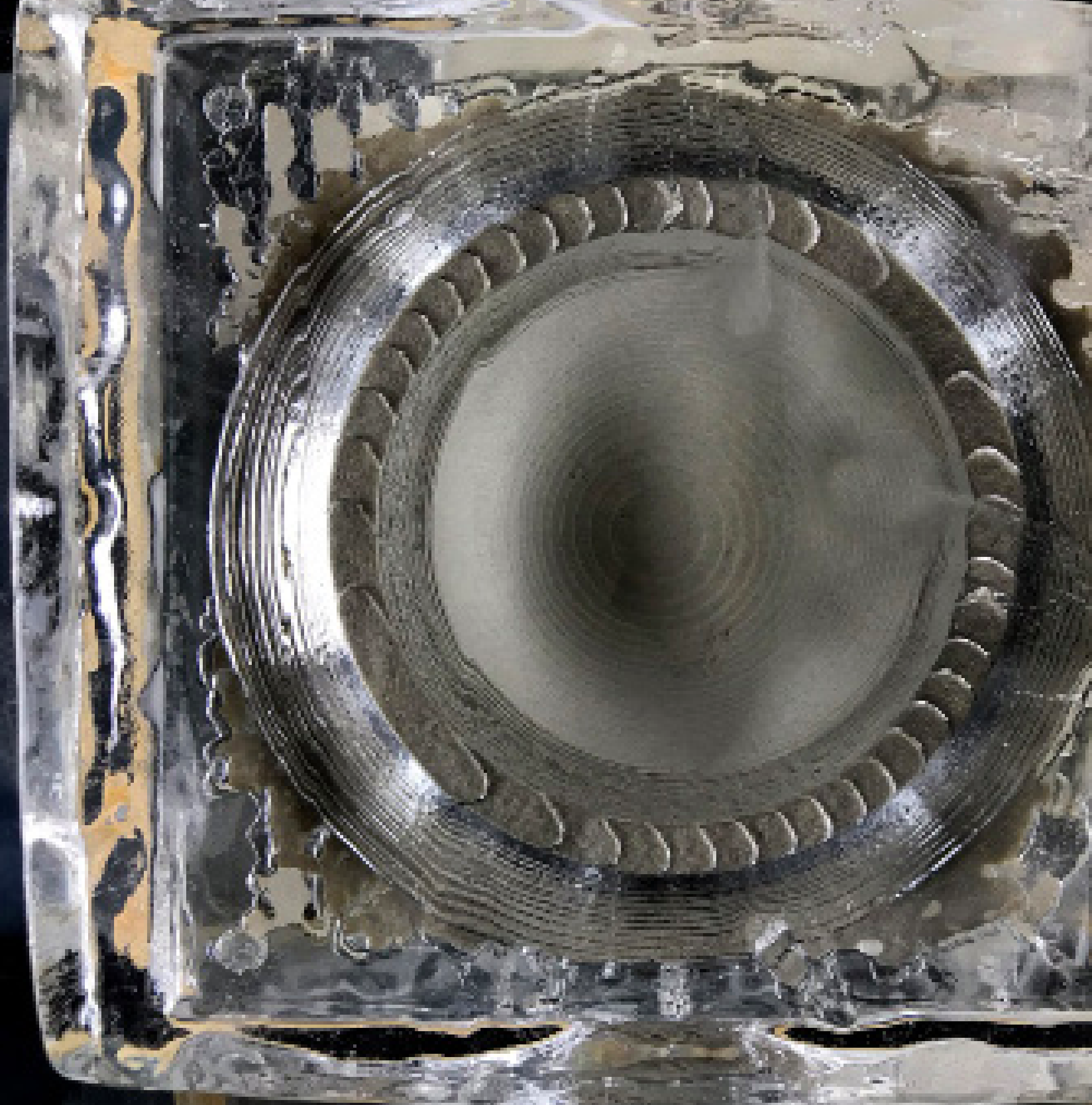




**Ice Formwork:
Digital Fabrication,
Complex Geometry and
High Performance Concrete**



inochrin

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Ice Form work

The Rationale and Potential of Ice-Based
Moulding Systems for the Production of
Complex-Geometry Precast Concrete

Vasily
Sitnikov

KTH 2020

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Part 1

**The Multifaceted
Problem of
Concrete Design
and Production**



1. Ecology of the Concrete Industry

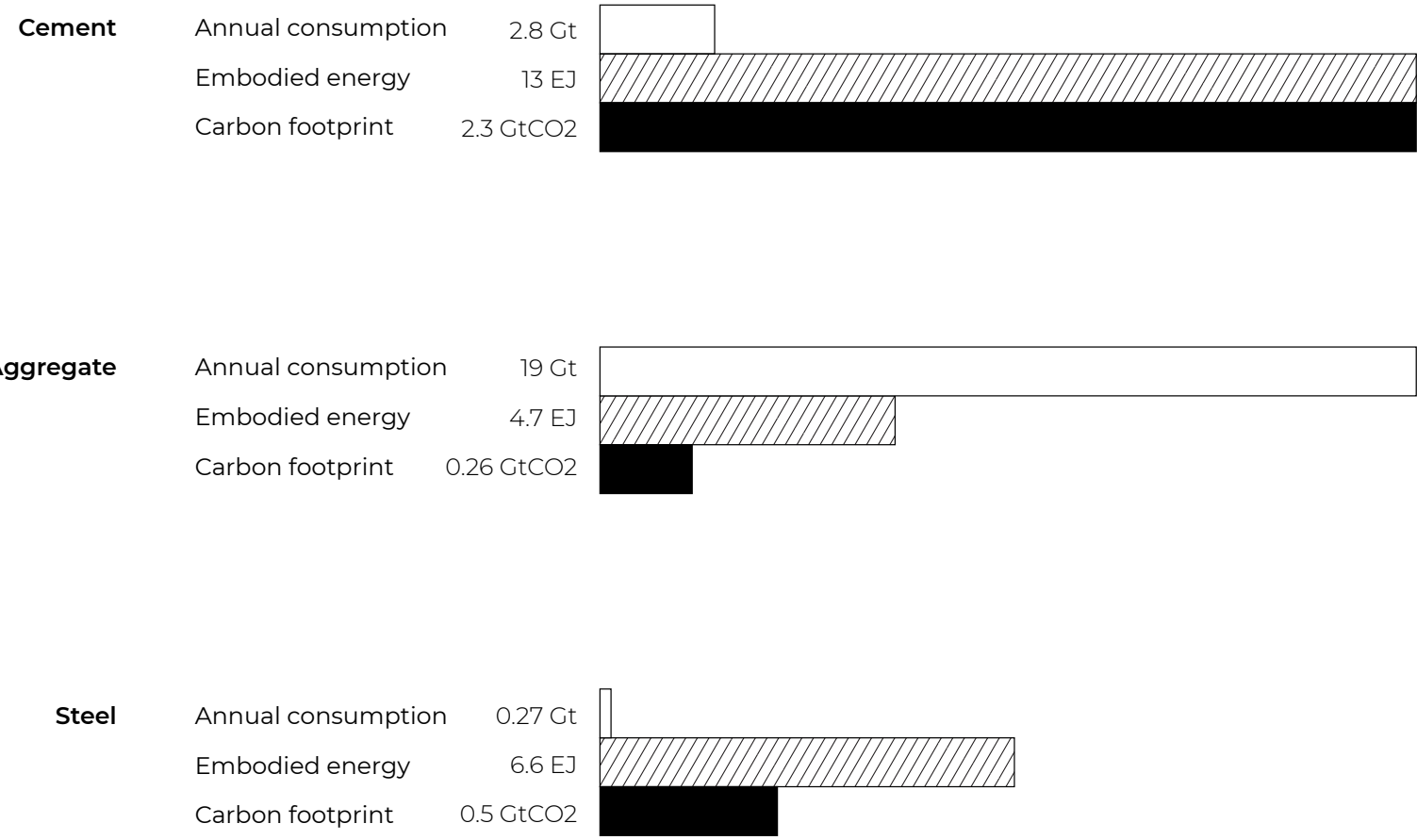
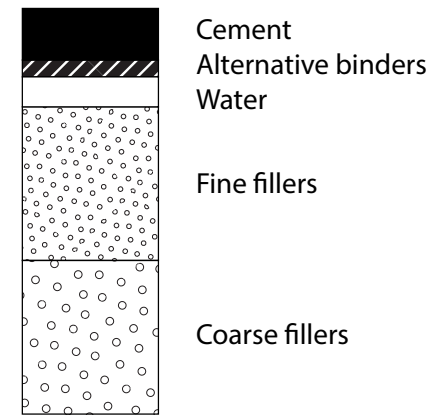


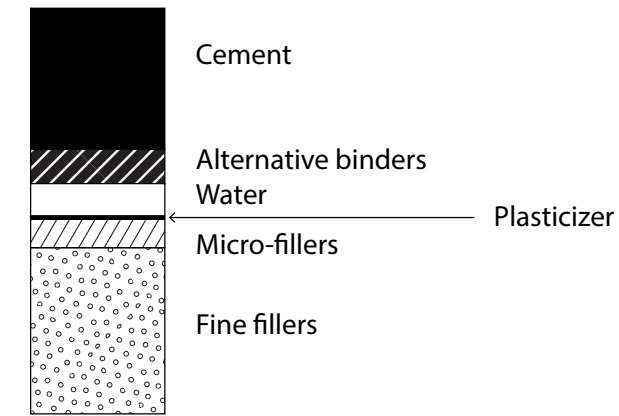
FIGURE 1.2 Comparative charts of the global consumption rates and the environmental impact of the main concrete constituent materials. (Sources: Allwood and Cullen 2012; Hamond and Jones 2011; graphical representation: author).

Basic composition

C30 Concrete Grade
Compressive strength 30 MPa



UHPFRC
Compressive strength 150 MPa



Structural application

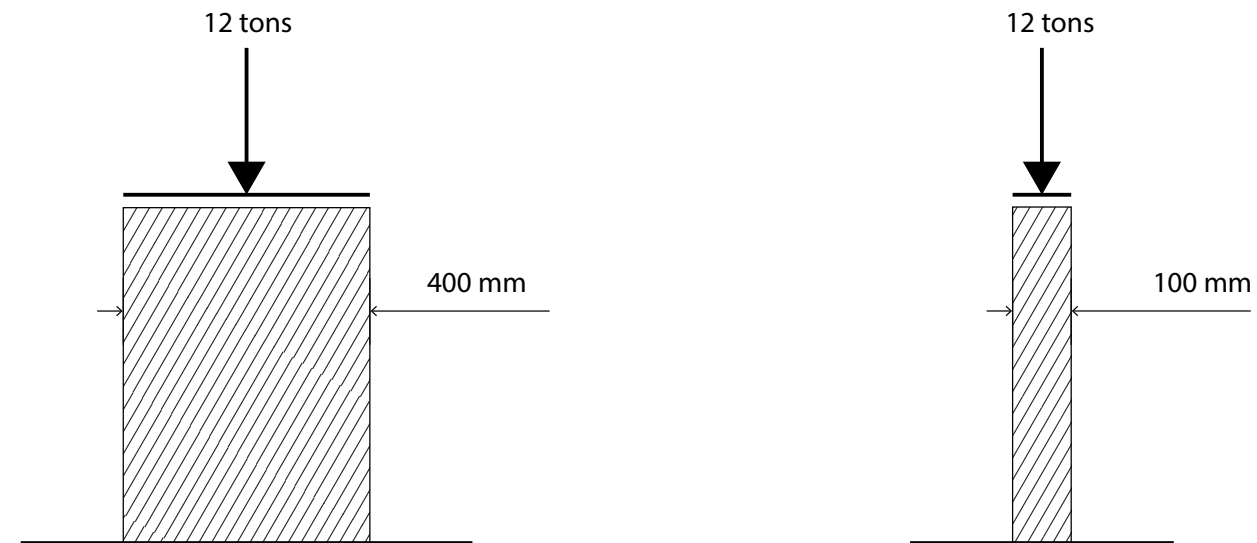
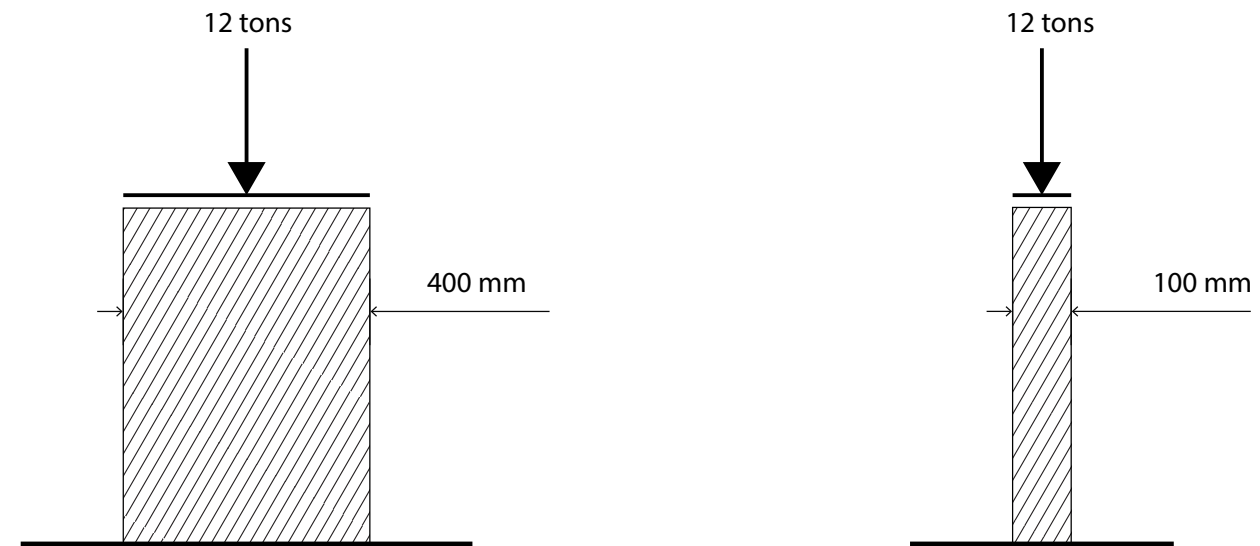


