ICE FORM WORK

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

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Sitnikov, Vasily. *Ice Formwork: The Rationale and Potential of Ice-Based Moulding Systems for the Production of Complex-Geometry Precast Concrete*. TRITA-ABE-DLT 2039. Diss. sammanfattning, Stockholm: Kungliga Tekniska högskolan, 2020.

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Part 1

The Multifaceted Problem of Concrete Design and Production

1. Ecology of the Concrete Industry

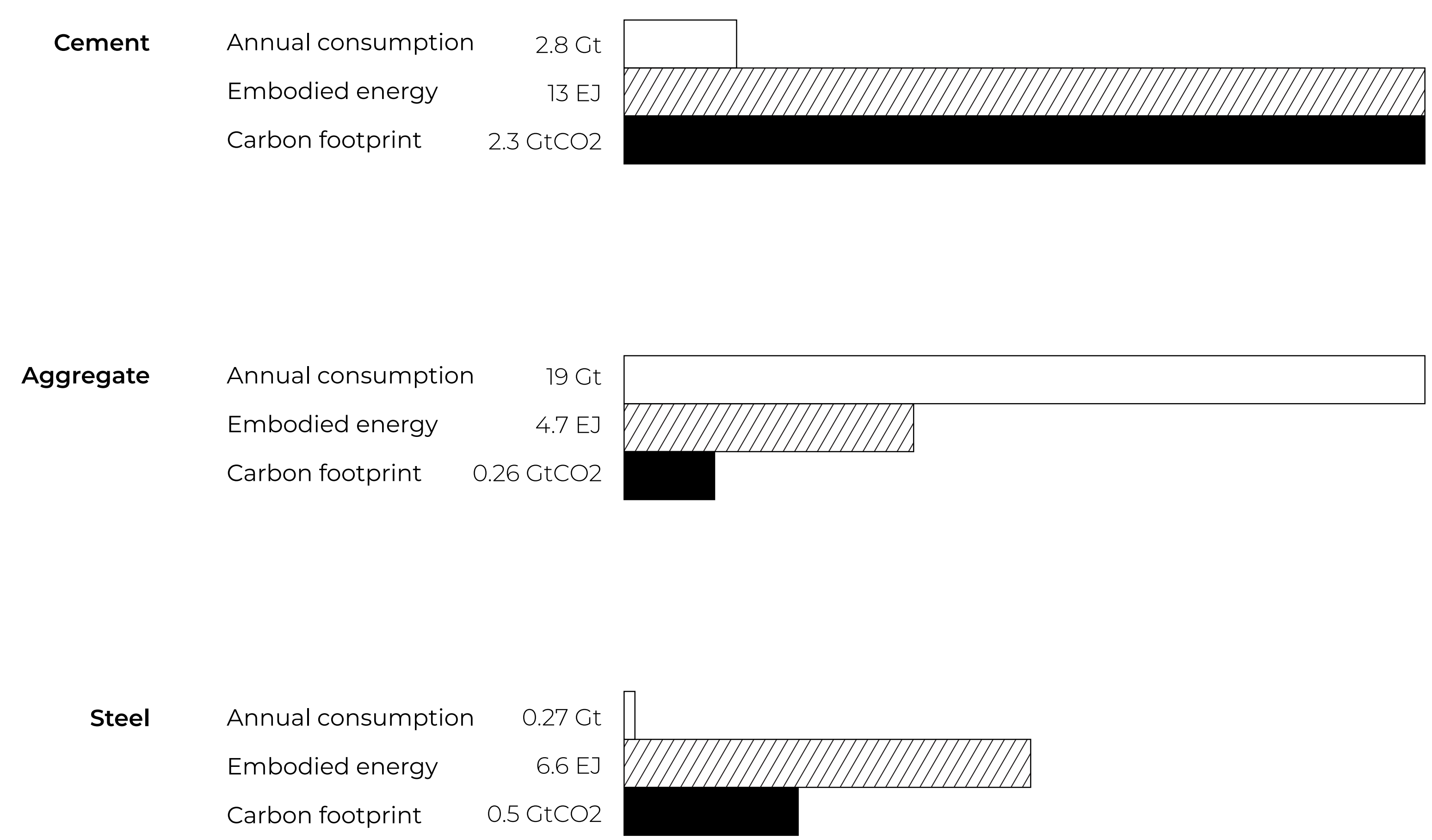


FIGURE 1.2 Comparative charts of the global consumption rates and the environmental impact of the main concrete constituent materials. (Sources: Allwood and Cullen 2012; Hamond and Jones 2011; graphical representation: author).

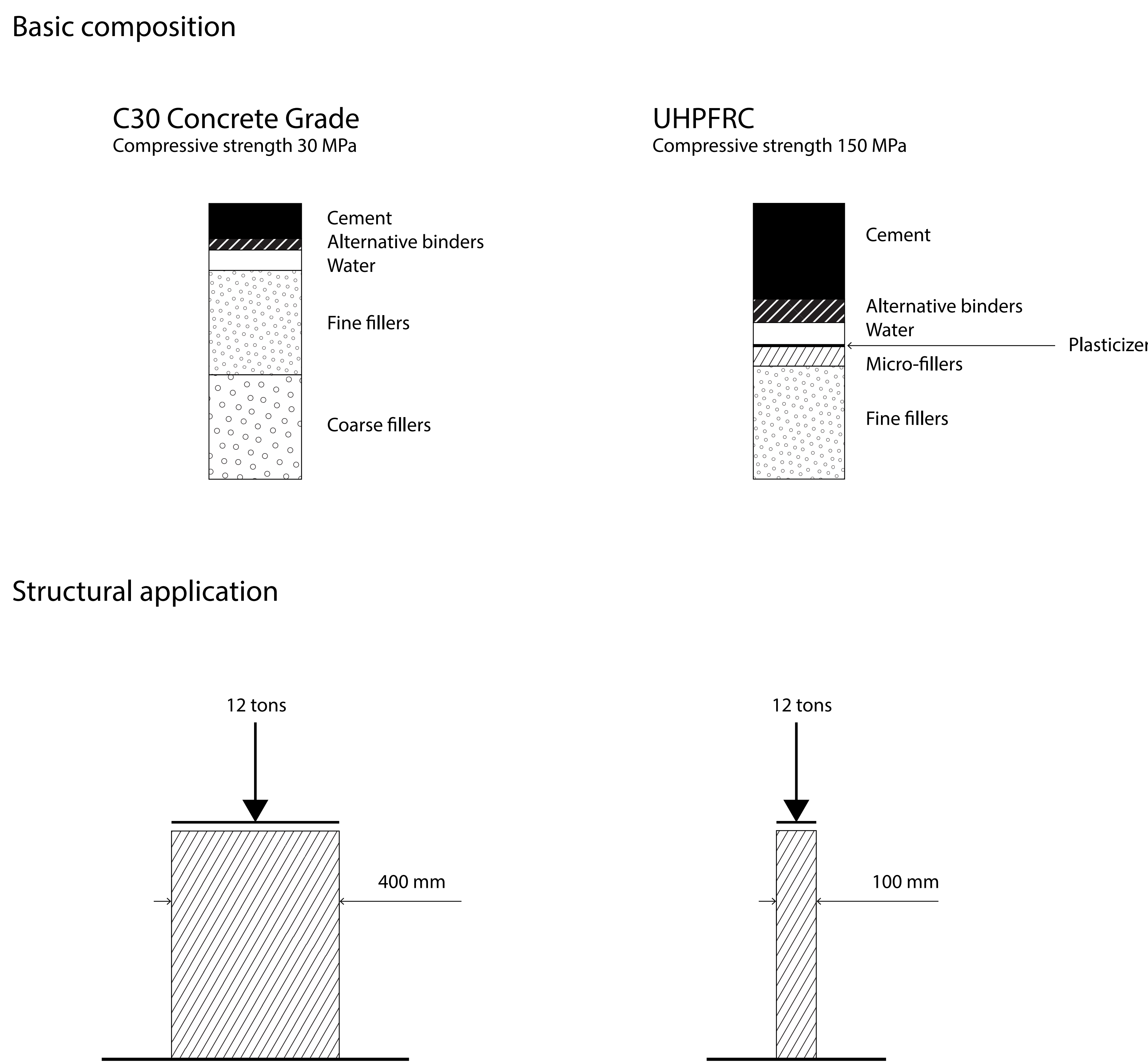
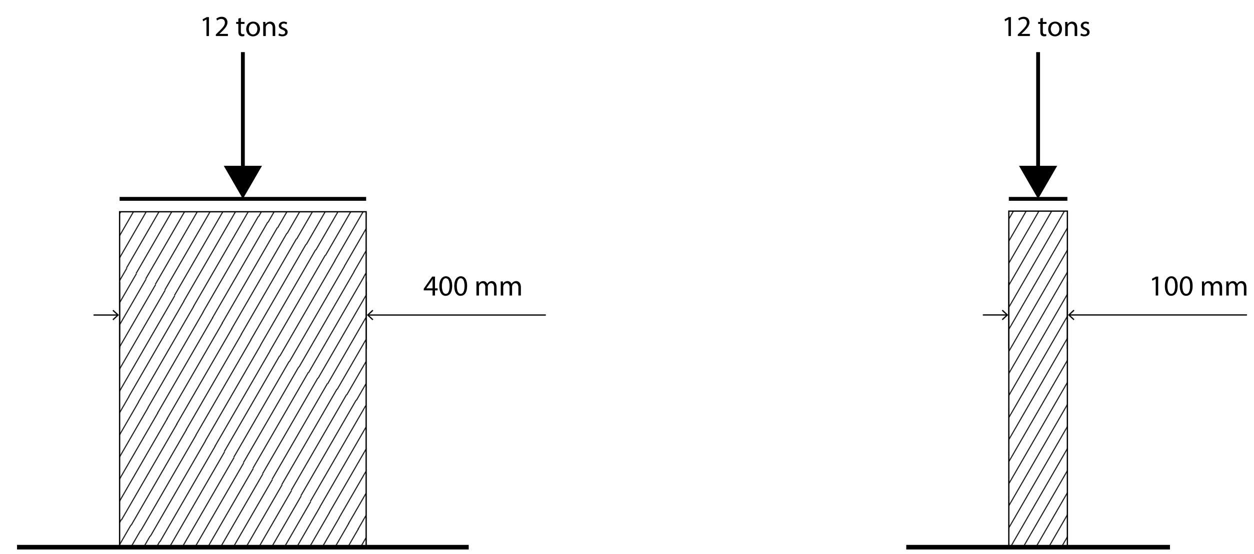


FIGURE 1.3 Comparison of cement and aggregate consumption in a structural application of C30 concrete and UHPC. The column profiles shown on the left are designed to carry an axial load of 3000 kg. Buckling deformations have been omitted (Sources: Stengel 2014; Voort 2008; Graphical representation: author).

Structural application



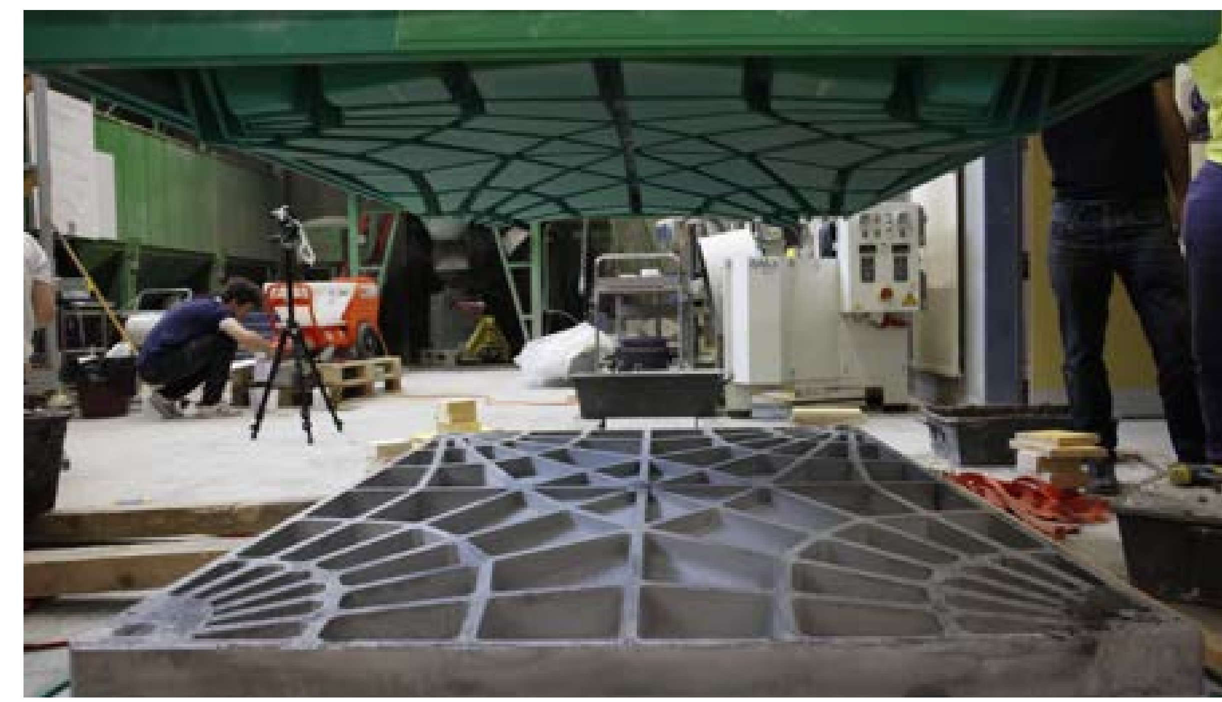
Actual material consumption at a structural case

		Embodied energy	Carbon footprint
Cement		280 MJ	52 kgCO2
Fine fillers		8 MJ	0.8 kgCO2
Coarse fillers		52 MJ	3.2 kgCO2
Total	320 kg/m	340 MJ	56 kgCO2

