Reinforcement of Layer-Extrusion 3-D Concrete Printing

ACI Spring Convention 2021

Dr. ir. Freek Bos

Built Environment

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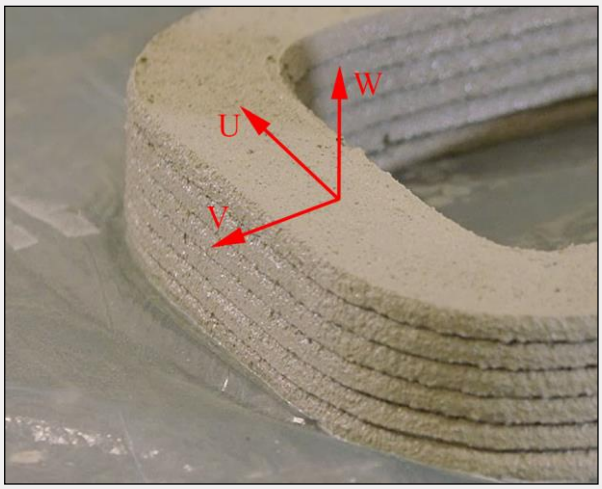
350th Anniversary Pavilion Cohesion, Innsbruck, Austria. Project by UIBK, Incremental3D, Baumit, PORR and TU/e.

Grasser, G., Pammer, L., Koell, H., Werner, E., & Bos, F. P. (2020). Complex Architecture in Printed Concrete: The Case of the Innsbruck University 350th Anniversary Pavilion COHESION. In F. Bos, S. Lucas, R. Wolfs, & T. Salet (Eds.), Second RILEM International Conference on Concrete and Digital Fabrication: Digital Concrete 2020 (pp. 1116-1127). (RILEM Bookseries; Vol. 28). Springer. https://doi.org/10.1007/978-3-030-49916-7_106

2

Reinforcement of Layer-Extrusion 3-D Concrete Printing



- Direction u: // to print path, in print plane
- Direction v: ⊥ to print path, in print plane, incidentally crossing layers
- Direction w: ⊥ to print path, perpendicular to print plane, crossing many layers

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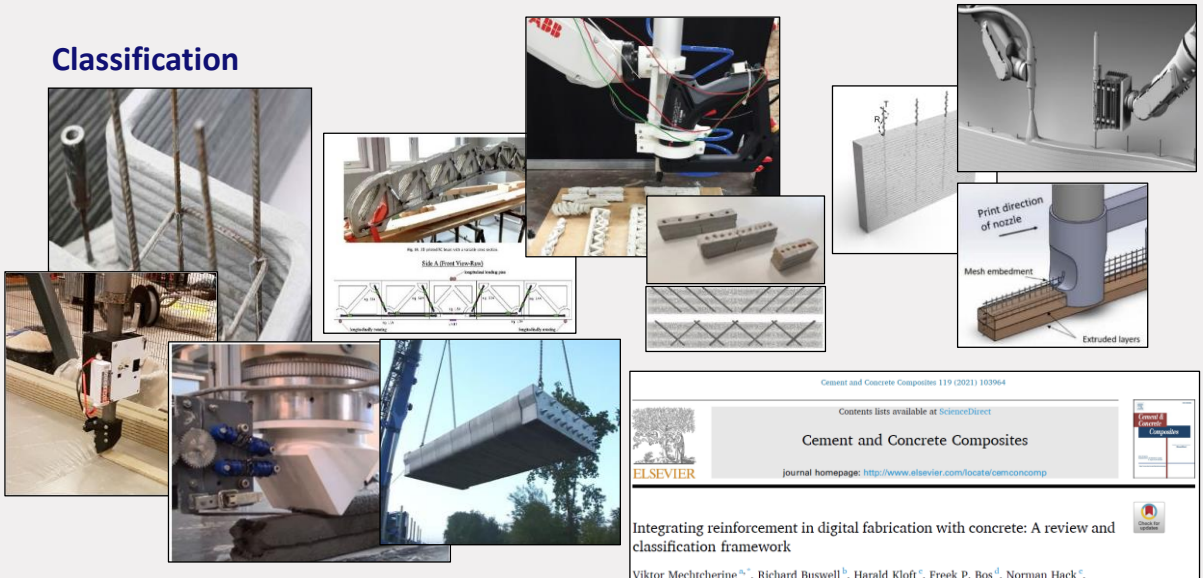
Classification