FIGURE 1.3 Comparison of cement and aggregate consumption in a structural application of C30 concrete and UHPFRC. The column profiles shown on the left are designed to carry an axial load of 3000 kg. Buckling deformations have been omitted (Sources: Stengel 2014; Voort 2008; Graphical representation: author).

Structural application



Actual material consumption at a structural case


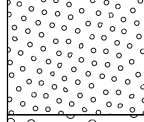
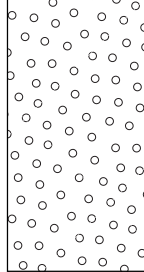


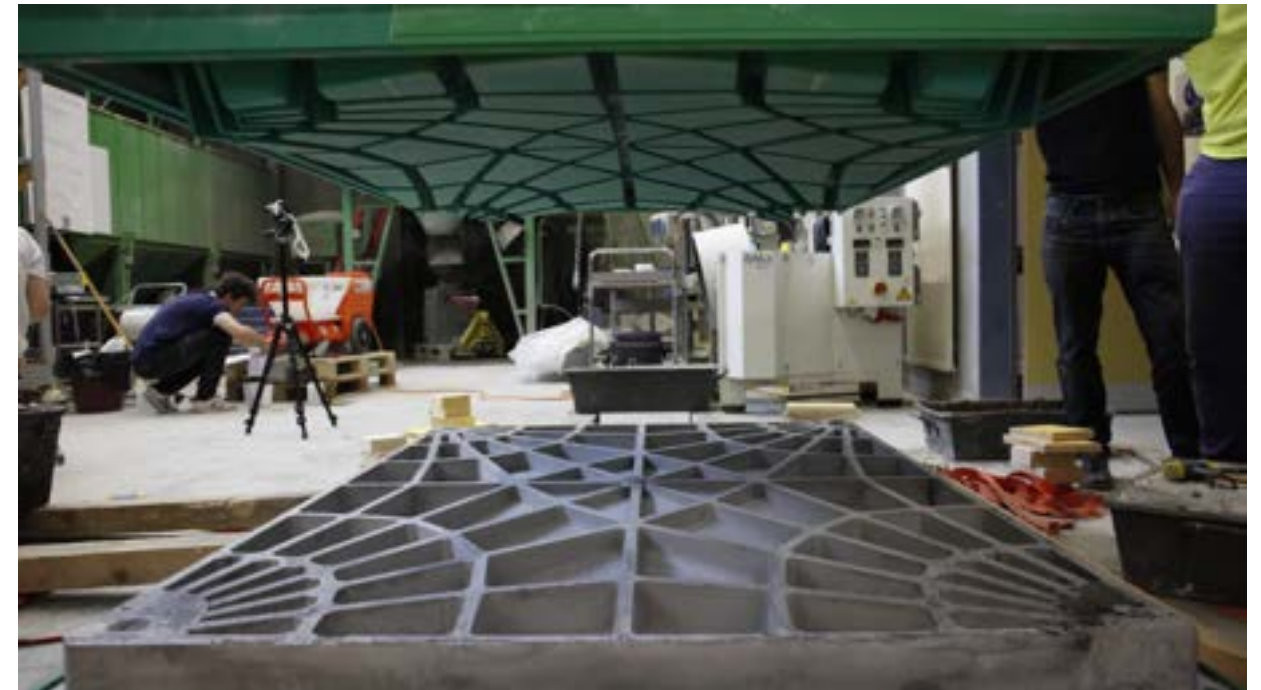
		Embodied energy	Carbon footprint
Cement		280 MJ	52 kgCO ₂
Fine fillers		8 MJ	0.8 kgCO ₂
Coarse fillers		52 MJ	3.2 kgCO ₂
Total	320 kg/m	340 MJ	56 kgCO₂
Cement		104 MJ	20 kgCO ₂
Fine fillers		4 MJ	0.4 kgCO ₂
Total	72 kg/m	108 MJ	20.4 kgCO₂

FIGURE 1.3 Comparison of cement and aggregate consumption in a structural application of C30 concrete and UHPC. The column profiles shown on the left are designed to carry an axial load of 3000 kg. Buckling deformations have been omitted (Sources: Stengel 2014; Voort 2008; Graphical representation: author).

2. Retooling in Concrete Industry

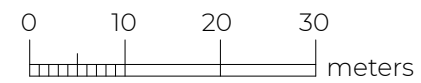
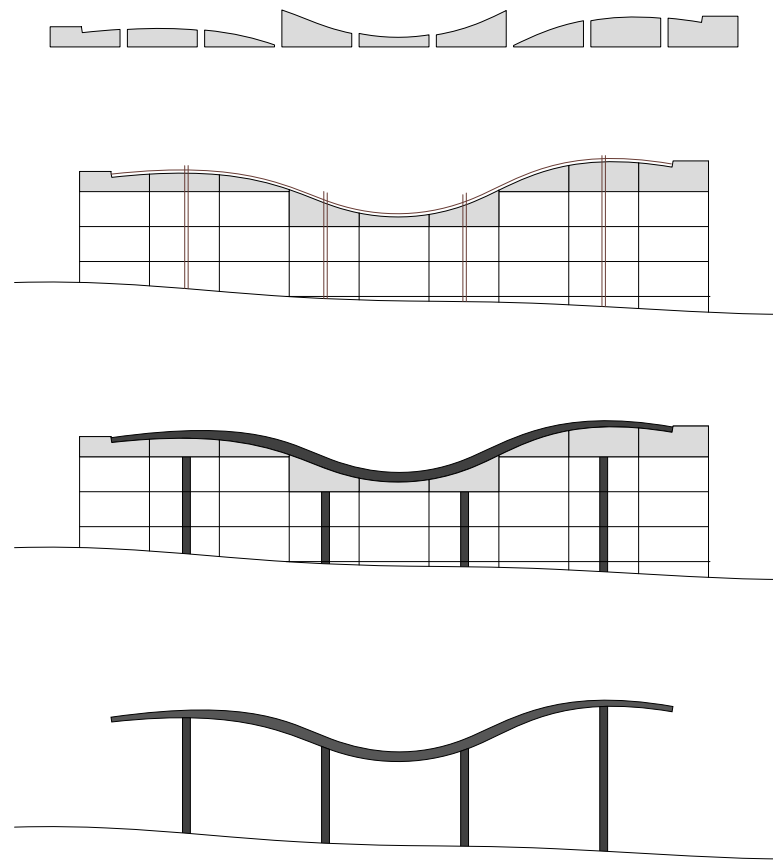


2. Retooling in the Concrete Industry

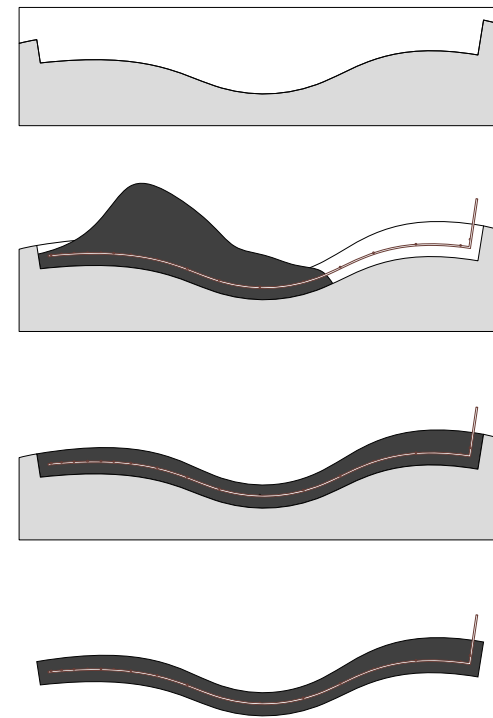


Normal Reinforced
Concrete

In Situ NC

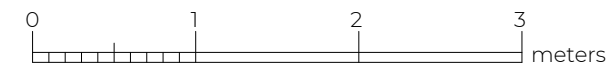
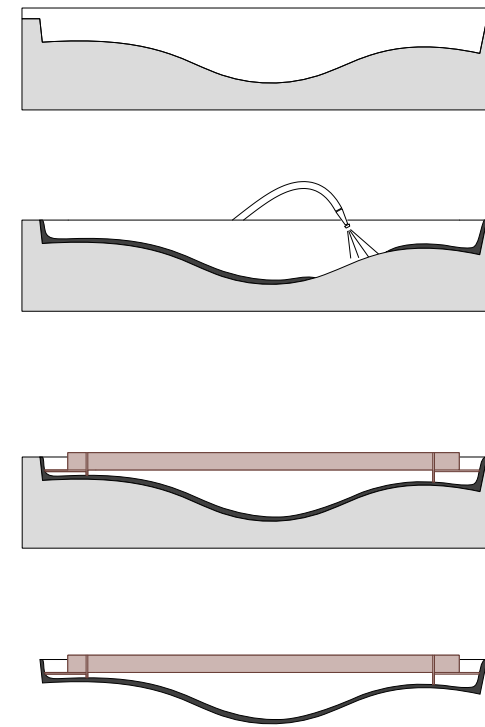