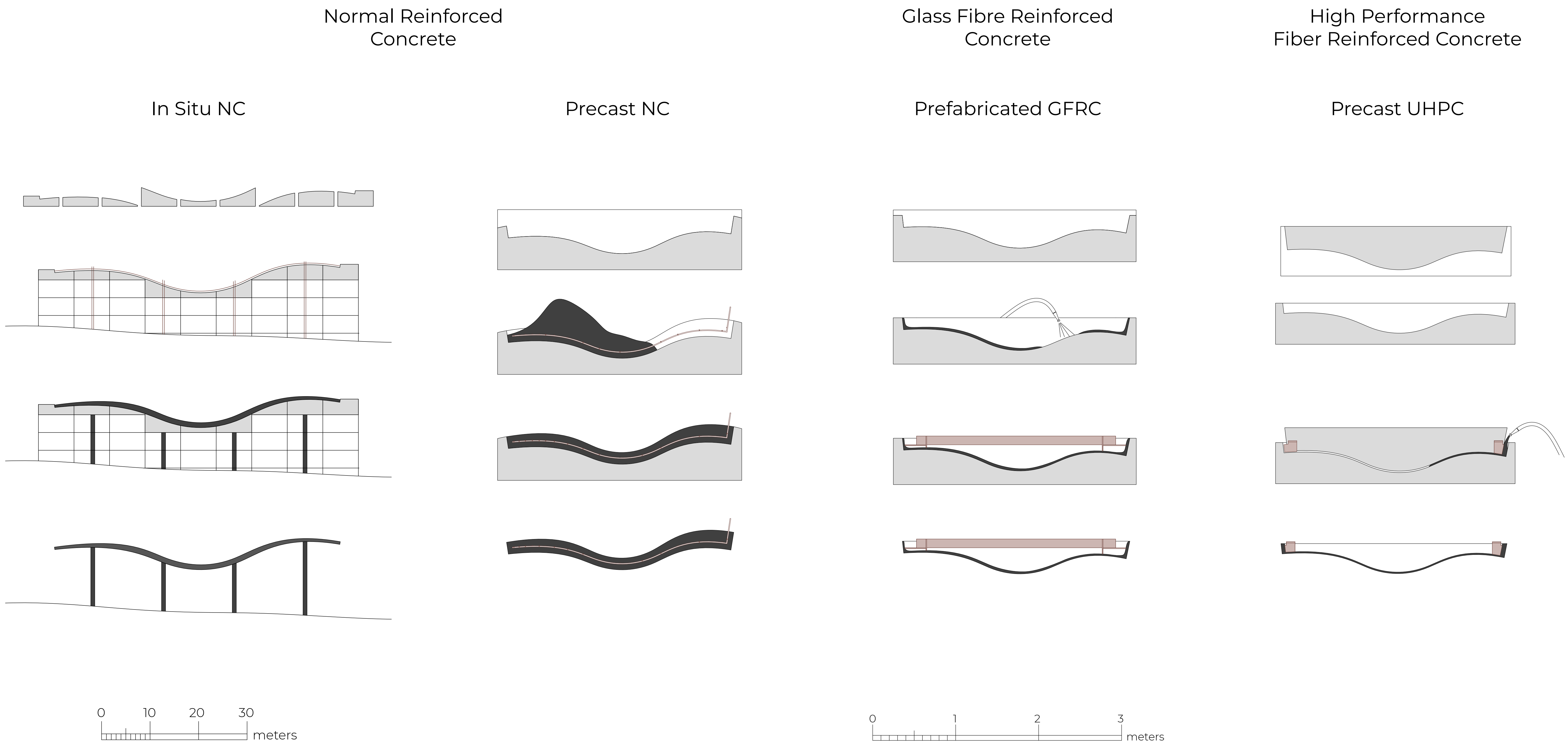
		Embodied energy	Carbon footprint
Cement		104 MJ	20 kgCO2
Fine fillers		4 MJ	0.4 kgCO2
Total	72 kg/m	108 MJ	20.4 kgCO2

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

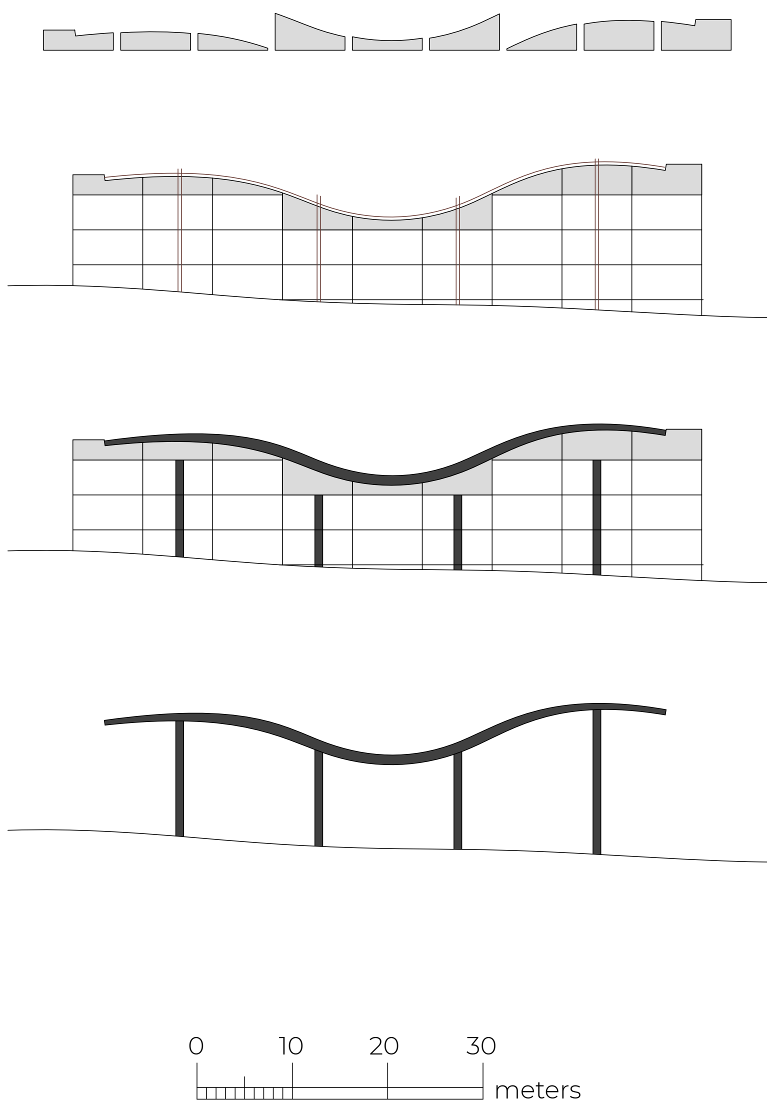


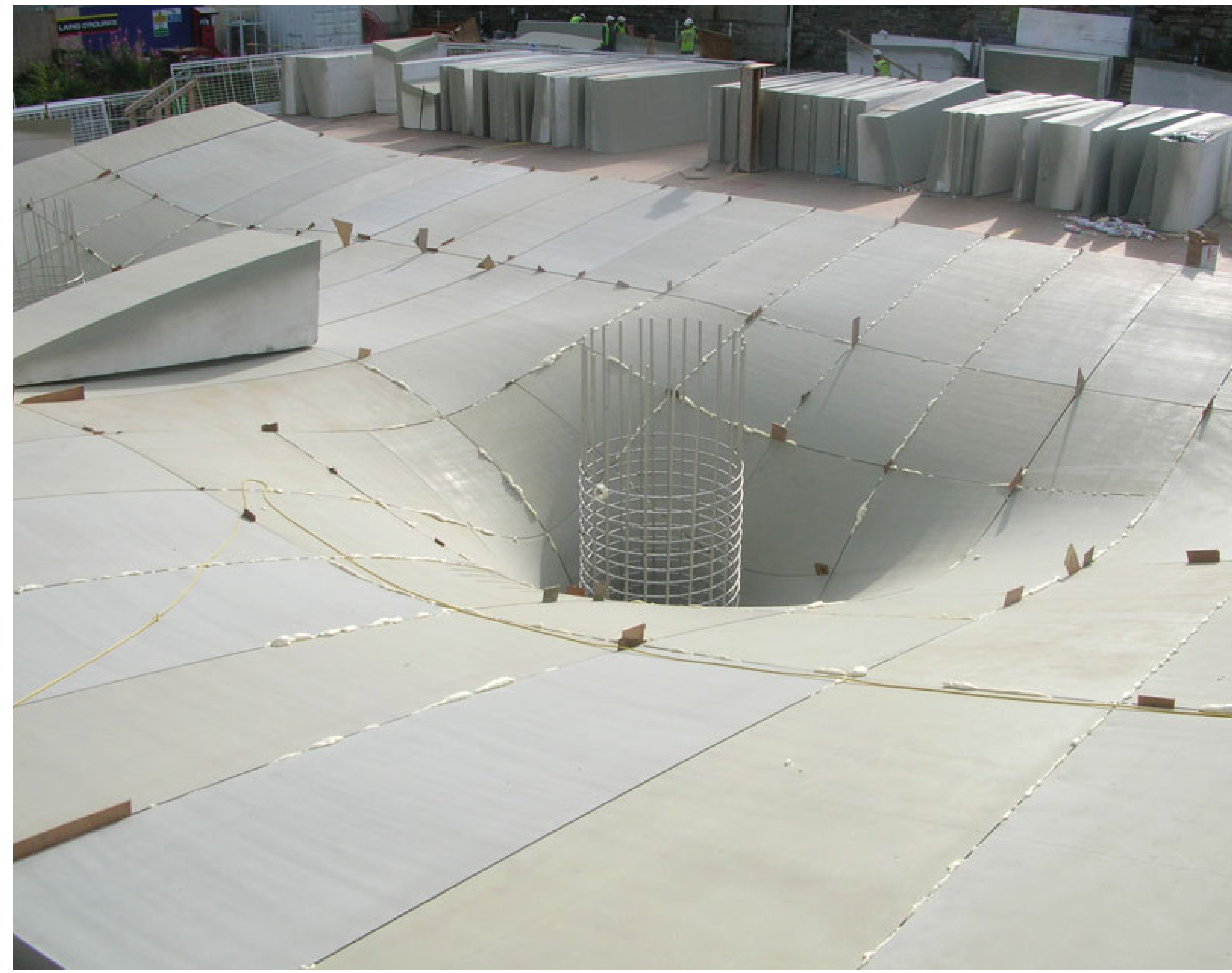
2. Retooling in the Concrete Industry



Normal Reinforced Concrete
Glass Fibre Reinforced Concrete
High Performance Fiber Reinforced Concrete
In Situ NC
Precast NC
Prefabricated GFRC
Precast UHPC
0 10 20 30 meters
0 1 2 3 meters