Cement and Concrete Composites 119 (2021) 103964
Contents lists available at ScienceDirect
Cement and Concrete Composites
journal homepage: http://www.elsevier.com/locate/cemconcomp

Integrating reinforcement in digital fabrication with concrete: A review and classification framework

Viktor Mechtcherine [a,*], Richard Buswell [b], Harald Kloft [c], Freek P. Bos [d], Norman Hack [c], Rob Wolfs [d], Jay Sanjayan [e], Behzad Nematollahi [e], Egor Ivaniuk [a], Tobias Neef [a]

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[b] School of Architecture, Building and Civil Engineering, Loughborough University, UK
[c] Institute of Structural Design, Technische Universität Braunschweig, Braunschweig, Germany
[d] Department of the Built Environment, Eindhoven University of Technology, the Netherlands
[e] Center for Smart Infrastructure and Digital Construction, Swinburne University of Technology, Hawthorn, 3122, Victoria, Australia

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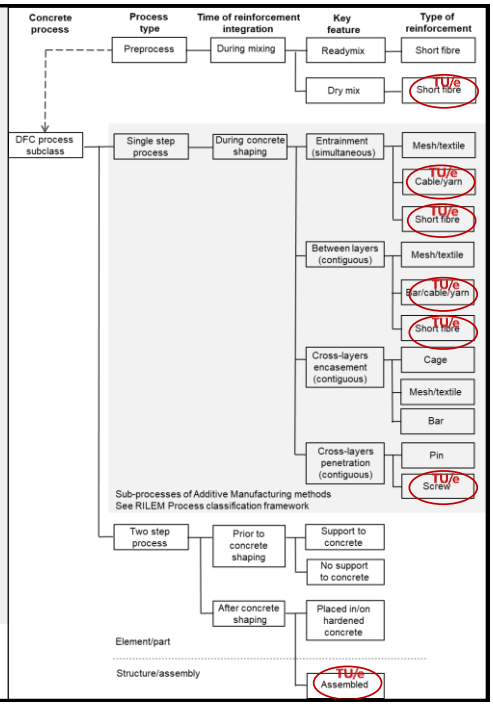
Classification

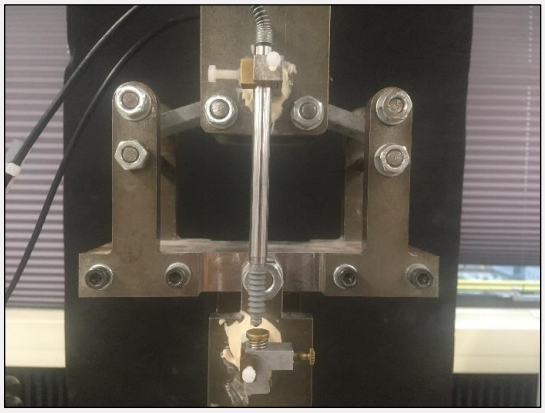
- Time of reinforcement integration
  - Preprocess, in print material
  - Prior to concrete shaping
  - After concrete shaping
  - During concrete shaping
- Key feature
  - Entrainment (simultaneous)
  - Between the layers (contiguous)
  - Cross-layers encasement (contiguous)
  - Cross-layers penetration (contiguous)

Mechtcherine, V., Buswell, R., Kloft, H., Bos, F. P., Hack, N., Wolfs, R. J. M., Sanjayan, J., Nematollahi, B., Ivaniuk, E., & Neef, T. (2021). Integrating reinforcement in digital fabrication with concrete: A review and classification framework. Cement & Concrete Composites, 119, [103964]. https://doi.org/10.1016/j.cemconcomp.2021.103964