Precast NC



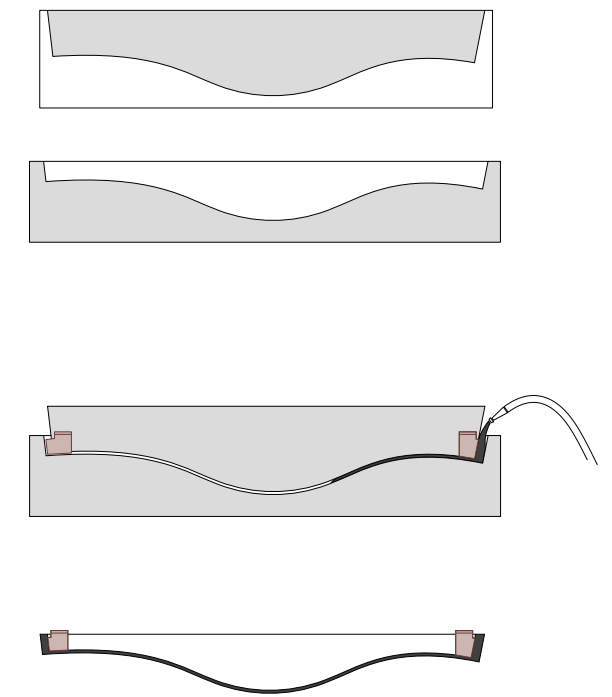
Glass Fibre Reinforced
Concrete

Prefabricated GFRC

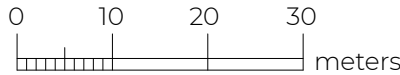
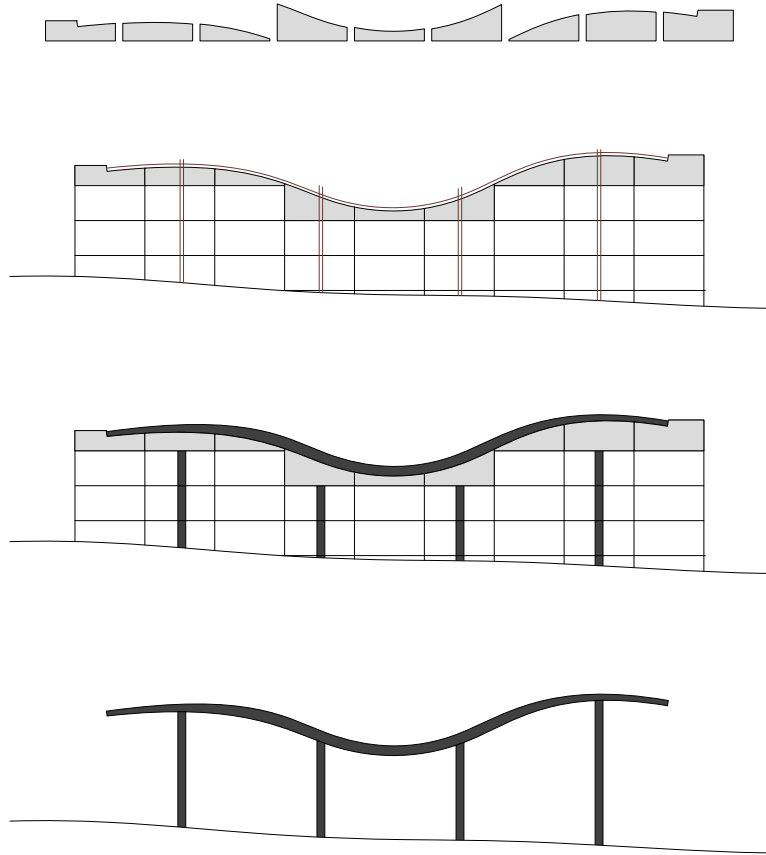


High Performance
Fiber Reinforced Concrete

Precast UHPC

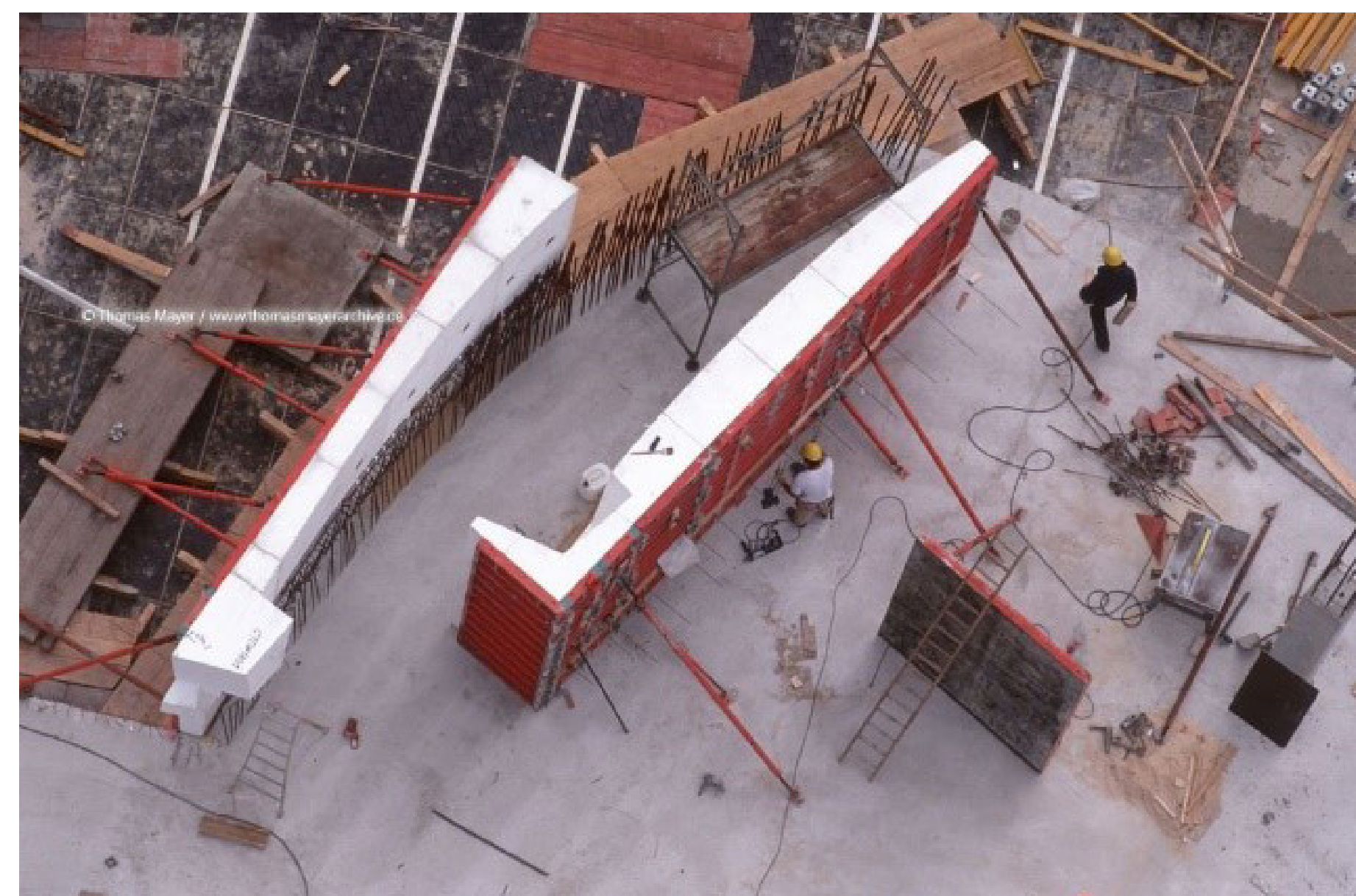


In-Situ Cast Normal Strength Concrete

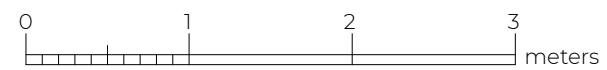
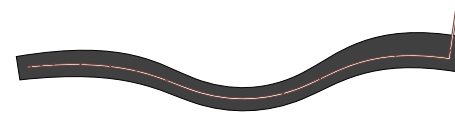
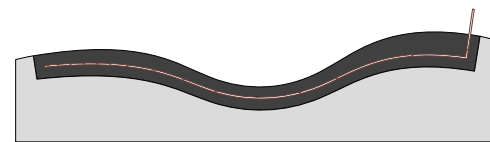
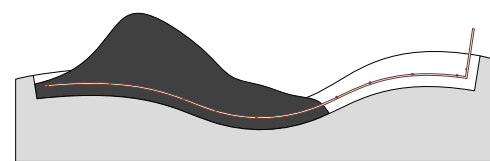
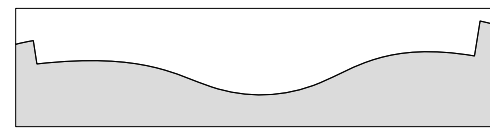




Project: Spencer Dock Bridge by AL_A (Future Systems)
Source: nedcam.com



Precast Normal Strength Concrete





Project: Neuer Zollhoff by Frank Gehry
Source: Thomas Mayer

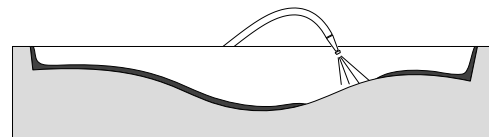
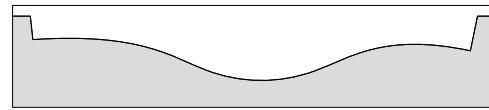


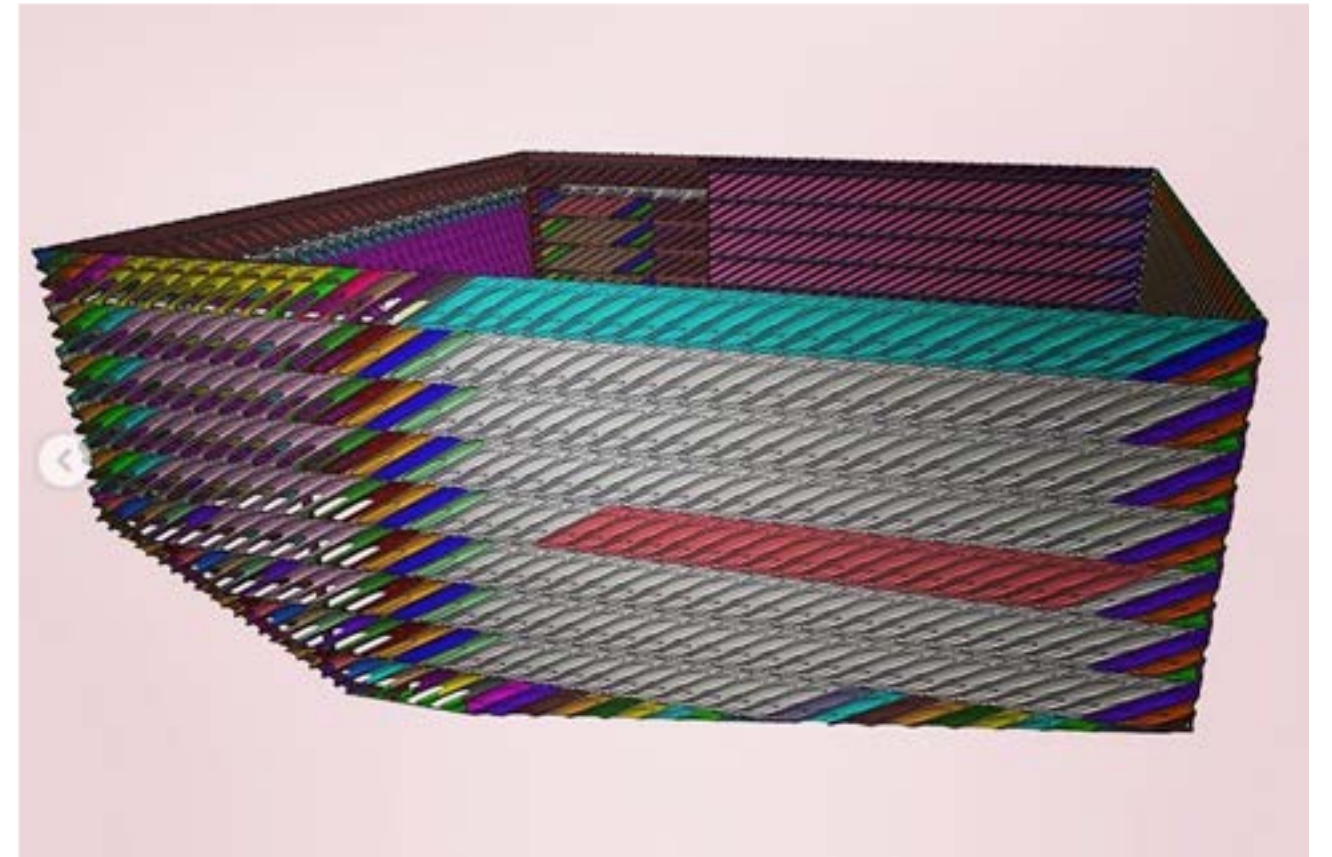
Project: Neuer Zollhof by Frank Gehry
Source: Thomas Mayer