In-Situ Cast Normal Strength Concrete





Project: Spencer Dock Bridge by AL_A (Future Systems)
Source: nedcam.com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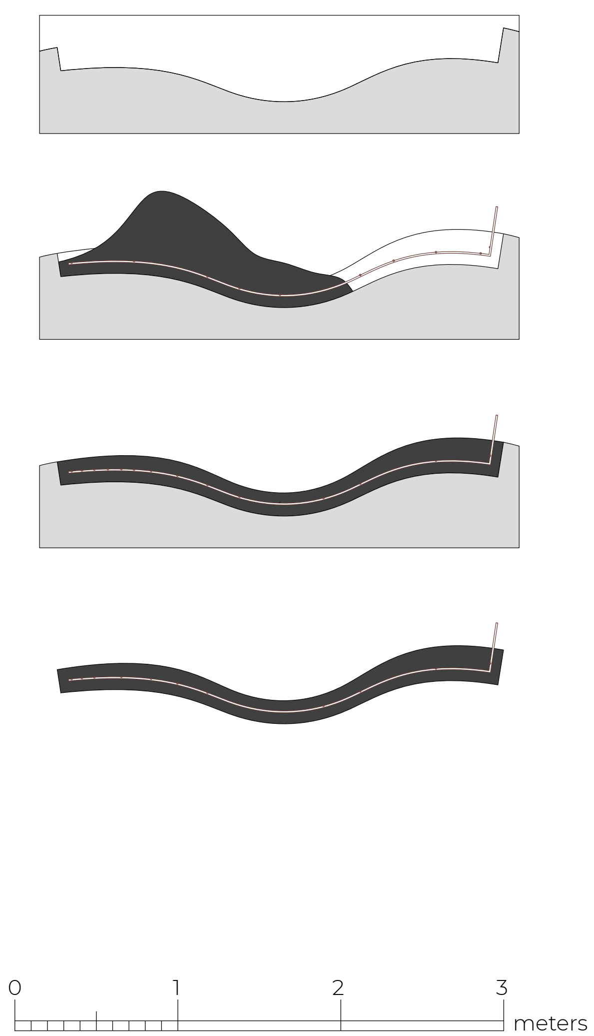
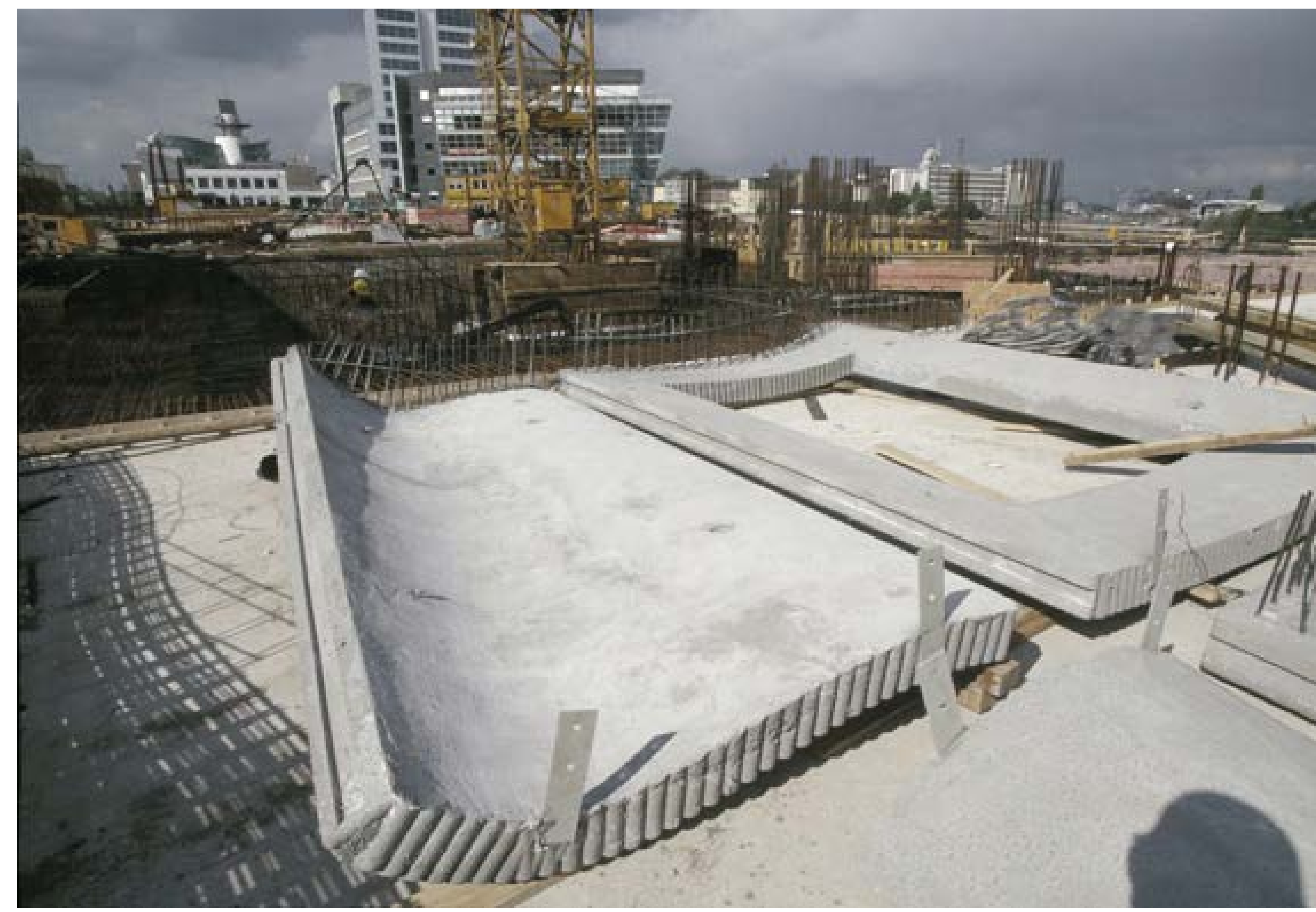
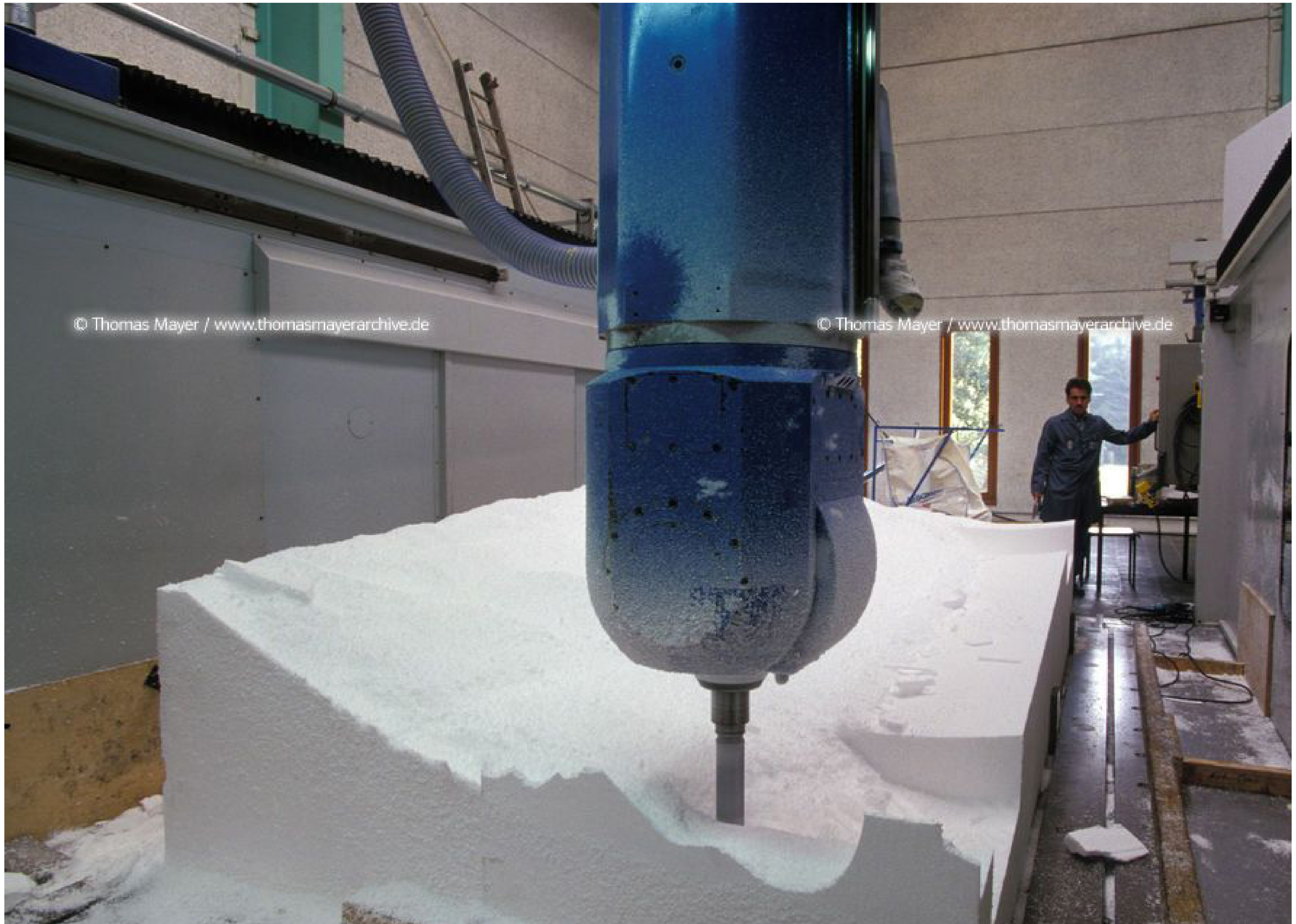
Precast Normal Strength Concrete







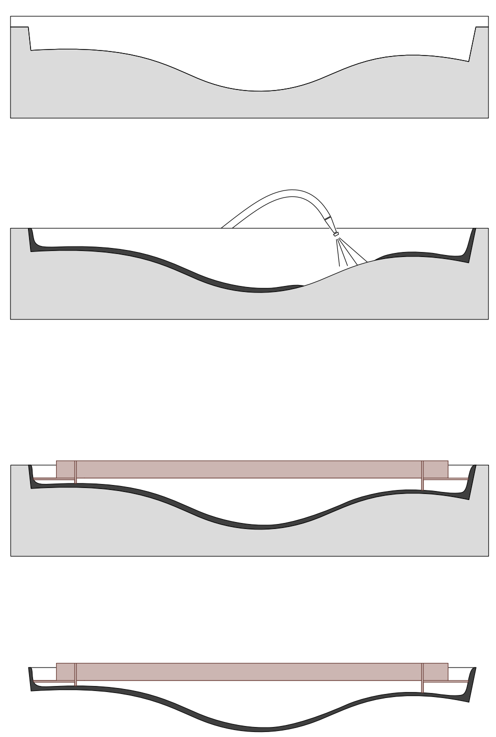
Project: Neuer Zollhoff by Frank Gehry
Source: Thomas Mayer

Project: Neuer Zollhoff by Frank Gehry
Source: Thomas Mayer

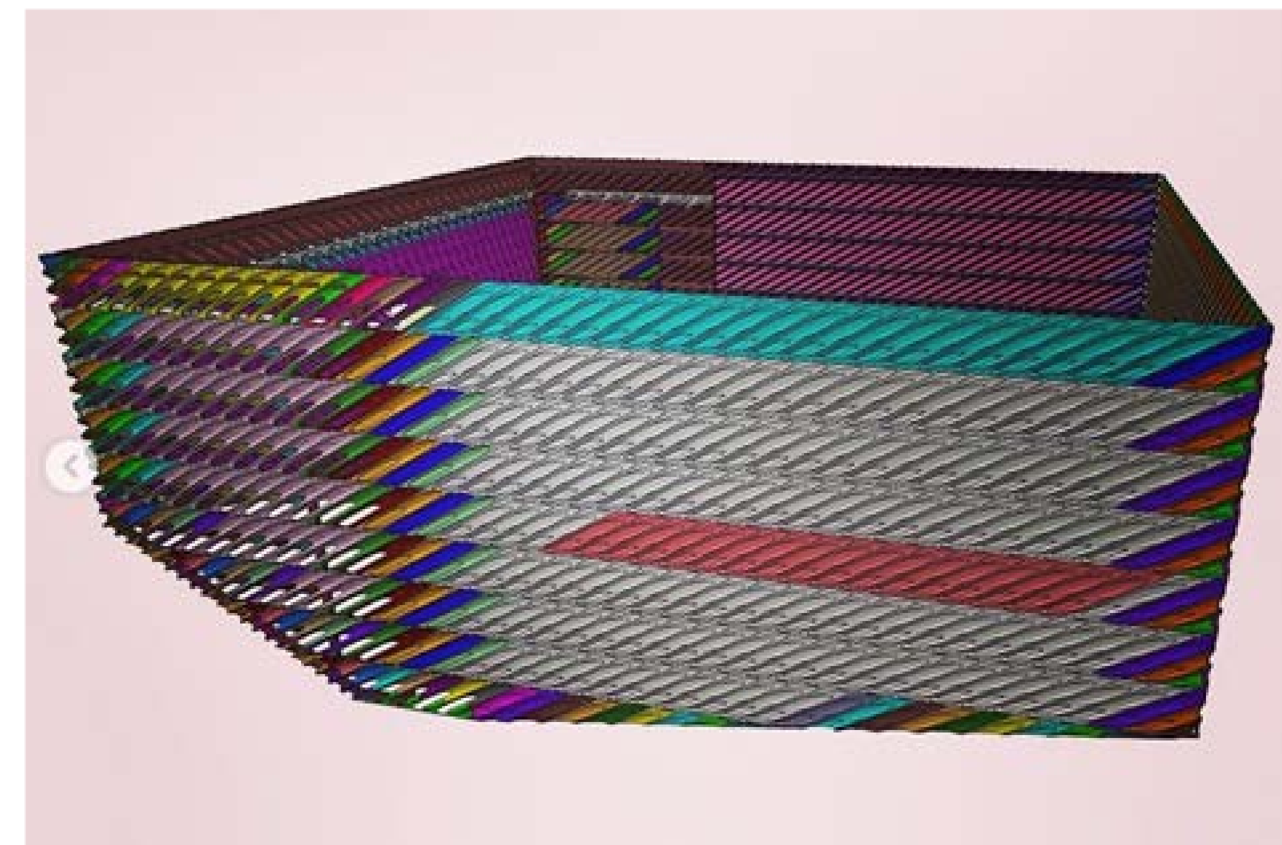
Glass Fibre Reinforced Concrete

Glass Fibre Reinforced Concrete

Prefabricated GFRC




Grand Av




seele




Prefabrication of Ultra-High Performance Concrete

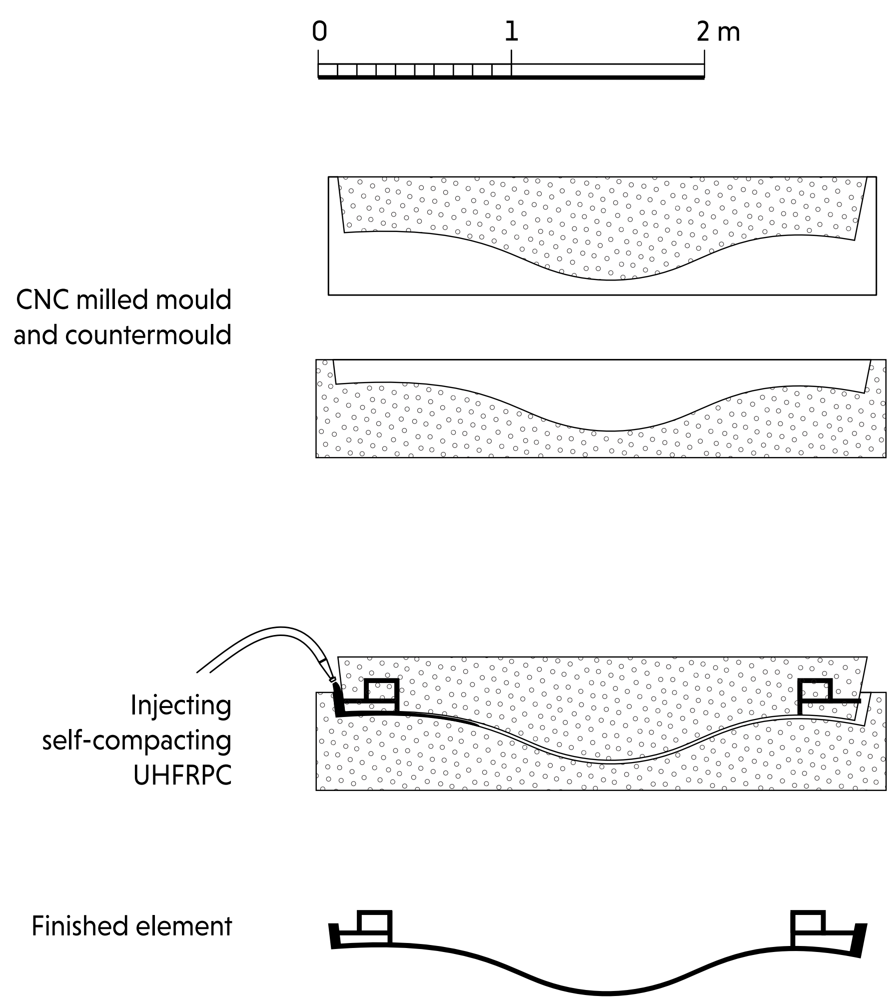


FIGURE 1.17 An illustration of the adhesion of high-performance concrete to an expanded polystyrene mould (Hi-Con, 2017) (Source: Hi-Con A/S).