Printable Strain Hardening Cementitious Composites 3DP/SHCC

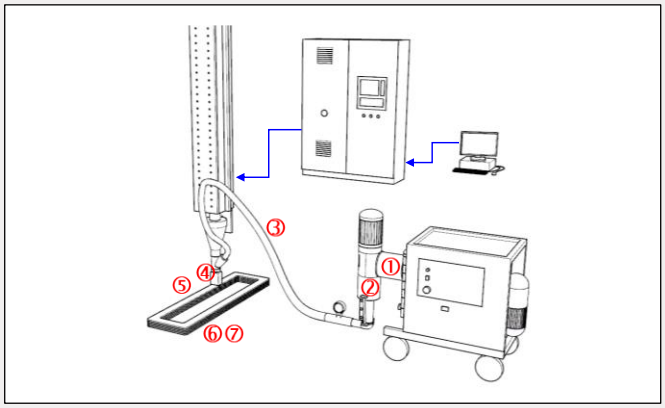
(a preprocess approach)



Unpublished research PhD candidate A.L. van Overmeir (TU Delft). NWO grant no 17251.

Printable Strain Hardening Cementitious Composites 3DP/SHCC

(a preprocess approach)



Schematic representation of the concrete 3D printing process. The numbers correspond to the stages of 3DCP as discussed in the text: 1. Mixing, 2. Pumping, 3. Transporting, 4. Extruding, 5. Building, 6. Curing, 7. Hardened.

Li, V., Bos, F. P., Yu, K., McGee, W., Ng, T. Y., Chaves Figueiredo, S., Nefs, K., Mechtcherine, V., Nerella, V., Pan, J., van Zijl, G., & Kruger, J. (2020). On the emergence of 3D printable Engineered, Strain Hardening Cementitious Composites (ECC/SHCC). Cement and Concrete Research, 132(132), [106038]. https://doi.org/10.1016/j.cemconres.2020.106038

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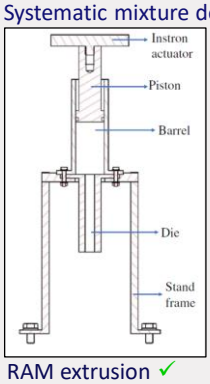
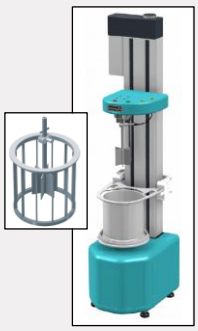
Printable Strain Hardening Cementitious Composites 3DP/SHCC

(a preprocess approach)

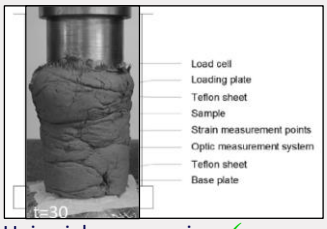
Systematic mixture design: suitability of characterization methods



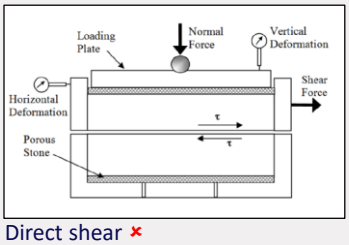
RAM extrusion ✓



Rheometer ✗



Uni-axial compression ✓



Direct shear ✗

Unpublished research TU Eindhoven.

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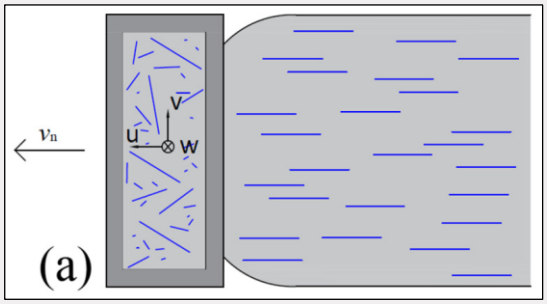
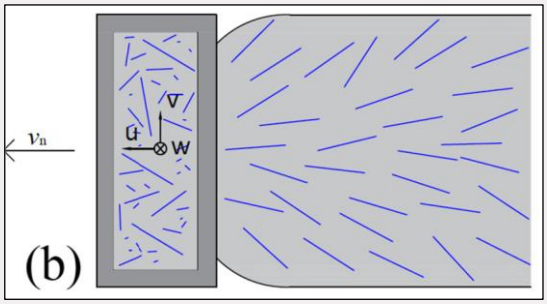
Printable Strain Hardening Cementitious Composites 3DP/SHCC

(a preprocess approach)

Directionality (performance in u-, v-, and w-direction)



Commonly assumed fibre orientation in extrusion-layer 3d concrete printing.



