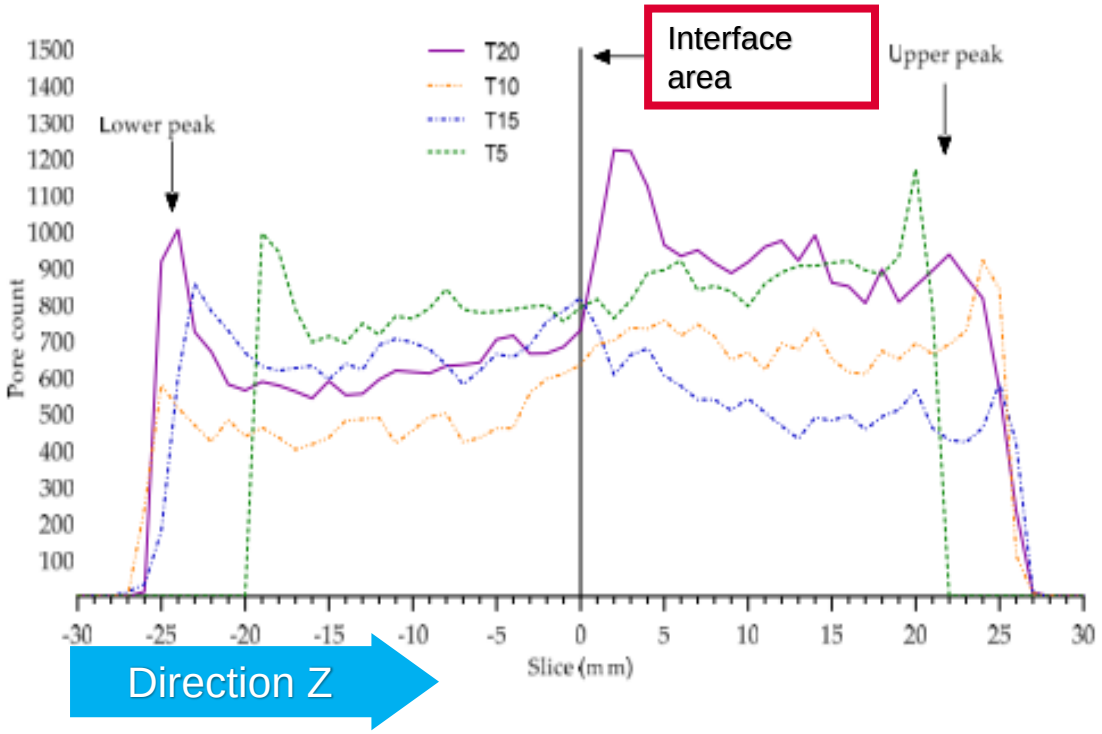
Uniaxial tensile test

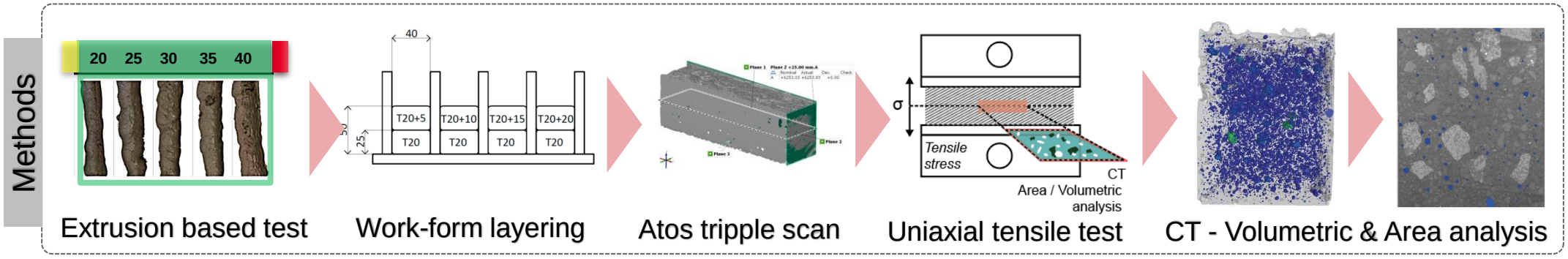


CT - Volumetric & Area analysis

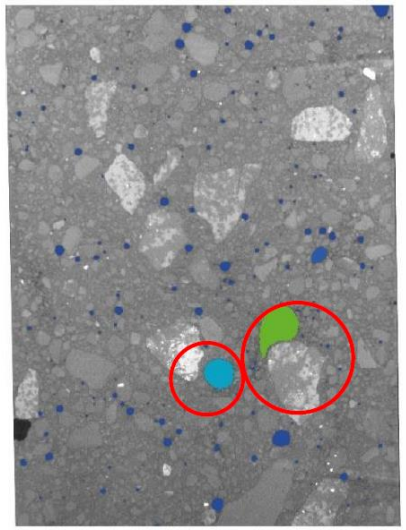
RESULTS AND DISCUSSION

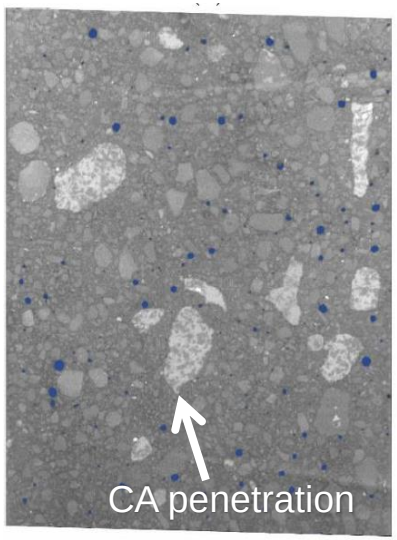


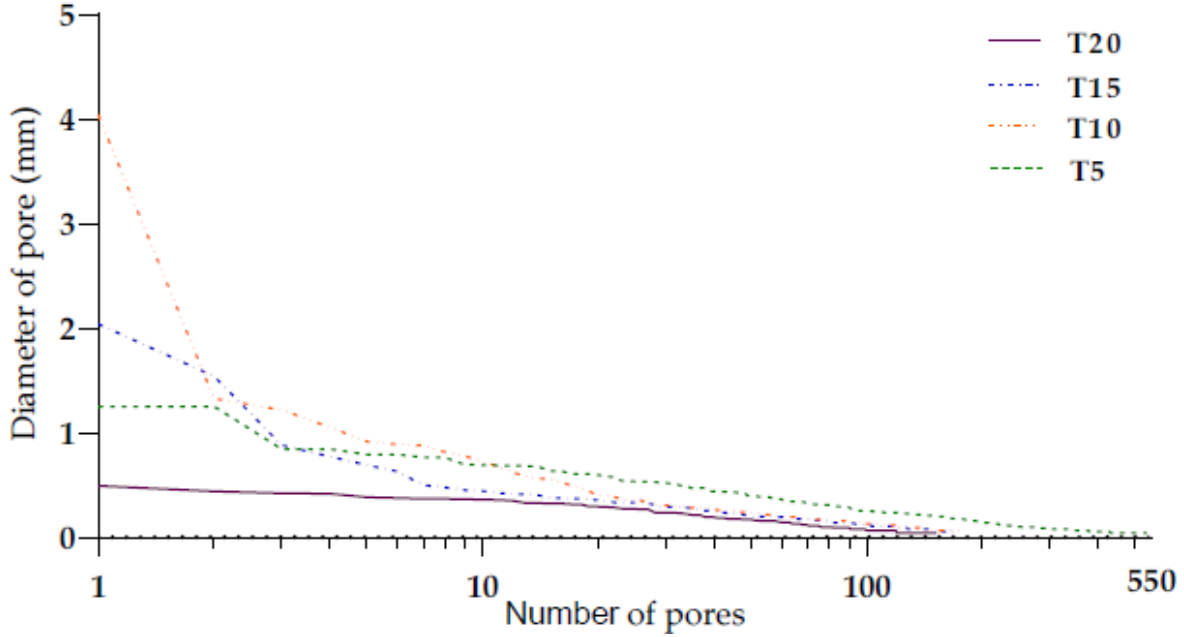




RESULTS AND DISCUSSION

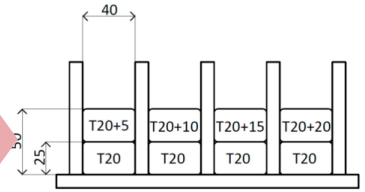




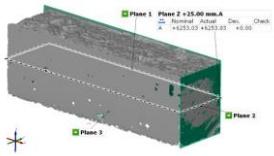


Methods

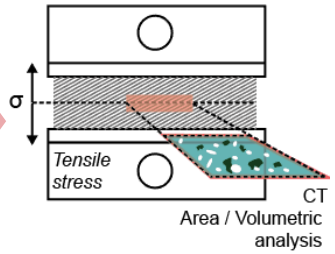
Extrusion based test



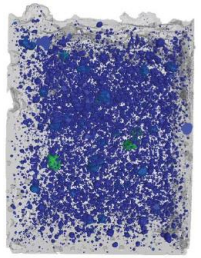
Work-form layering

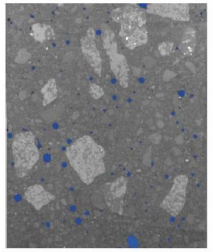


Atos tripple scan



Uniaxial tensile test





CT - Volumetric & Area analysis

SCIENTIFIC QUESTIONS AND HYPOTHESES

Hypotheses:

With large time delay, increase number of pores would be observed at the interface area close to the coarse aggregate grains. That couses lower level of interlayer strength.

Answer to Q1 based on hypotheses:

- *Increasing occurrence of large air pores at interface with increasing time-delay was not confirmed and has no negative effect on the interlayer strength.*

NOT CONFIRMED

Peer-reviewed and published:

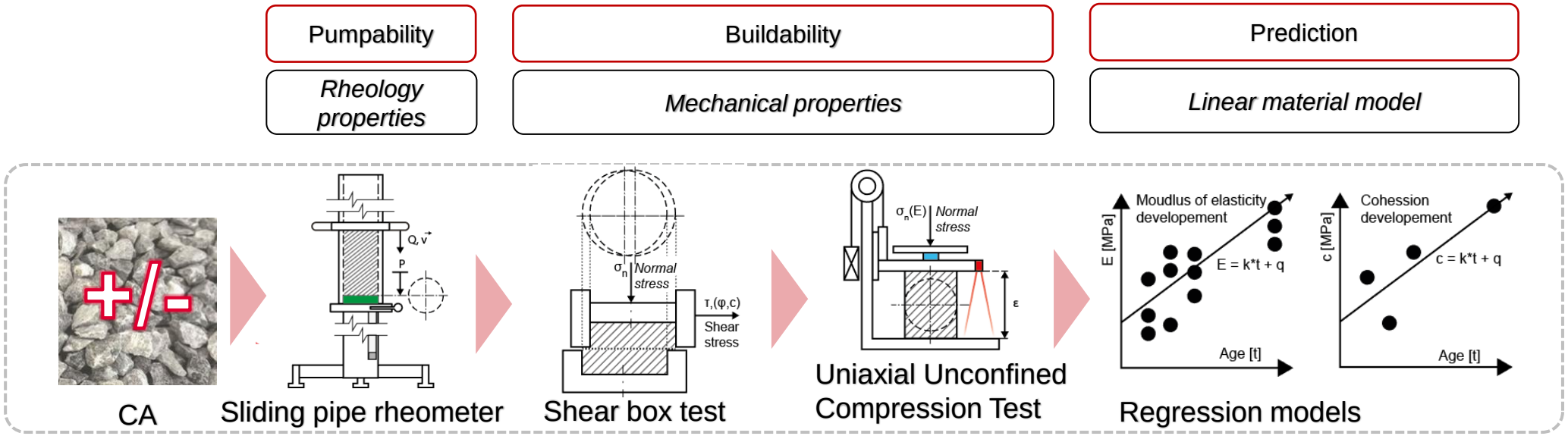
VESPALEC, A.**; NOVÁK, J.; KOHOUTKOVÁ, A.; VOSYNEK, P.; PODROUŽEK, J.; ŠKAROUPKA, D.; ZIKMUND, T.; KAISER, J.; PALOUŠEK, D. Interface Behavior and Interface Tensile Strength of a Hardened Concrete Mixture with a Coarse Aggregate for Additive Manufacturing. Materials 2020, 25, 5147. **(Q1, IF: 3.748)

SCIENTIFIC QUESTIONS AND HYPOTHESES

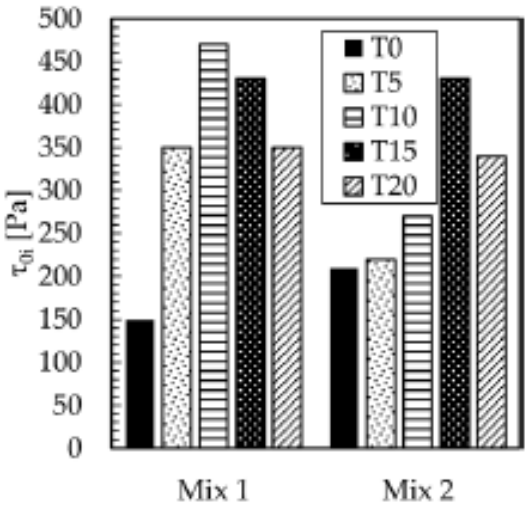
Scientific question Q2:
What effect does the coarse aggregate of 8 millimetres have on the development of green strength in comparison to the same material without coarse aggregate?

Hypotheses:
The coarse aggregate presence reinforce the mixture resulted in the increased load bearing capacity. Based on normal and shear stresses responds, both materials should show a similar linear development.

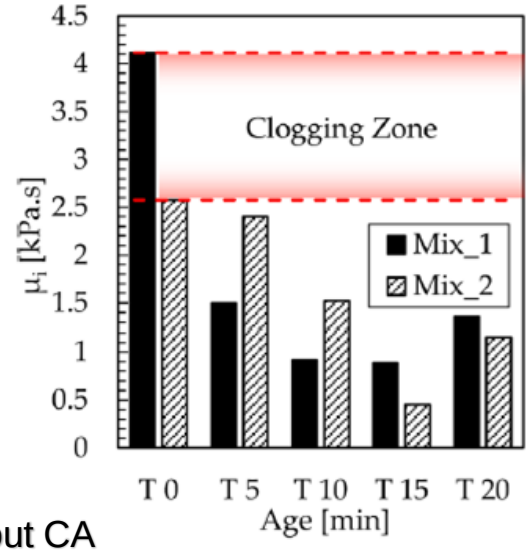
Workflow and methods:



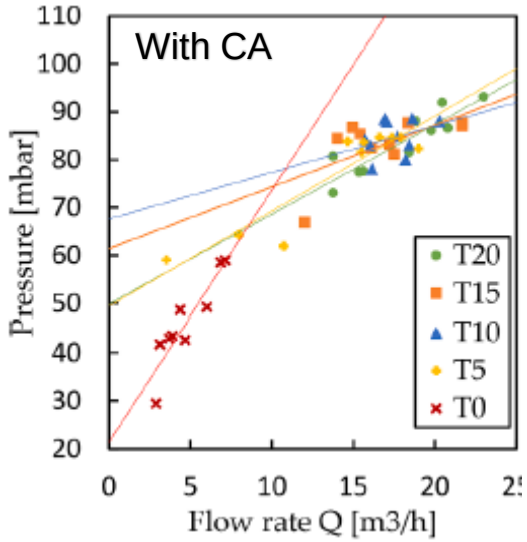
RESULTS AND DISCUSSION

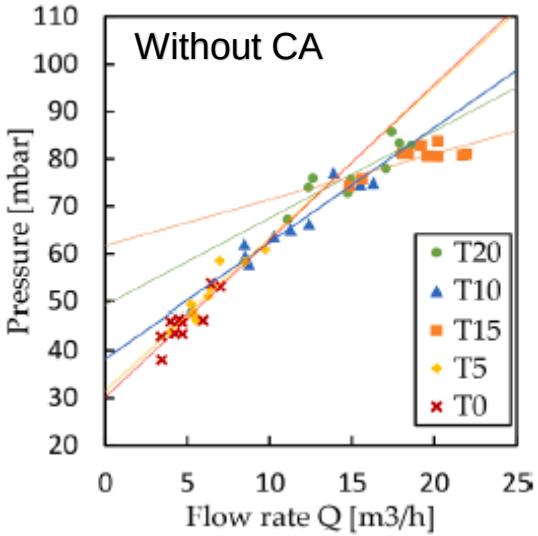


With CA



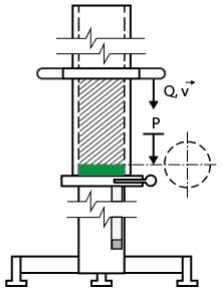
Without CA



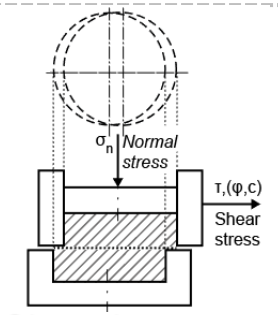


Methods

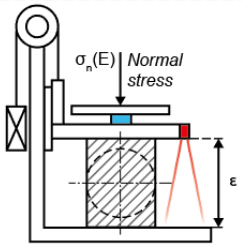
CA



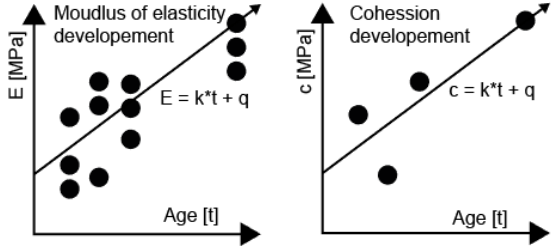
Sliding pipe rheometer



Shear box test

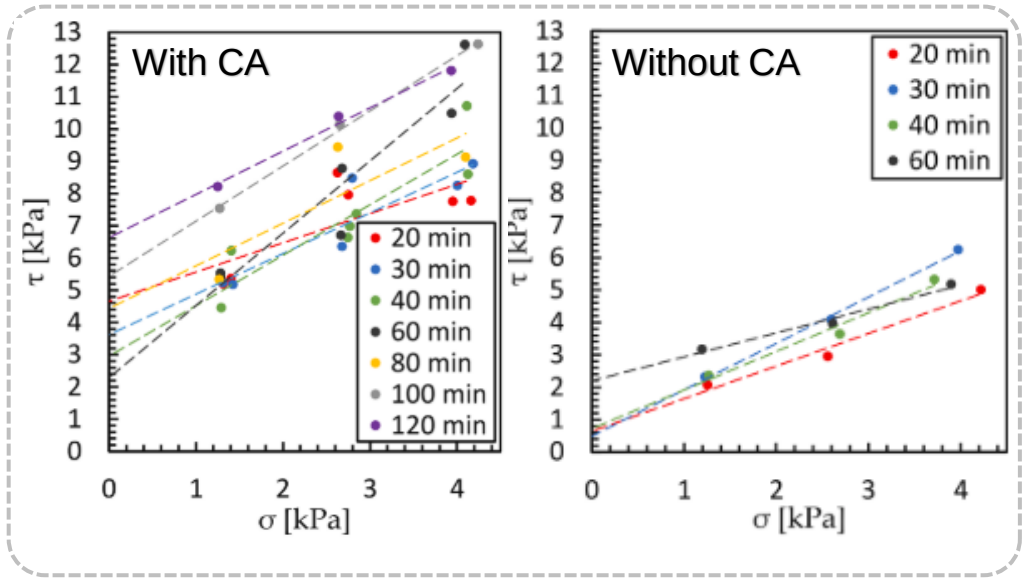