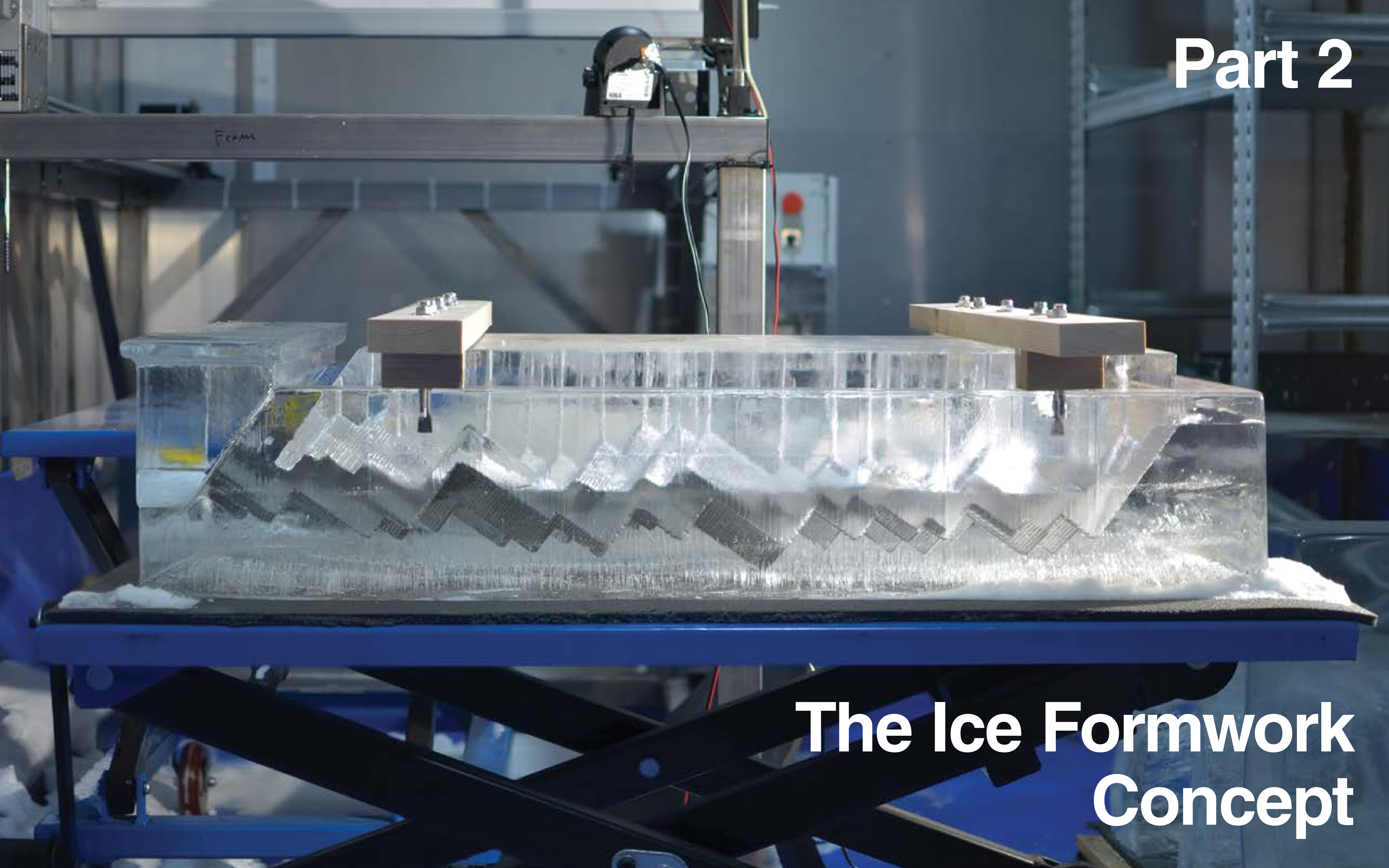
Ultra-High Performance Fibre Reinforced Concrete

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).

