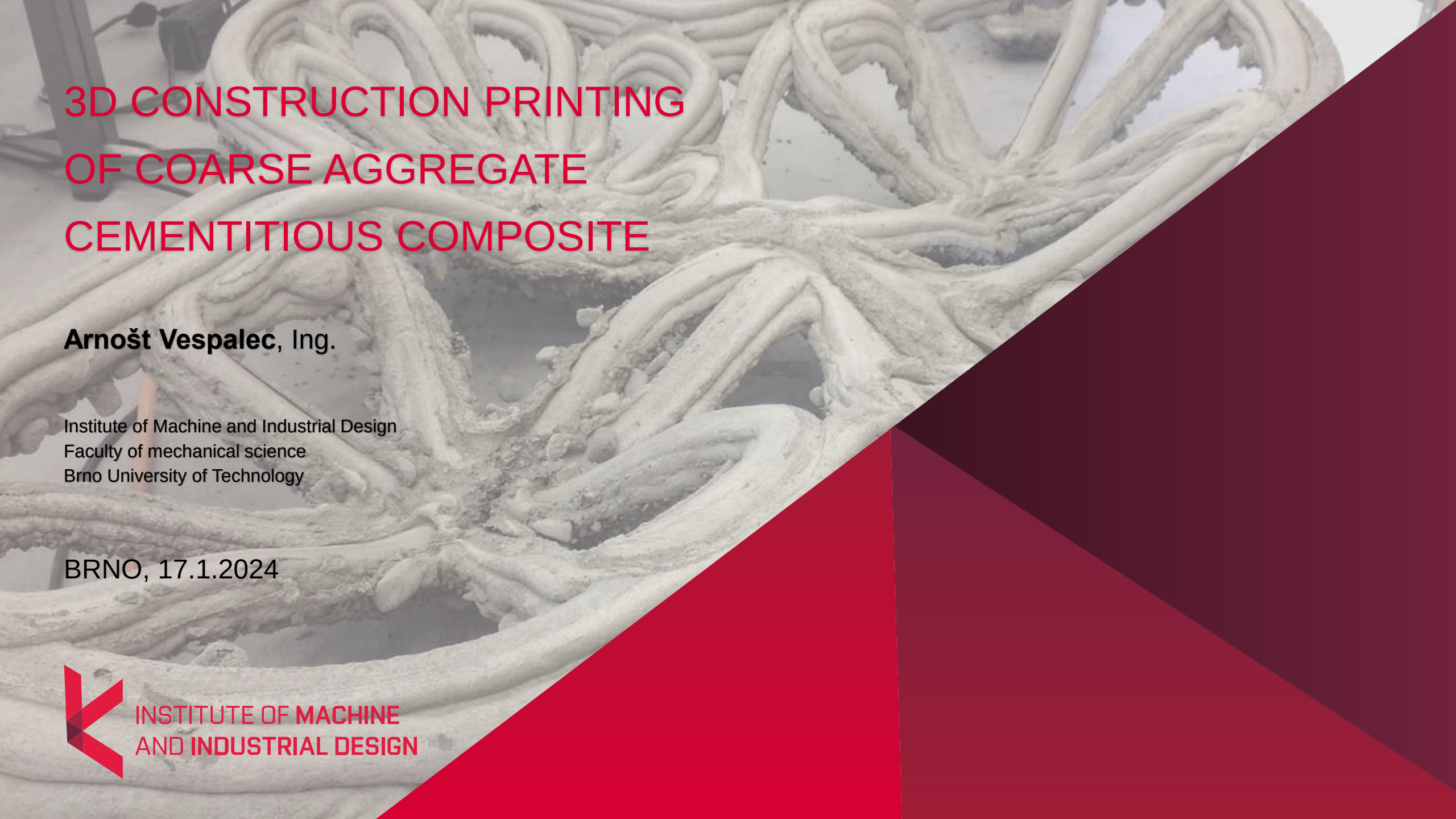


3D CONSTRUCTION PRINTING OF COARSE AGGREGATE CEMENTITIOUS COMPOSITE

Arnošt Vespalec, Ing.

Institute of Machine and Industrial Design
Faculty of mechanical science
Brno University of Technology

BRNO, 17.1.2024

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

Actual Problems interconnected with Construction Industry

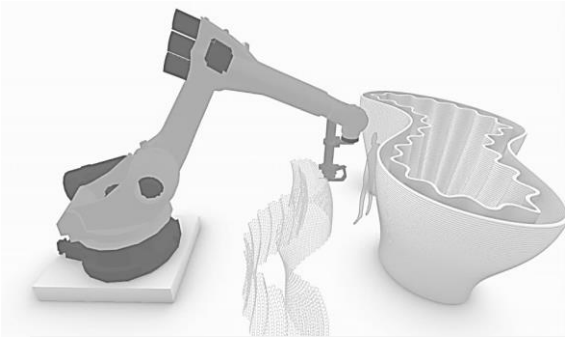
- Climate changes - Construction Industry global production of CO_2 is 39%, where Cement 5-10%
- Material consumption - Unregulated mining, ineffective material utilization
- Human resources - Fatal accidents, Lack of qualified workers

Efficiency of Conventional Construction doesn't meet future needs

Digital Fabrication Increase efficiency (?)