Fibre orientation according to Chaves Figueiredo et al. 2020 (next slide).

Li, V., Bos, F. P., Yu, K., McGee, W., Ng, T. Y., Chaves Figueiredo, S., Nefs, K., Mechtcherine, V., Nerella, V., Pan, J., van Zijl, G., & Kruger, J. (2020). On the emergence of 3D printable Engineered, Strain Hardening Cementitious Composites (ECC/SHCC). Cement and Concrete Research, 132(132), [106038]. https://doi.org/10.1016/j.cemconres.2020.106038

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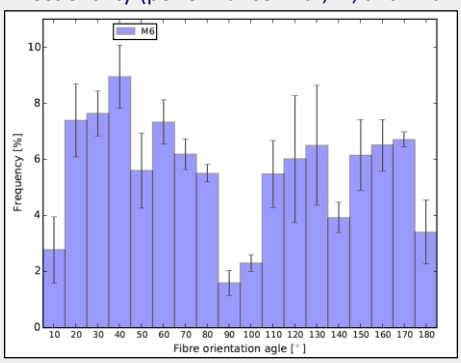
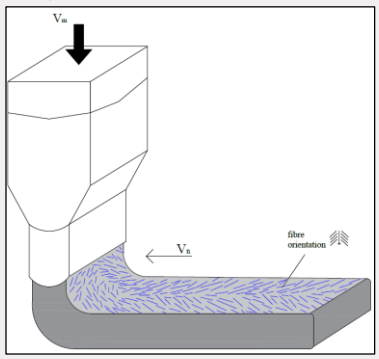
Printable Strain Hardening Cementitious Composites 3DP/SHCC

(a preprocess approach)

Directionality (performance in u-, v-, and w-direction)





Chaves Figueiredo, S., Romero Rodríguez, C., Ahmed, Z. Y., Bos, D. H., Xu, Y., Salet, T. A. M., Çopuroglu, O., Schlangen, E., & Bos, F. P. (2020). Mechanical Behavior of Printed Strain Hardening Cementitious Composites. Materials, 13(10), [2253]. https://doi.org/10.3390/ma13102253

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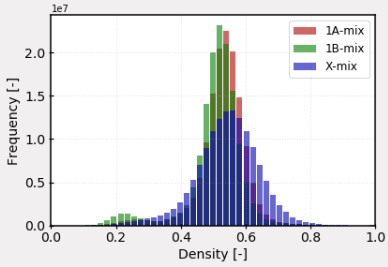
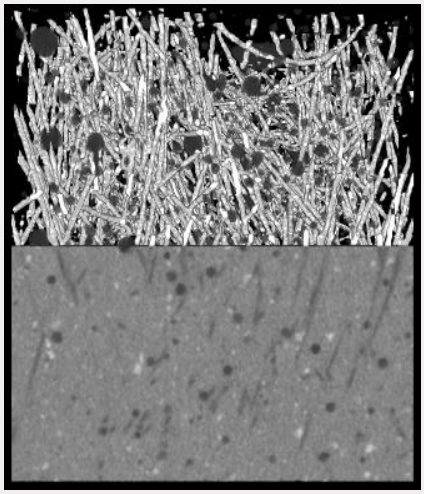
Printable Strain Hardening Cementitious Composites 3DP/SHCC

(a preprocess approach)

Directionality (performance in u-, v-, and w-direction)





Unpublished research by PhD candidate K. Nefs. NWO grant no 17251.

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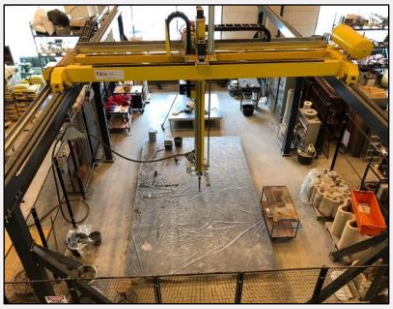
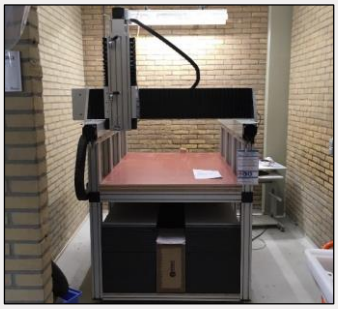
3DP/SHCC

