Building with Martian Regolith

Experimental Research on Efficient and Sustainable Production Process and Construction Method

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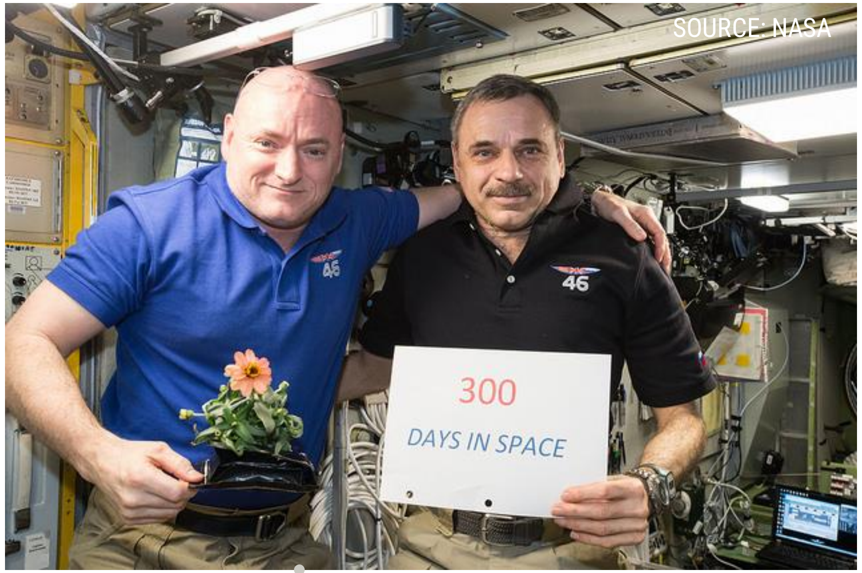
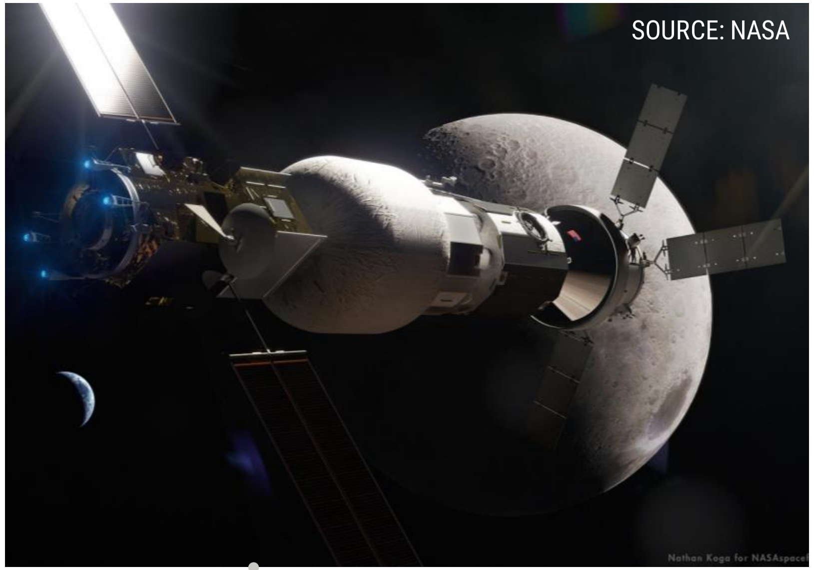
Graduation Studio: Sustainable Design Graduation Studio

Mentors: Fred Veer (1st mentor), Oguzhan Copuroglu (2nd mentor), David Peck (3rd mentor)

Supervisors: Layla van Ellen, Fernando Franca de Mendonca Filho





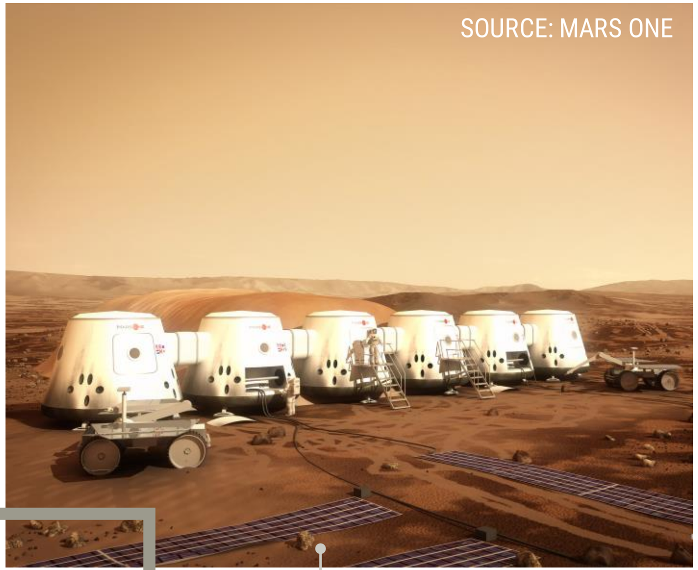
1961

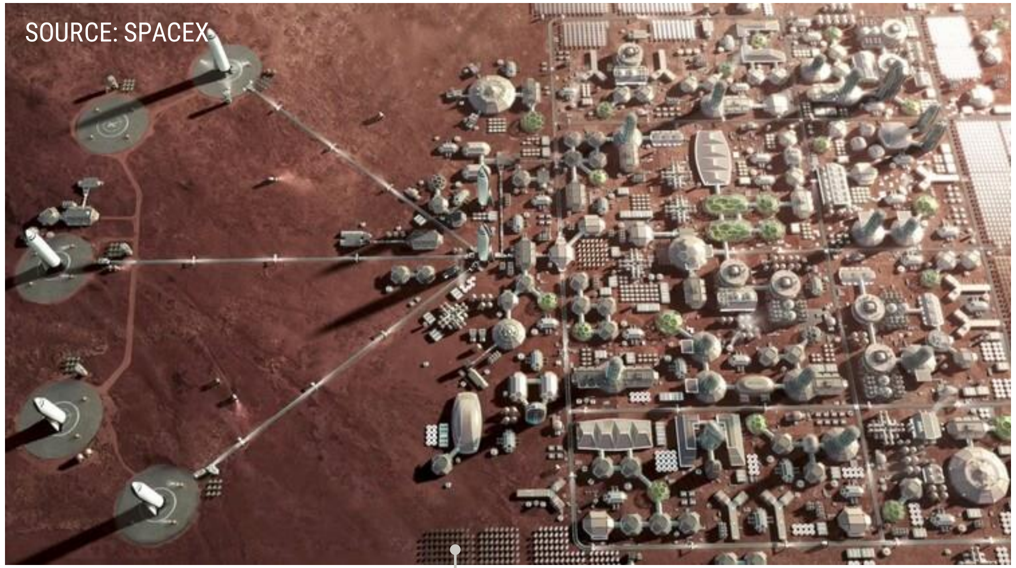
2016

2025-30

Humans presence in space


SOURCE: NASA


SOURCE: MARS ONE


SOURCE: SPACEX

2030

2035

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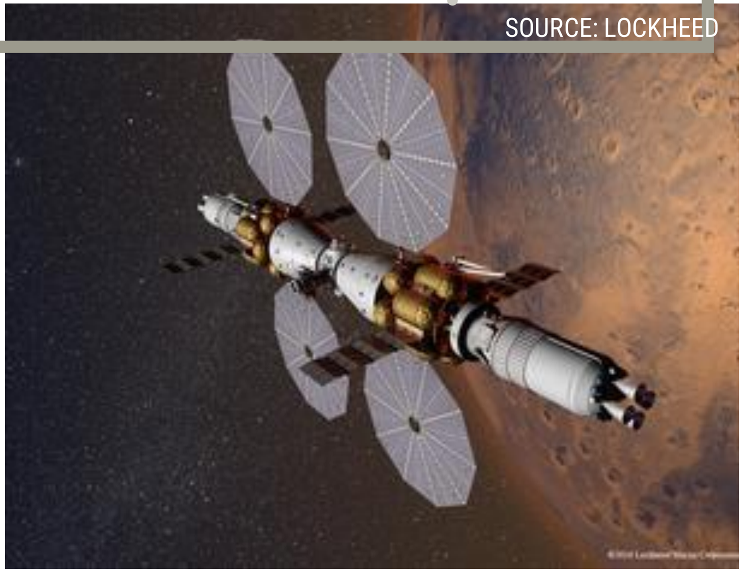
TECHNOLOGICAL PROGRESS
&
HUMAN PRESENCE IN SPACE