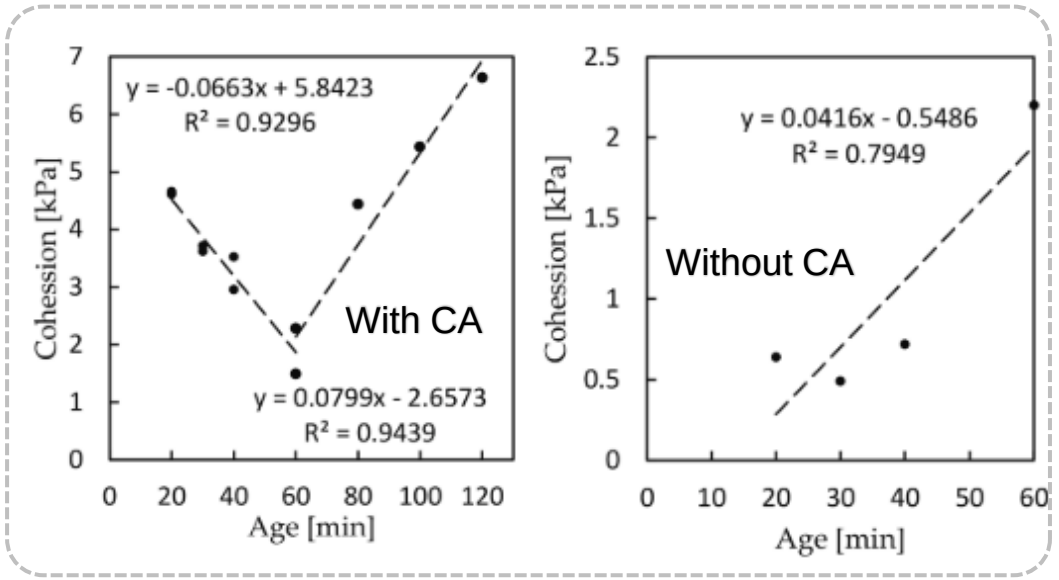
Uniaxial Unconfined Compression Test



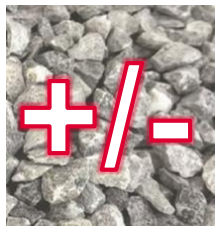
Regression models

RESULTS AND DISCUSSION

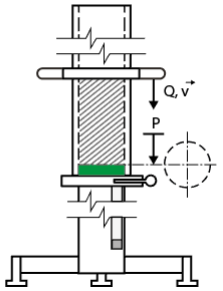




Methods



CA



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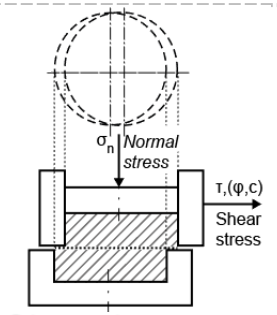
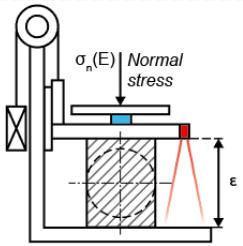
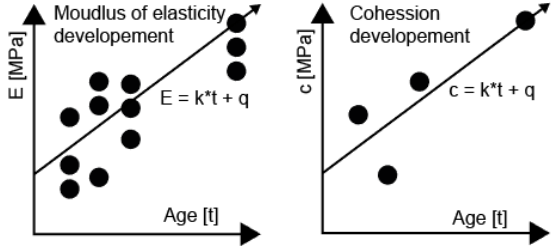