(a preprocess approach)

Interaction between mixture and equipment: size matters…





Eindhoven Delft

Eindhoven Delft

Chaves Figueiredo, S., Overmeir, van, A. L., Nefs, K., Schlangen, E., Salet, T. A. M., Savija, B., Suiker, A. S. J., & Bos, F. P. (2020). Quality Assessment of Printable Strain Hardening Cementitious Composites Manufactured in Two Different Printing Facilities. In F. Bos, S. Lucas, R. Wolfs, & T. Salet (Eds.), Second RILEM International Conference on Concrete and Digital Fabrication: Digital Concrete 2020 (pp. 824-838). (RILEM Bookseries; Vol. 28). Springer. https://doi.org/10.1007/978-3-030-49916-7_81

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Printable Strain Hardening Cementitious Composites 3DP/SHCC

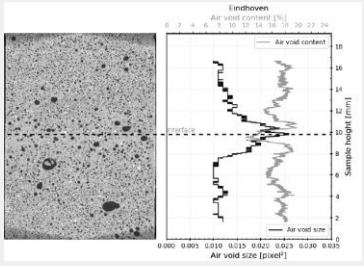
(a preprocess approach)

Interaction between mixture and equipment:

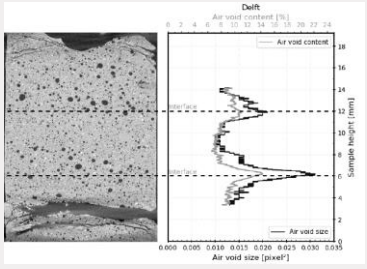
- fibre balls, dispersion, blockages,
- Air entrainment,
- batch size effects.

→ significantly different results

Delft



Eindhoven



Delft

13

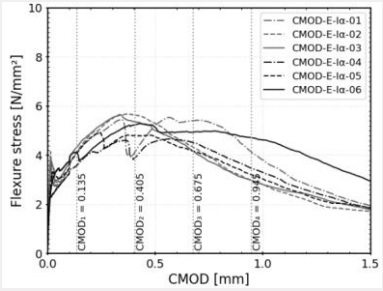
Printable Strain Hardening Cementitious Composites 3DP/SHCC

(a preprocess approach)

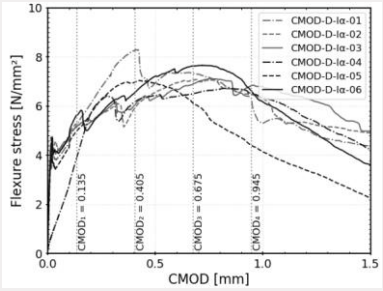
Interaction between mixture and equipment:

- fibre balls, dispersion, blockages,
- Air entrainment,
- batch size effects.

→ significantly different results



Eindhoven



Delft

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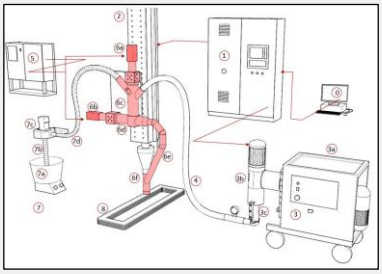
Online fiber reinforced printable concrete FR3DCP

(Entrainment during concrete shaping)



Ahmed, Z. Y., Bos, F. P., van Brunschot, M. C. A. J., & Salet, T. A. M. (2020). On demand additive manufacturing of functionally graded concrete. Virtual and Physical Prototyping, 15(2), 194-210. https://doi.org/10.1080/17452759.2019.1709009

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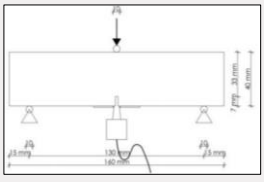
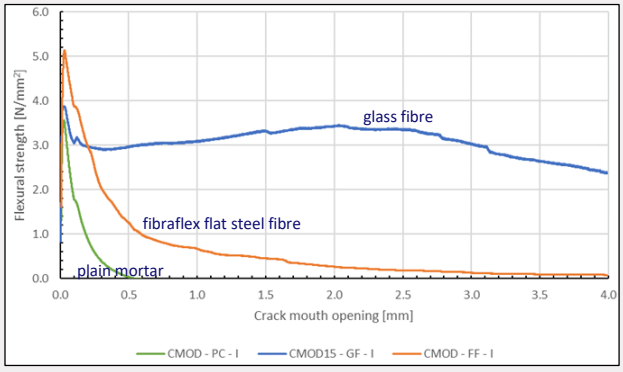
Online fiber reinforced printable concrete FR3DCP