Main motivation

Conventional Construction *(Freepik)*



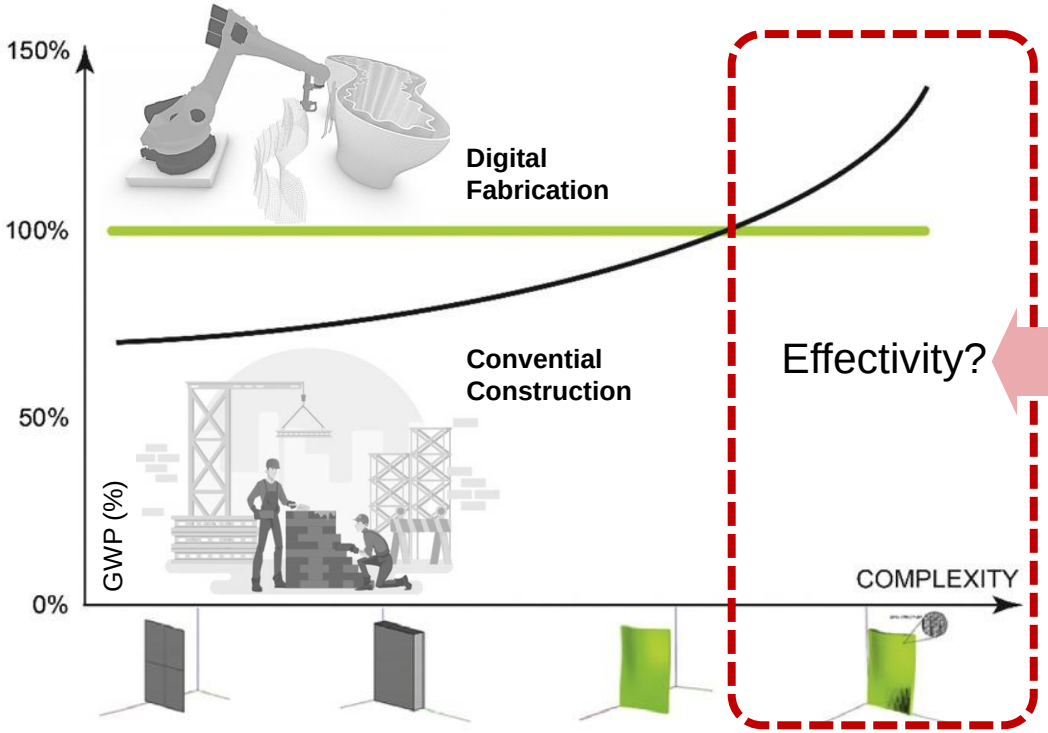
Digital Fabrication *(IAAC)*

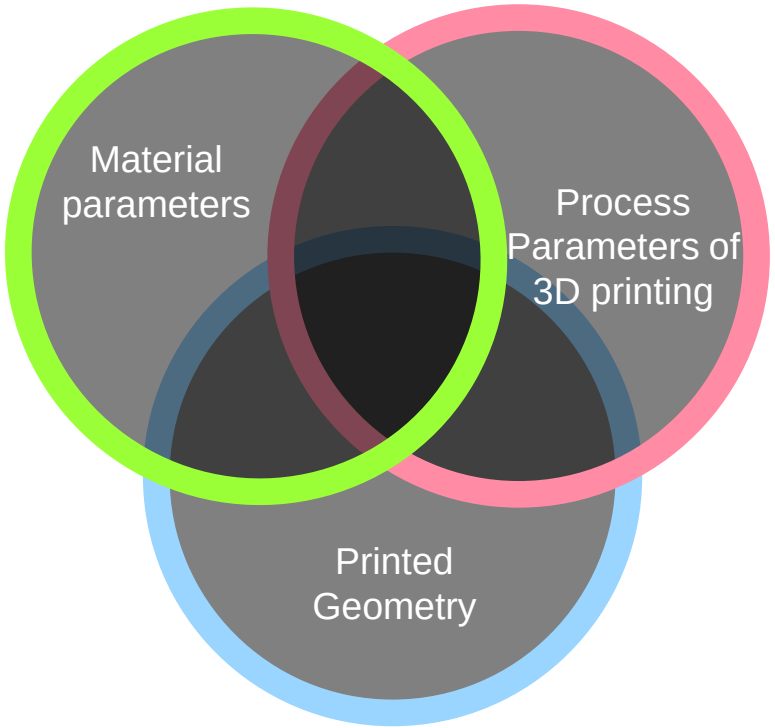
Improvement of material use for 3DCP

MOTIVATION

Actual Problems interconnected with Construction Industry

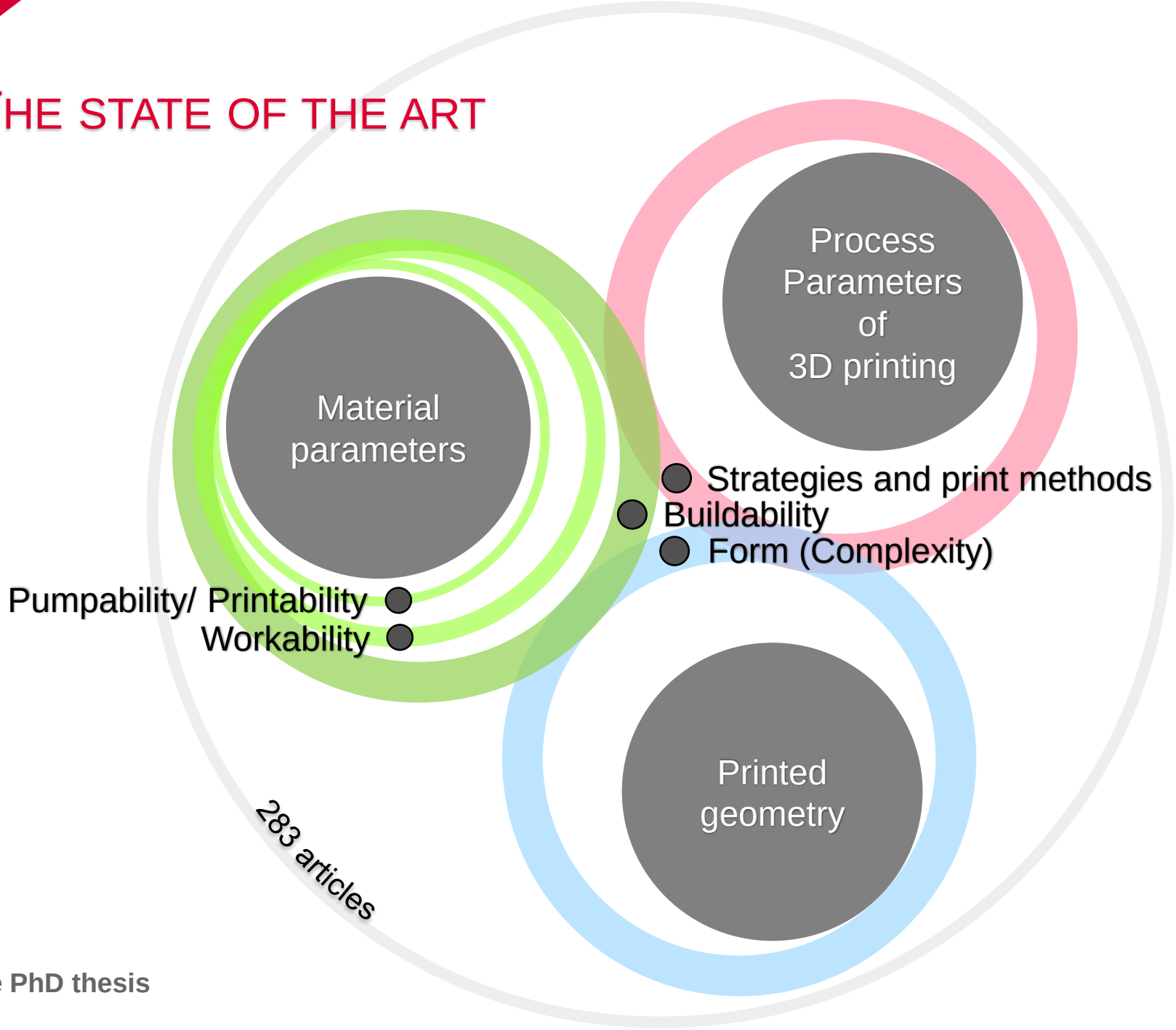
- Climate changes - Construction Industry global production of CO_2 is 39%, where Cement 5-10%
- Material consumption - Unregulated mining, ineffective material utilization
- Human resources - Fatal accidents, Lack of qualified workers





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

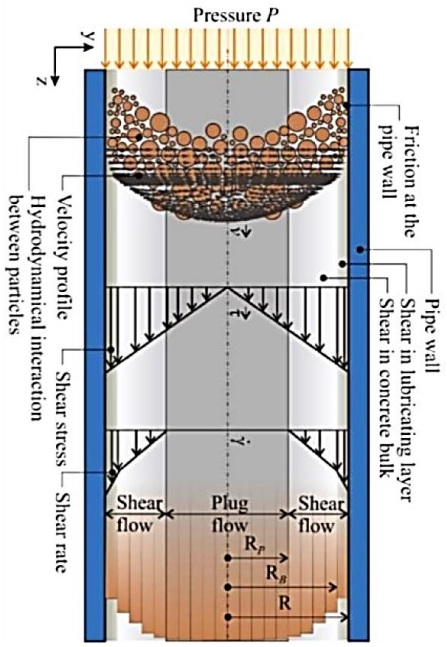
THE STATE OF THE ART



THE STATE OF THE ART – Material Domain

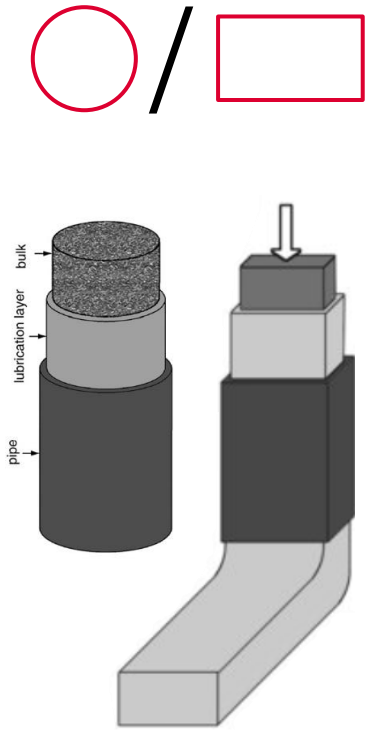
2018

Secrieru, E. et. al.