Shear box test

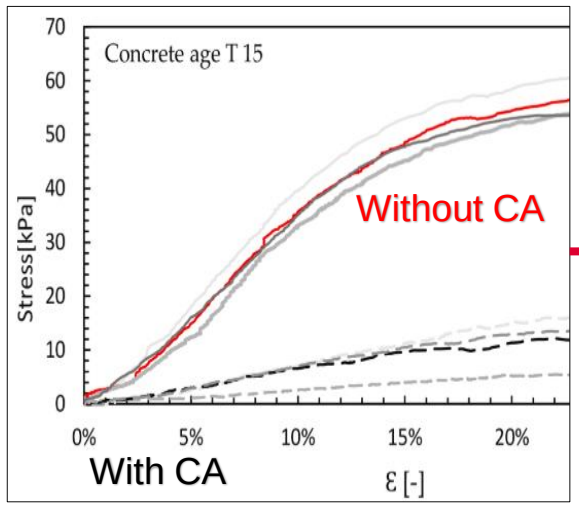


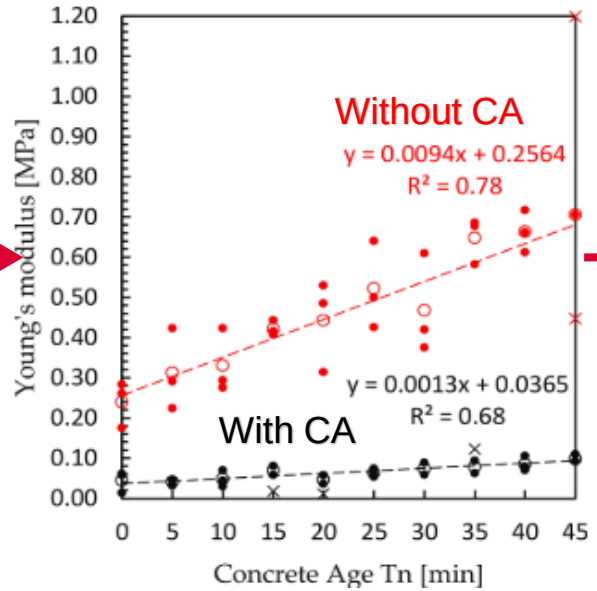
Uniaxial Unconfined Compression Test

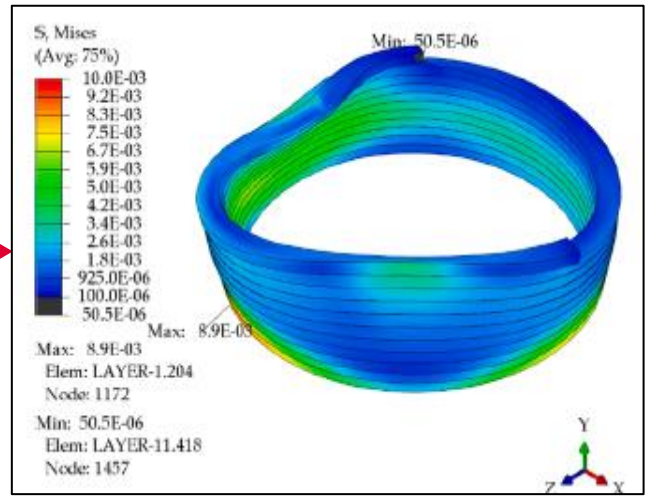


Regression models

RESULTS AND DISCUSSION

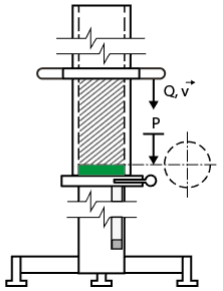




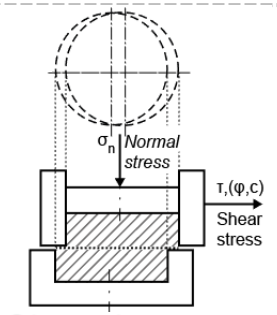


Methods

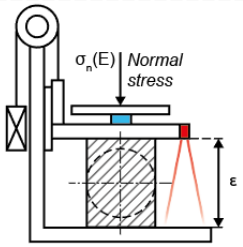
CA



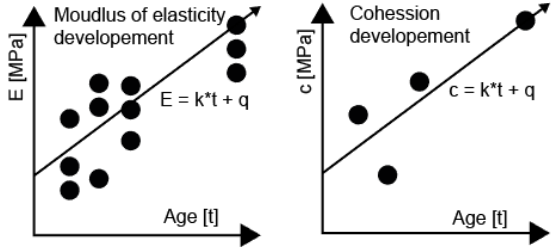
Sliding pipe rheometer



Shear box test



Uniaxial Unconfined Compression Test



Regression models

SCIENTIFIC QUESTIONS AND HYPOTHESES

Hypotheses:
The coarse aggregate presence reinforce the mixture resulted in the increased load bearing capacity. Based on normal and shear stresses responds, both materials should show a similar linear development.

Answer to Q2 based on hypotheses

- *Fresh concrete cohesion varies, where the mixture with coarse aggregates shows bi-linear behaviour.*
- *Mixture without coarse aggregate is more brittle in comparation to mixture with coarse aggregate, which is more ductile and has not as good mechanical properties.*

NOT CONFIRMED

Peer-reviewed and published:

***VESPALEC, A.**; PODROUŽEK, J.; BOŠTÍK, J.; MIČA, L.; KOUTNÝ, D. Experimental study on time dependent behaviour of coarse aggregate concrete mixture for 3D construction printing. Construction and Building Materials 2023, 376.*
(Q1-D1, IF: 7.693)

SCIENTIFIC QUESTIONS AND HYPOTHESES

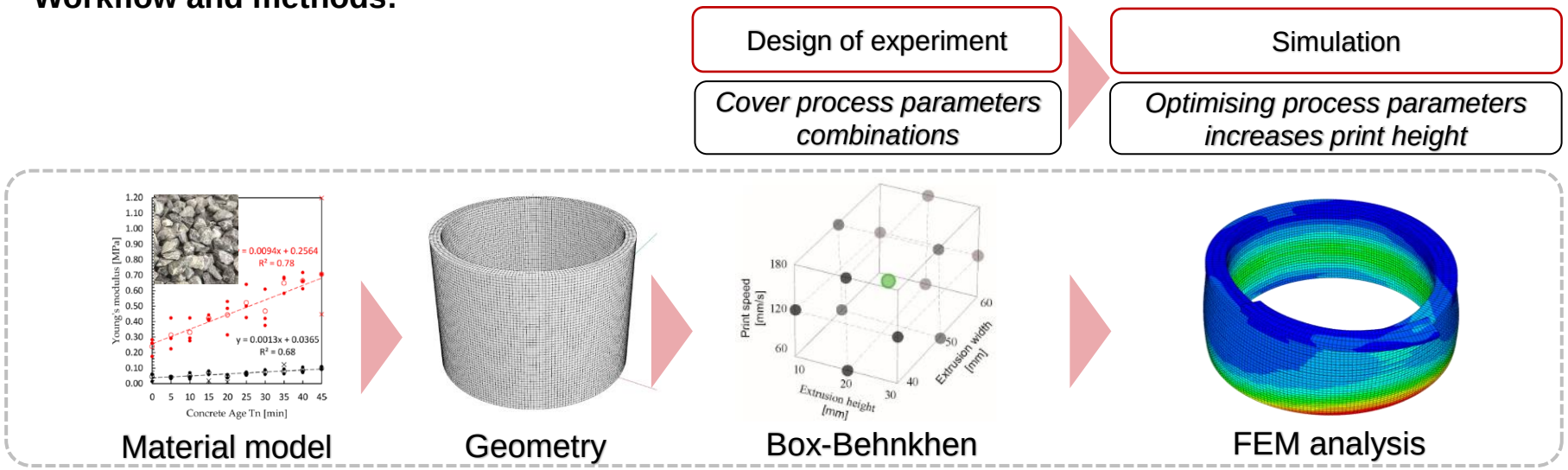
Scientific question Q3:

What is the impact of an optimized configuration of controllable parameters (print track dimension, print velocity) on the buildability of a cylindrical geometry printed using a cement mixture containing a larger aggregate fraction (8 mm) and waste reduction?

Hypotheses:

Optimising controllable parameters like proportion of a layer and print velocity should increase buildability while maintaining uncontrollable parameters as a properties of material with large aggregate.