SOURCE: LOCKHEED


SOURCE: FIRST SERIE

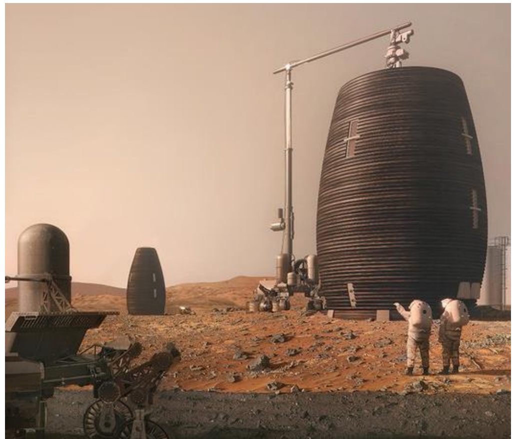
PROBLEM STATEMENT

Context

1ST MISSIONS – 2030-35

TECHNOLOGY AVAILABILITY

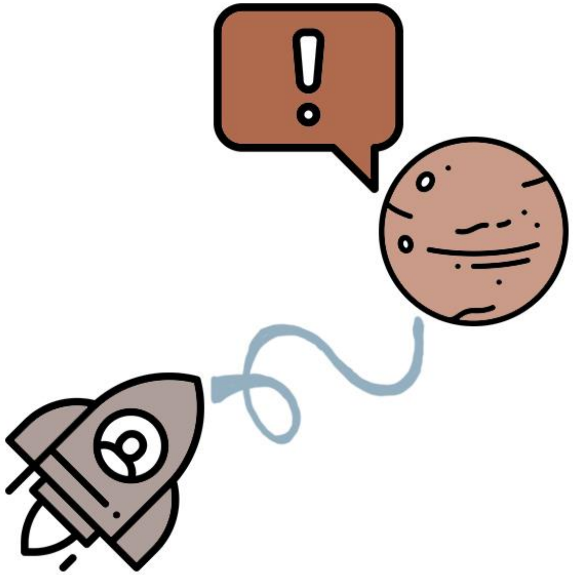
LONG-TERM SETTLEMENT



Source: IA SpaceFactory and Plomp

Source: Martian movie

Issues related to the topic



MISSION CONDITIONS

MARTIAN CONDITIONS

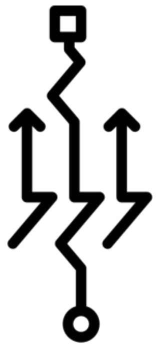
COMMON APPROACH

PROBLEM STATEMENT

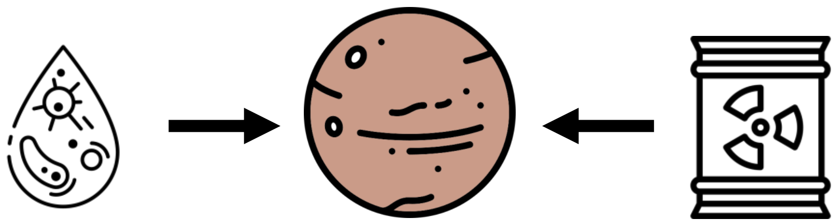
Common approach

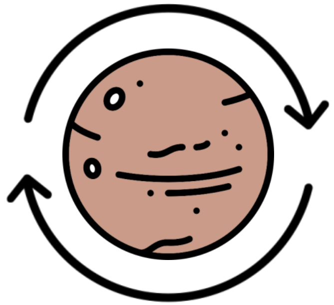
Research approach

HIGH-TECH → EFFICIENCY, TECHNOLOGY AVAILABLE



LACK OF SUSTAINABILITY → IMPLEMENTING SUSTAINABILITY





OBJECTIVES

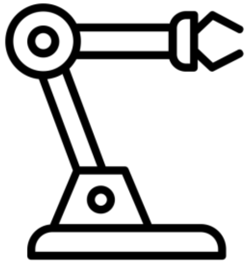
Main objectives

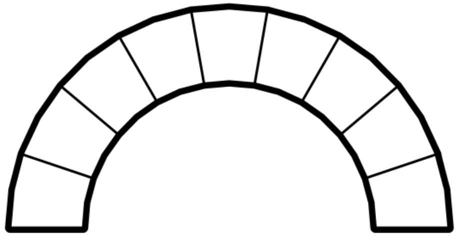
BUILDING ON MARS

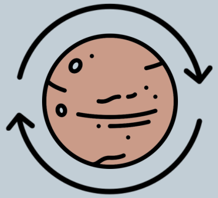
BUILDING MATERIAL

PRODUCTION PROCESS

CONSTRUCTION METHOD





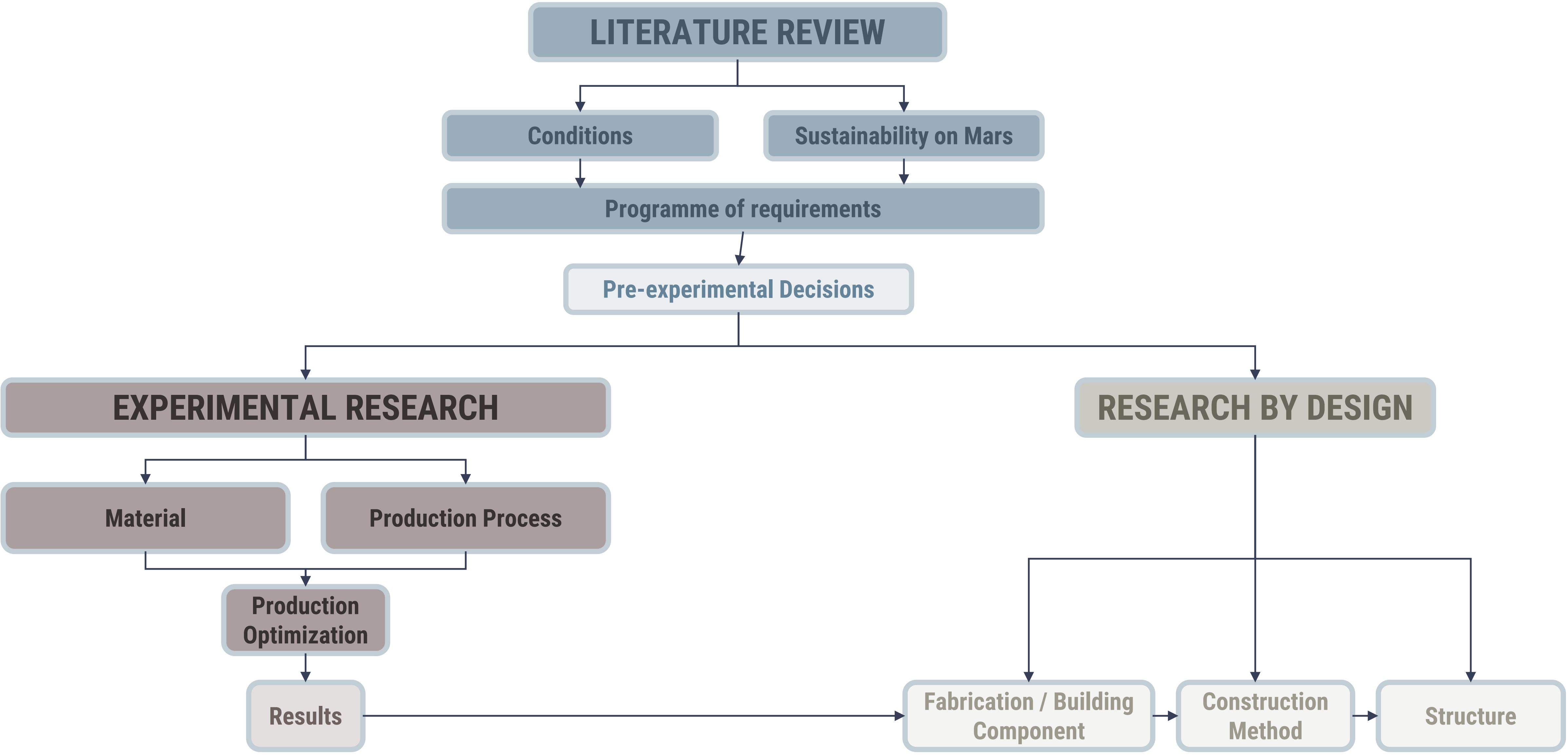


EFFICIENCY, TECHNOLOGICAL AVAILABILITY

IMPLEMENTING SUSTAINABILITY

Research question

HOW TO SUSTAINABLY BUILD WITH MARTIAN REGOLITH USING ENERGY EFFICIENT IN-SITU PRODUCTION PROCESS AND CONSTRUCTION METHOD ?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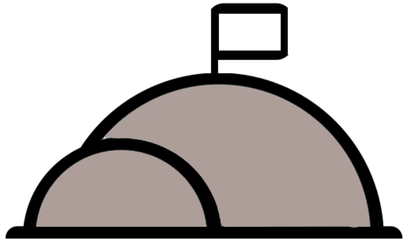
TRAVEL/TRANSPORT