Glass Fibre Reinforced Concrete

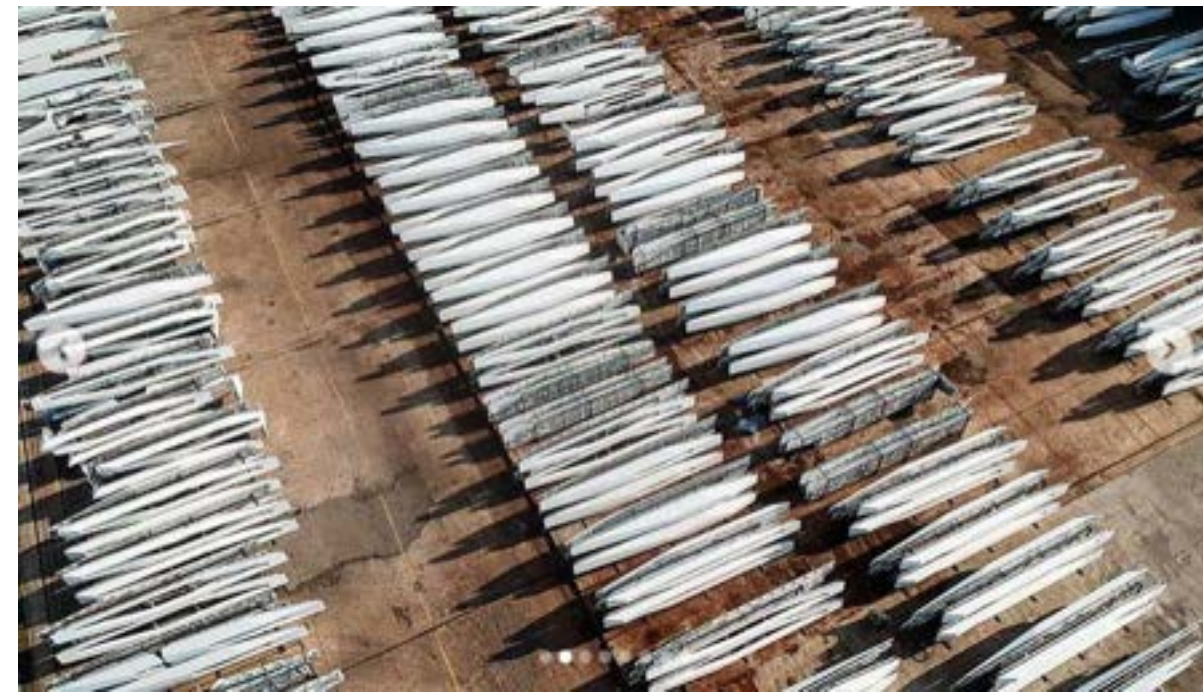
Glass Fibre Reinforced
Concrete

Prefabricated GFRC









Prefabrication of Ultra-High Performance Concrete

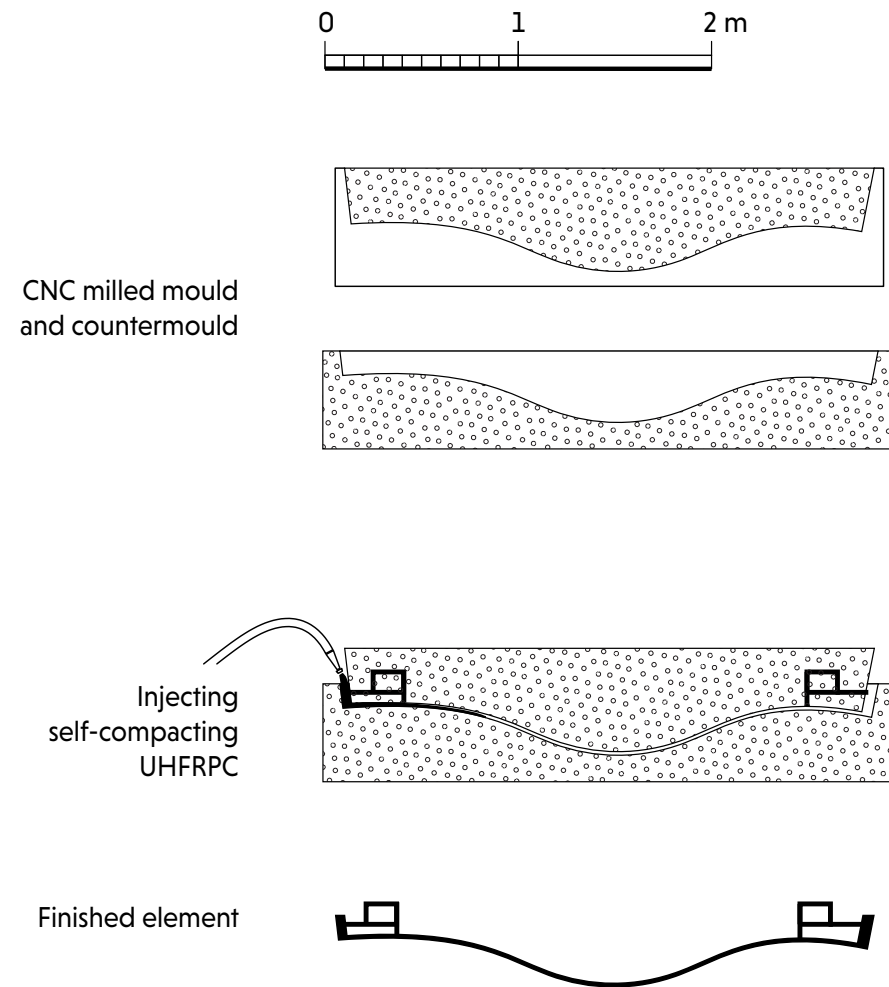


FIGURE 1.17 An illustration of the adhesion of high-performance concrete to an expanded polystyrene mould (Hi-Con, 2017) (Source: Hi-Con A/S).



Ultra-High Performance Fibre Reinforced Concrete



3. Emerging Methods of Digital Concrete Fabrication



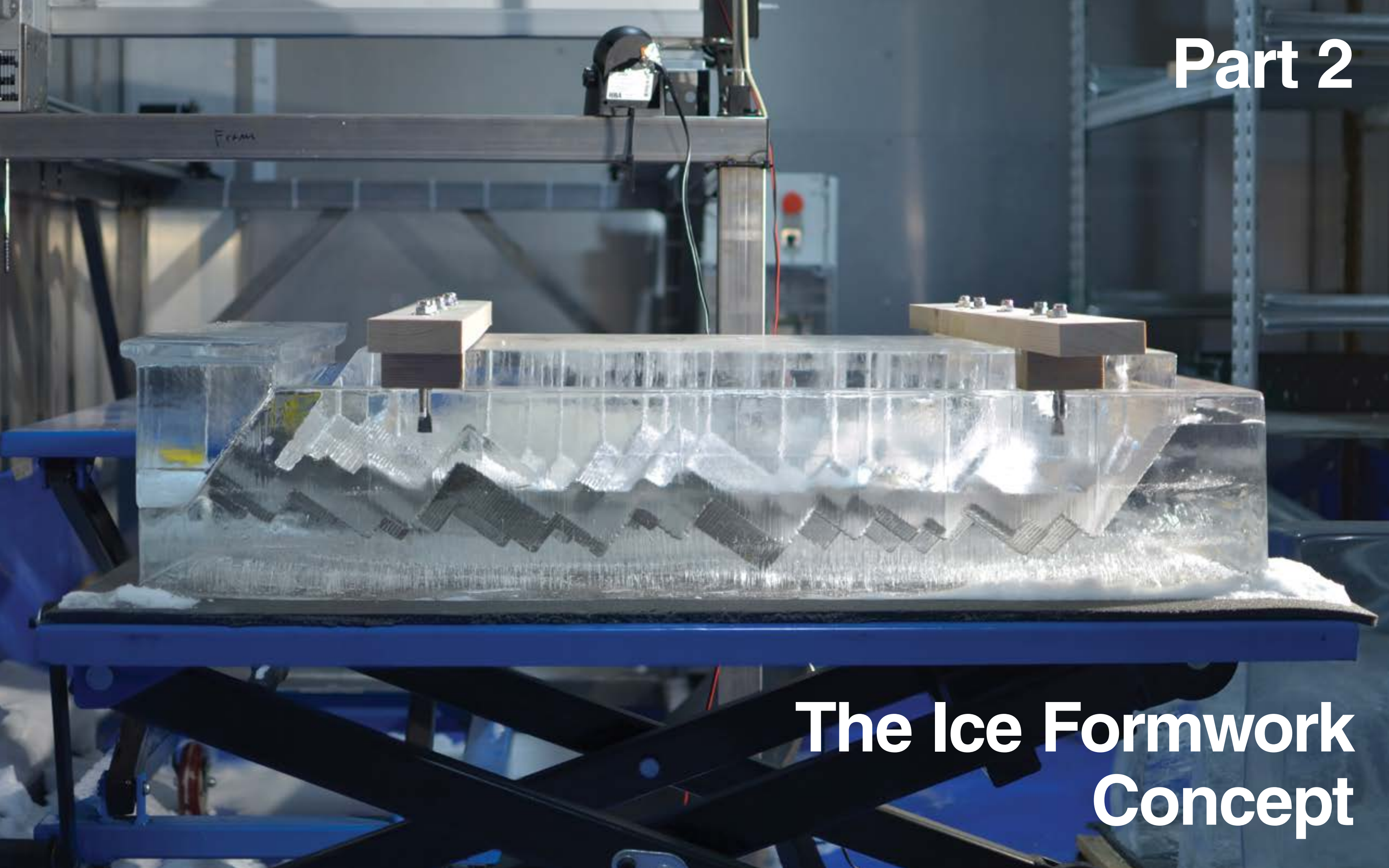
FIGURE 1.19 TailorCrete project, a zero-waste wax formwork for concrete (Source: ROK Rippmann Oesterle Knauss GmbH).



FIGURE 1.18 A concrete prototype cast in water-soluble 3D-printed PVA formwork (Source: Digital Building Technologies, ETHZ. Photo: Matthias Leschok).