Workflow and methods:



RESULTS AND DISCUSSION

Input parameters – influencing factors

Uncontrollable factors
- material properties – Material with coarse aggregate

Controllable factors
- Process parameters – velocity, track height and width
- Printed Geometry – hollow cylinder 500 mm in height

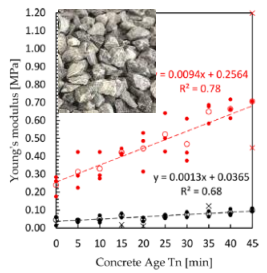
Design of Experiment – Box Behnkhen method
- Count simulation reduction; 84 => 13

No.	v [mm/s]	E_w [mm]	E_h [mm]	H [mm]
1	60	40	20	191.043
2	180	40	20	189.835
3	60	60	20	283.219
4	180	60	20	264.265
5	60	50	10	285.645
6	180	50	10	244.727
7	60	50	30	285.557
8	180	50	30	285.506
9	120	40	10	257.226
10	120	60	10	350.549
11	120	40	30	229.959
12	120	60	30	253.671
13 *	120	50	20	285.032

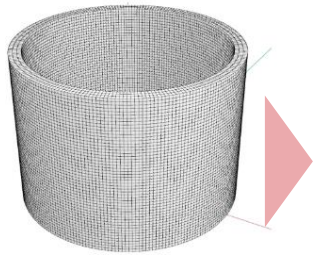
* Central point.

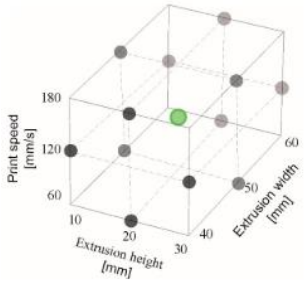
- **160 mm diference**

Methods

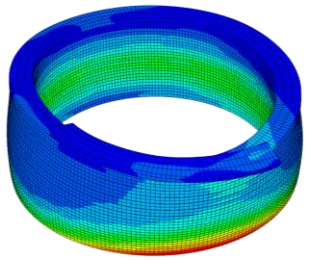


Material model

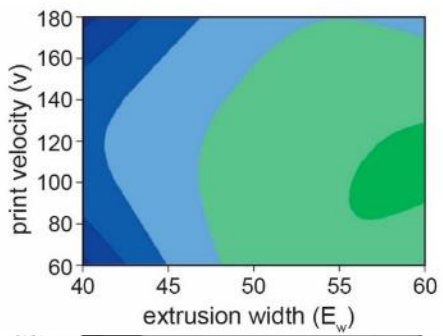

Geometry

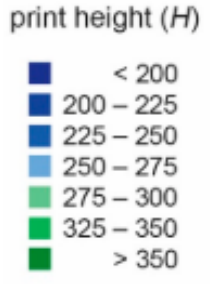


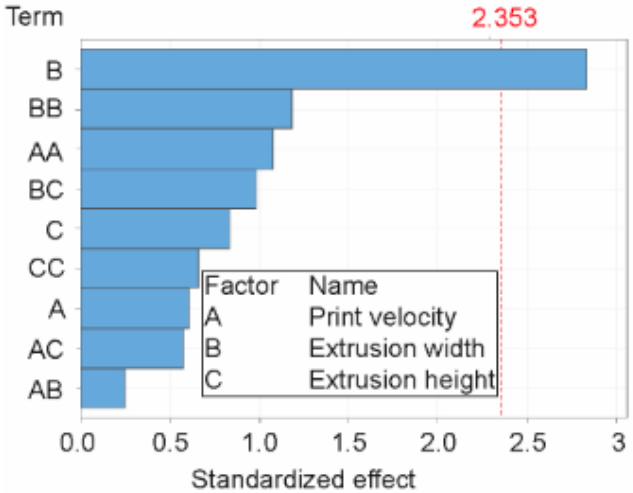
Box-Behnkhen


FEM analysis

RESULTS AND DISCUSSION



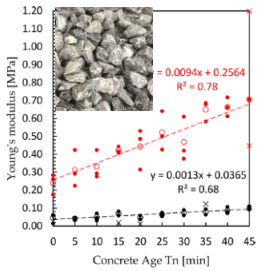




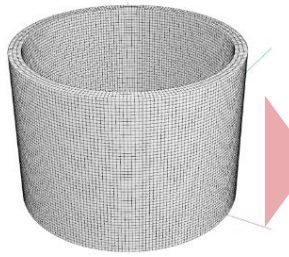
Good/ Bad result

- 84% improvement

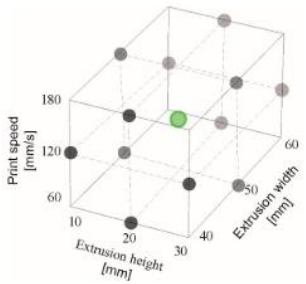
Methods



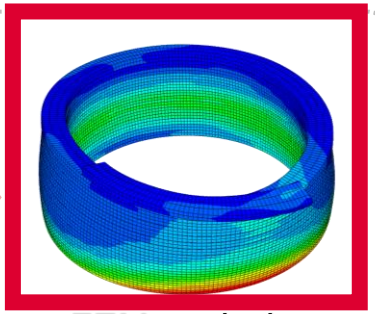
Material model



Geometry



Box-Behnkhen



FEM analysis

RESULTS

Hypotheses:

Optimising controllable parameters like proportion of a layer and print velocisty should increase buildability while maintaining uncontrollable parameters as a properties of material with large aggregate.