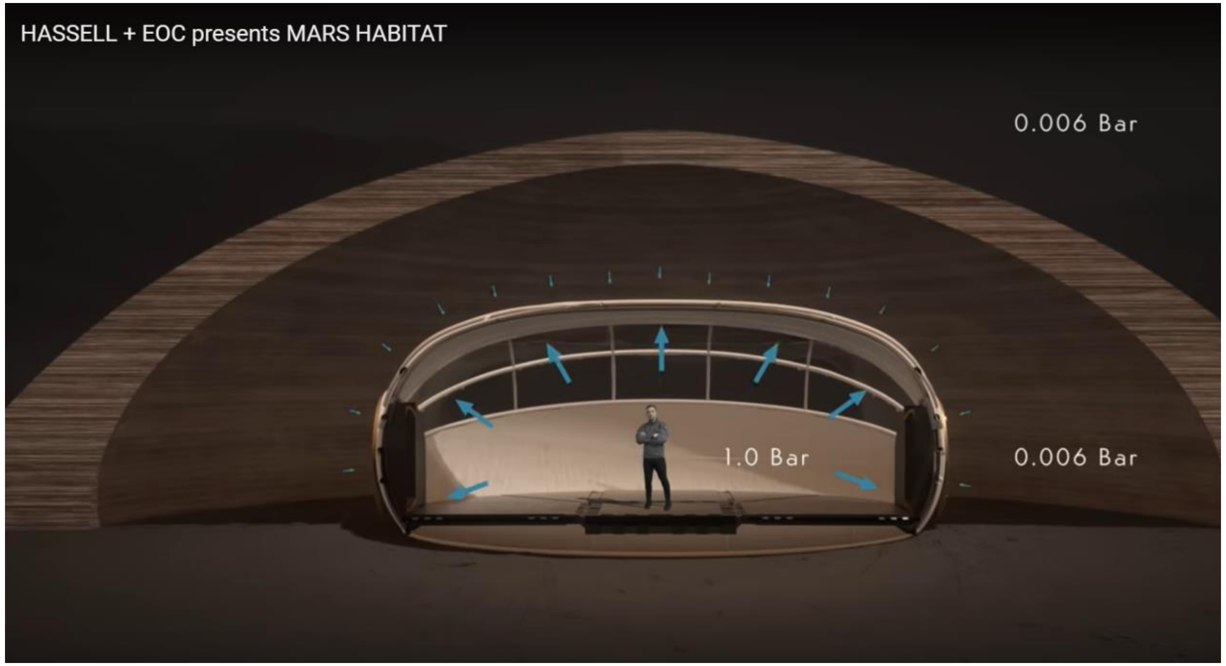
ISSUE	EFFECT
launch windows - 26 months	autonomous / independent
payload - 16 800 kg	ISRU resources
multiple missions	adaptable building

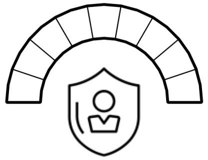
ARCHITECTURE



ISSUE	EFFECT
crew size - 6x	150m^3 – habitat volume
crew safety	protection against hazardous conditions
adaptability	modular structure
mission-functional	modular configuration - zoning

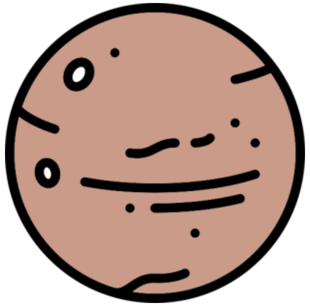
ARCHITECTURE





protection against
hazardous conditions

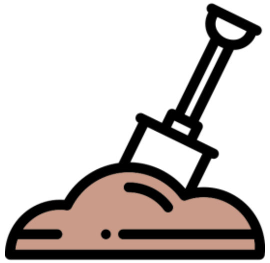
HAZARDS

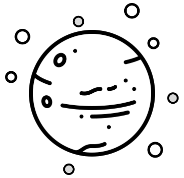
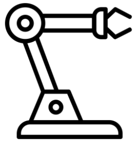
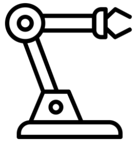


ISSUE		EFFECT
micrometeorites	7,0 km/s	structure resistance to local damage
wind	max 25 m/s	structure resistant to wind load
radiation	lethal dose	structure thickness 1m
temperature & pressure	-143-35˚C & 0,4-0,87 kPa	production process issues (water)

LITERATURE REVIEW – MARTIAN CONDITIONS

RESOURCES



ISSUE		EFFECT
dust form homogenous 	→	 adaptable to different regions
fine grains 	→	 direct usage

RESOURCES

ISSUE		EFFECT
solar	→	power – max 0,38 kW per m^2 maintenance limitations
nuclear energy	→	power – max 1-10 kWe radioactive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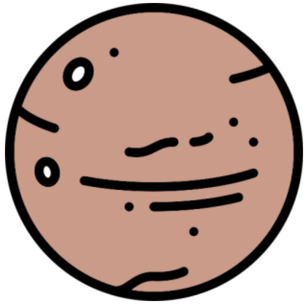

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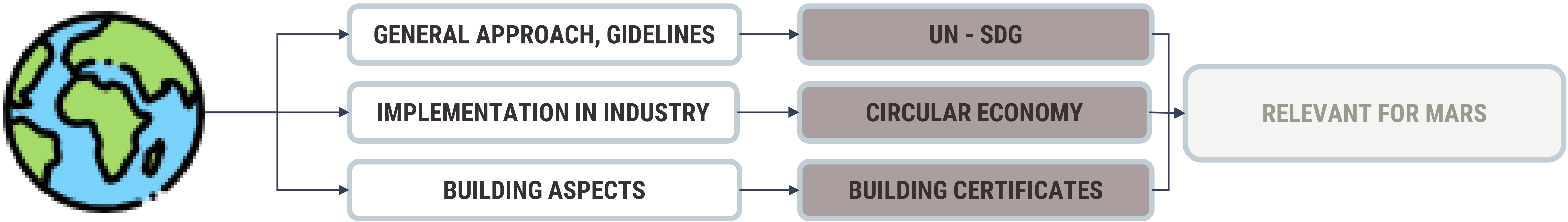
WHAT IS SUSTAINABILITY

1

Brundtland Commission Report – „sustainable development is a development which meets the needs of the present without compromising the ability of future generations to meet their own needs

SUSTAINABILITY - METHODOLOGY

WHAT IS SUSTAINABILITY | HOW TO IMPLEMENT | CONCLUSIONS



CONCLUSIONS

RELEVANT FOR MARS

- environment protection
- renewable and clean energy
- sustainable management and efficient use of resources
- minimize waste
- circularity

WHAT IS SUSTAINABILITY	HOW TO IMPLEMENT		CONCLUSIONS
	GENERAL APPROACH, GIDELINES	UN - SDG	RELEVANT FOR MARS
	IMPLEMENTATION IN INDUSTRY	CIRCULAR ECONOMY	
	BUILDING ASPECTS	BUILDING CERTIFICATES	
	ANY REGULATIONS?	SPACE LAW	WHAT IS MISSING?
	GIDELINES	UN REGULATIONS	
	CURRENT SITUATION	SPACE AGENCIES APPROACH	

CONCLUSIONS

WHAT IS RELEVANT?

- environment protection
- sustainable management and efficient use of resources
- circularity
- renewable and clean energy
- minimize waste

WHAT IS MISSING

- environmental impacts / sustainable materials
- long-term issue
- big scale
- commercial exploration

SUSTAINABILITY - METHODOLOGY

WHAT IS SUSTAINABILITY | HOW TO IMPLEMENT | CONCLUSIONS

GENERAL APPROACH, GIDELINES → UN - SDG

IMPLEMENTATION IN INDUSTRY → CIRCULAR ECONOMY

BUILDING ASPECTS → BUILDING CERTIFICATES

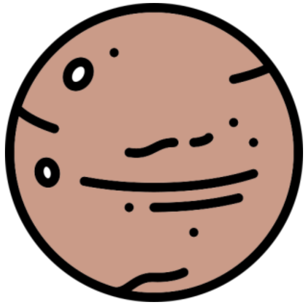
RELEVANCE FOR MARS

ANY REGULATIONS? → SPACE LAW

GIDELINES → UN REGULATIONS

CURRENT SITUATION → SPACE AGENCIES APPROACH

WHAT IS MISSING?



IMPLEMENTED IN FIRST MISISONS?

IMPLEMENTED IN RESEARCH

CONCLUSIONS

WHAT IS RELEVANT?

environment protection

sustainable management and efficient use of resources

circularity

renewable and clean energy

minimize waste

HOW TO SUSTAINABLY BUILD WITH MARTIAN REGOLITH USING ENERGY EFFICIENT IN-SITU PRODUCTION PROCESS AND CONSTRUCTION METHOD ?