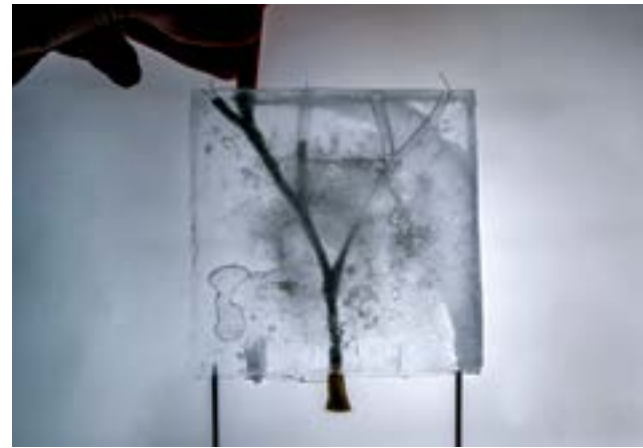
Part 2



The Ice Formwork
Concept

Methodology of Experimental Programme

Phase 0 - Thought Experiment



Phase 1 - Material Testing



Phase 2 - Design Probes and Production Prototyping



Phase 3 - Ecological Evaluation



Appendix 1
Appendix 2



Appendix 3
Appendix 4
Appendix 5



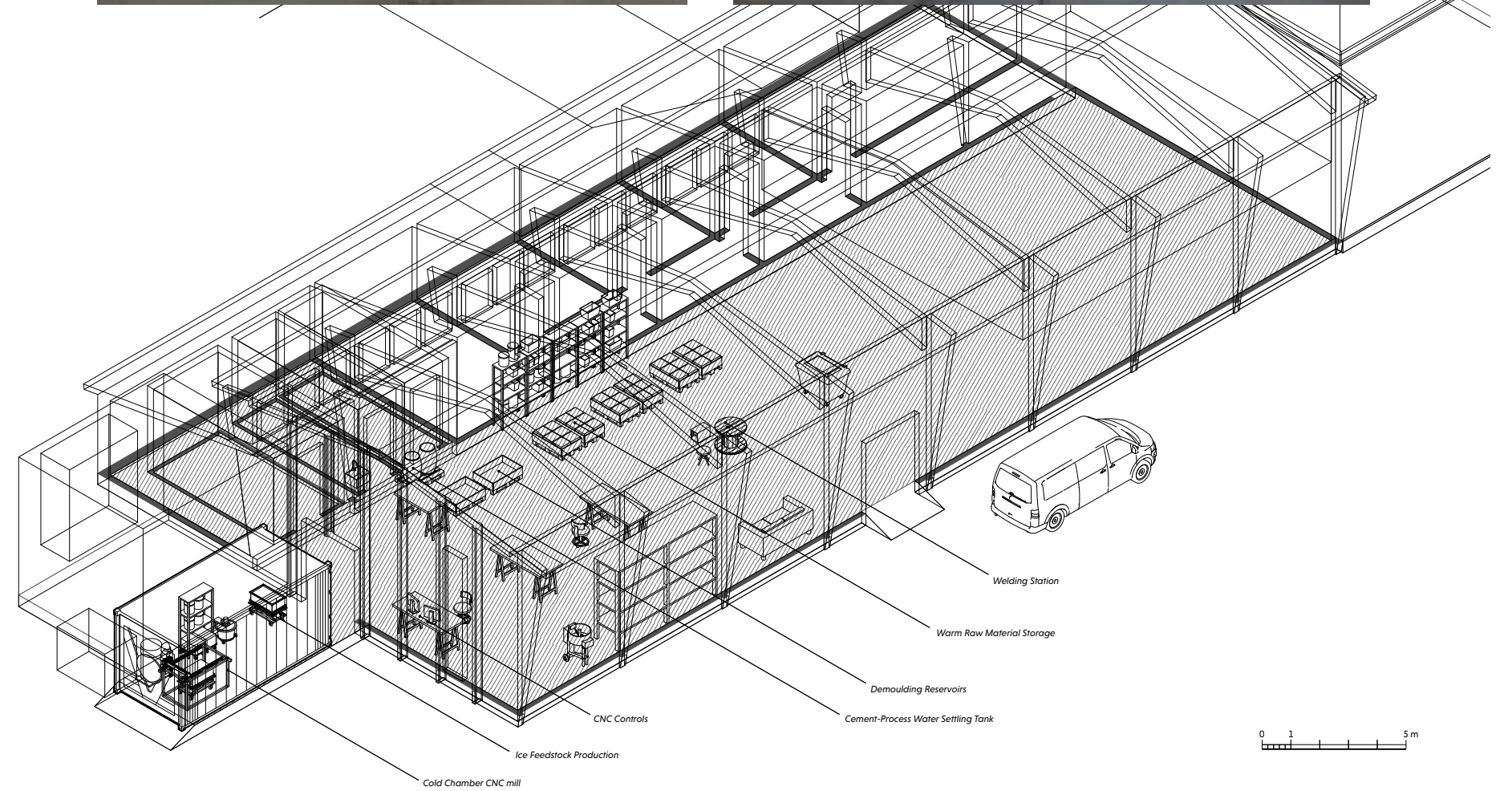
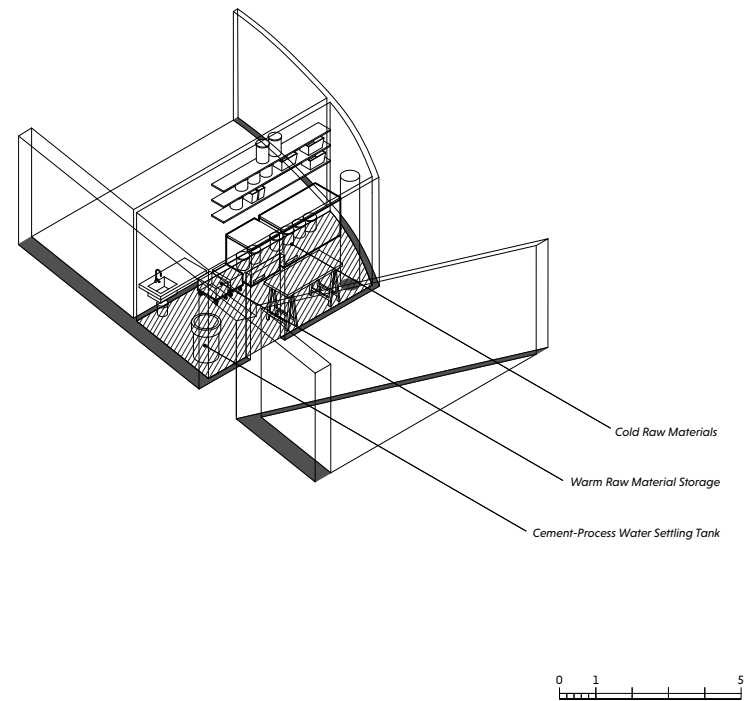
Appendix 6



Experimntal Rig 1



Experimntal Rig 3



Phase 2.1

Ice manual processing

Experimental Rig 1

Area: 12 m²

Cold volume: 1.5 m³

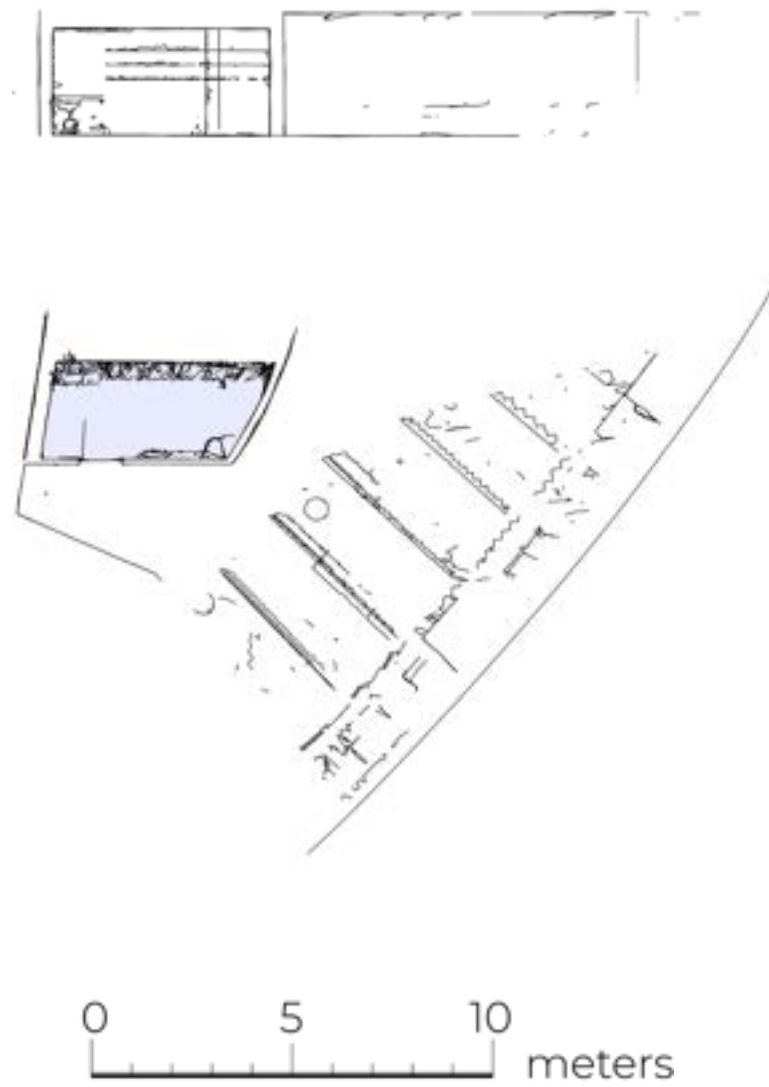






FIGURE 2.28 Ice mould for the concrete panel 170721-ME-MUR1 produced via thermal melting (see Film 2) (Source: author).



FIGURE 2.35 A scale reference for 180611-ME-JULx (Source: author).
FIGURE 2.36 180611-ME-JULx during demoulding (Source: author).

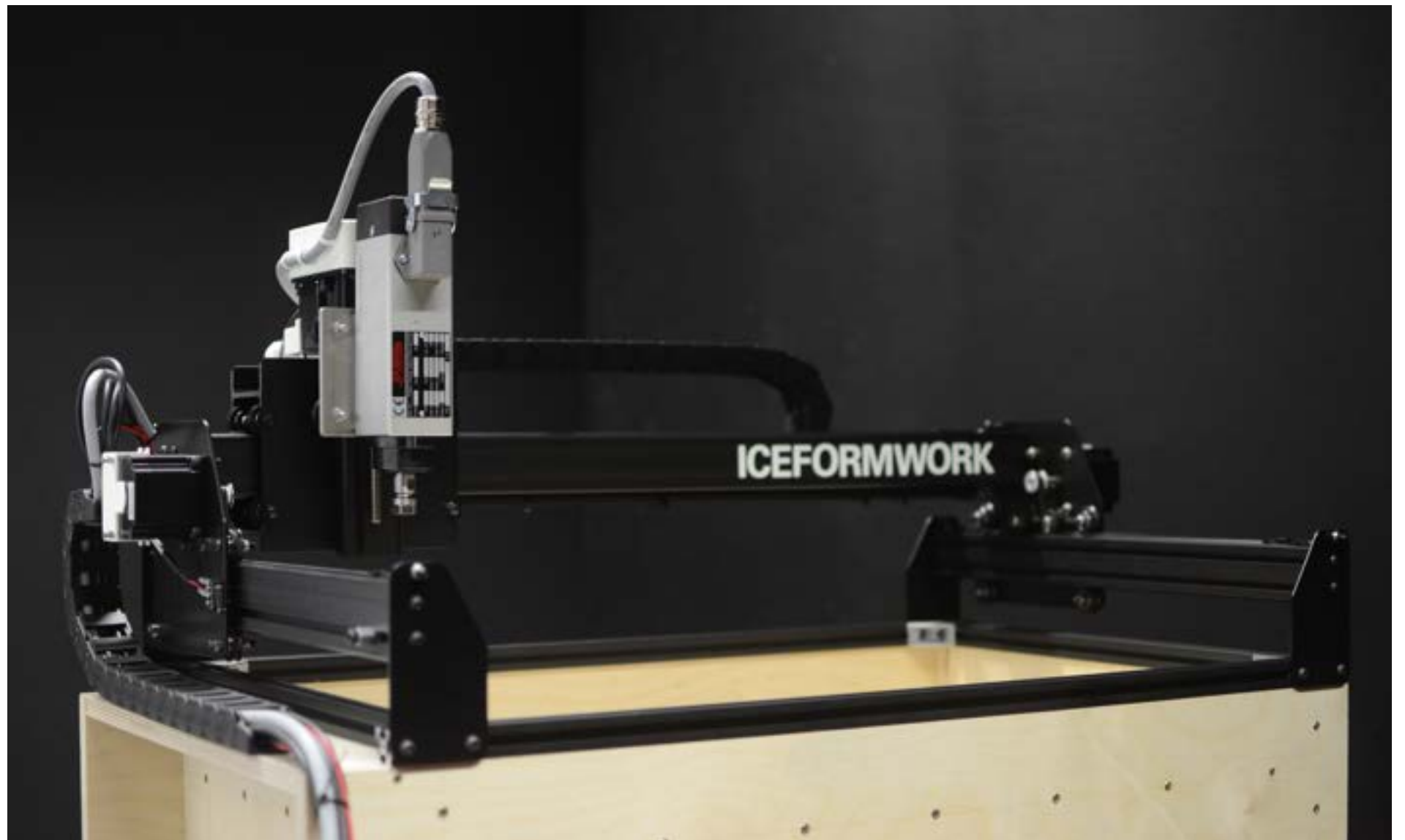
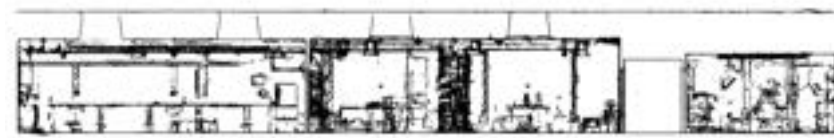
Phase 2.2

Ice manual processing

Experimental Rig 2

Area: 100 m²

Cold volume: 3.3 m³





End mill

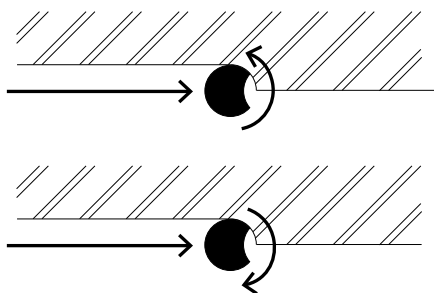
Single Flute Straight Flat End
Cutting diameter: 1/4 in
Cutting length: 1 in
...

Machine settings

Speed: 9'000..15'000 rpm
Feed: 2000 mm/min
...