(Entrainment during concrete shaping)





CMOD performance in Weber 3D 145-2 printable mortar

Ahmed, Z. Y., Bos, F. P., van Brunschot, M. C. A. J., & Salet, T. A. M. (2020). On demand additive manufacturing of functionally graded concrete. Virtual and Physical Prototyping, 15(2), 194-210. https://doi.org/10.1080/17452759.2019.1709009

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Online cable reinforcement

(Entrainment during concrete shaping)

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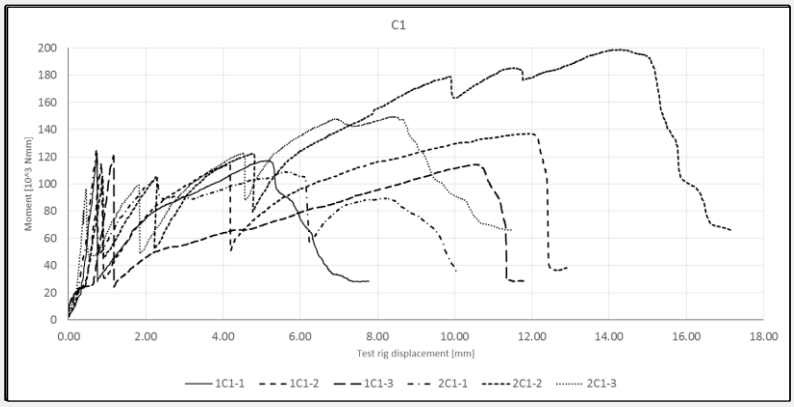
Online cable reinforcement

(Entrainment during concrete shaping)



Bos, F. P., Ahmed, Z. Y., Wolfs, R. J. M., & Salet, T. A. M. (2017). 3D printing concrete with reinforcement. In D. A. Hordijk, & M. Luković (Eds.), High Tech Concrete: where technology and engineering meet (pp. 2484-2493). Springer. https://doi.org/10.1007/978-3-319-59471-2_283

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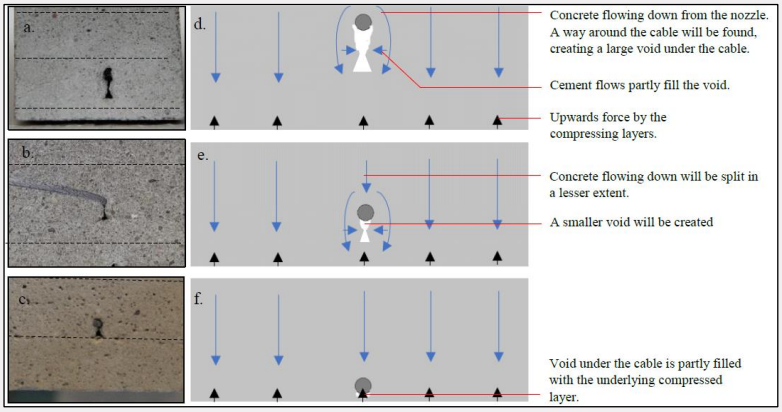
Online cable reinforcement

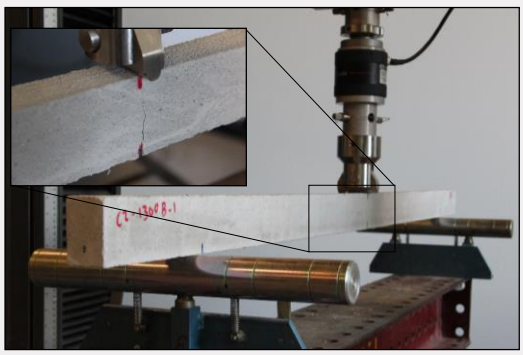
(Entrainment during concrete shaping)