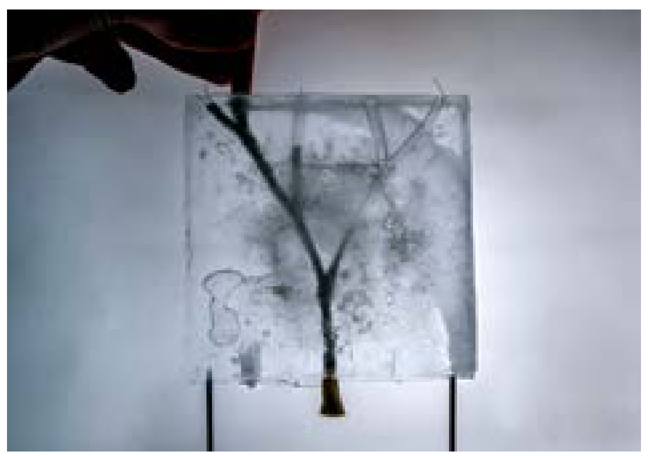
Part 2



The Ice Formwork Concept

Methodology of Experimental Programme

Phase 0 - Thought Experiment

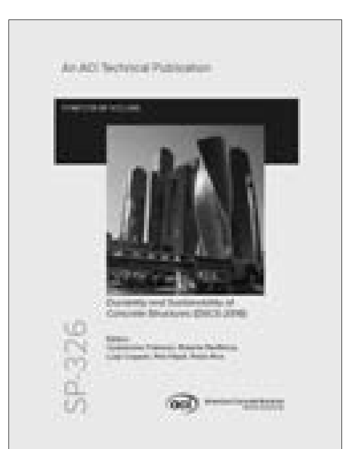


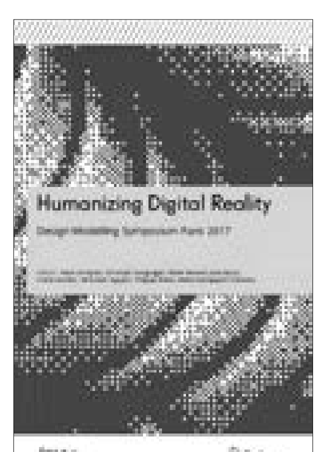
Phase 1 - Material Testing

Phase 2 - Design Probes and Production Prototyping

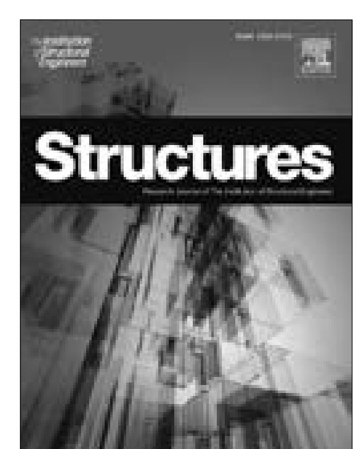
Phase 3 - Ecological Evaluation

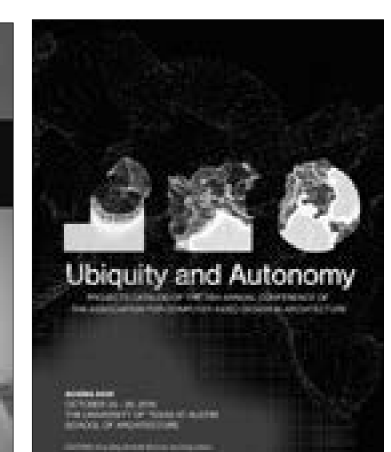
Appendix 1
Appendix 2

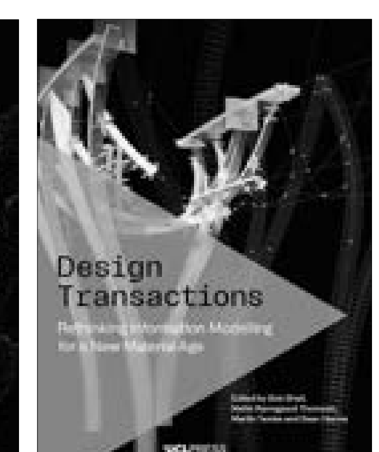




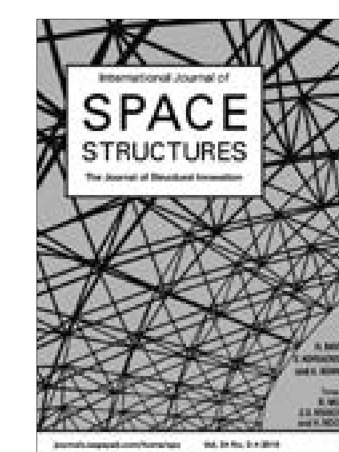
Appendix 3
Appendix 4
Appendix 5





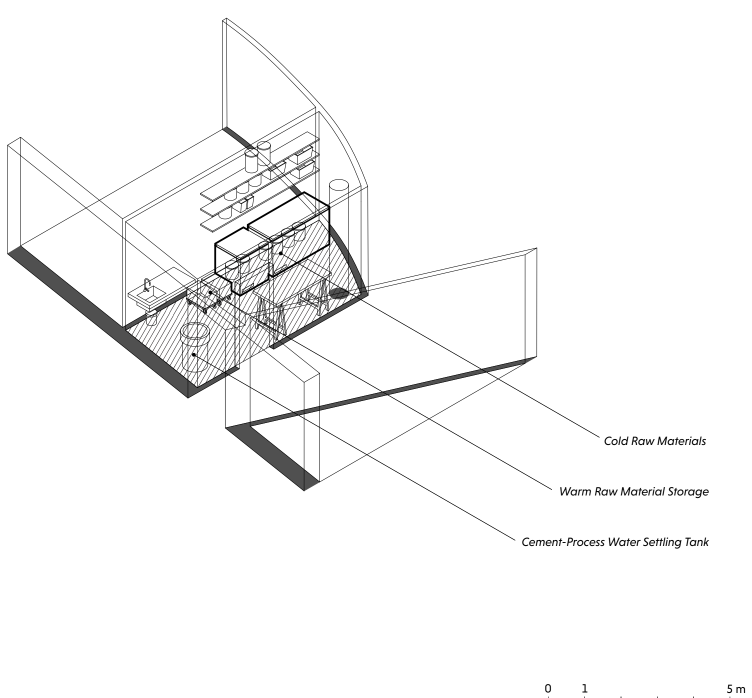


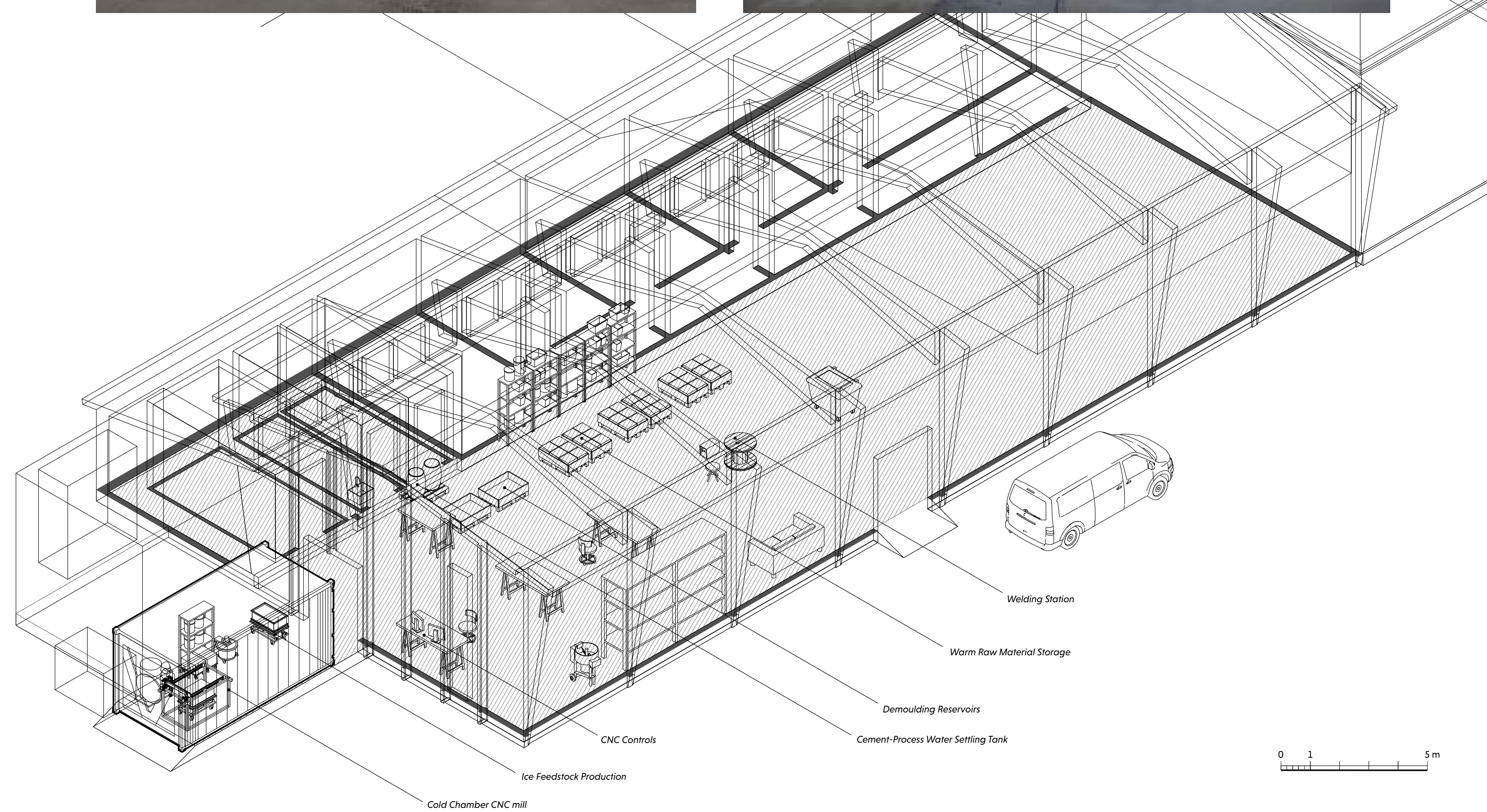
Appendix 6



Experimntal Rig 1

Experimntal Rig 3



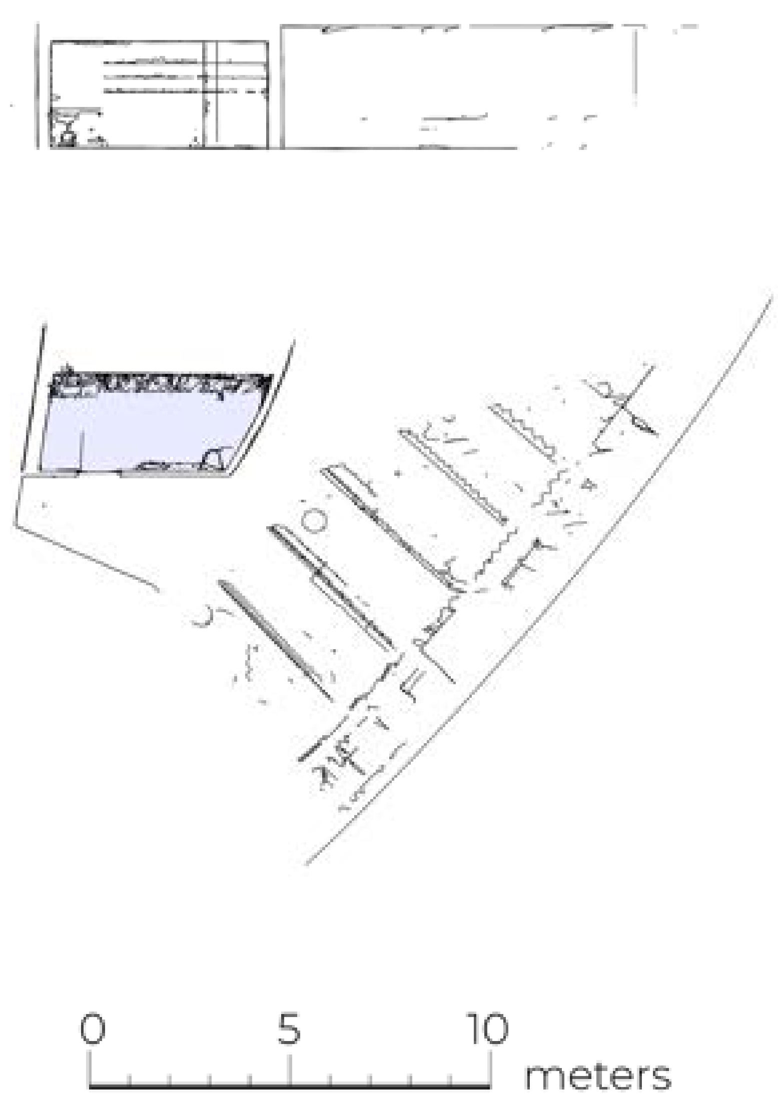


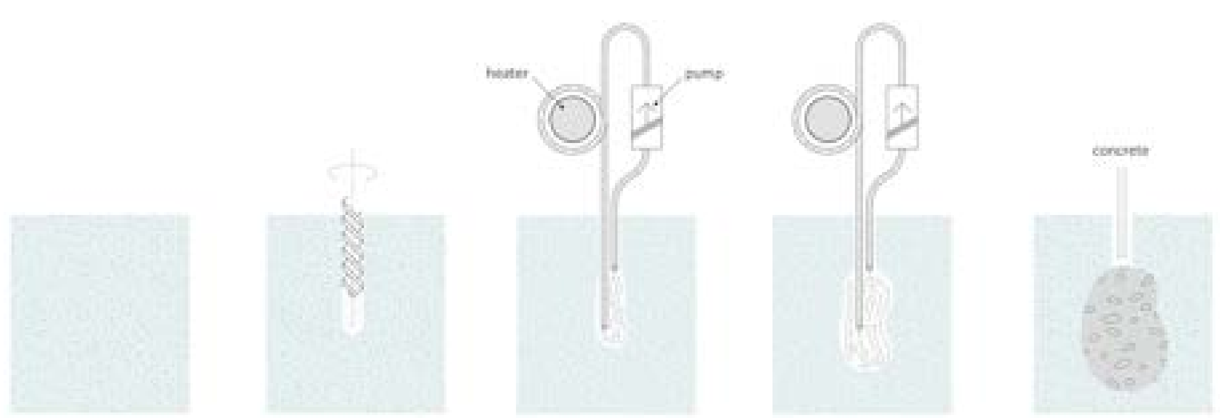
Phase 2.1

Ice manual processing

Experimental Rig 1

Area: 12 m^2
Cold volume: 1.5 m^3




heater
pump
concrete

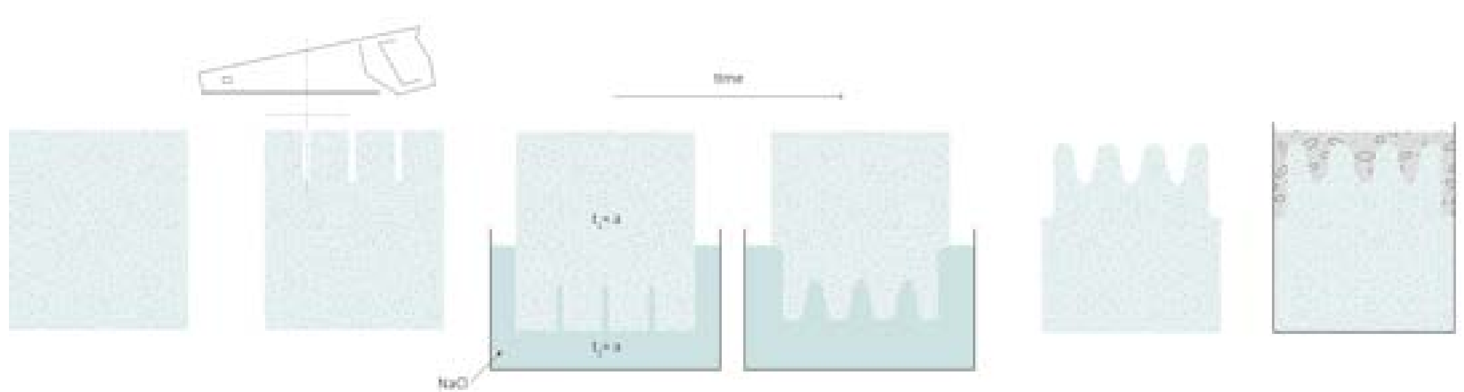

time
NaCl

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

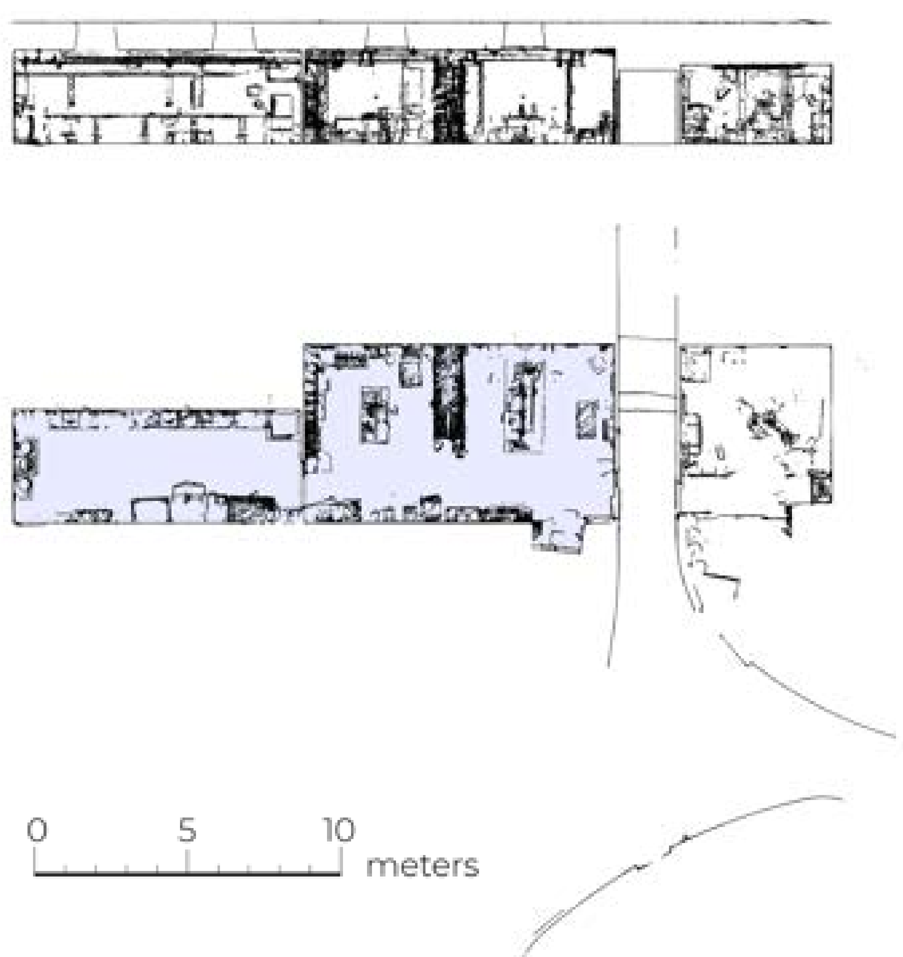
FIGURE 2.35 A scale reference for 180611-ME-JULx (Source: author).
FIGURE 2.36 180611-ME-JULx during demoulding (Source: author).

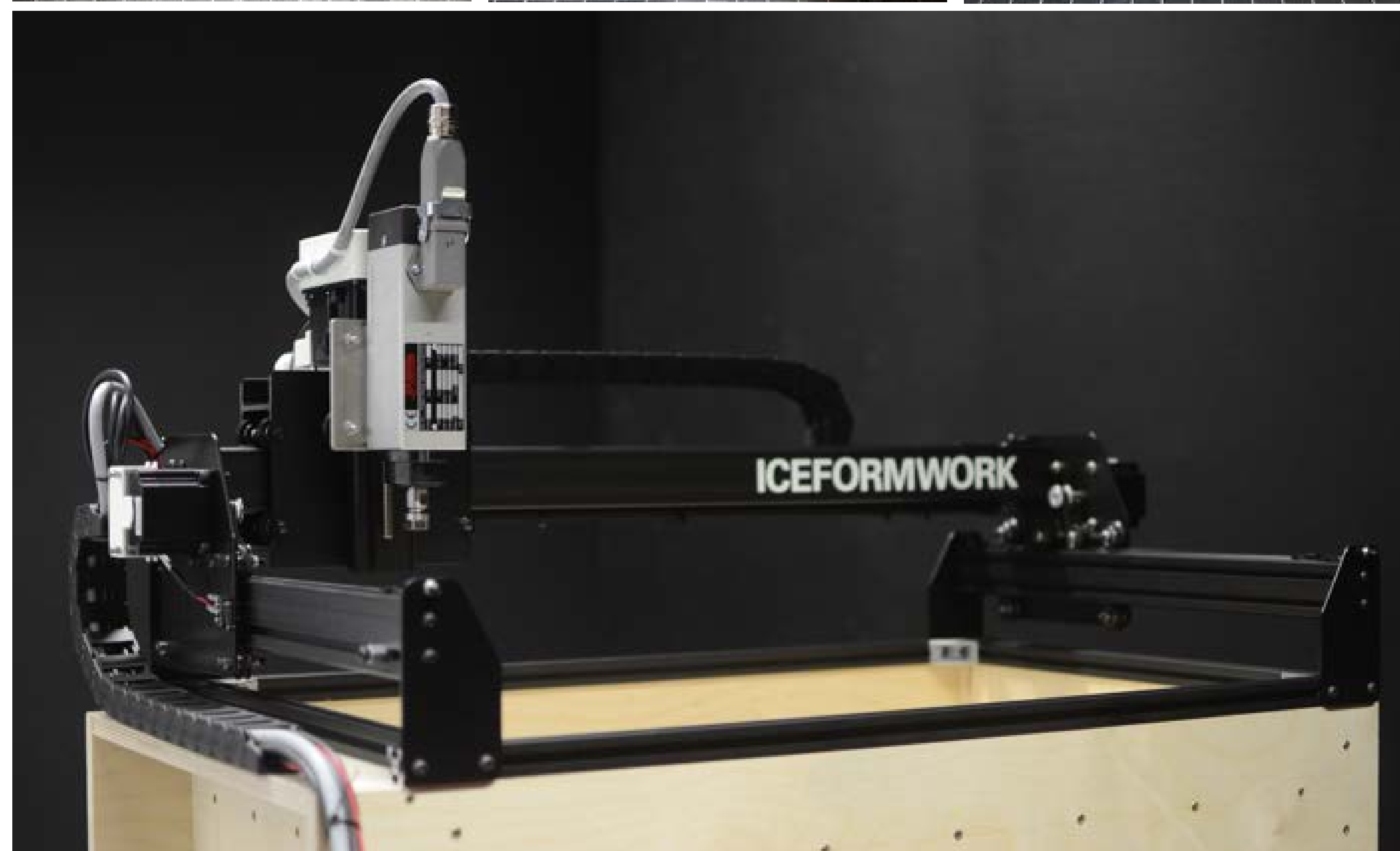
Phase 2.2

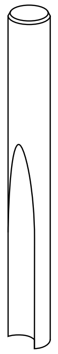
Ice manual processing

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:

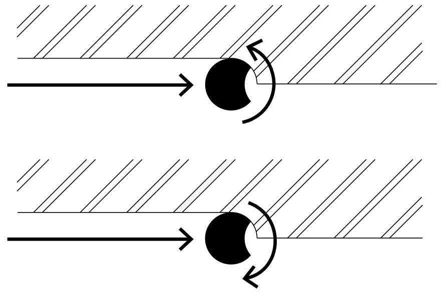
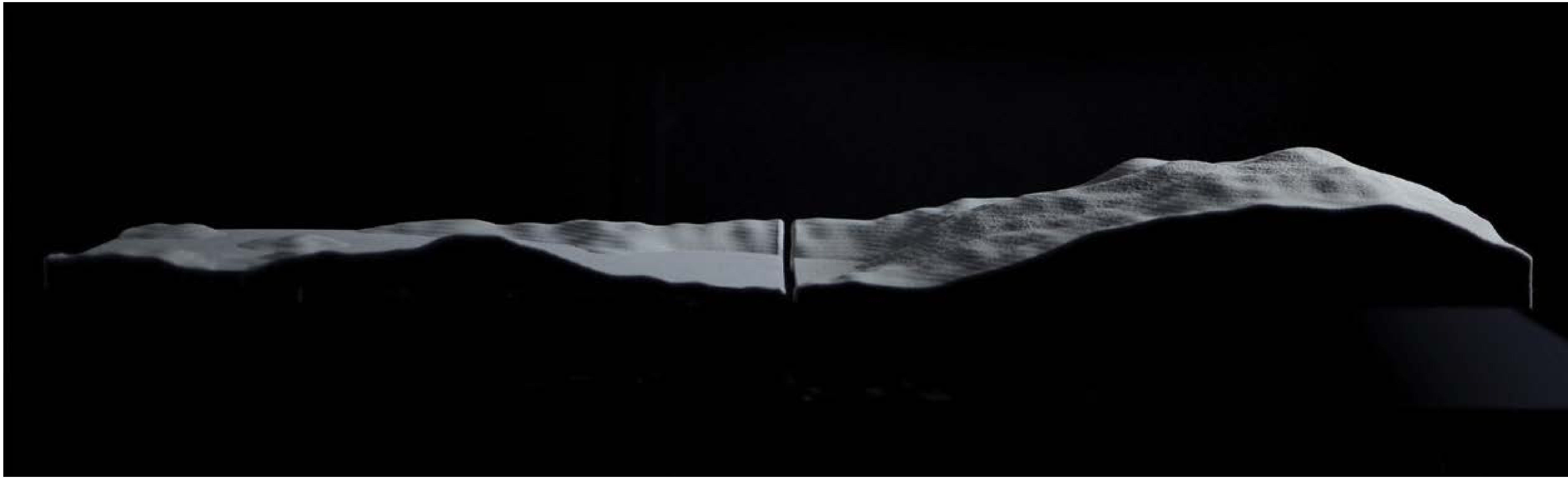


FIGURE 2.39 The tile series 180423-DP-TILx cast in fine processed ice moulds (Source: author).