IMPLEMENTED IN THE FIRST MISSIONS?

test approach

analyse impacts

test technology

establish collaboration and regulations

IMPLEMENTED IN RESEARCH

material and energy efficient strategy

avoid waste production

solar + limited nuclear energy

material 100% in-situ

recyclable structure / material

weathers when abandoned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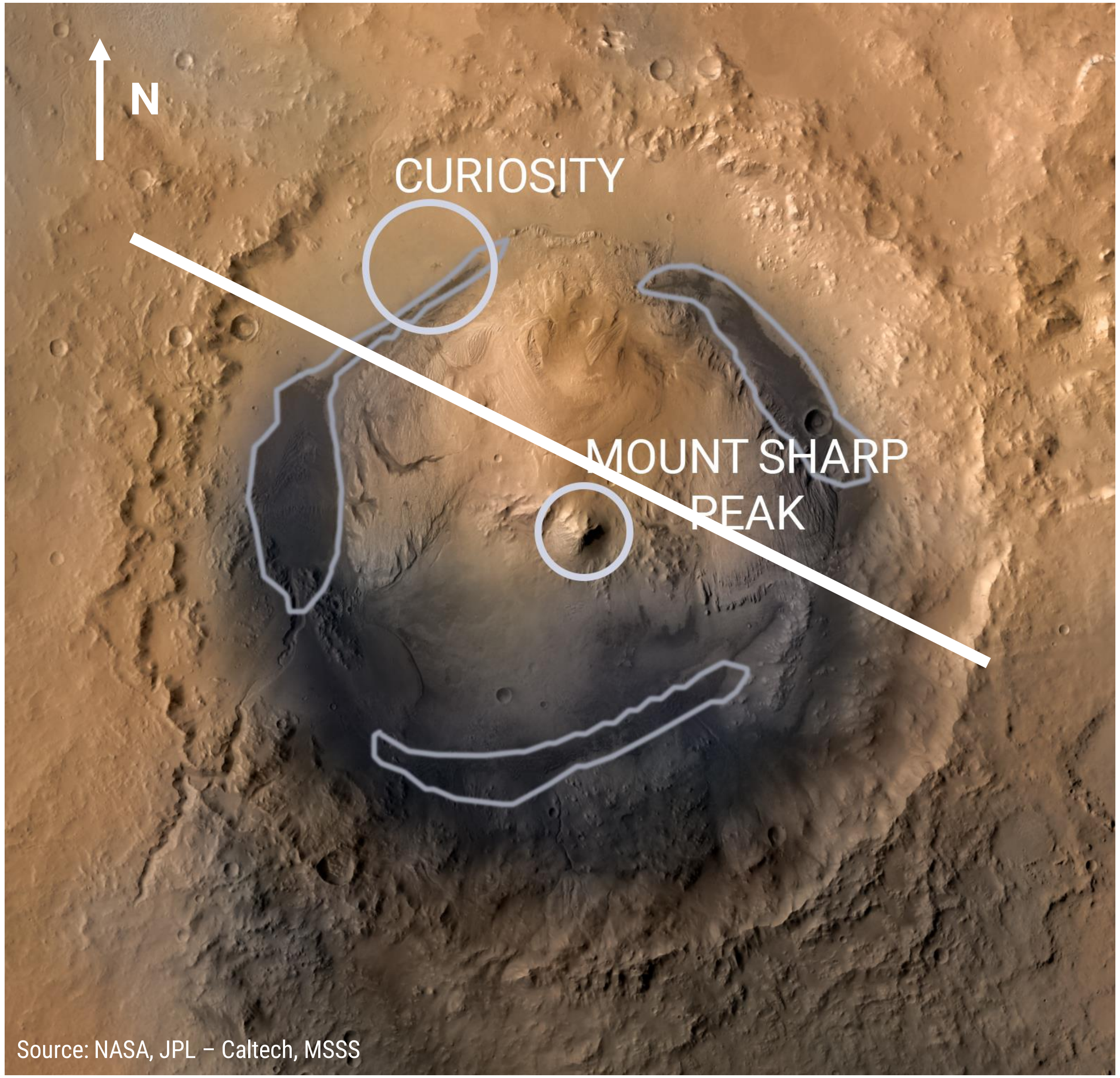
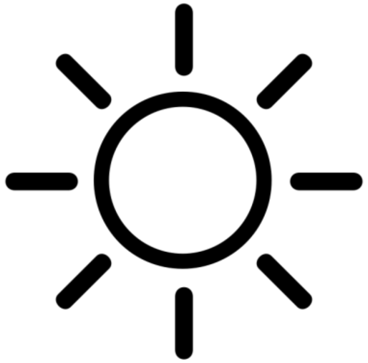
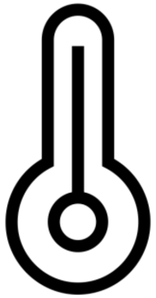




- daily solar power output:
  1034 W/m^2 - 1470 W/m^2



- average temperature:
  -70˚C - 0˚C

- wind speed:
  4m/s – 25m/s

Simulant preparation

ROCKNEST NAMIB

available on Earth

SIMULANT, MGS-1	
Mineral	**Weight %**
70%	
Sodic Plagioclase	41,6
Highly Forsteritic Olivine	21
single bronzite-variety pyroxene	31
Magnetite (as black iron oxide)	2,9
Anhydrite	1,3
Hematite (as red iron oxide)	1,7
30%	
Ferrihydrite	4
Basaltic Glass	65
Hydrated Silica (as diatomaceous earth)	14
ferric-sufate (iron (III) sulfate pentahydrate)	20
Fe-carbonate (siderite)	4

Source: Cannon K. et.al., 2019

Cannon, et.al. (2019). Mars global simulant MGS-1: A Rocknest based open standard for basaltic martian regolith simulants.

Addition of water on Earth

Source: M.Timothy O'Keefe/Getty Images

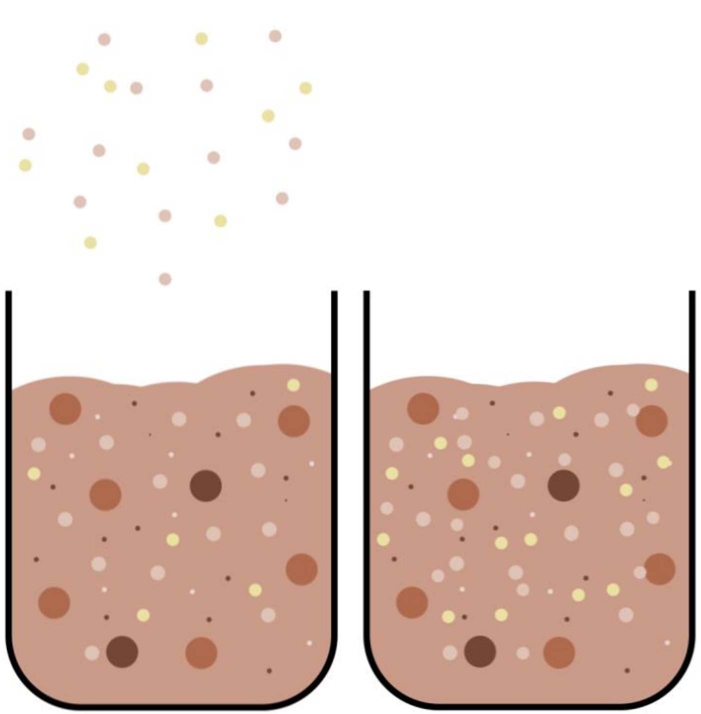
Source: Green Building

What could be the binder on Mars ?