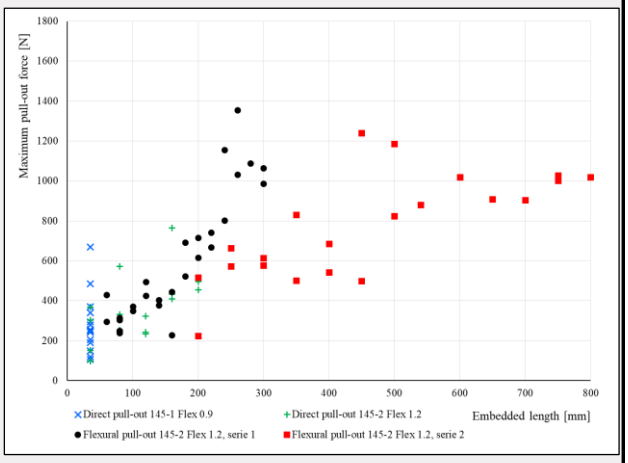


Bos, F. P., Dezaire, S., Ahmed, Z. Y., Hoekstra, A., & Salet, T. A. M. (2020). Bond of Reinforcement Cable in 3D Printed Concrete. In F. Bos, S. Lucas, R. Wolfs, & T. Salet (Eds.), Second RILEM International Conference on Concrete and Digital Fabrication: Digital Concrete 2020 (pp. 584-600). (RILEM Bookseries; Vol. 28). Springer. https://doi.org/10.1007/978-3-030-49916-7_60

Online cable reinforcement

(Entrainment during concrete shaping)

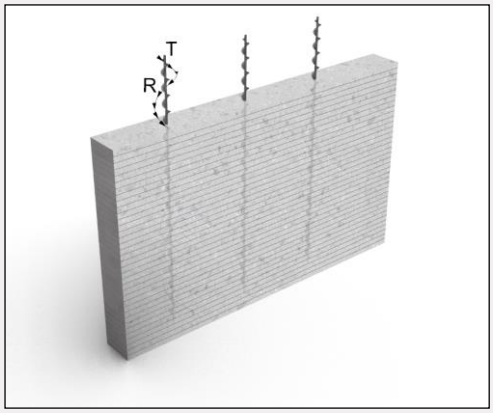


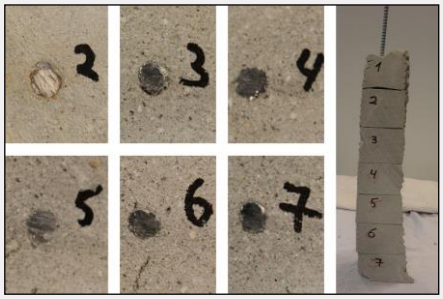


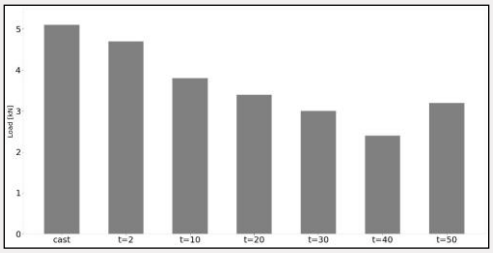
Bos, F. P., Dezaire, S., Ahmed, Z. Y., Hoekstra, A., & Salet, T. A. M. (2020). Bond of Reinforcement Cable in 3D Printed Concrete. In F. Bos, S. Lucas, R. Wolfs, & T. Salet (Eds.), Second RILEM International Conference on Concrete and Digital Fabrication: Digital Concrete 2020 (pp. 584-600). (RILEM Bookseries; Vol. 28). Springer. https://doi.org/10.1007/978-3-030-49916-7_60

Screw-type reinforcement

(Contiguous placement during concrete shaping)







Hass, L., & Bos, F. P. (2020). Bending and Pull-Out Tests on a Novel Screw Type Reinforcement for Extrusion-Based 3D Printed Concrete. In F. Bos, S. Lucas, R. Wolfs, & T. Salet (Eds.), Second RILEM International Conference on Concrete and Digital Fabrication: Digital Concrete 2020 (pp. 632-645). (RILEM Bookseries; Vol. 28). Springer. https://doi.org/10.1007/978-3-030-49916-7_64

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Concluding remarks

- Due to the nature of the 3DCP process, a one-size-fits-all solution for reinforcement is unlikely.