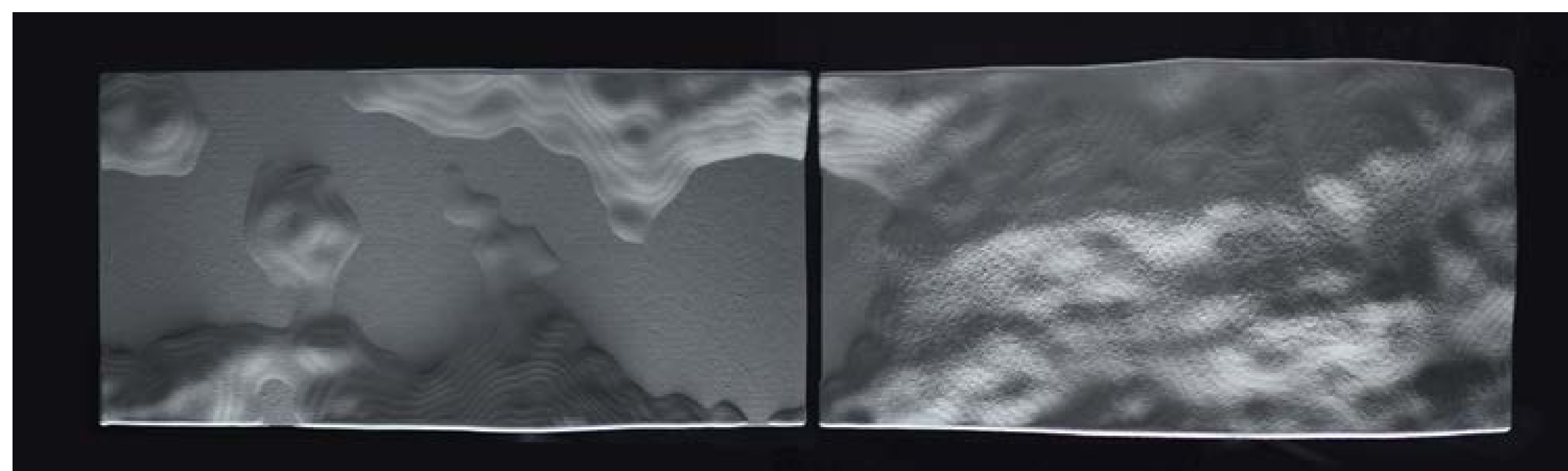


FIGURE 2.43 The front and top view of the prototype 180622-DP-TER1 produced using fine CNC-processing (Source: author).
FIGURE 2.44 The prototype 180622-DP-TER1 during the demoulding process (Source: author).
FIGURE 2.45 The surface quality detail of the prototype 180622-DP-TER1 (Source: author).

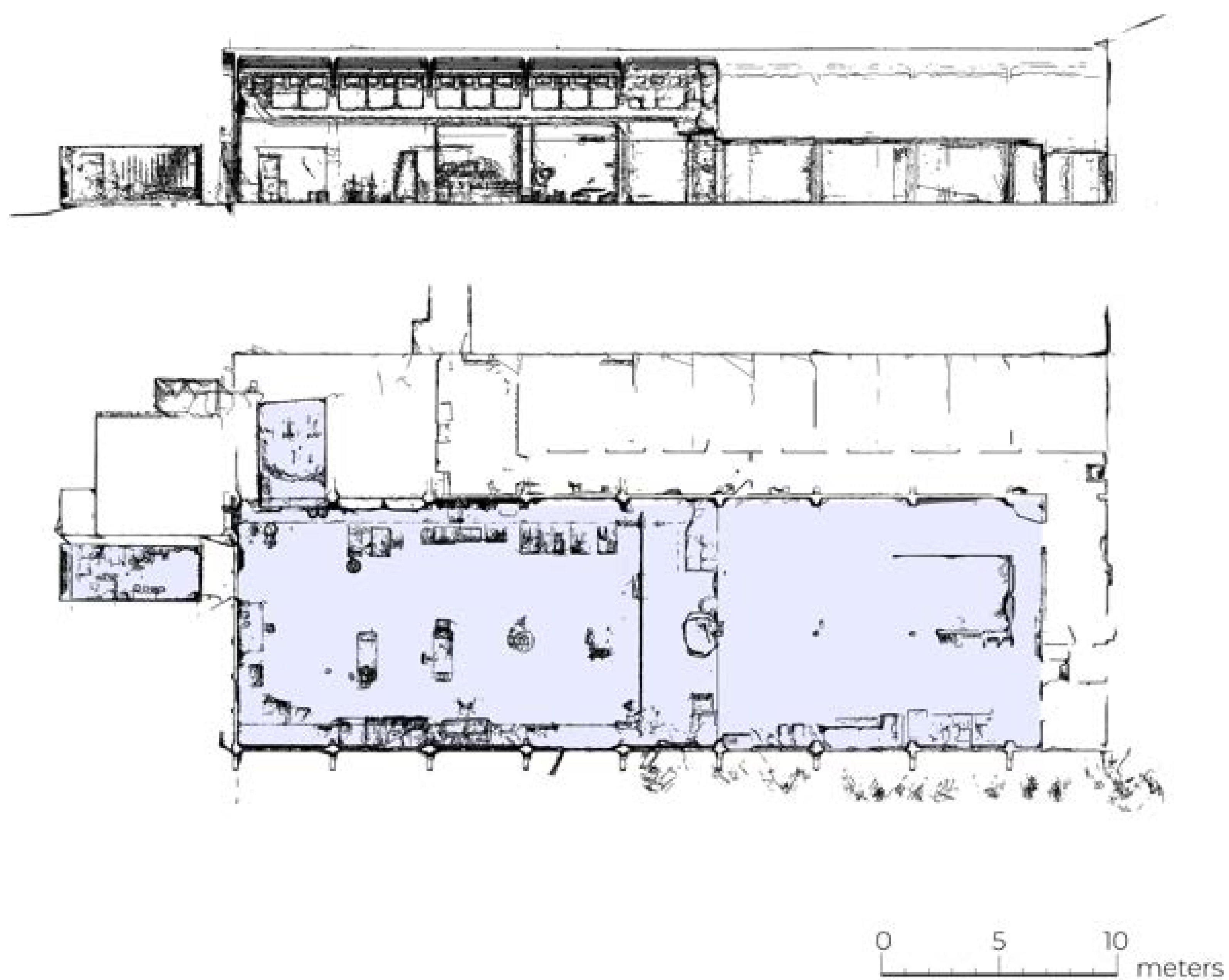
FIGURE 2.40 The prototype 180805-DP-APE1 made using a two-party ice mould assembly (Source: author).