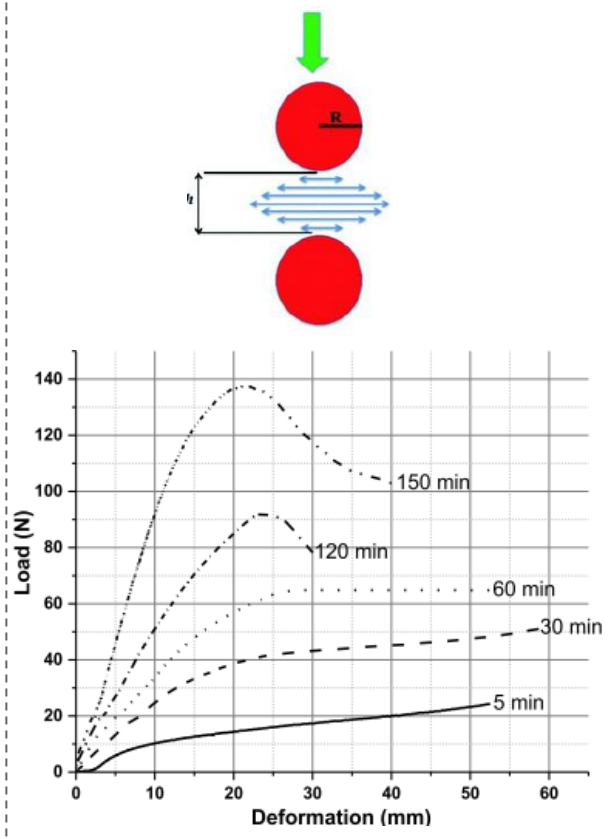
2018

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



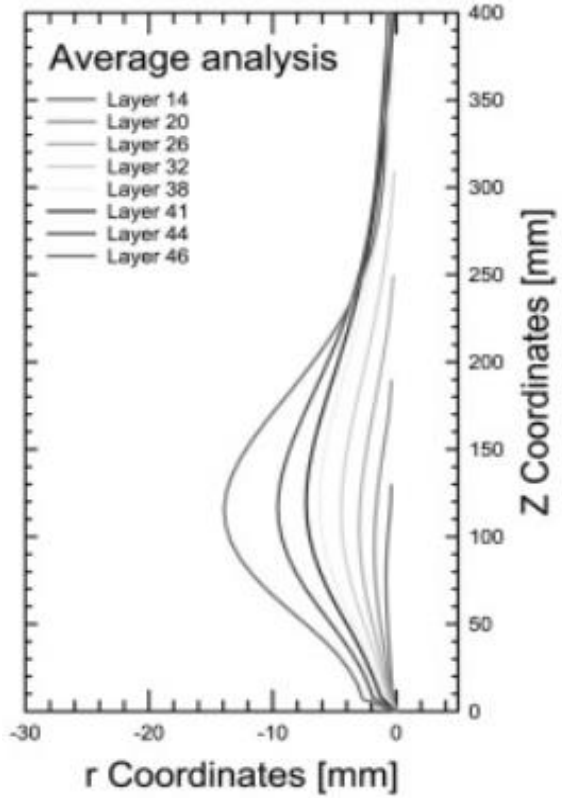
2019

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



2018

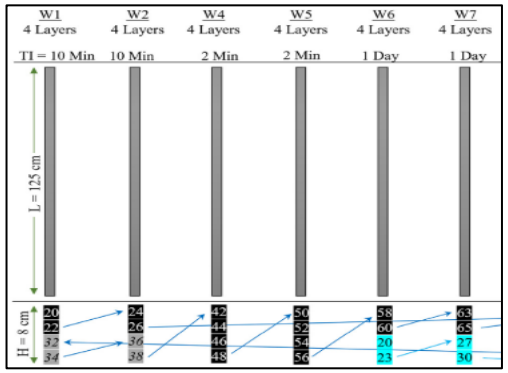
Wolfs, R.J.M. et. al.

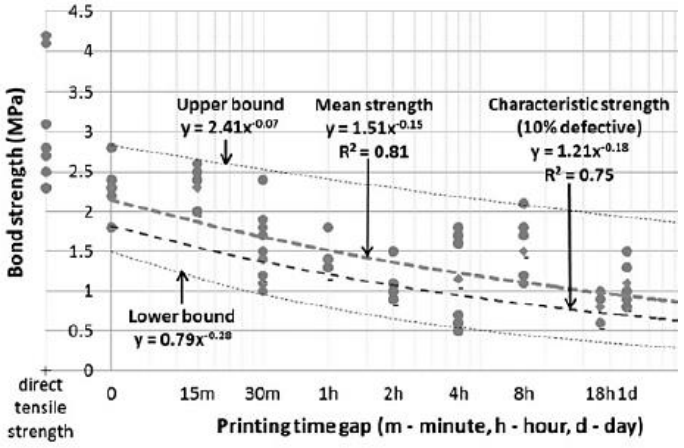


THE STATE OF THE ART – Process Parameters and Geometry Domain

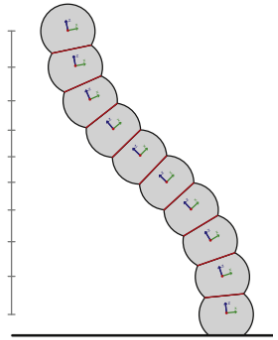
2012 Process Parameters | 2016 | 2018 Form (complexity) | 2019

Lee et. al.; Nerella et. al

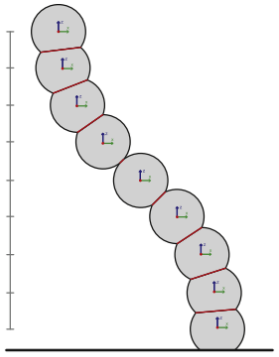




Gosselin, C. et. al.; Constanzi et. al.

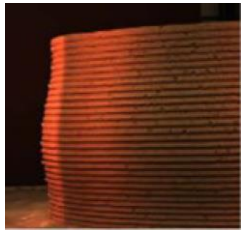


Constant contact surface

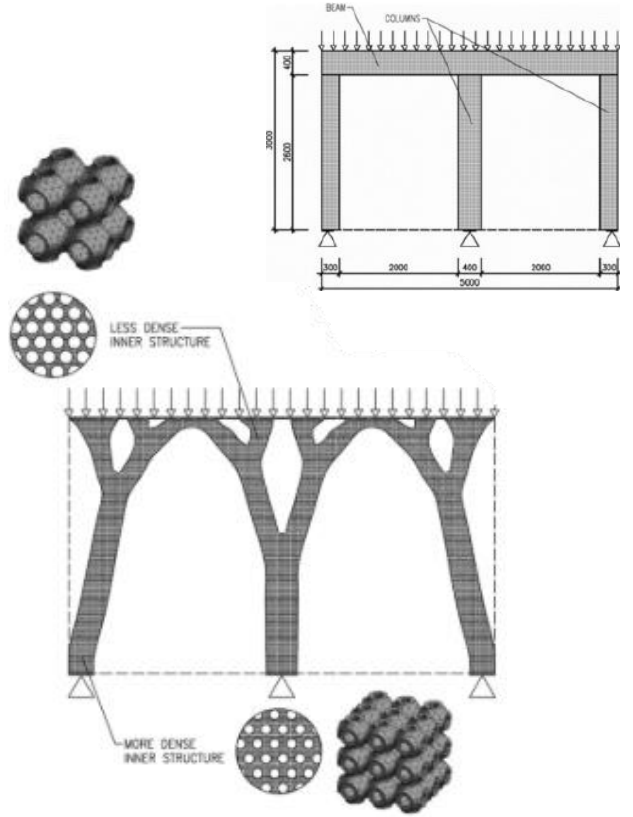


Constant layer height

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



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



SUMMARY OF LITERATURE REVIEW

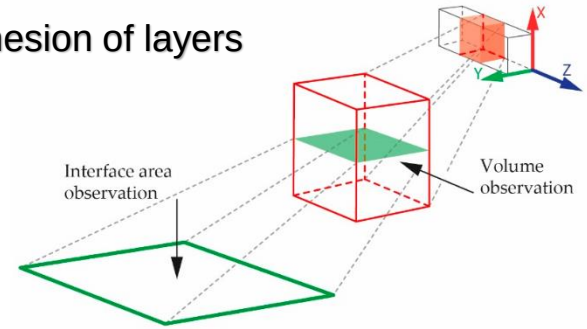
IMPORTANT ASPECTS ASSOCIATED WITH 3DCP

Material parameters	Pumpability/ Printability ▪ *Lubricating layer* Workability ▪ *Open time* ▪ *Adhesion of layers* Buildability ▪ *Green strength*
Process Parameters	▪ *Print track geometry*
Print Geometry	▪ *Geometry* ▪ *FEM Analysis of print*

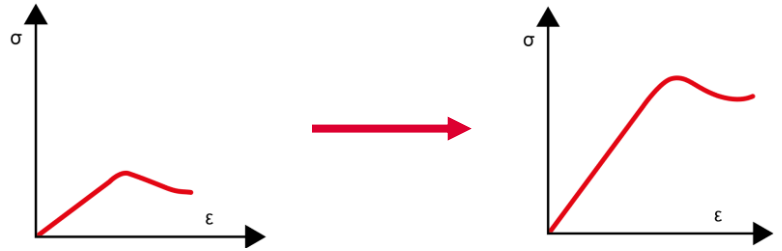
Larger aggregate mixture exploration in context of 3DCP technology