The main challenges encountered in the presented studies are:

- The integration of reinforcement placement in the layer-extrusion 3DCP process,
- The interaction between reinforcement materials and elements with the equipment,
- The interaction between reinforcement materials and elements with the print mortar,
- To provide reinforcement in each direction.

Additional challenges:

- Durability

Nevertheless, many concepts are under development with promising results. These issues will be solved.

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New RILEM Technical Committees on 3D Concrete Printing

RILEM TC PFC: Performance Requirements and Testing of Fresh Printable Cement-based Materials (Chair: N. Roussel; Vice-Chair: D. Lowke).

- https://www.rilem.net/groupe/pfc-performance-requirements-and-testing-of-fresh-printable-cement-based-materials-427
- Kick-off meeting: April 9, 2021, 9:00 – approx. 13:00 CEST (UTC+2)

RILEM TC ADC: Assessment of Additively Manufactured Concrete Materials and Structures (Chair: V. Mechtcherine; Vice-Chair: F. Bos).

- https://www.rilem.net/groupe/adc-assessment-of-addiively-manufactured-concrete-materials-and-structures-428
- Kick-off meeting: April 9, 2021, 13:30 – approx. 17:00 CEST (UTC+2)

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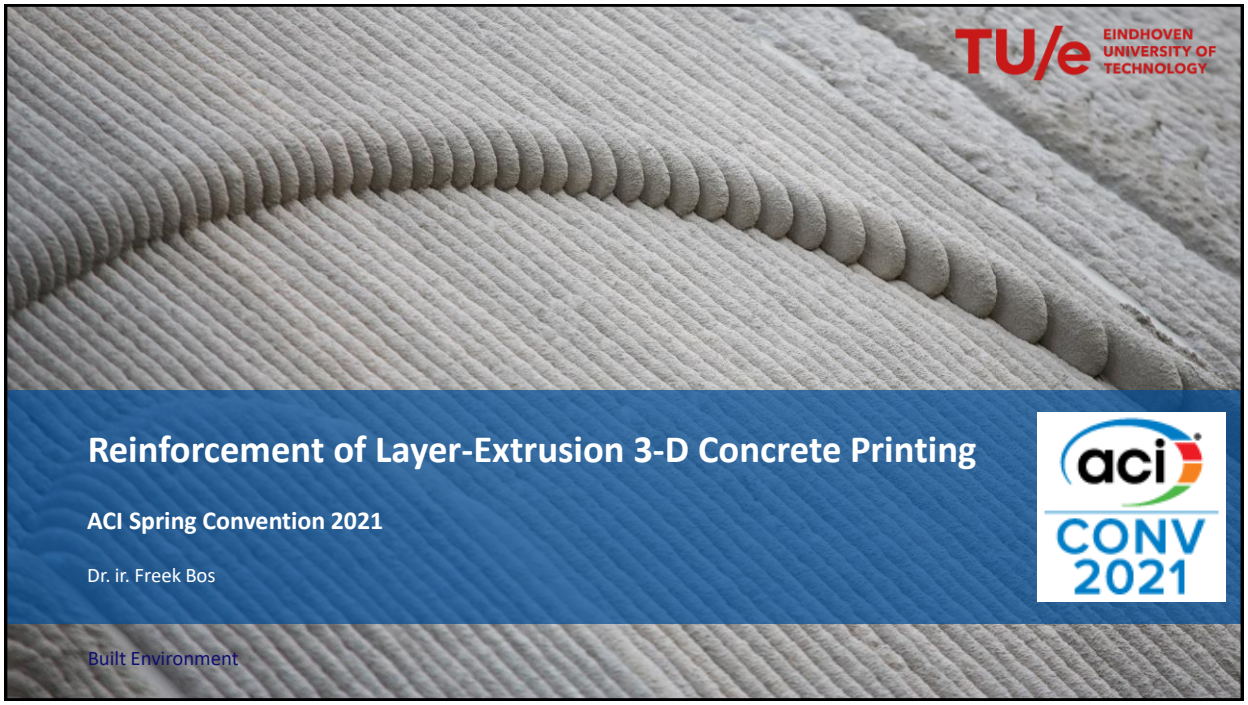

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