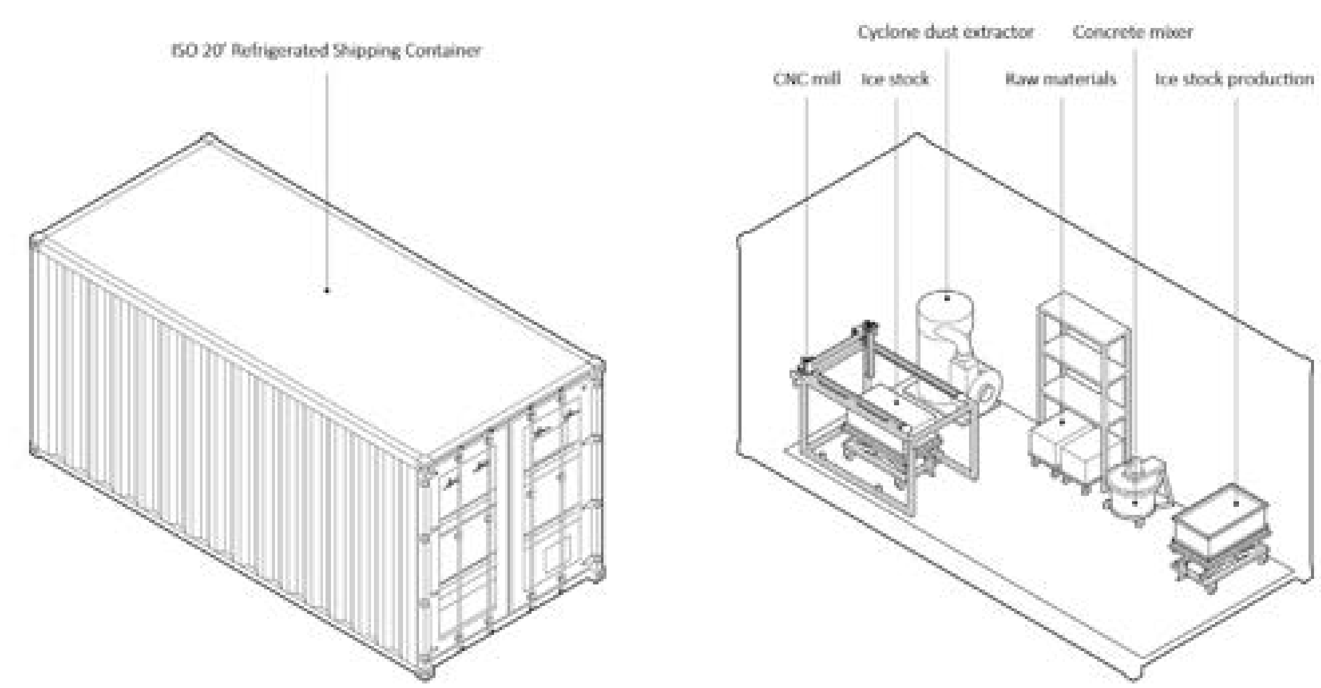
Phase 2.3

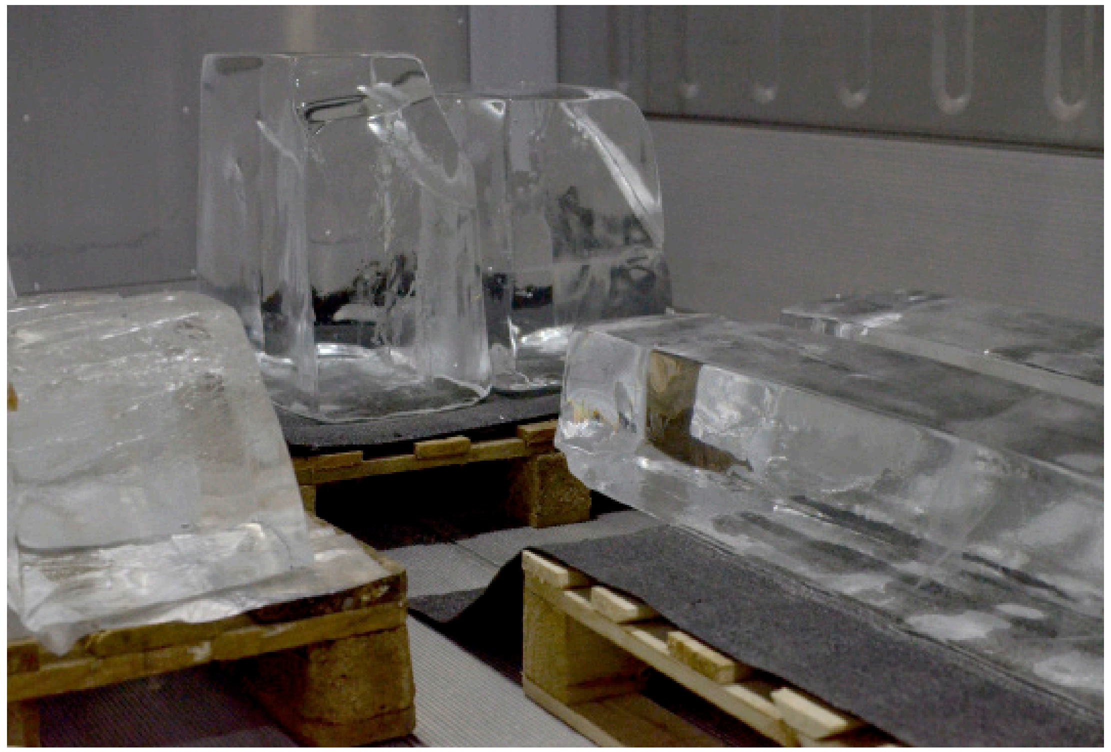
Ice manual processing

Experimental Rig 3

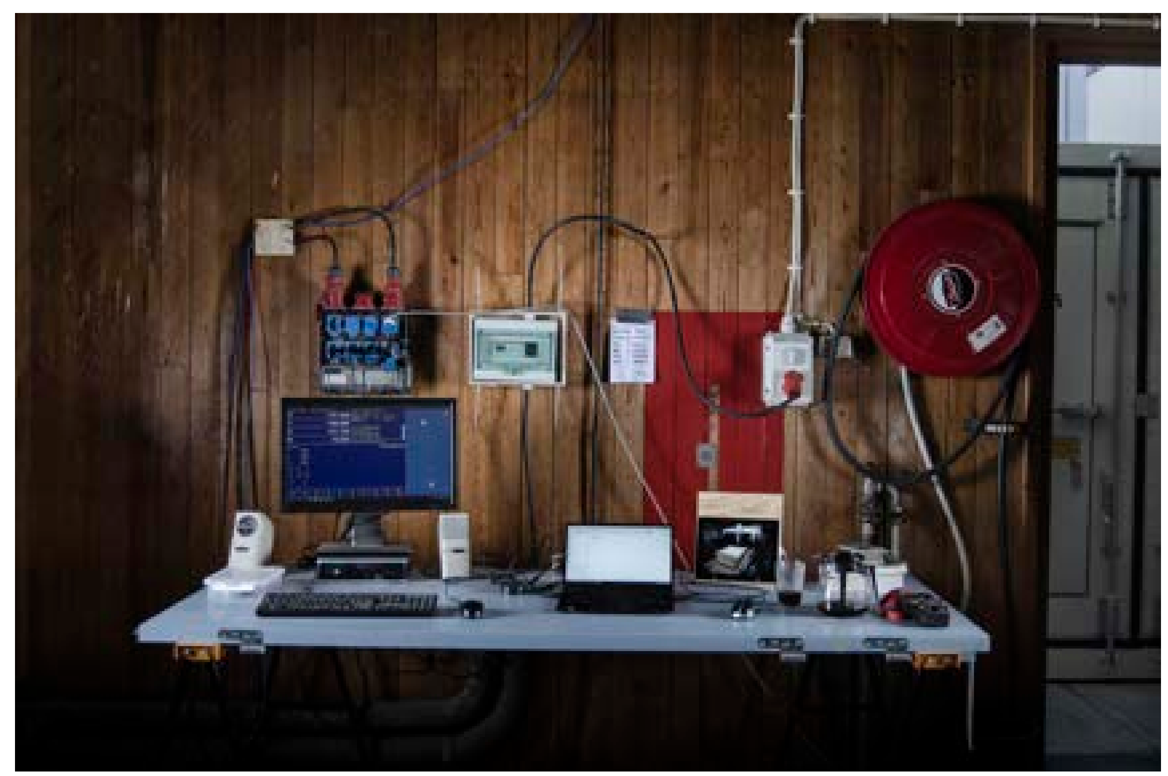
Area: 389 m^2
Cold volume: 54 m^3











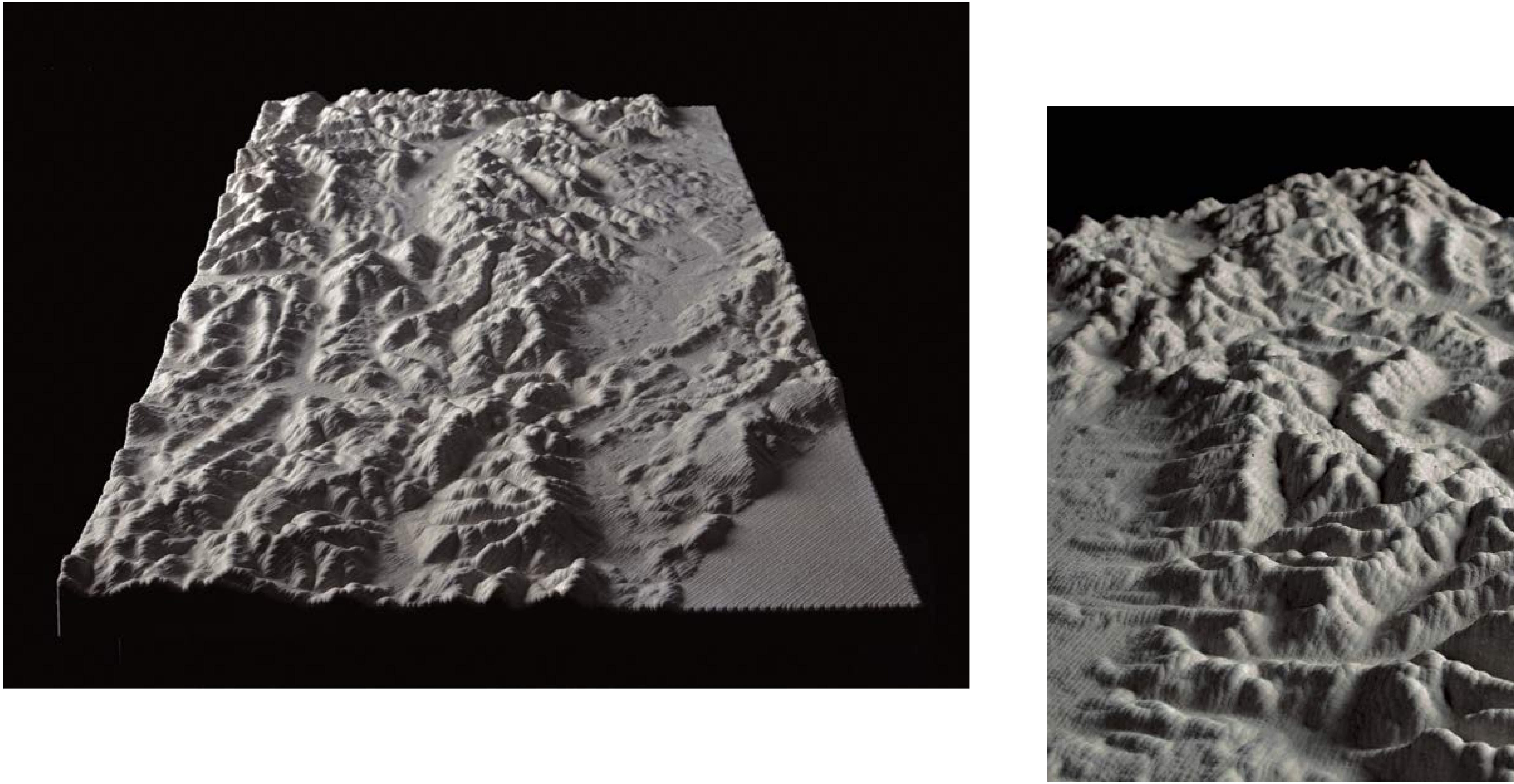
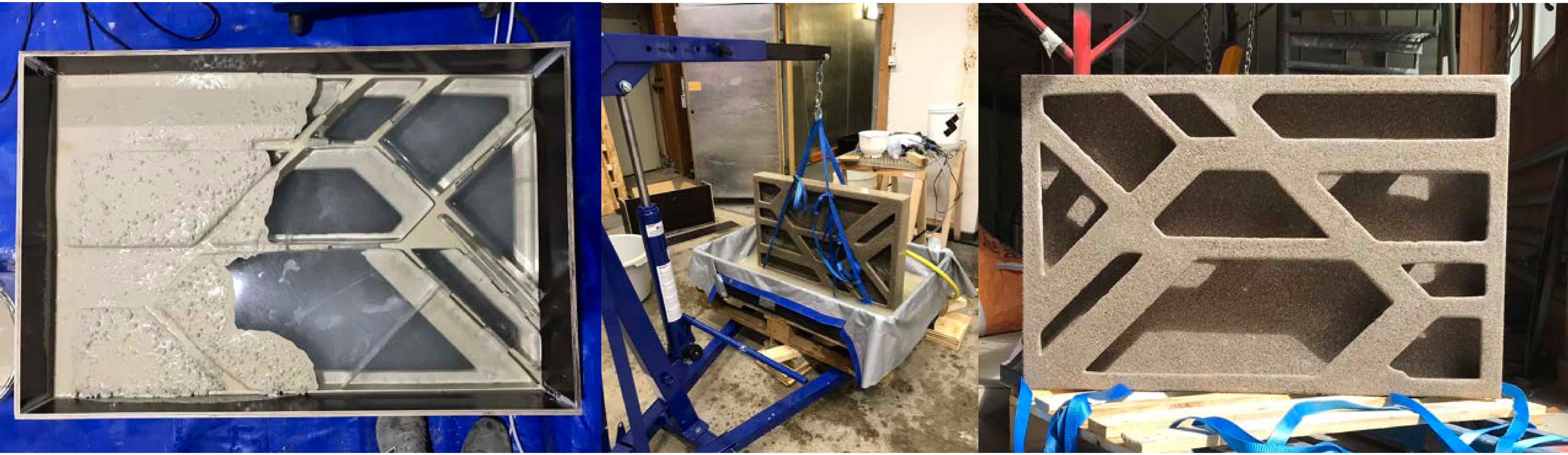
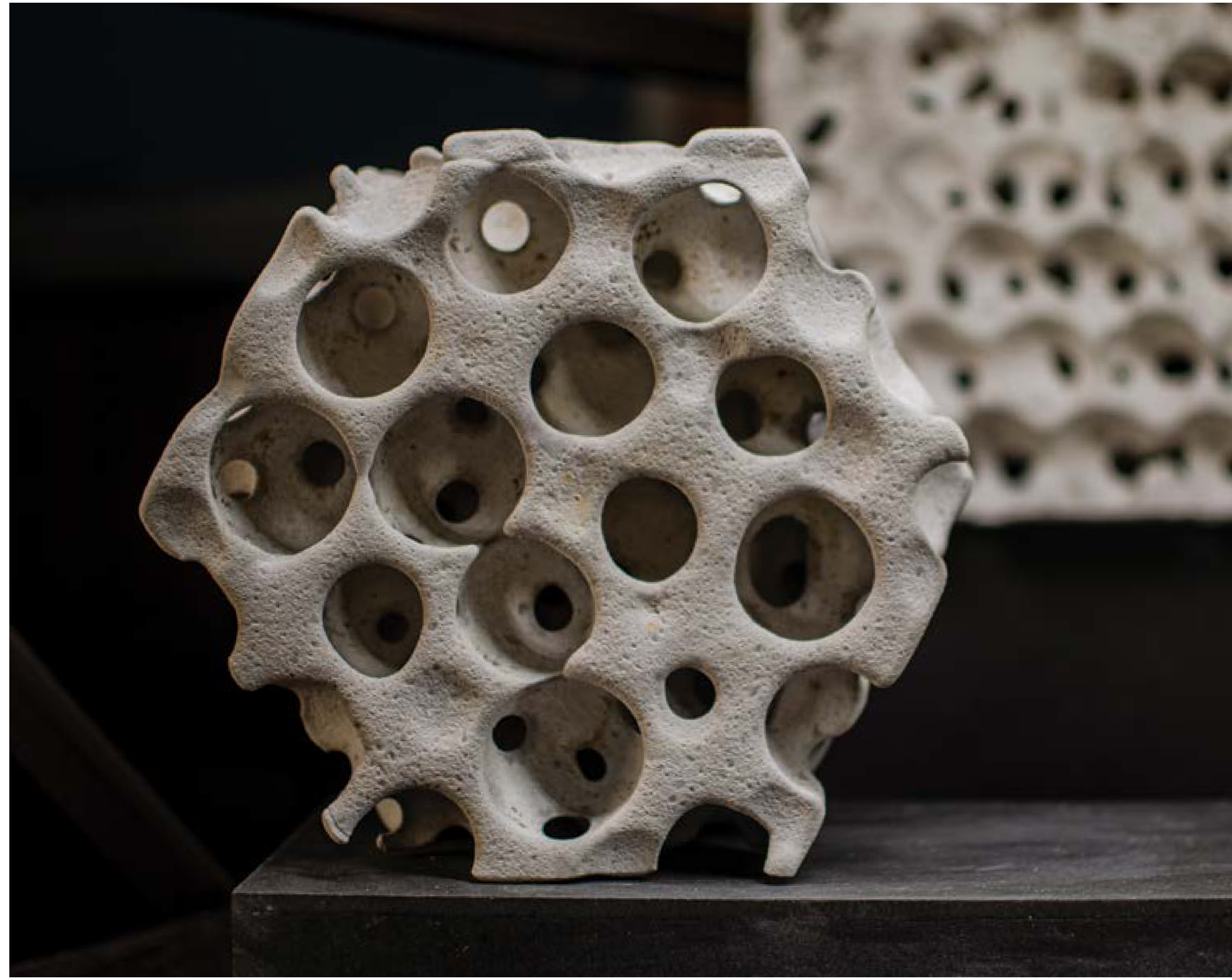



FIGURE 2.48 The 191116-DP-TER2 prototype (Source: author).