UNKNOW ASPECTS

- Adhesion of layers



- Mechanical behaviour



- Limits of Process Parameters

THE MAIN GOAL OF DOCTORAL THESIS

The main goal

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

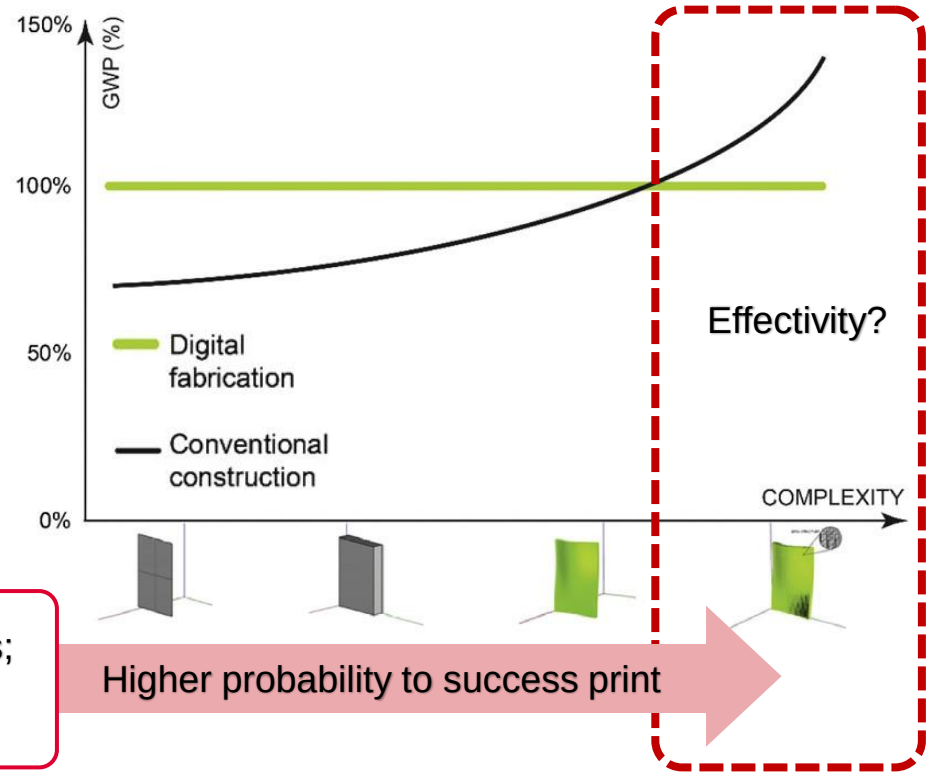
The benefit of thesis

- Achieve full potential of material with coarse aggregate size up to 8 mm in 3DCP technology
- Reduction of waste, human resources and CO_2 emission
- Generalised material description

Application potential ?

Material behaviour prediction → Print prediction; reduction of experiments; reduction of waste → Higher probability to success print

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



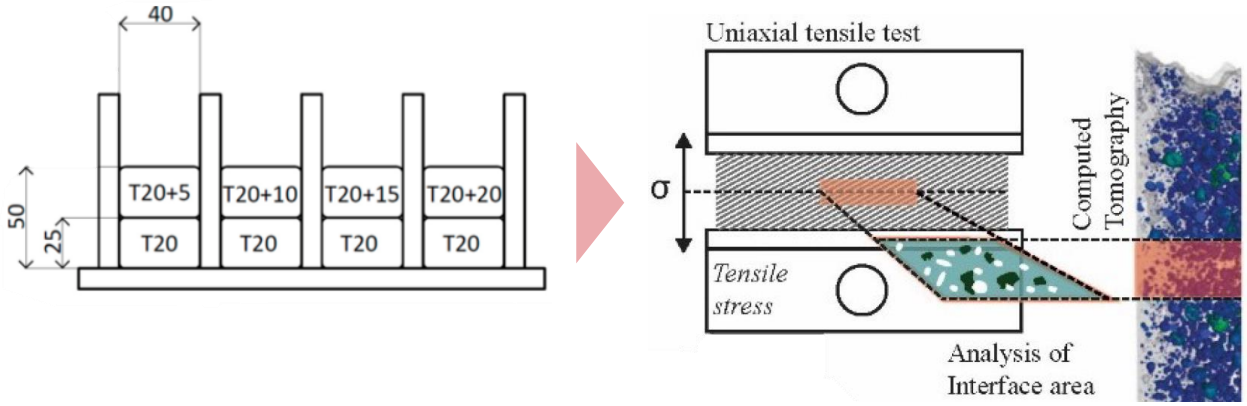
SCIENTIFIC QUESTIONS AND HYPOTHESES

Scientific question Q1:
How do aggregate size fraction (8mm), mix freshness, and application time affect the adhesion of the layer?

Hypotheses:
The roughed surface of the first layer may lock air bubbles during the application of the next layer, resulting in more pores near the coarse aggregate at the interface of layers applied after a longer time interval, weakening the printed layers' interface strength.

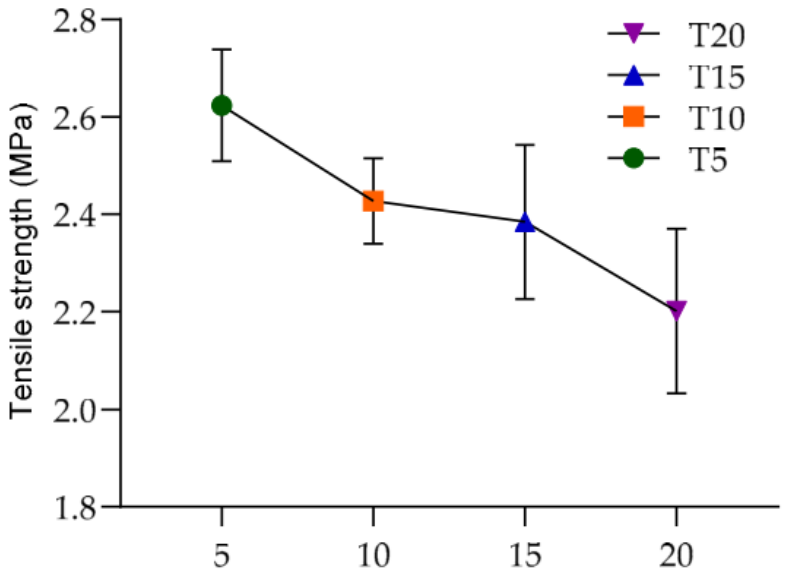
Workflow and methods:

Input	Workability	Open time	Output	Input for
Material	*Setting open time*	*Interface strength of mixture*	Publish Results	Follow – up research