Tool rotation vs feed side:



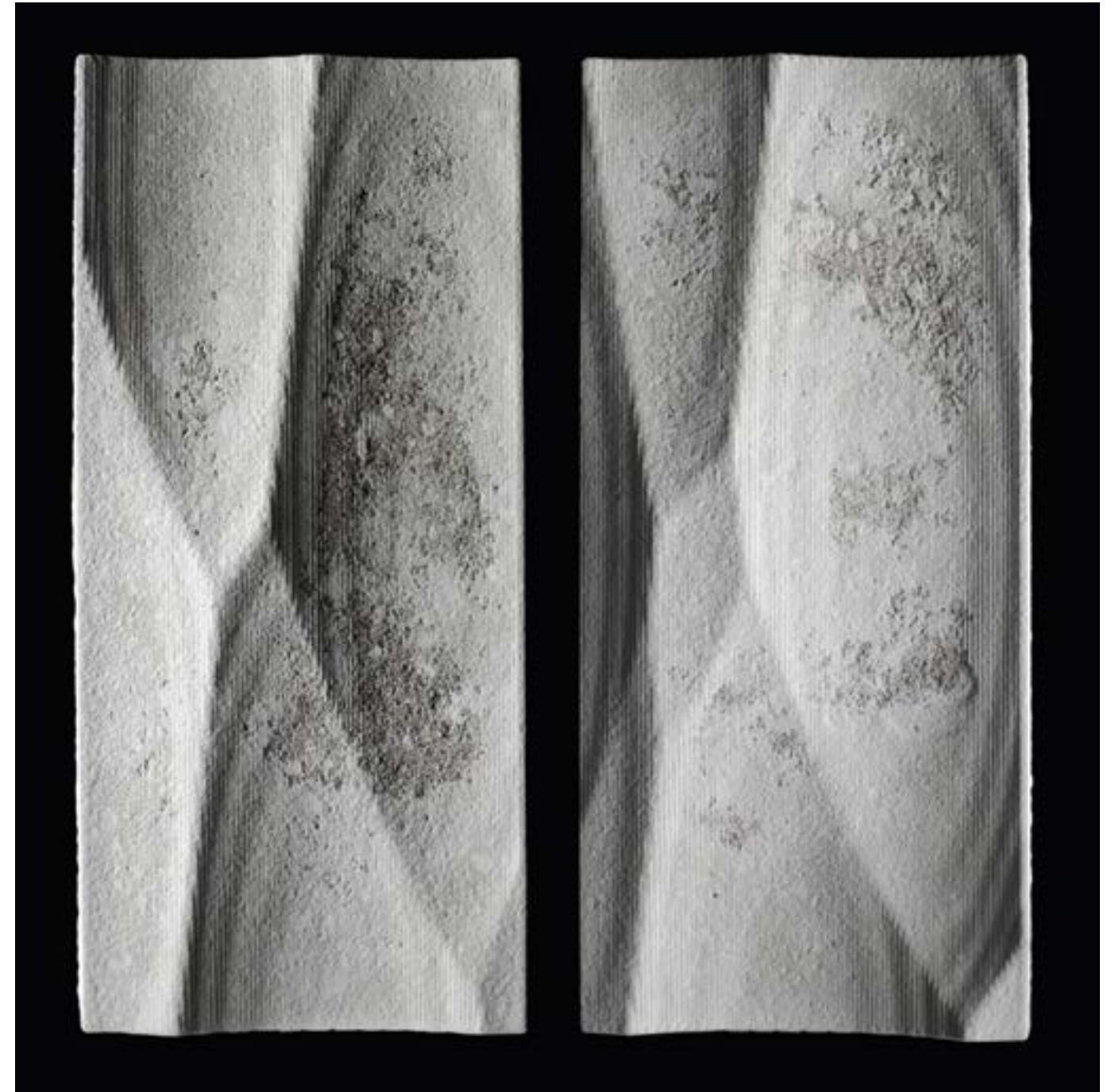


FIGURE 2.39 The tile series 180423-DP-TILx cast in fine processed ice moulds (Source: author).

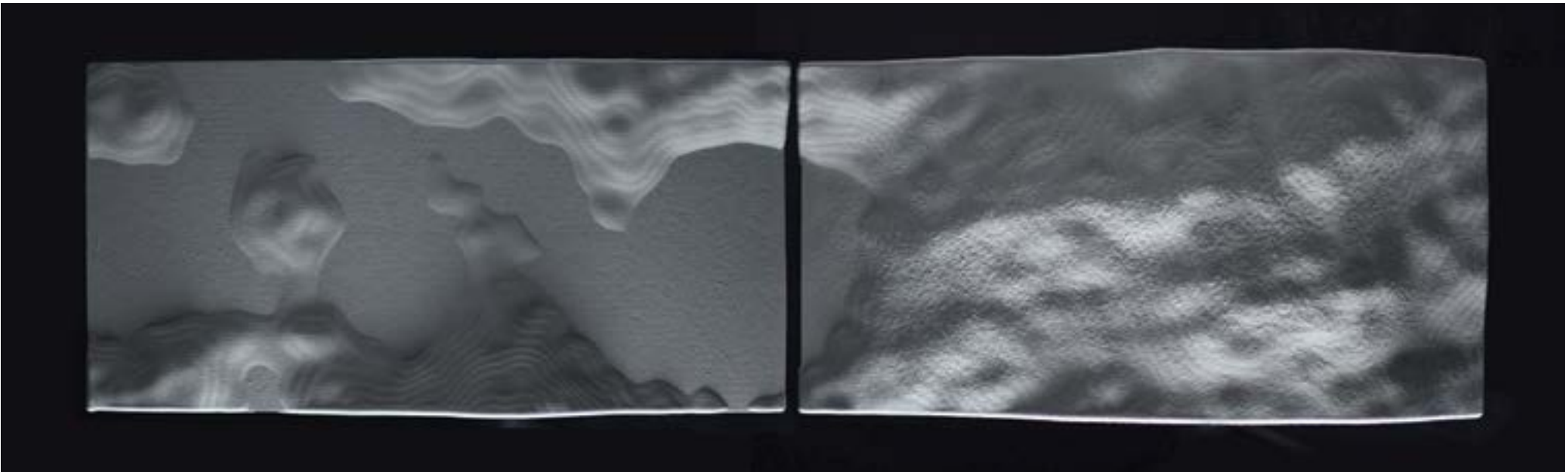


FIGURE 2.43 The front and top view of the prototype 180622-DP-TER1 produced using fine CNC-processing (Source: author).

FIGURE 2.44 The prototype 180622-DP-TER1 during the demoulding process (Source: author).

FIGURE 2.45 The surface quality detail of the prototype 180622-DP-TER1 (Source: author).

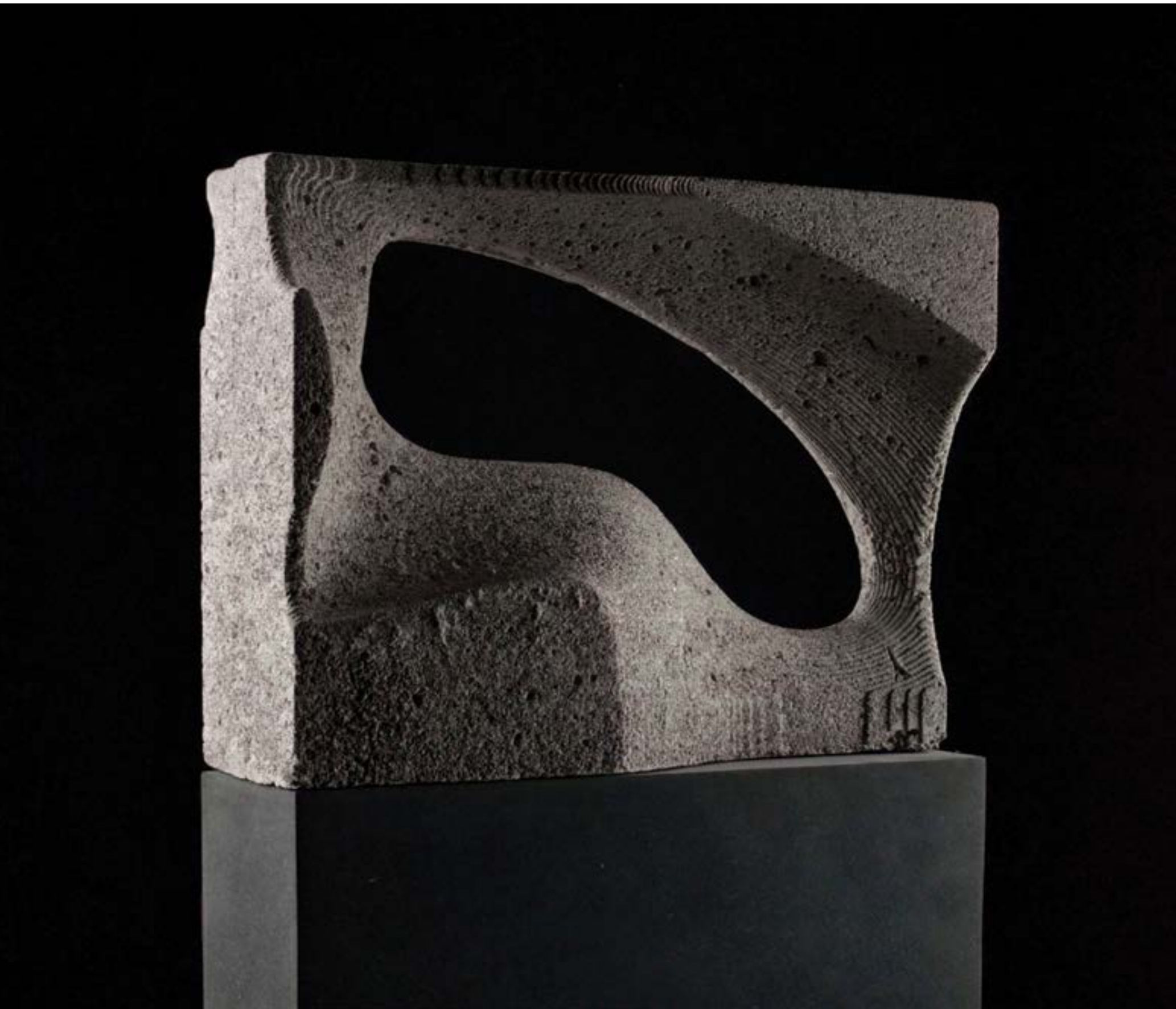


FIGURE 2.40 The prototype 180805-DP-APE1 made using a two-party ice mould assembly (Source: author).