Source: Cannon K. et.al., 2019

Potential binders

1

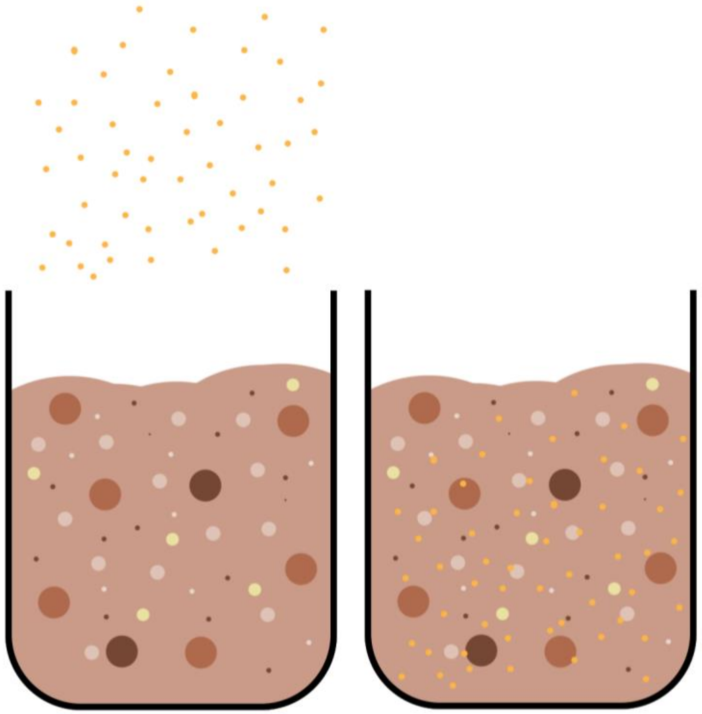


lowest melting point

Plagioclase – 600-800˚C

Ferric-sulfate – 480˚C

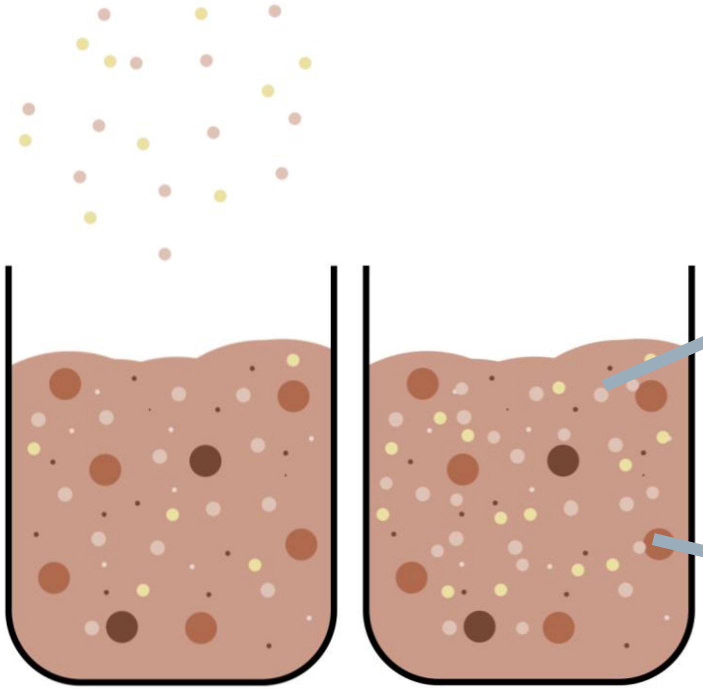
2



molten sulfur

Sulfur – 120˚C

Potential binders

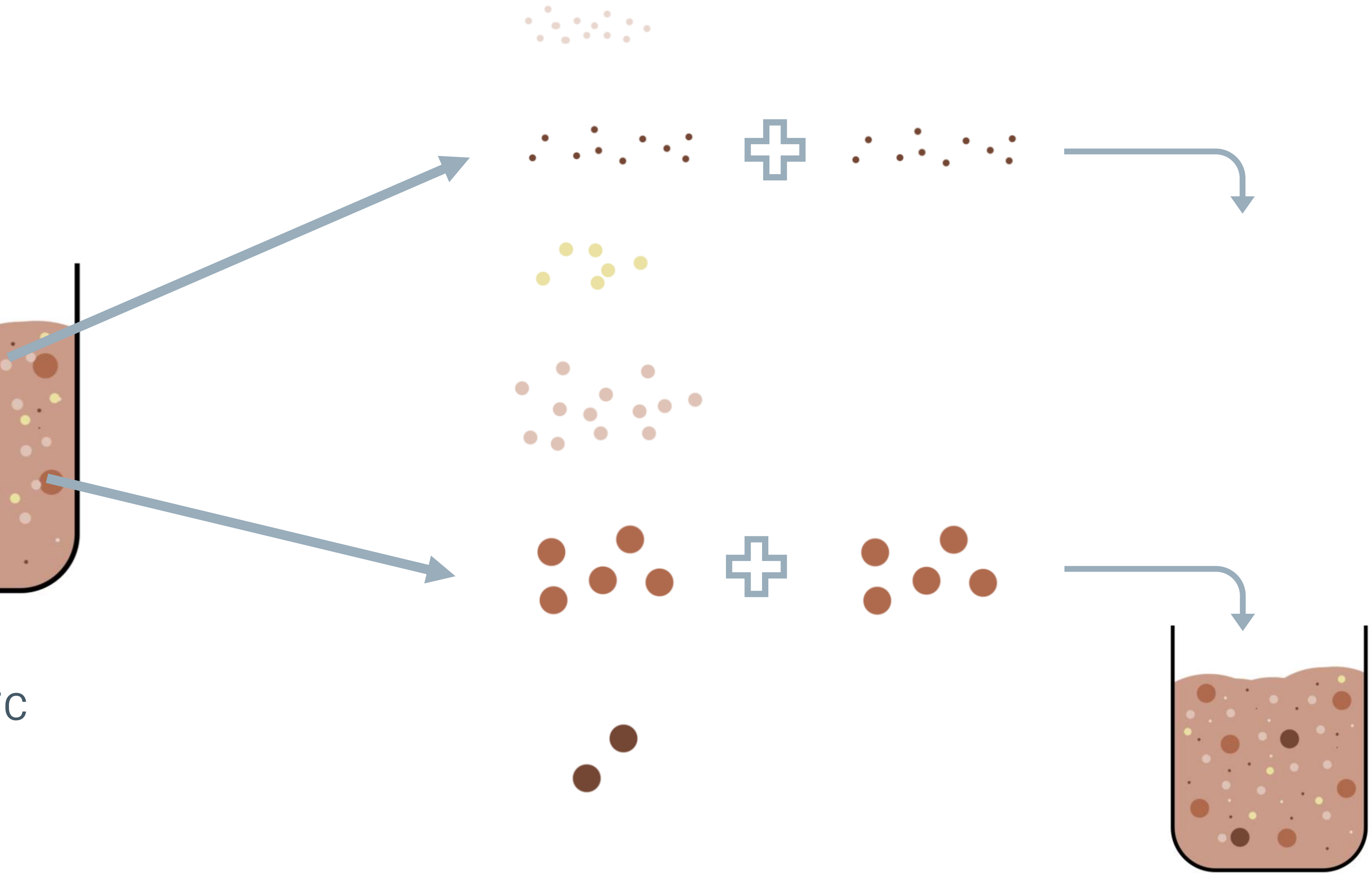


lowest melting point

Plagioclase – 600-800˚C

Ferric-sulfate – 480˚C

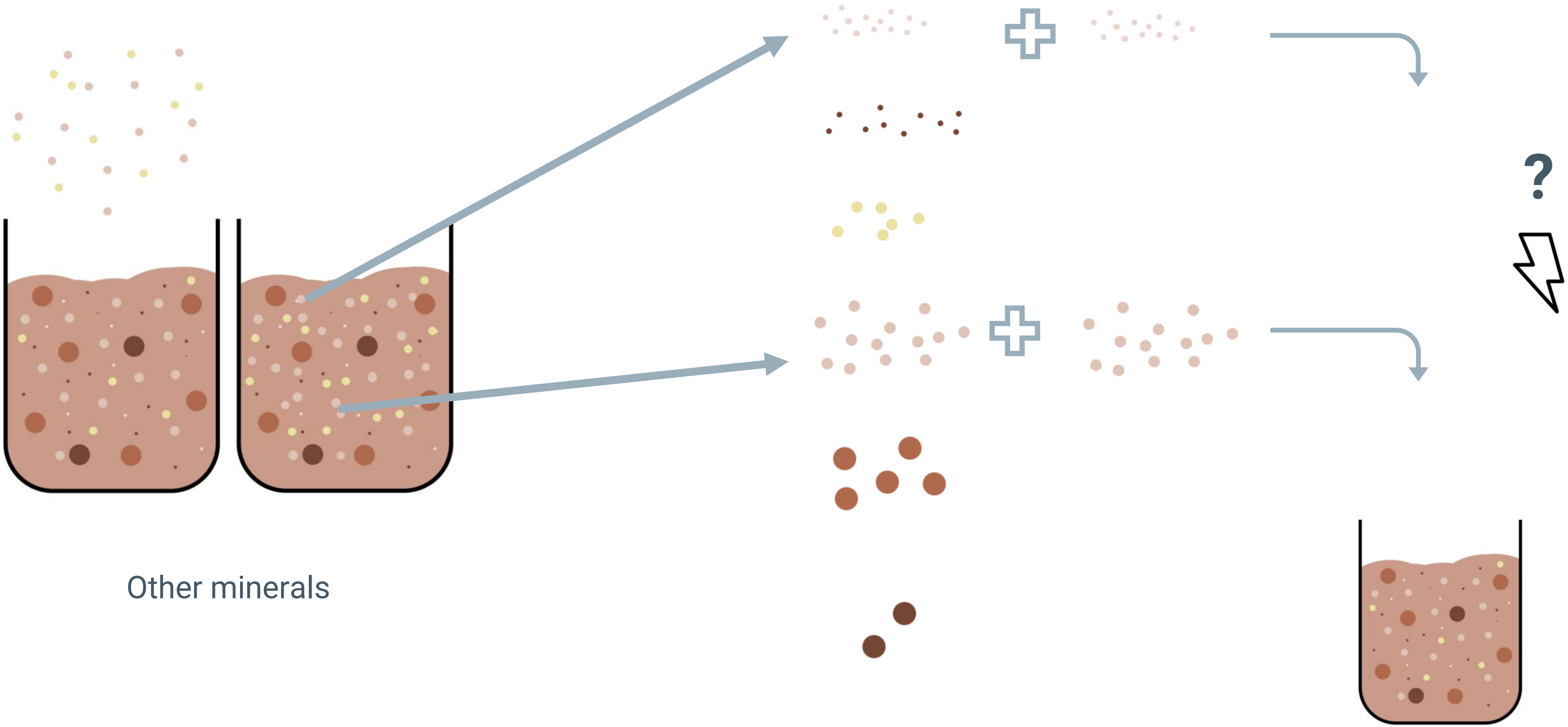
Grain size - sieving



Research: Achilles, et.al. (2017). Mineralogy of an active eolian sediment from the Namib dune, Gale crater, Mars