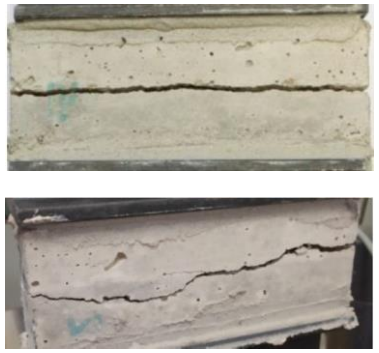


RESULTS AND DISCUSSION

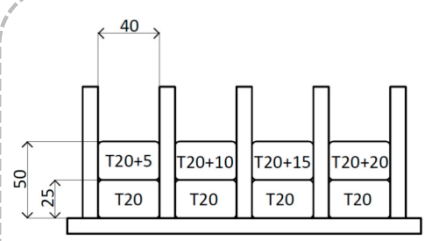
- Open time
- Different crack patterns



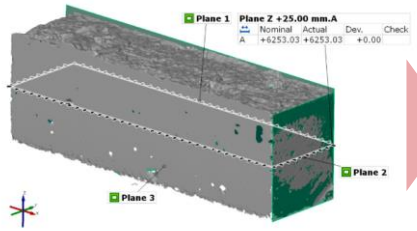
- Crack patterns



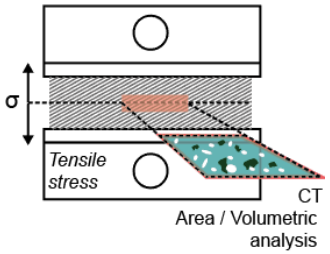
Methods



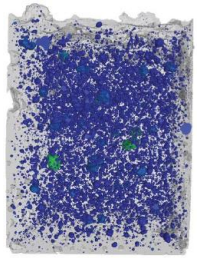
Work-form layering



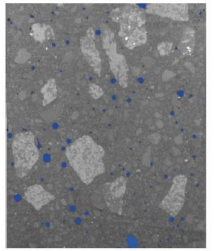
Atos tripple scan



Uniaxial tensile test

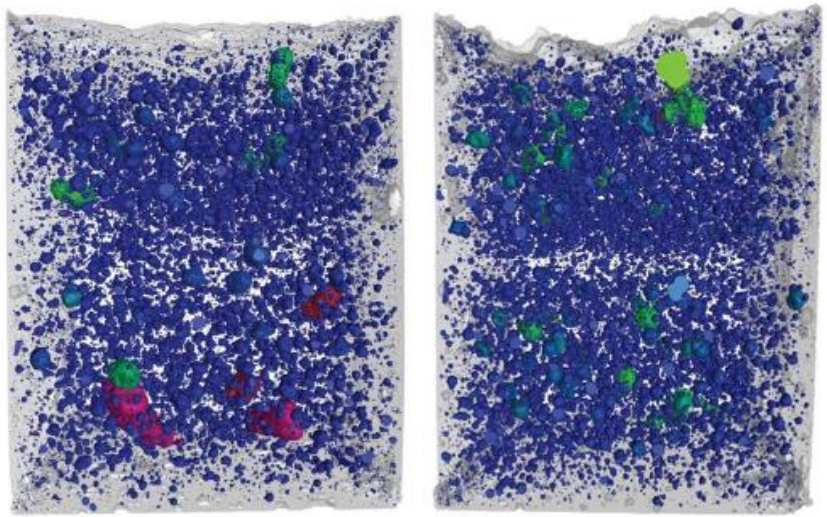


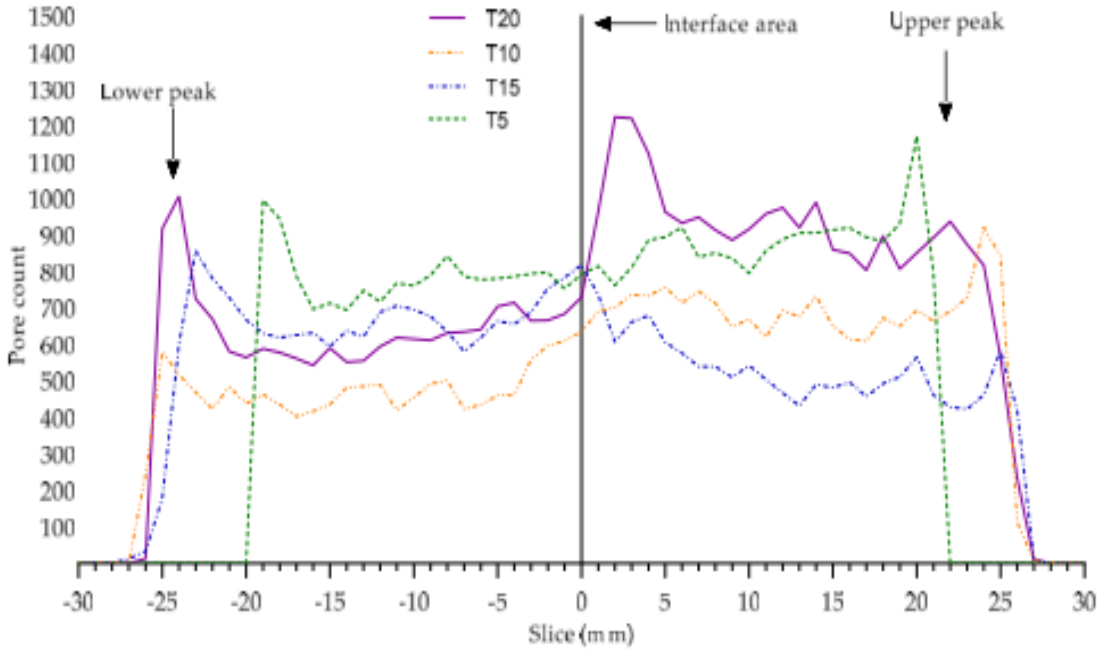
CT - Volumetric & Area analysis



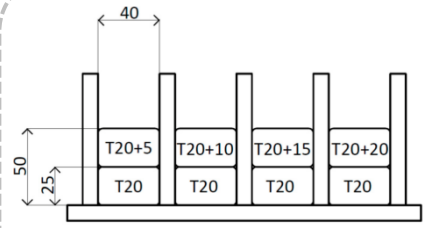
RESULTS AND DISCUSSION

- Pore distribution
- Layer interface

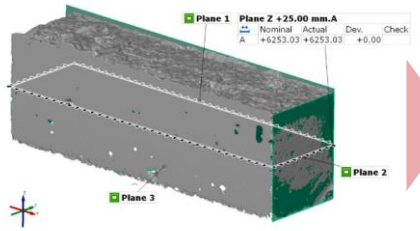




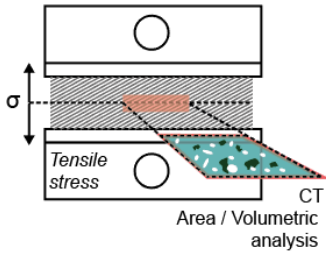
Methods



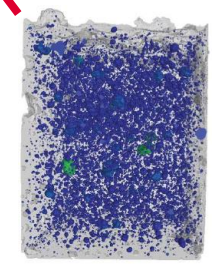
Work-form layering



Atos tripple scan



Uniaxial tensile test



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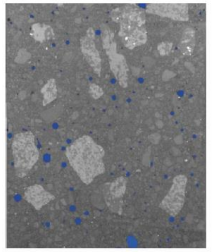
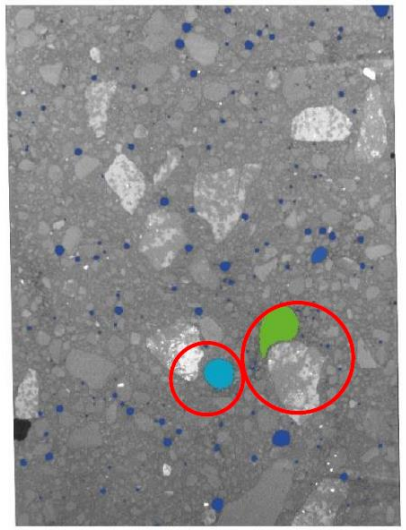
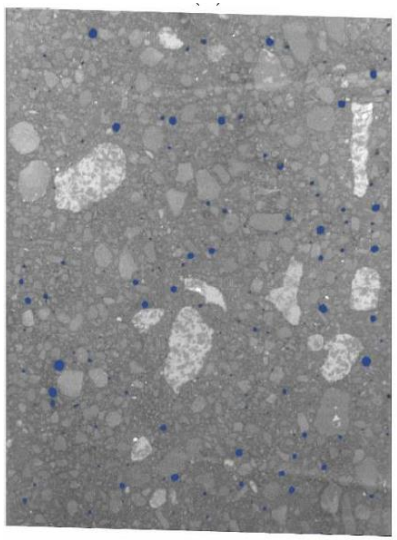
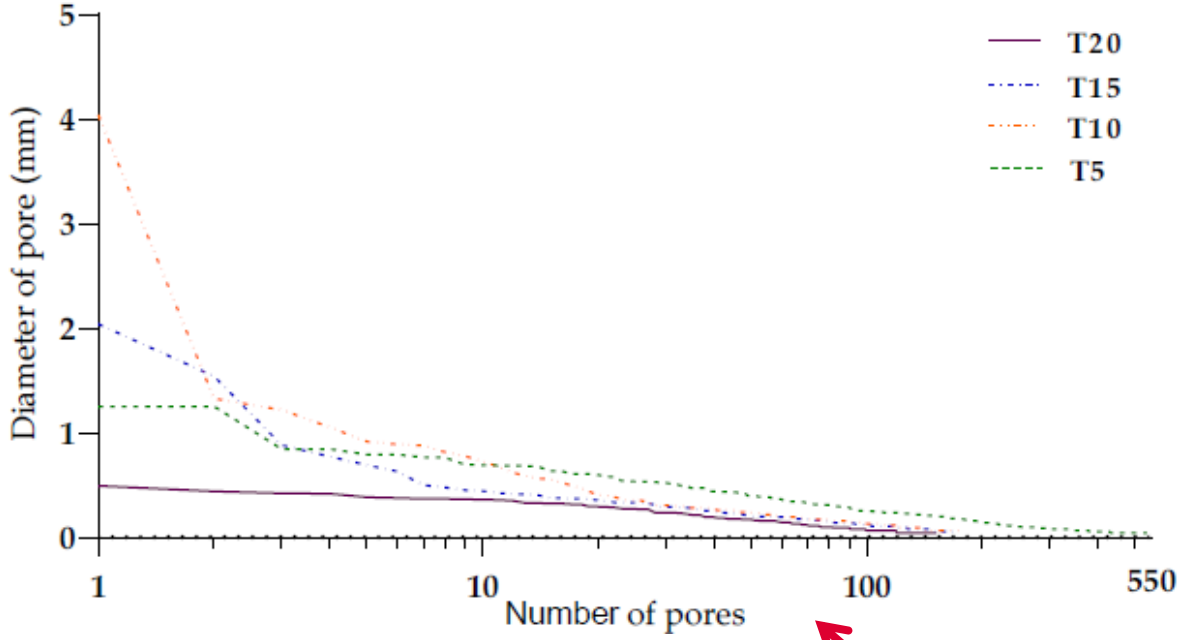