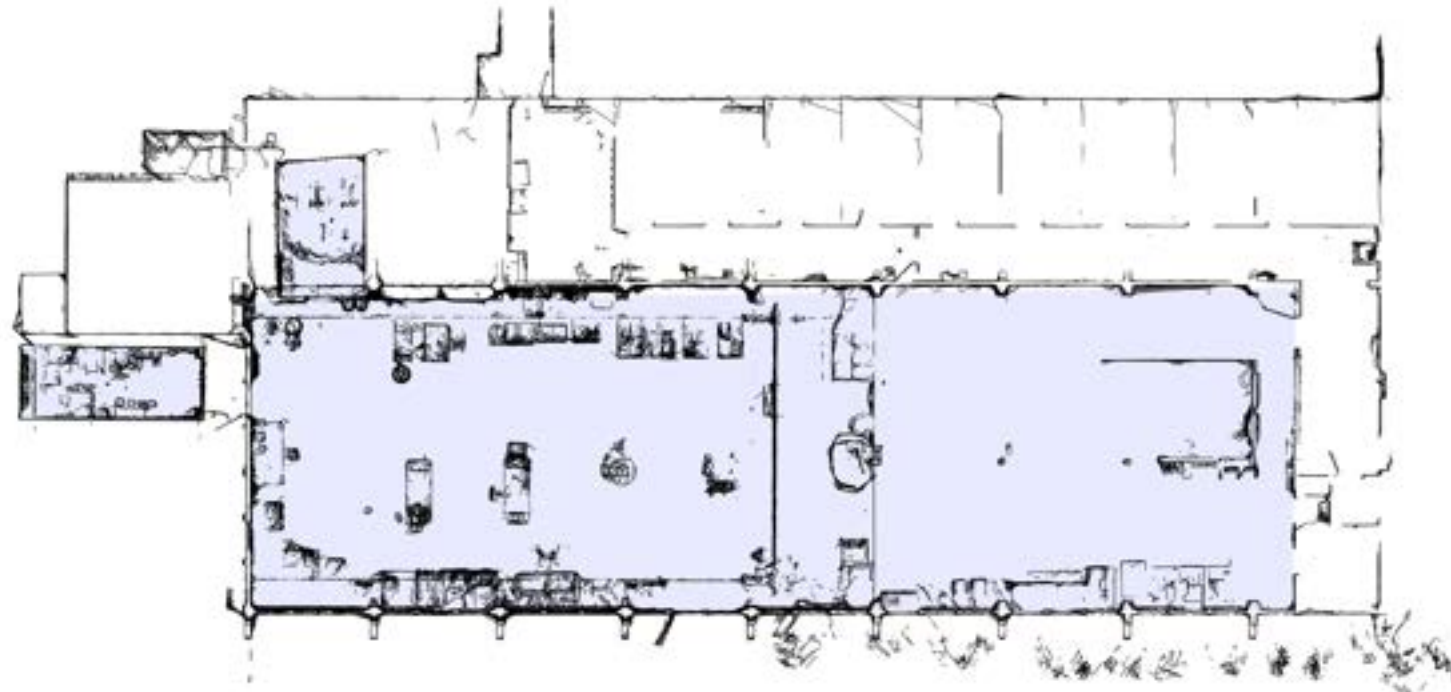
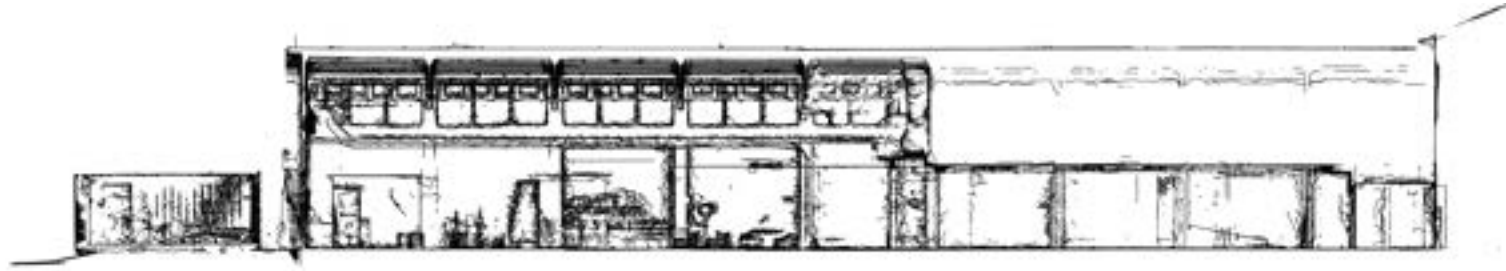
Phase 2.3

Ice manual processing

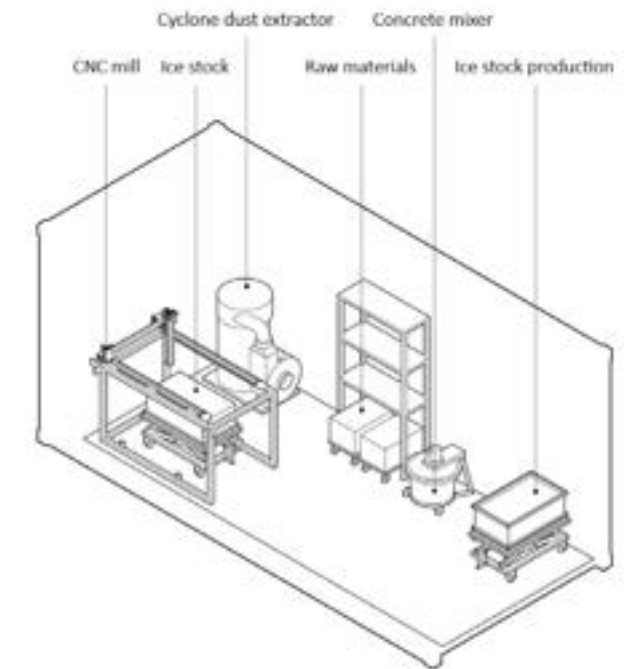
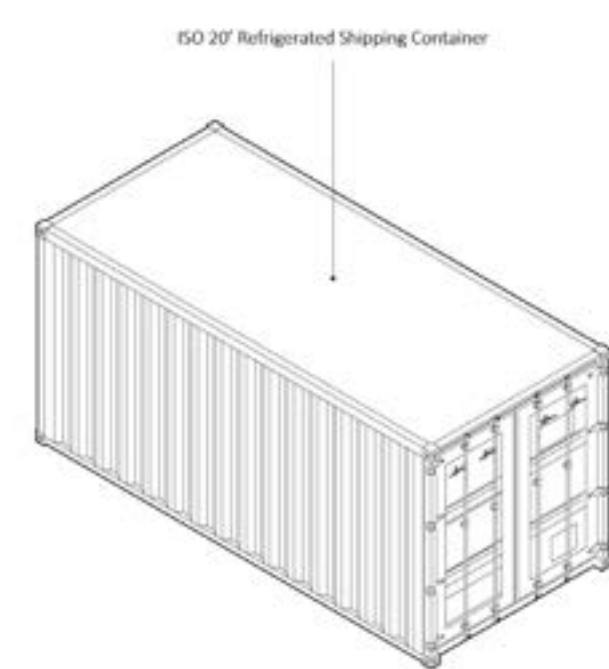
Experimental Rig 3

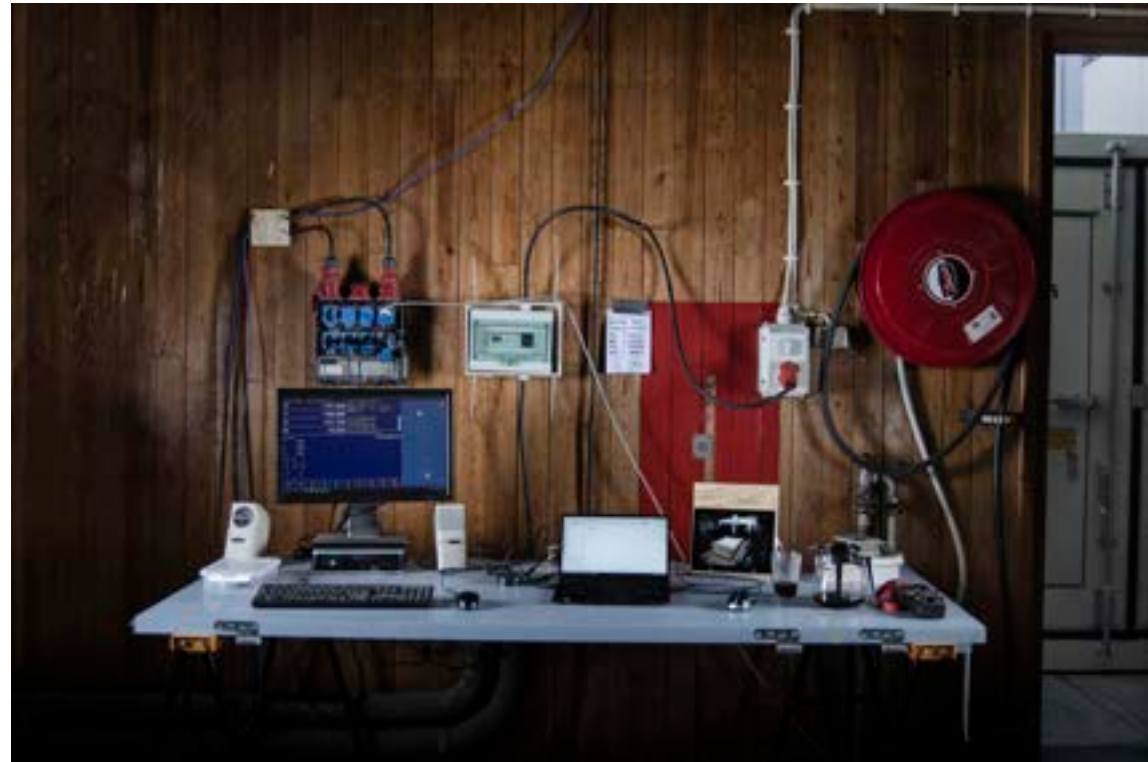
Area: 389 m²

Cold volume: 54 m³



0 5 10 meters





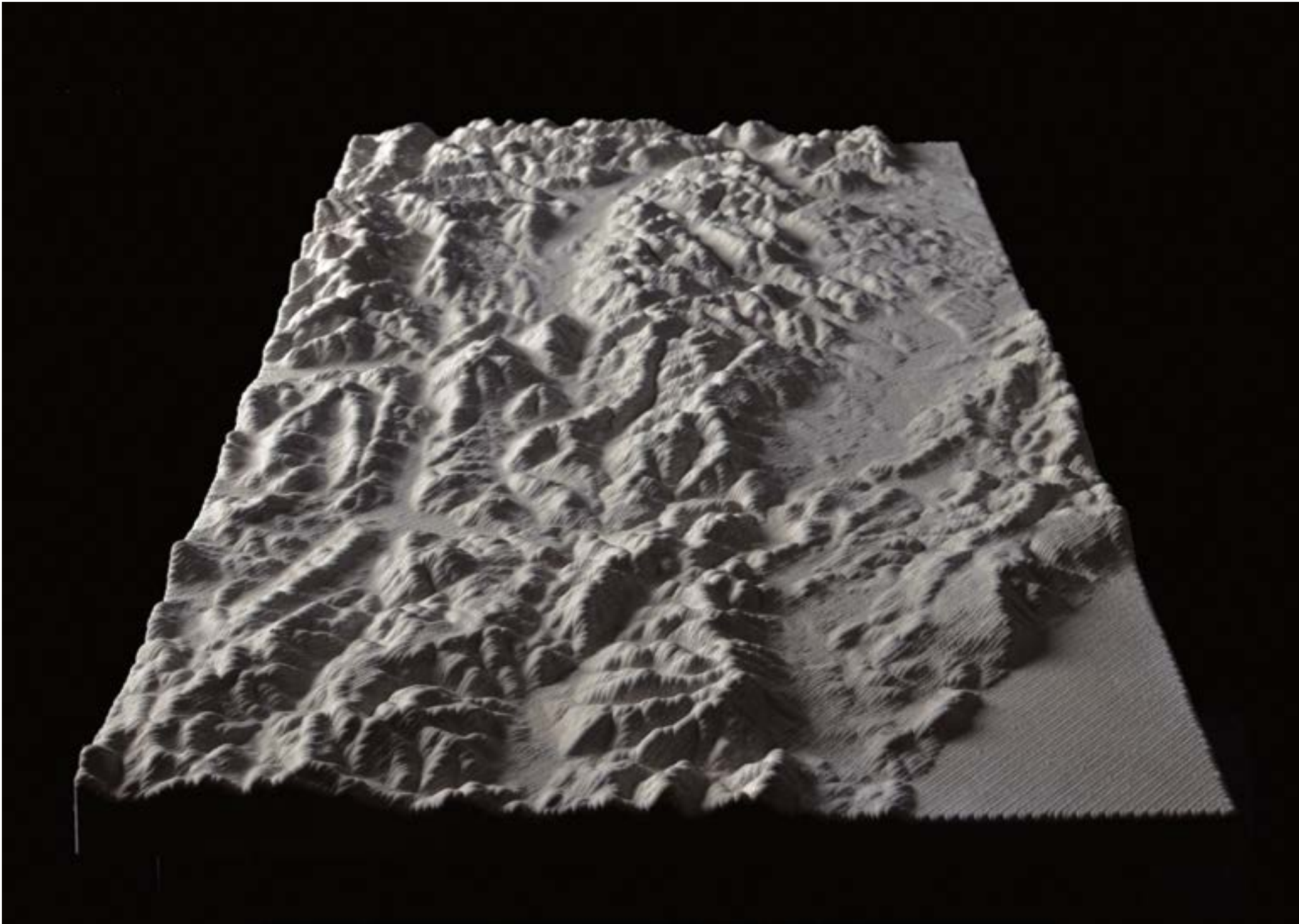


FIGURE 2.48 The 191116-DP-TER2 prototype (Source: author).