Answer to Q3 based on hypotheses

- *Buildability improved by an 84% from original height (189 mm), relative to scale (350 mm).*
- *Extrusion width with is a the statisticaly significant factor in this case.*

CONFIRMED

Peer-reviewed and published:

VESPALEC, A.**; PODROUŽEK, J.; KOUTNÝ, D. DoE Approach to Setting Input Parameters for Digital 3D Printing of Concrete for Coarse Aggregates up to 8 mm. Materials 2023, 16, 3418.* ***(Q1, IF: 3.748)

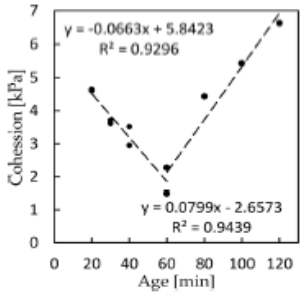
CONCLUSION

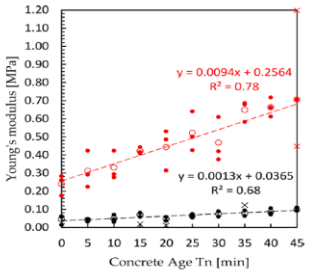
Novel findings

- Description of real concrete with 8mm of grain size.
- Material equations; Bi-Linear Cohession developement (previously unreported)
- Theoretical boundaries of pumpability, workability and buildability

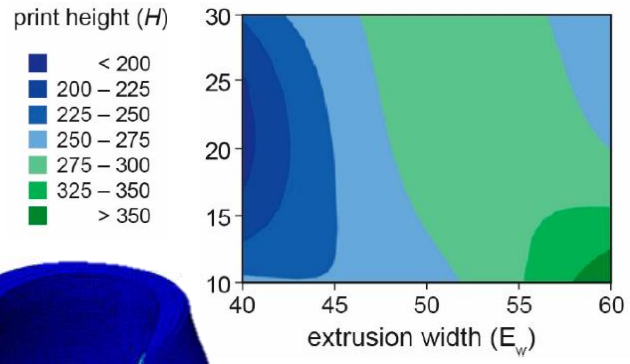
Application potential:

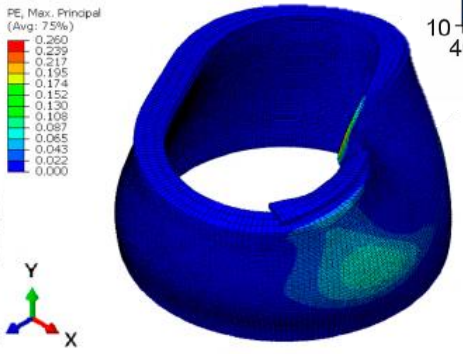
Material Behaviour Prediction





Print prediction - reduction of experiments, waste, HR





Higher probability to successful print

LIST OF PUBLICATION

Journals with impact factor:

Citation:

I. *VESPALEC, A.; NOVÁK, J.; KOHOUTKOVÁ, A.; VOSYNEK, P.; PODROUŽEK, J.; ŠKAROUPKA, D.; ZIKMUND, T.; KAISER, J.; PALOUŠEK, D. Interface Behavior and Interface Tensile Strength of a Hardened Concrete Mixture with a Coarse Aggregate for Additive Manufacturing. Materials 2020, 25, 5147. (**Q1, IF: 3.748**)* — ***15*** — materials

II. *VESPALEC, A.; PODROUŽEK, J.; BOŠTÍK, J.; MIČA, L.; KOUTNÝ, D. Experimental study on time dependent behaviour of coarse aggregate concrete mixture for 3D construction printing. Construction and Building Materials 2023, 376. (**Q1-D1, IF: 7.693**)* — ***4*** — Construction and Building MATERIALS

III. *VESPALEC, A.; PODROUŽEK, J.; KOUTNÝ, D. DoE Approach to Setting Input Parameters for Digital 3D Printing of Concrete for Coarse Aggregates up to 8 mm. Materials 2023, 16, 3418. (**Q1, IF: 3.748**)* — ***Not yet*** — materials

Conference proceedings:

- *VESPALEC, A.; NOVÁK, J.; KOHOUTKOVÁ, A.; VOSYNEK, P.; PODROUŽEK, J.; ŠKAROUPKA, D.; ZIKMUND, T.; KAISER, J.; PALOUŠEK, D. Interface Tensile Strength of a Concrete Mixture for Additive Manufacturing. 60th International Conference of Machine Design Departments, 2019, 249 (September), 237–243.*

Other results:

- VESPALEC, A.; DIAKOV, J.; Brno University of Technology, Antonínská 548/1, 602 00 Brno, Veveří, Česká republika: Print head nozzle with adjustable rectangular cross-section for 3D printing of concrete. 34622, ***UTILITY MODEL***. (2020)

THANK YOU FOR YOUR ATTENTION

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AND **INDUSTRIAL DESIGN**

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QUESTIONS

***Questions of* Sławomir Czarnecki**

1. It is known that in various cementitious composites the adhesion of the layers is assured by the chemical and physical behaviour. The Author mainly focused on setting time and the wet-to-wet cementitious material application. However by evaluating also the layer surface morphology it can be predicted the potential adhesion within the layers of old-to-new (hardened already with fresh mixture) concrete. Has the Author tried to evaluate the properties of such behaviour, fresh mixture applied on hardened already layer. And Has the author analyse the properties of the surface in terms of morphological parameters, not only the surface area but also the others?

2. Does the Author see the potential of expanding this technology in this shape to make it usable for ordinary concretes containing 16mm or even 32 mm coarse aggregates? What should be done to make it possible?

3. What future of 3D printing of cementitious composites does the Author expect? Is it going to be a still and constant improvement in devices/machines or rather modification of composites mixtures leading to be more prone to printing instead to traditional casting into the moulds.