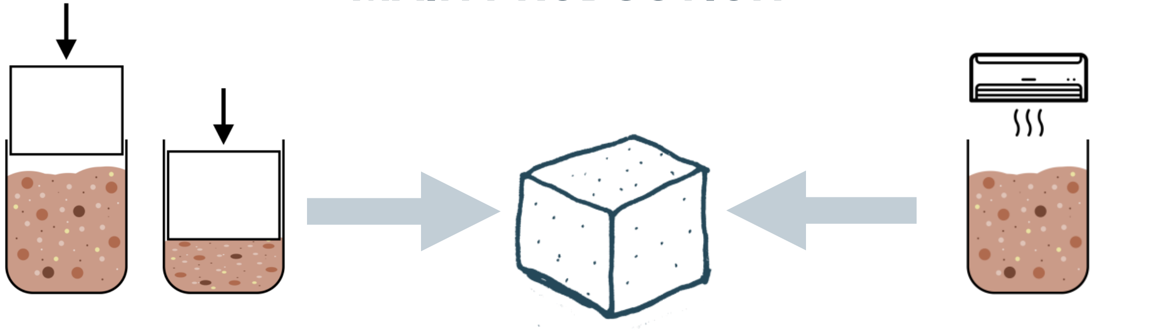
Potential optimization

Grain size sieving



Other minerals

MAIN PRODUCTION



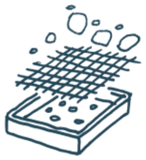
Compression

Thermal treatment

ADDITIONAL PROCESSES – PREPARATION AND OPTIMIZATION

Mixing

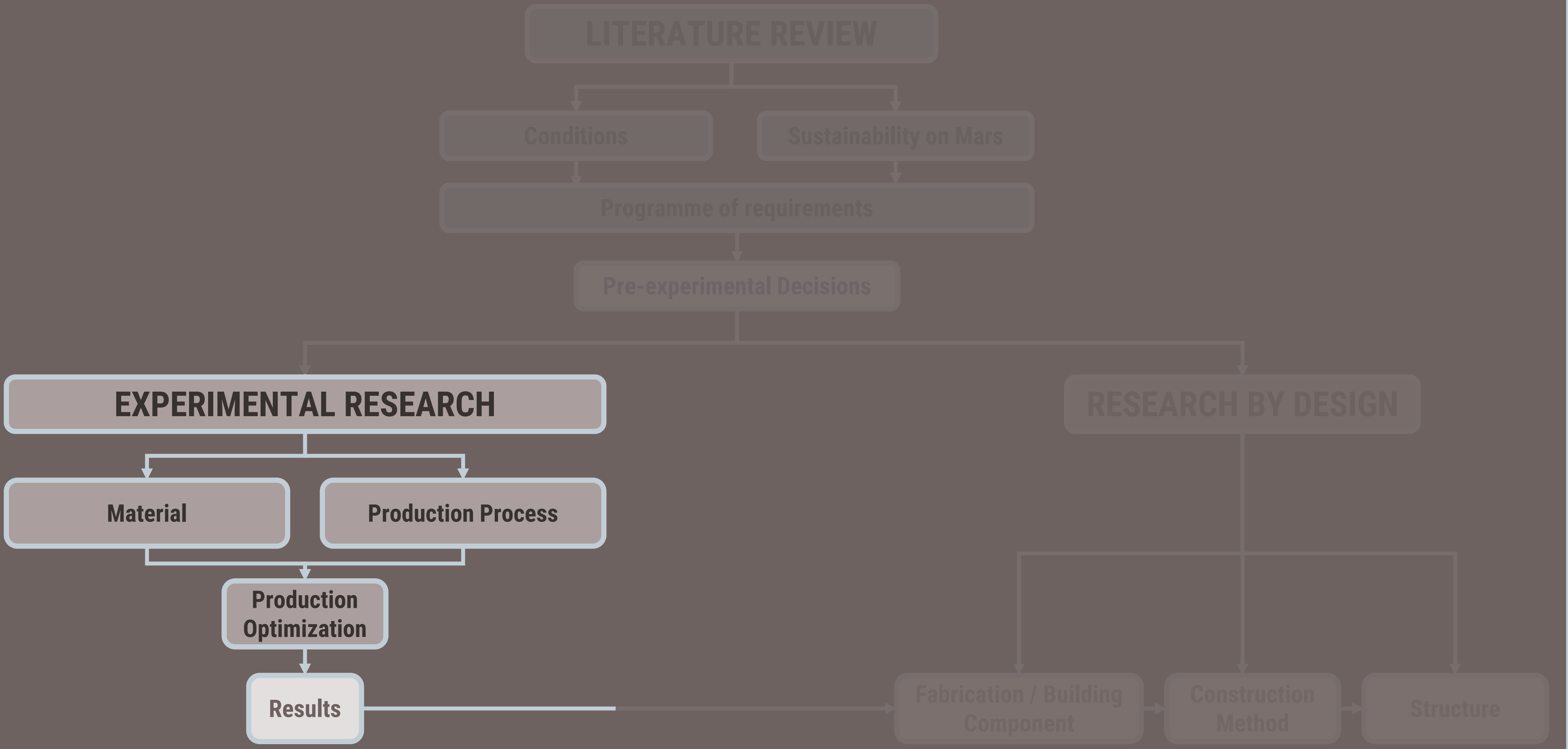
Particles size reduction



Sieving

BUILDING COMPONENT

- Compressive strength : 1,5 – 2 MPa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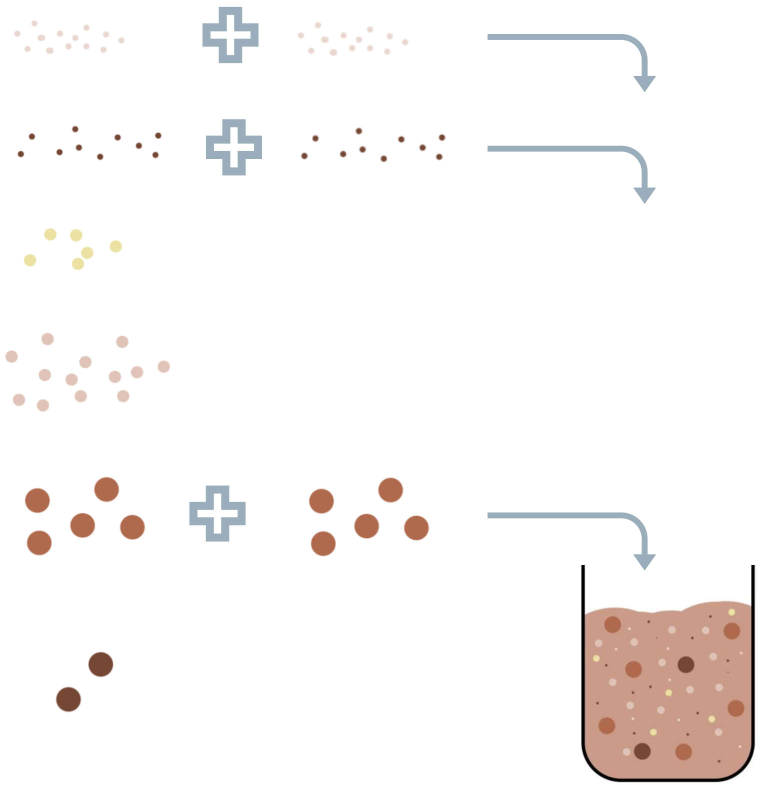
EXPERIMENTS -METHODOLOGY