RESULTS AND DISCUSSION

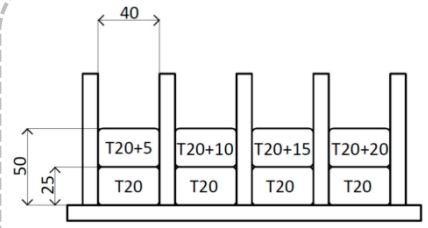
- Large air pores



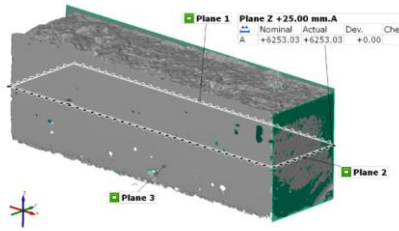




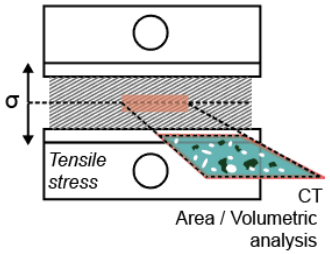
Methods



Work-form layering

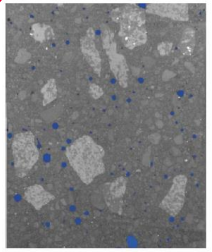


Atos tripple scan



Uniaxial tensile test

CT - Volumetric & Area analysis



SCIENTIFIC QUESTIONS AND HYPOTHESES

Answer to Q1 based on hypotheses:

With increased layering time:

- *the interface strength decreases, where in time from 20 min the layers did not connect homogenously.*
- *the increasing occurrence of large air pores at the interface has not been confirmed.*
- *the occurrence of the large air pores near the Coarse Aggregate has been confirmed in early ages.*

- ***The hypotheses was not falsified***

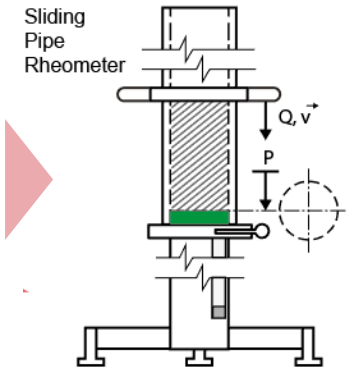
SCIENTIFIC QUESTIONS AND HYPOTHESES

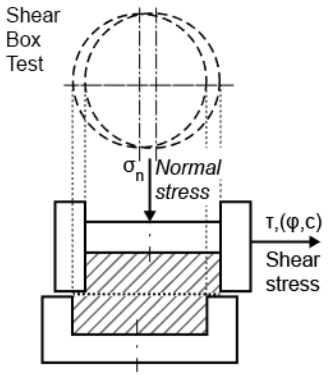
Scientific question Q2:
What effect does the coarse aggregate of 8 millimetres have on the development of green strength in comparison to the same material without coarse aggregate?

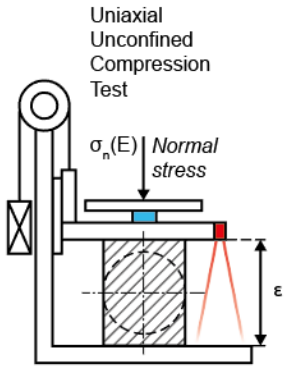
Hypotheses:
The coarse aggregate presence reinforce and strengthen the mixture resulted in the increased load capacity.
Based on their response to normal and shear stresses, both materials should show a linear development with increasing cohesion, with coarse aggregate showing higher values.

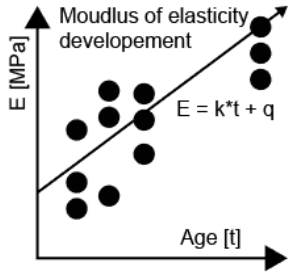
Workflow and methods:

Input from	Cement-based composite	Pumpability	Buildability	Prediction	Output	Input
Previous research results	*With and without Coarse aggregate*	*Rheology properties*	*Mechanical properties*	*Linear material model*	Publish Results	Follow – up research