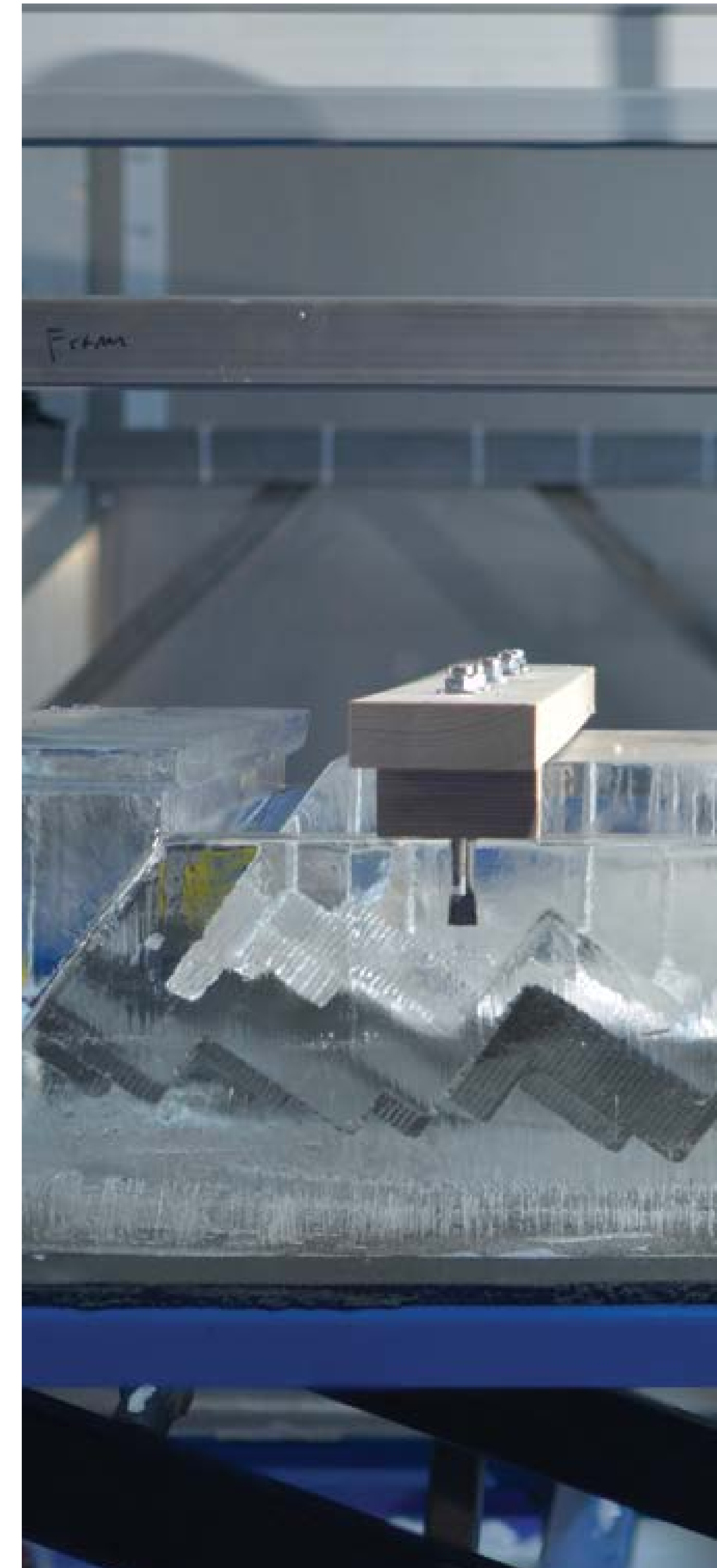


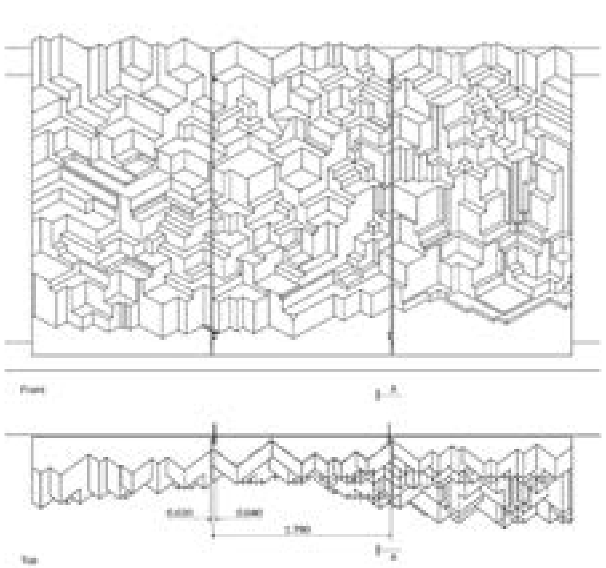



0 1 5 10 cm


0 1 5 10 cm


0 1 5 10 cm



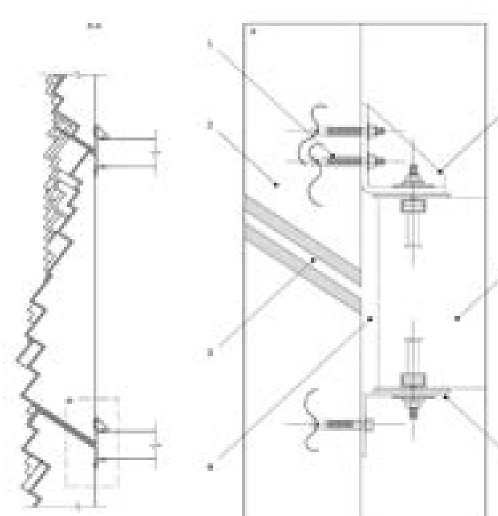
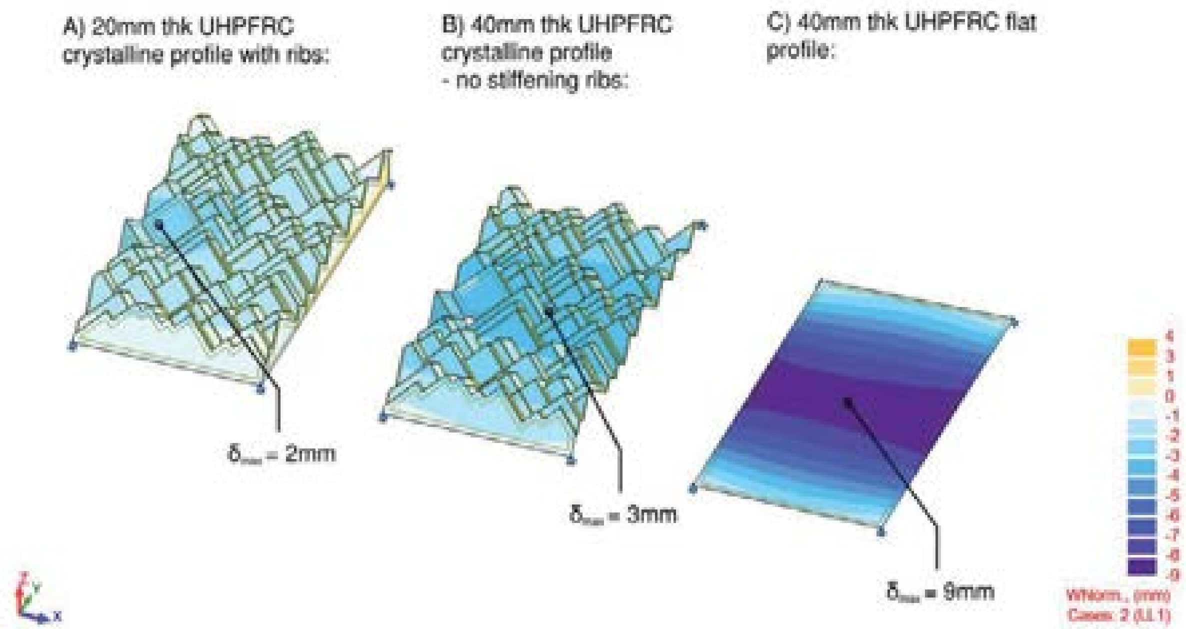
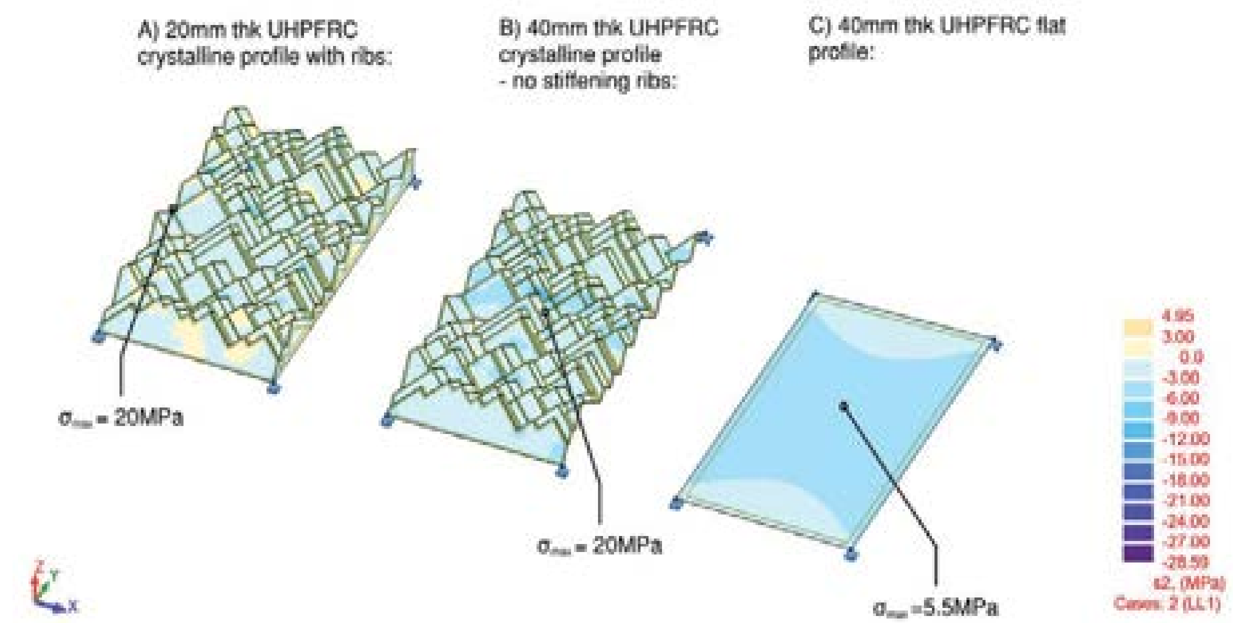
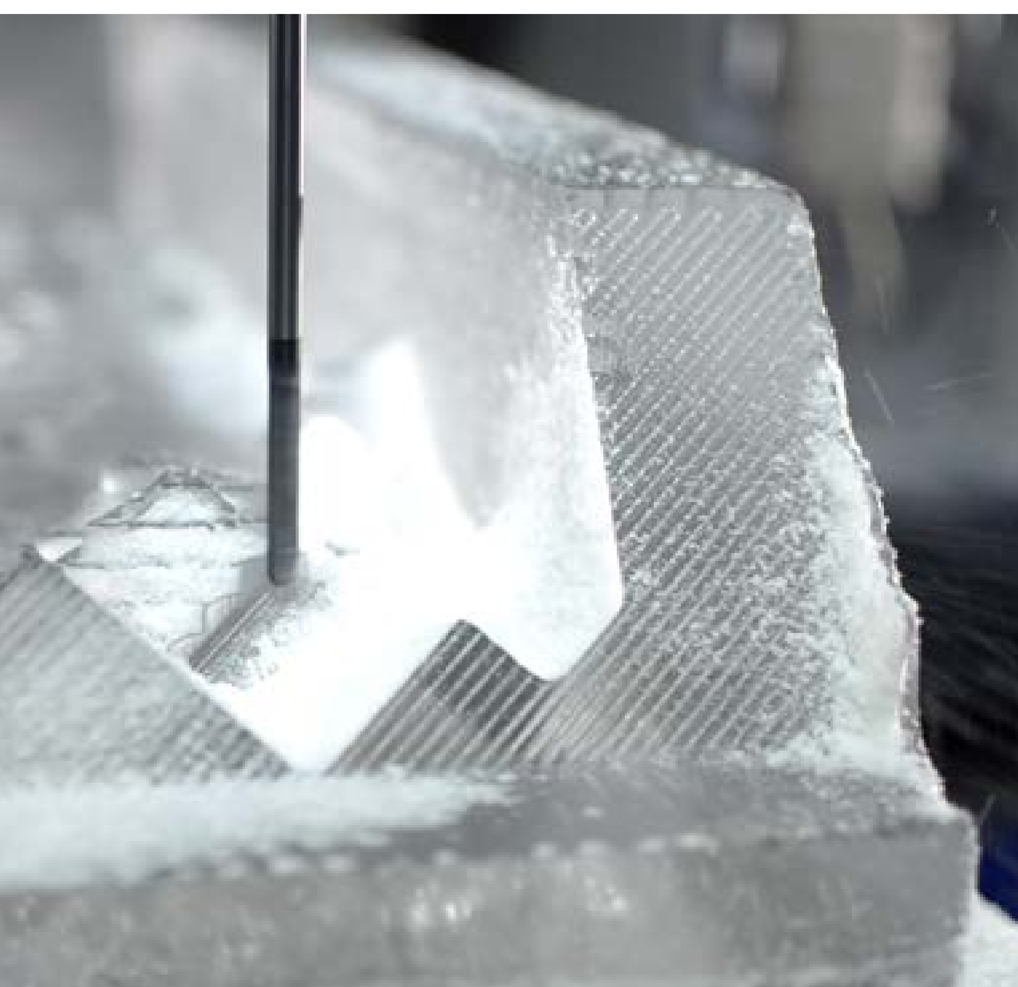


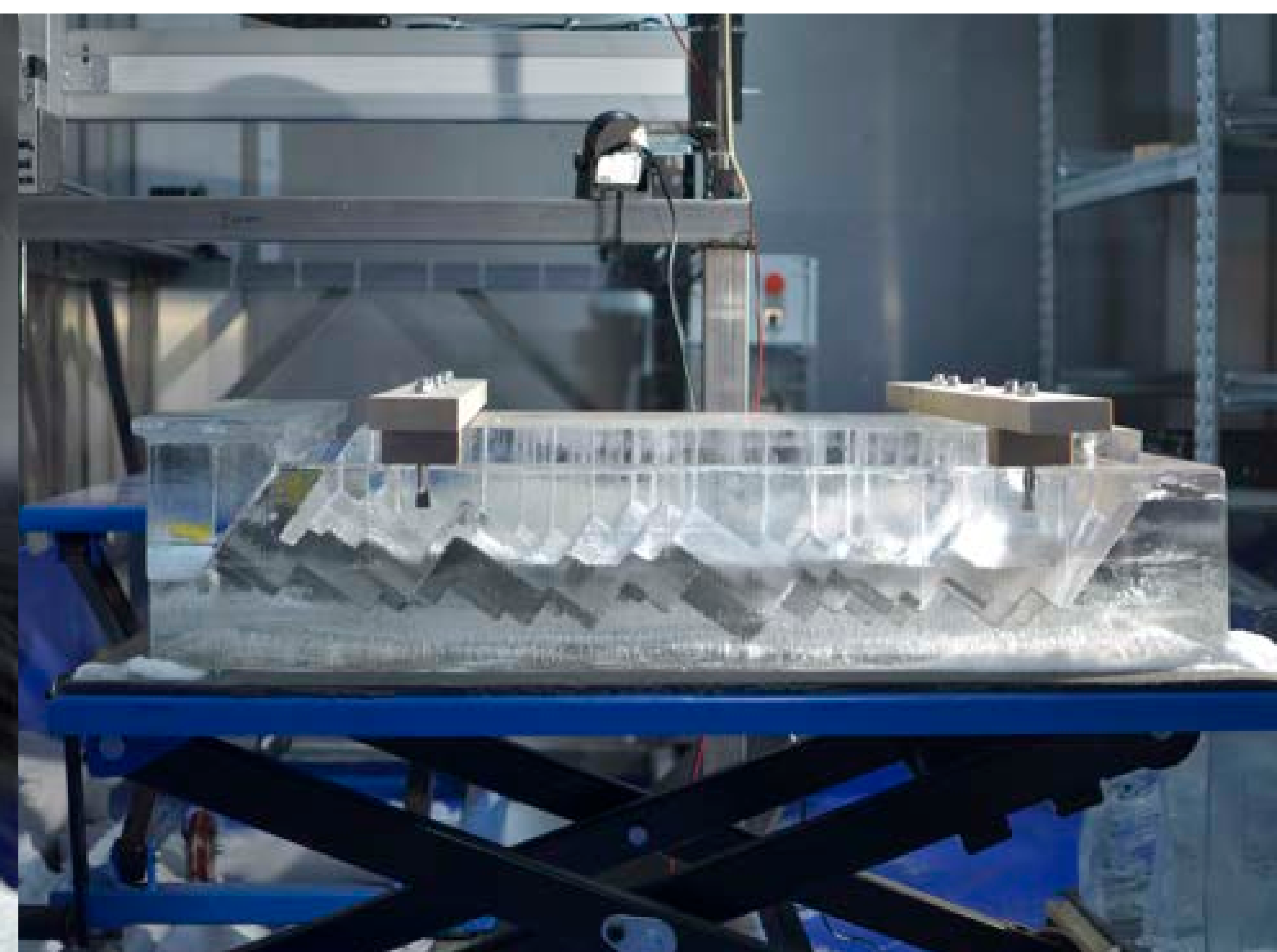
FIGURE 2.55 The fixing detail and the back side of the 190912-DP-FAC2 prototype (Source: author).

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:
δ_{max} = 2mm
δ_{max} = 3mm
δ_{max} = 9mm
4
3
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
Cases: 2 (LL1)


A) 20mm thk UHPFRC crystalline profile with ribs:
B) 40mm thk UHPFRC crystalline profile - no stiffening ribs:
C) 40mm thk UHPFRC flat profile:
σ_{max} = 20MPa
σ_{max} = 20MPa
σ_{max} =5.5MPa
4.95
3.00
0.0
-3.00
-6.00
-9.00
-12.00
-15.00
-18.00
-21.00
-24.00
-27.00
-28.59
s2, (MPa)
Cases: 2 (LL1)





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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ICE FORM WORK

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