STEP

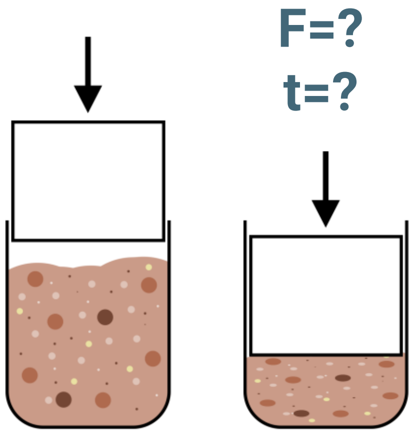
PREPARATION

GRAIN SIZES | MIXING | BATCHES



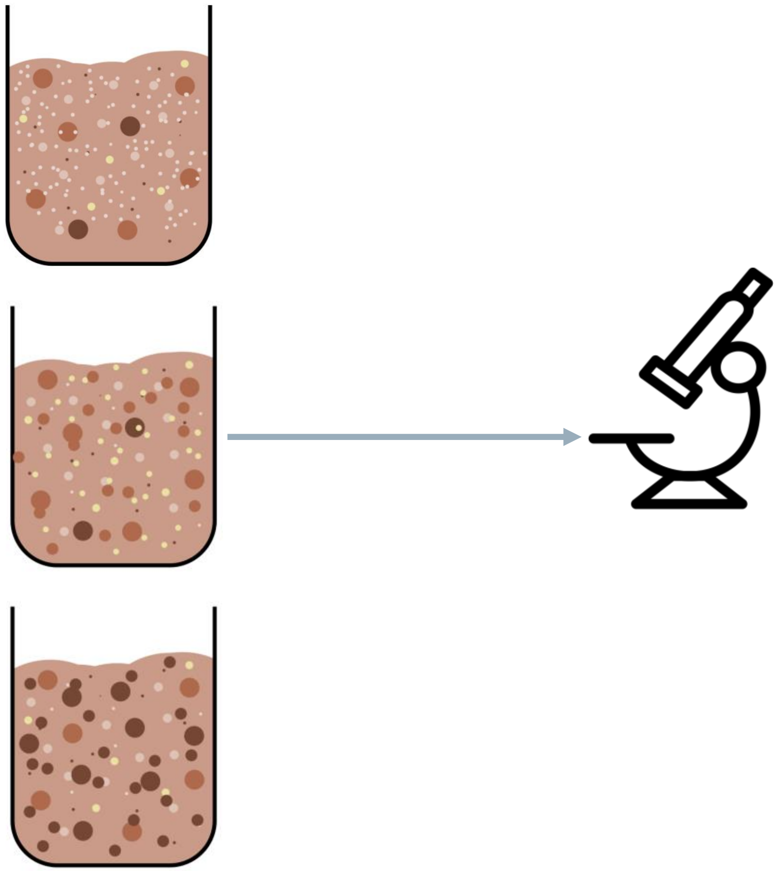
PILOT TEST

COMPRESSION



OPTIMISATION

DIFFERENT BATCHES | MICROSCOPIC ANALYSIS

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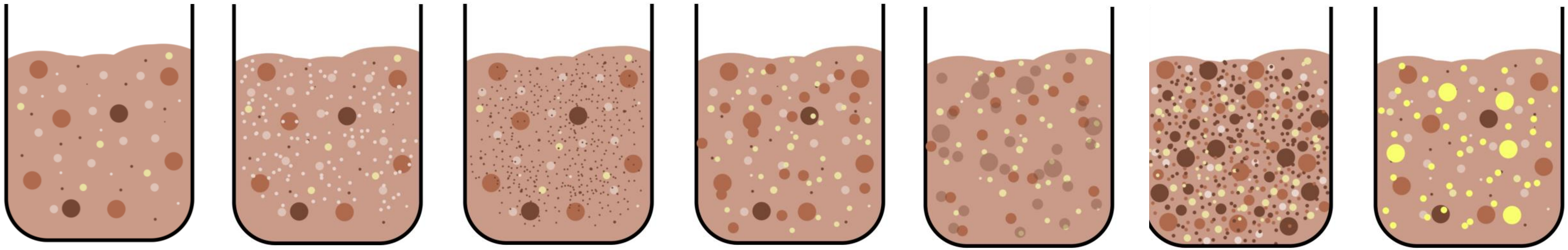
Compositions

1	2	3	4	5	6	7
original	+5% amorphous phase	+5% nano-particle ferric oxide	+ 5% albite	+5% ferric-sulfate	particle packing method	+ sulfur powder (10, 20, 30, 50%)



comparison

improved results of the compression process

minerals with lowest melting point

more compact material

molten sulfur as a binder

Chow, et al., 2017, "Direct formation of structural components using a martian soil simulant"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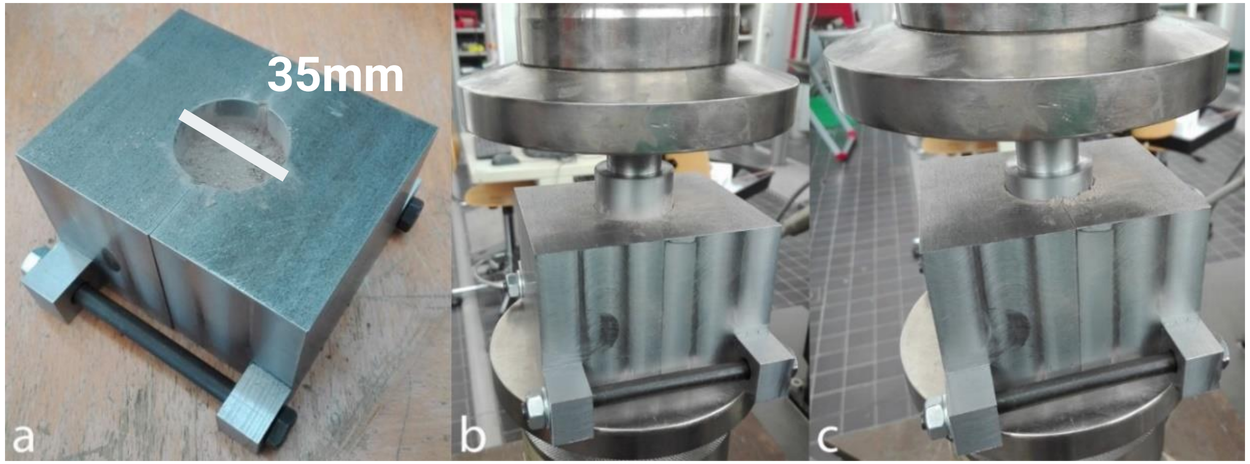
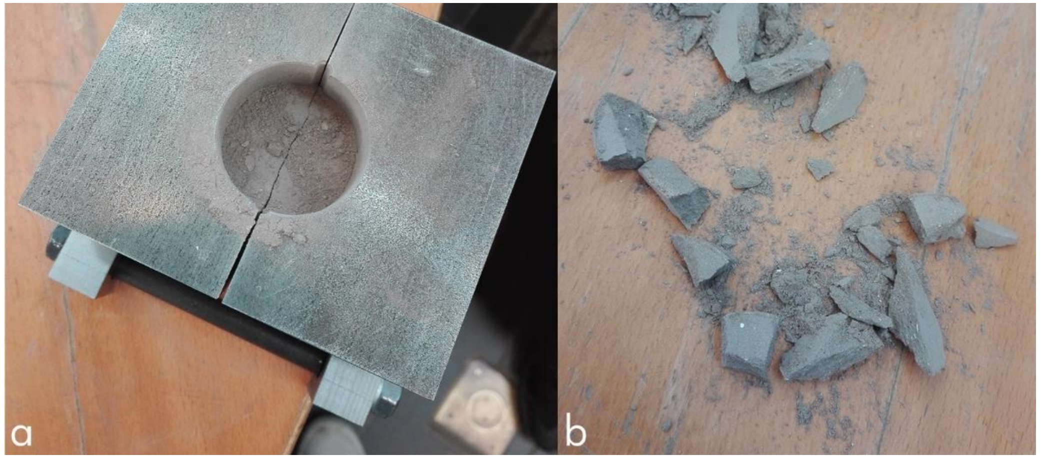
1. PILOT TEST





F = 9,5 kN
t = 10 min (later 5)

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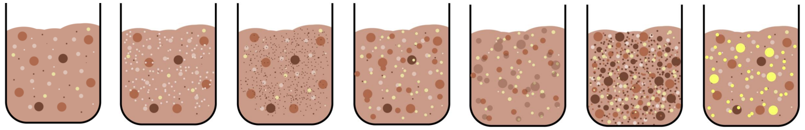
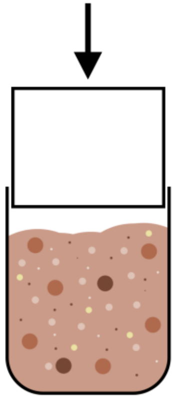
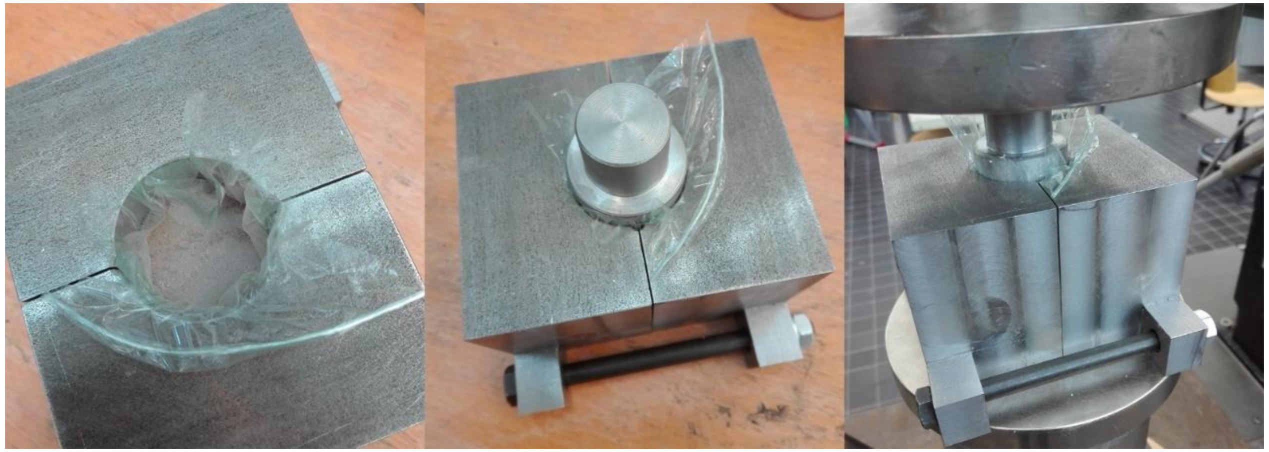
EXPERIMENTS - DIFFERENT BATCHES