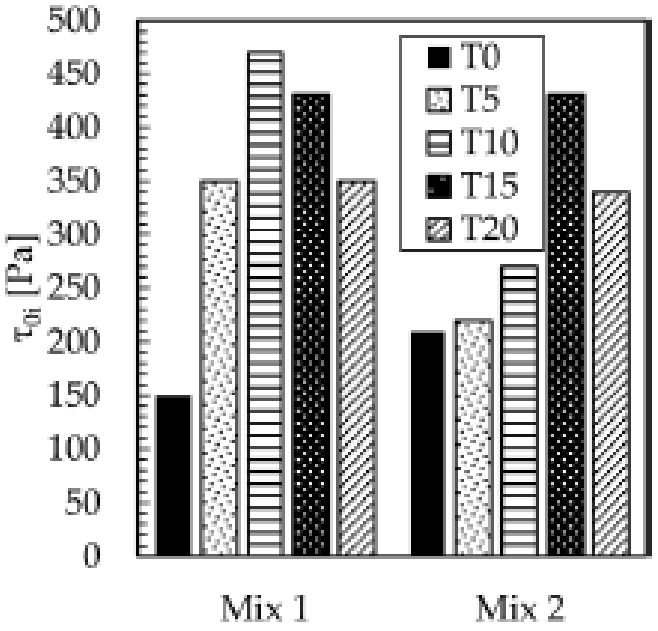


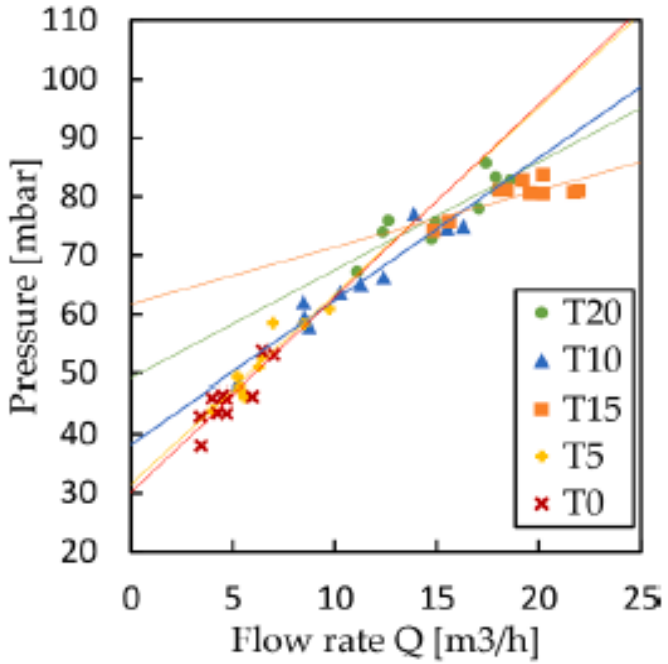




RESULTS AND DISCUSSION

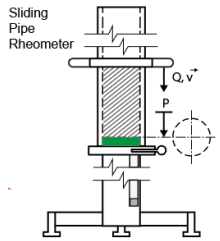
- Pumpability



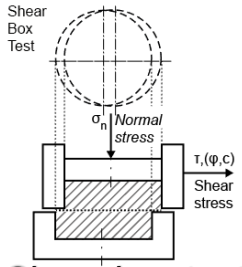


Methods

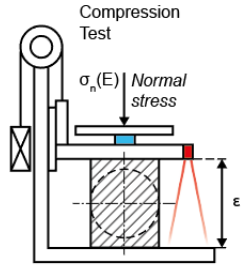
CA



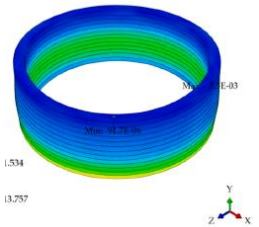
Sliding pipe rheometer



Shear box test



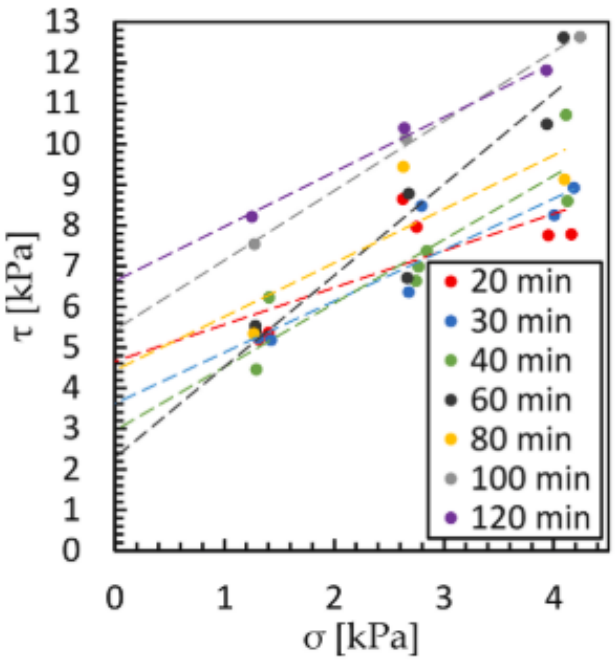
Uniaxial Unconfined Compression Test

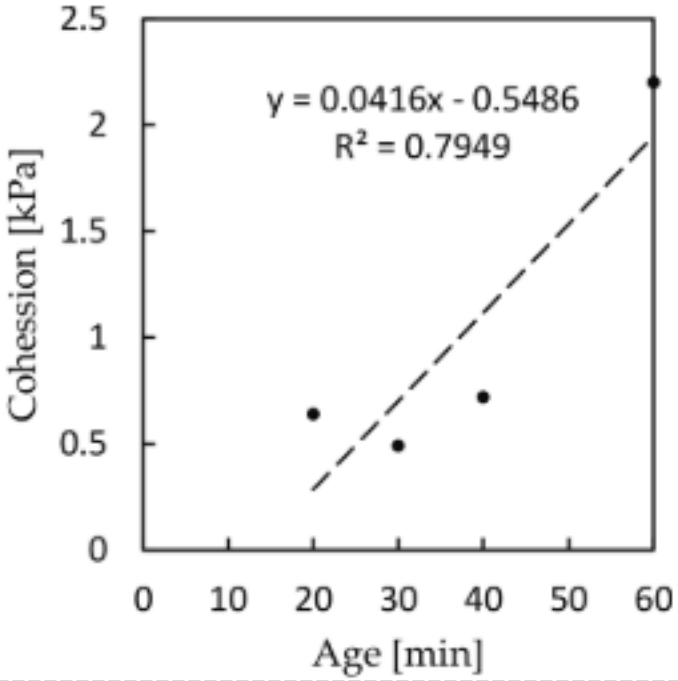


FEM analysis

RESULTS AND DISCUSSION

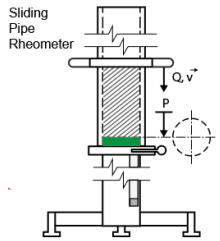
- Mohr coulomb criterion



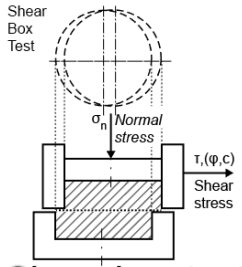


Methods

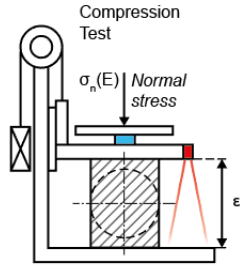
CA



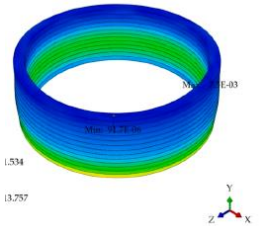
Sliding pipe rheometer



Shear box test



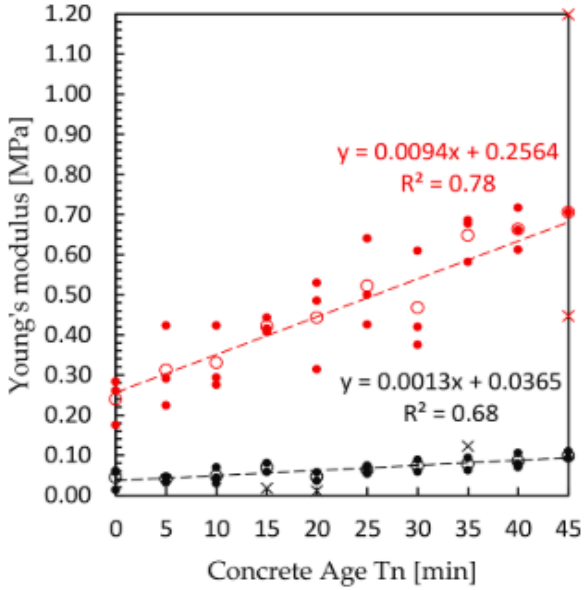
Uniaxial Unconfined Compression Test

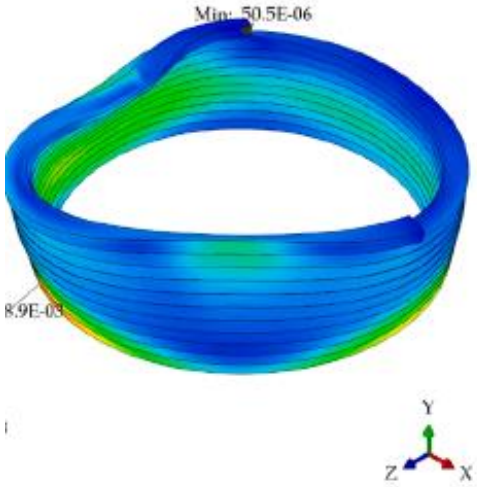


FEM analysis

RESULTS AND DISCUSSION

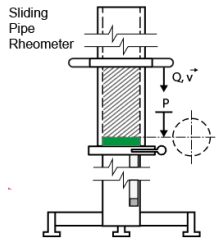
- Buildability sensitivity



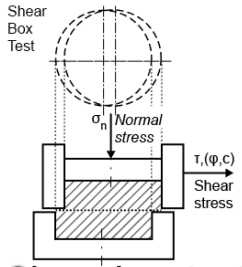


Methods

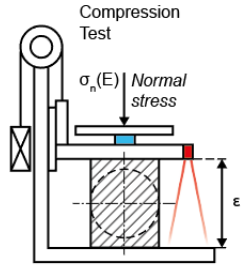
CA



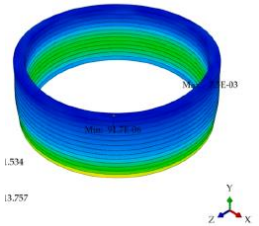
Sliding pipe rheometer



Shear box test



Uniaxial Unconfined Compression Test



FEM analysis

SCIENTIFIC QUESTIONS AND HYPOTHESES

Answer to Q2 based on hypotheses

- *Fresh concrete cohesion varies significantly, with coarse aggregates exhibiting negative cohesion slope initially and positive slope later, addressed by a bi-linear model.*
- *Mixture with coarse aggregate is more ductile than mixture without the coarse aggregate, which is more brittle.*
- *Mixture containing coarse aggregate has less buildability than the mixture without coarse aggregate.*

- ***The hypotheses was falsified***

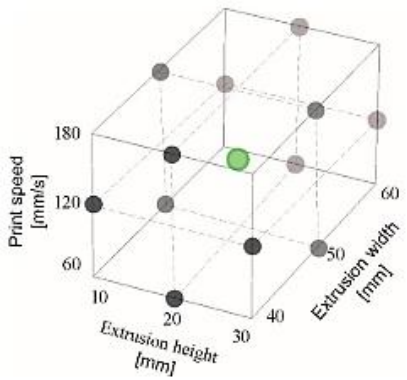
SCIENTIFIC QUESTIONS AND HYPOTHESES

Scientific question Q3:
What is the impact of an optimized configuration of controllable parameters on the buildability of a cylindrical geometry printed using a cement mixture containing a larger aggregate fraction (8 mm) and waste reduction?

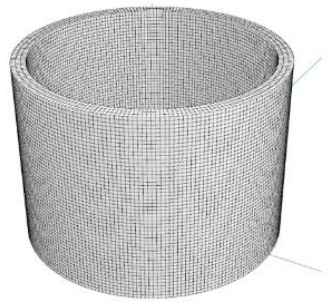
Hypotheses:
The optimised configuration of controllable parameters should increase buildability while maintaining the uncontrollable parameters – material properties of a mixture with an 8 millimetres fraction of coarse aggregate.