0 1 5 10 cm



0 1 5 10 cm



0 1 5 10 cm





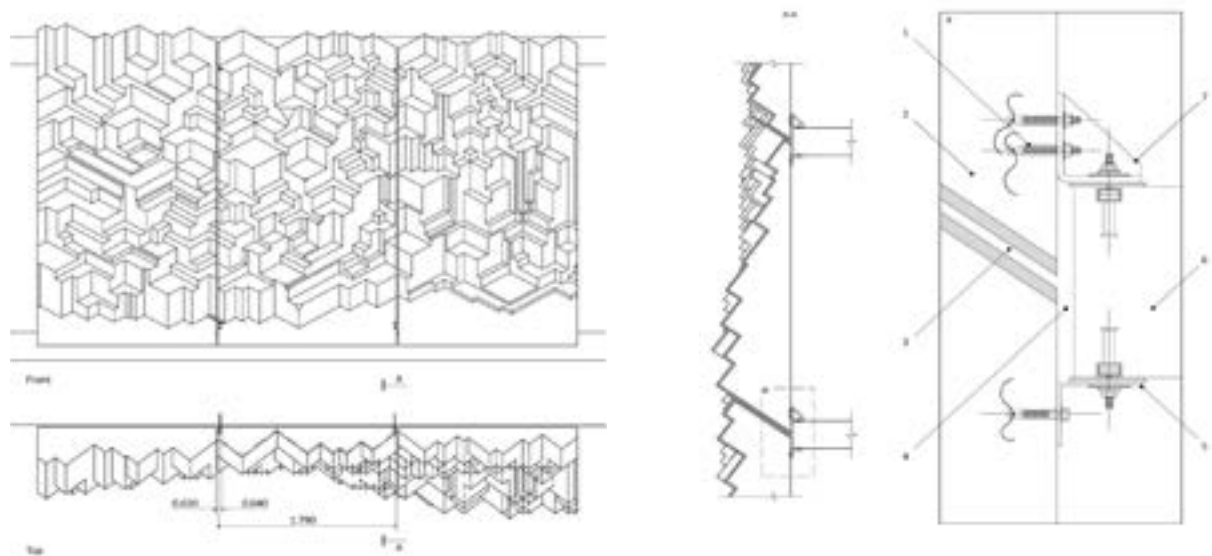
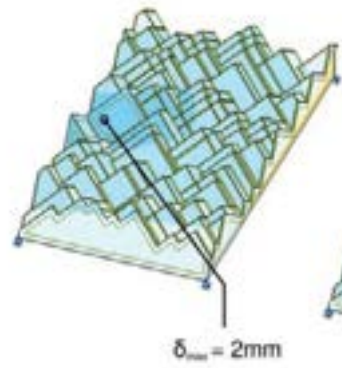


FIGURE 2.55 The fixing detail and the back side of the 190912-DP-FAC2 prototype (Source: author).

FIGURE 2.56 The ice mould assembly of the 190912-DP-FAC2 prototype (Source: author).

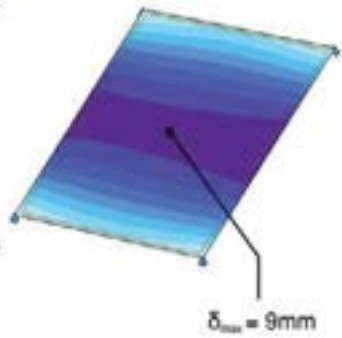
A) 20mm thk UHPFRC crystalline profile with ribs:



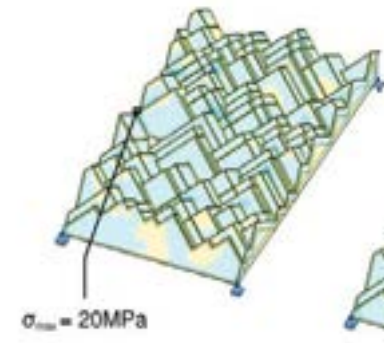
B) 40mm thk UHPFRC crystalline profile - no stiffening ribs:



C) 40mm thk UHPFRC flat profile:



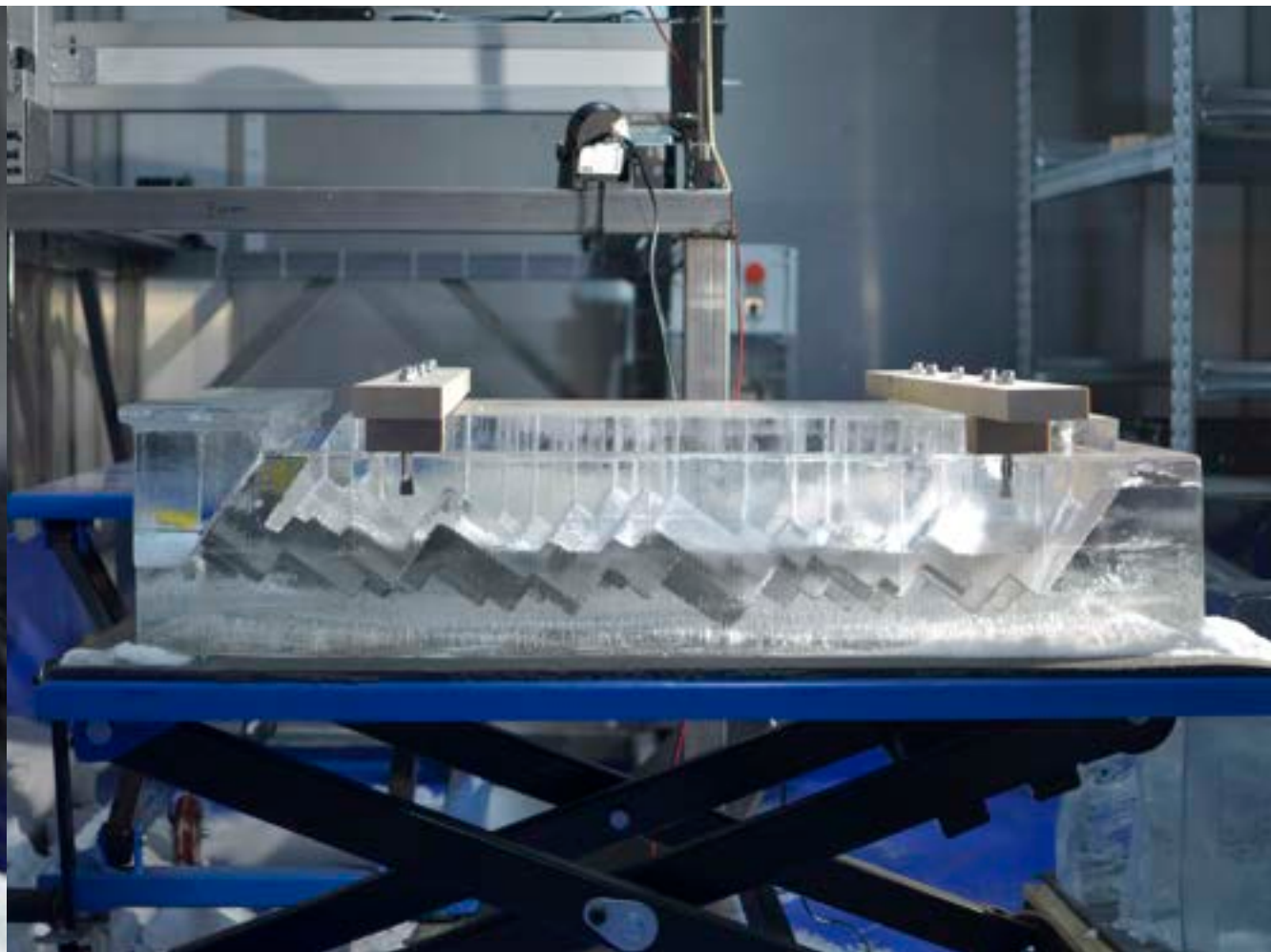
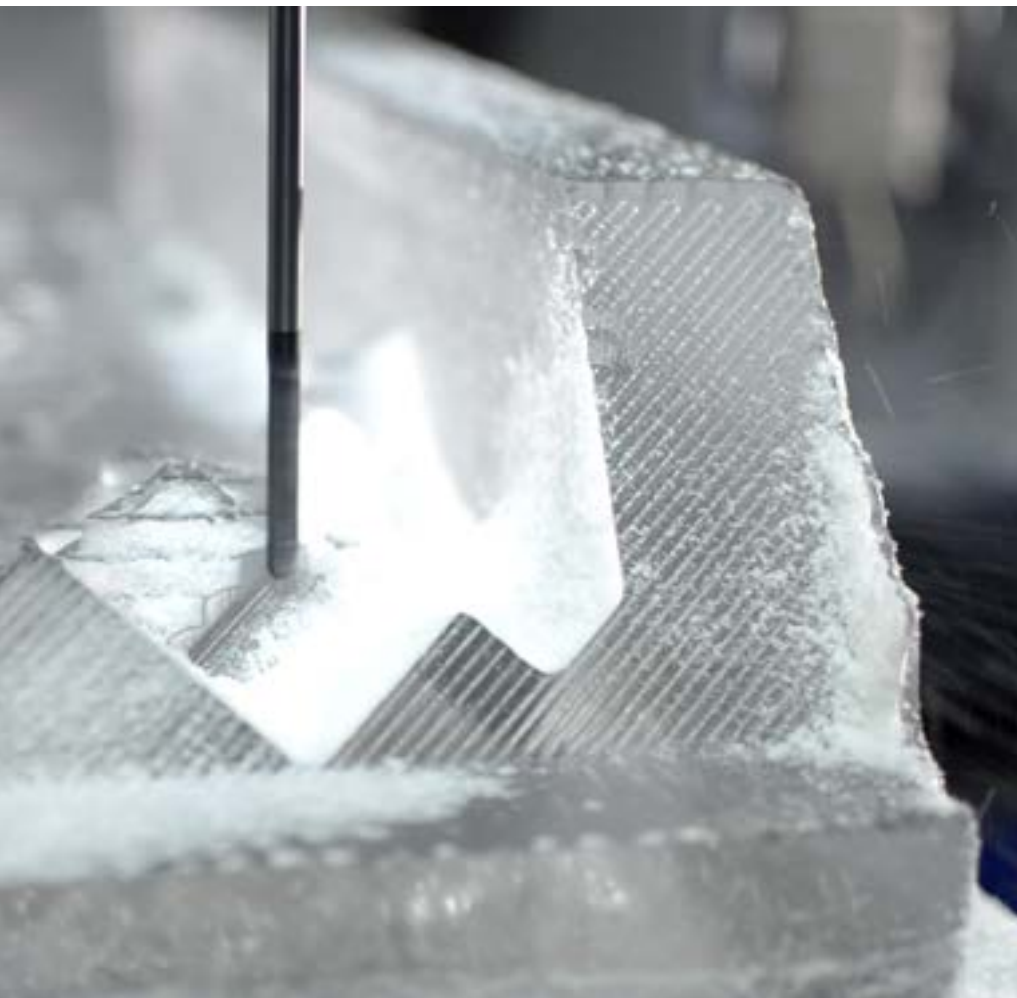
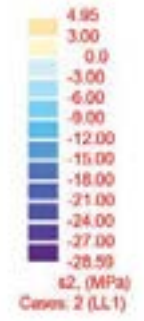
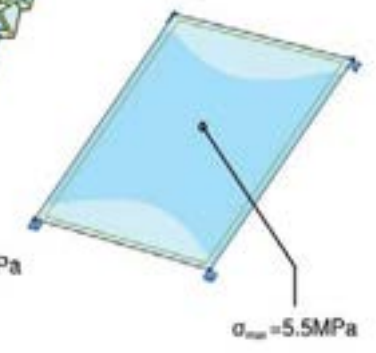
A) 20mm thk UHPFRC crystalline profile with ribs:



B) 40mm thk UHPFRC crystalline profile - no stiffening ribs:



C) 40mm thk UHPFRC flat profile:



The Ice Formwork system is a digital fabrication method proposed, studied and tested in the course of this doctoral research. The method enables production of bespoke design geometry using artificially frozen water as the moulding material in lieu of the petrochemical or engineered wood products conventionally used for this purpose. Water replaces the conventional non-recyclable moulding materials and can be continuously reused, forming an optimal closed-loop material flow in the production process.

It has been identified that the Ice Formwork method can significantly reduce the embodied energy and carbon footprint of the derivative concrete products and allows reduced cement consumption as it is compatible with UHPC, and that it fully supports the production of complex and mass-optimized concrete structures. In addition, a unique practical advantage of Ice Formwork is the rapid and autonomous demoulding process facilitated by simple melting of the ice moulds. The method thus allows the robotic fabrication of design geometry that would be unfeasible with other production methods.



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