Workflow and methods:

Input from	Design of experiment	Simulation	Output	Input
Previous research results	*Cover process parameters combinations*	*Optimising process parameters increases print height*	Publish Results	Follow – up research



Influencing Factor	Mix 1
Young's modulus [MPa]	$E(t) = 0.0013t + 0.0365$
Cohesion [MPa]	0.00429
Density [kg/m^3]	2218
Friction angle [°]	54.72
Dilation angle [°]	13
Poisson constant [-]	0.3



RESULTS AND DISCUSSION

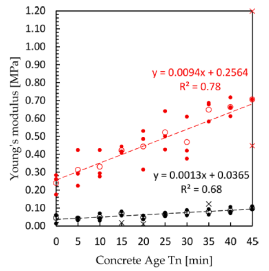
Input parameters – influencing factors

Controllable
- Process parameters
- Printed Geometry

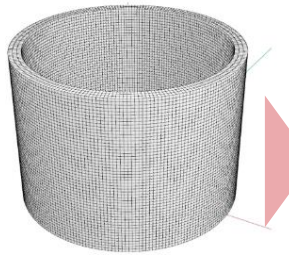
Uncontrollable
- material properties

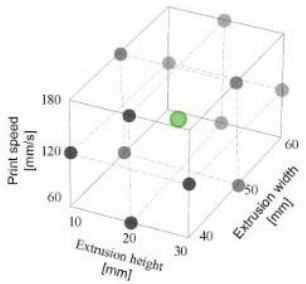
Design of Experiment – Box Behnkhen method
- Reduction of simulation count

Methods

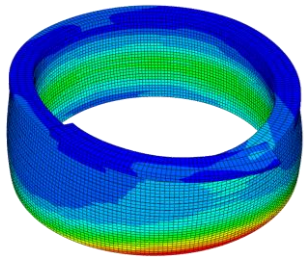


Material model


Geometry

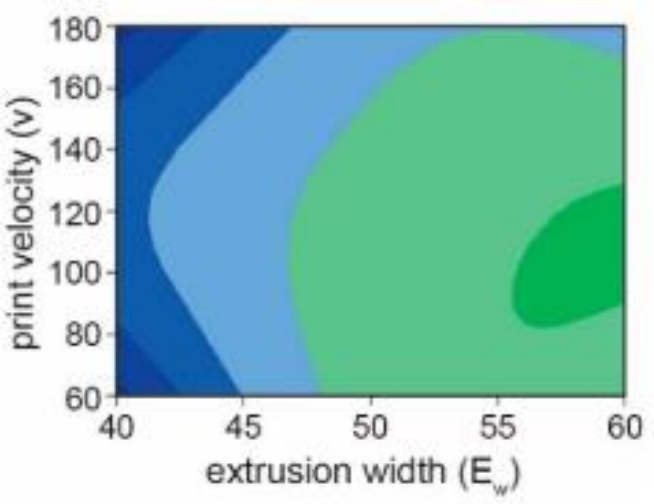


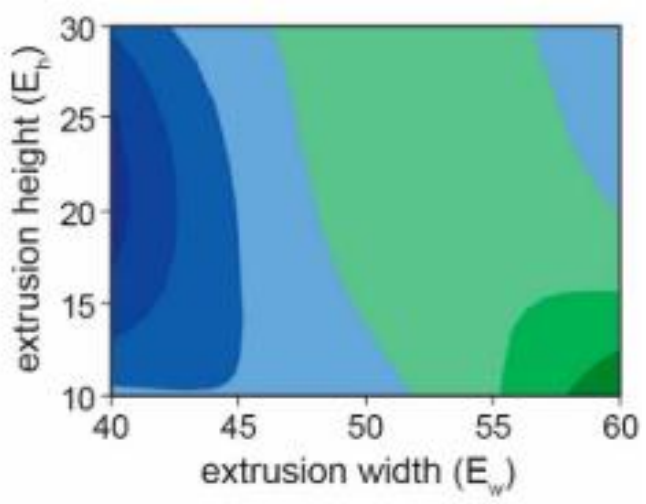
Design of Experiment


FEM analysis

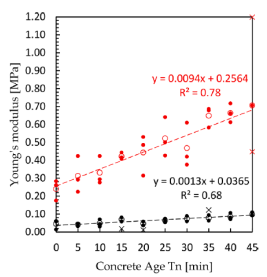
RESULTS AND DISCUSSION

- Surface response
- Statistical Significance altitude

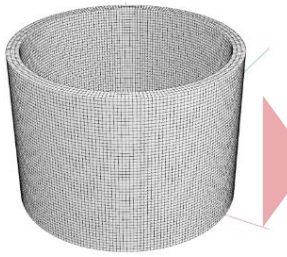




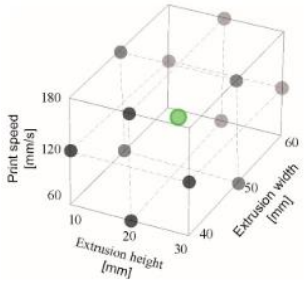
Methods



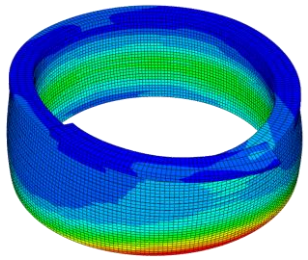
Material model



Geometry



Design of Experiment



FEM analysis

RESULTS

Answer to Q3 based on hypotheses

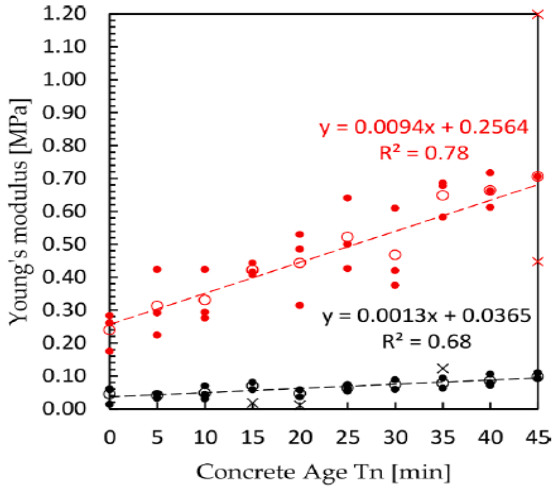
- *The utilisation of process parameters (Extrusion width and height, print velocity) has resulted in enhanced print stability.*
- *Significant factor; other factors and their combinations are statistically insignificant according to the tests.*
- *Buildability improvent*
- *Reduces of need for other material components by about 16%*
- *Coarse aggregate presence can save average 52 kg CO_2 per m^3 of concrete.*

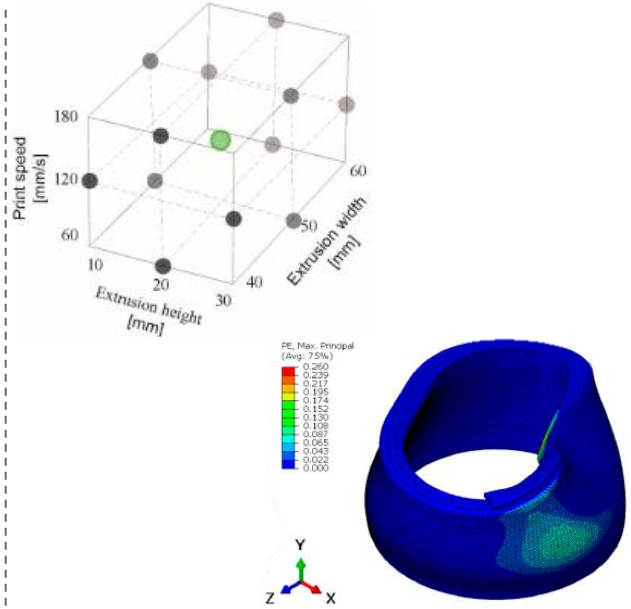
- ***The hypotheses was confirmed***

CONCLUSION

Novel findings tahat extends the use of coarse aggregate mixtrue in 3DCP

- Basic material equations, Cohession developement
- Theoretical boundaries of mixture in terms of pumpability, workability and buildability





Application potential

Material Behaviour Prediction

Print prediction; reduction of experiments, waste

Higher probability to successful print

LIST OF PUBLICATION

Journals with impact factor:

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**)*

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, IF: 7.693**)*

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**)*

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

Arnošt Vespalec, Ing.

Arnost.Vespalec@vut.cz

INSTITUTE OF **MACHINE**
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