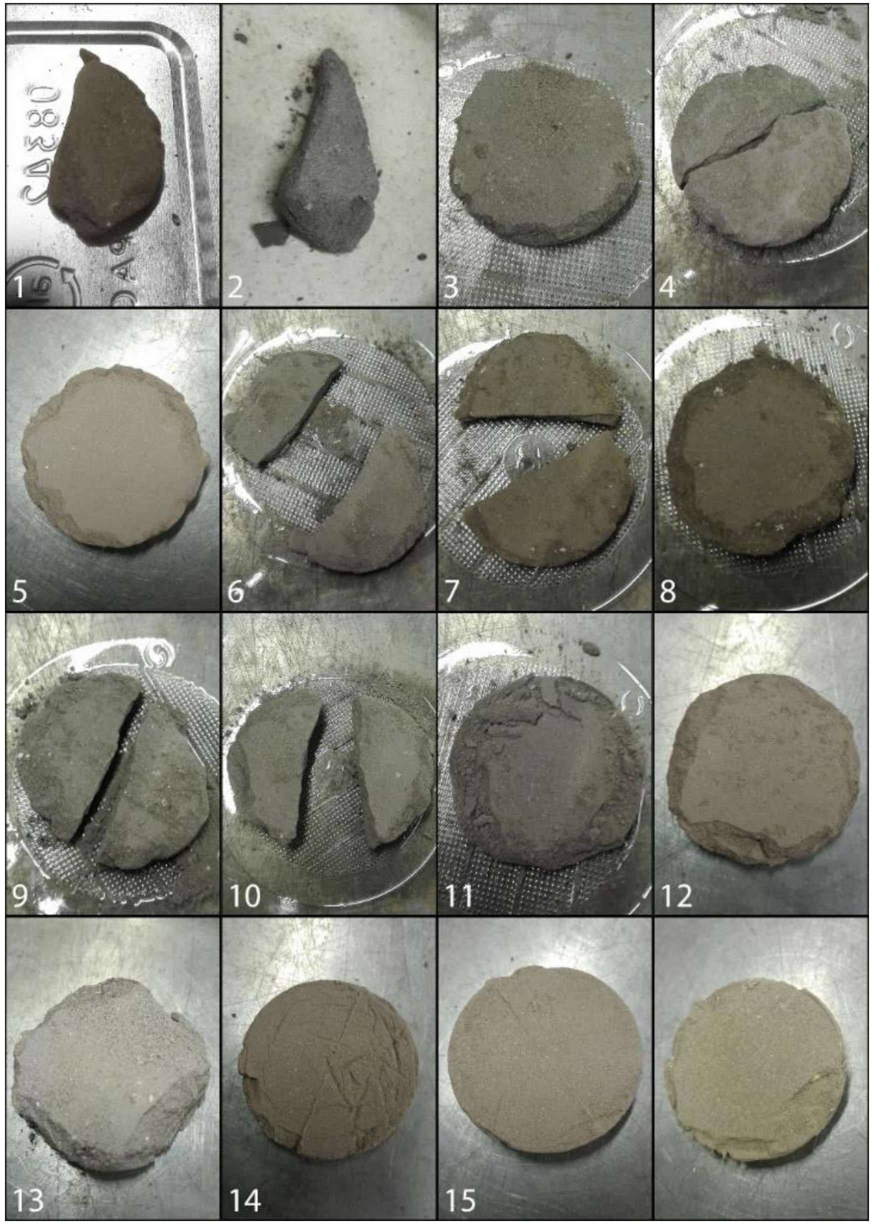
COMPRESSION PROCESS





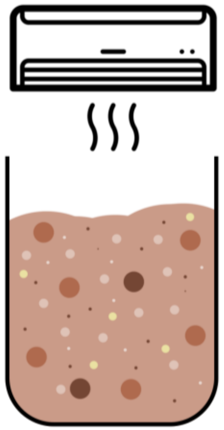
F=95000 N
t= 10min

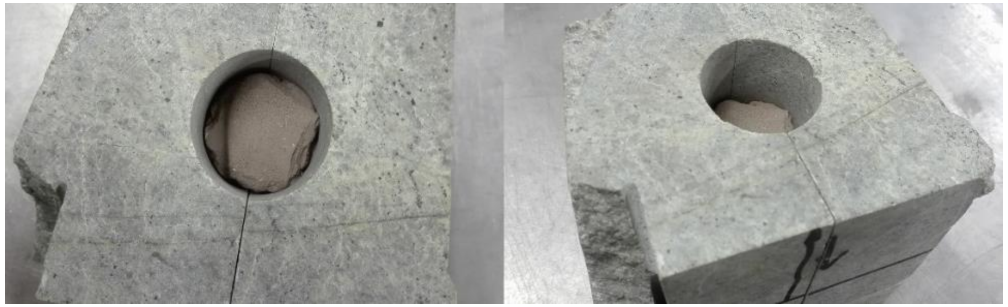


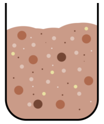


EXPERIMENTS - DIFFERENT BATCHES

THERMAL TREATMENT







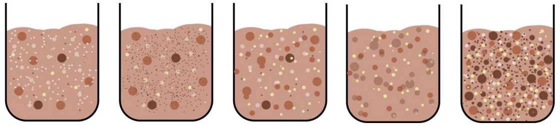
batch 1

0°C

600°C

800°C

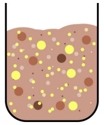
1000°C



batch 2-6

0°C

600°C



batch 7

10%

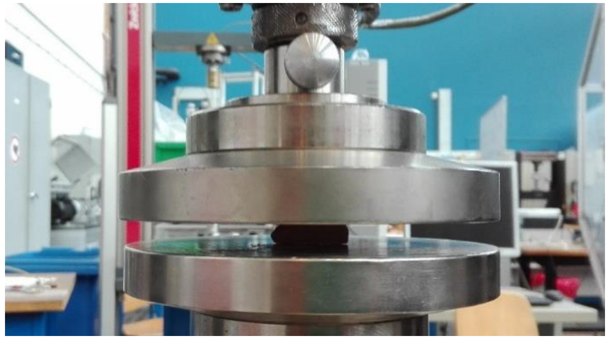
20%

30%

50%

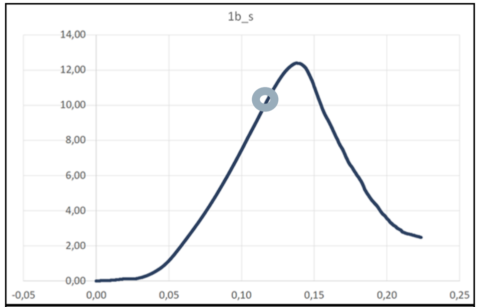
EXPERIMENTS - DIFFERENT BATCHES

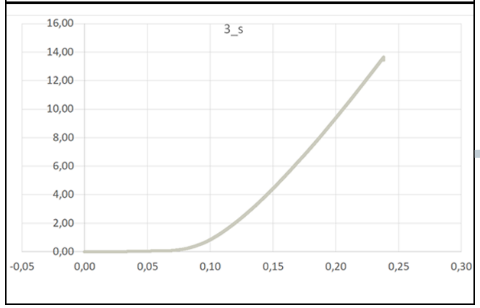
COMPRESSION TEST



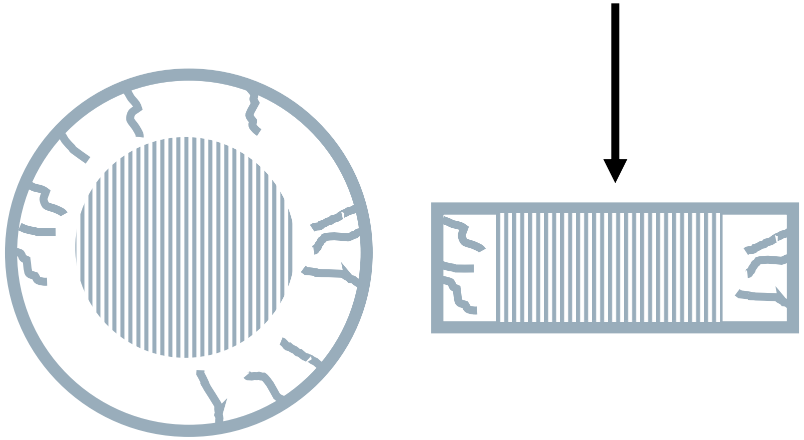
STRESS/STRAIN GRAPH

x 2 load settings impact

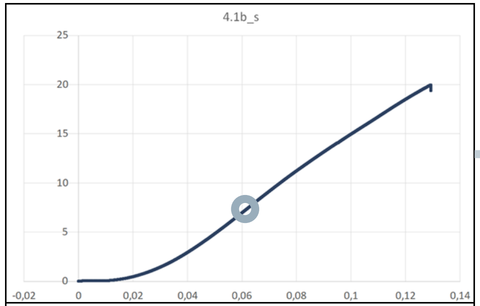




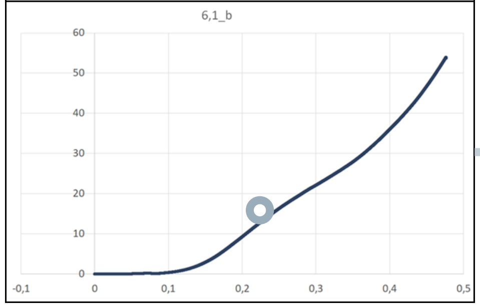
no break in second loading



shape impact

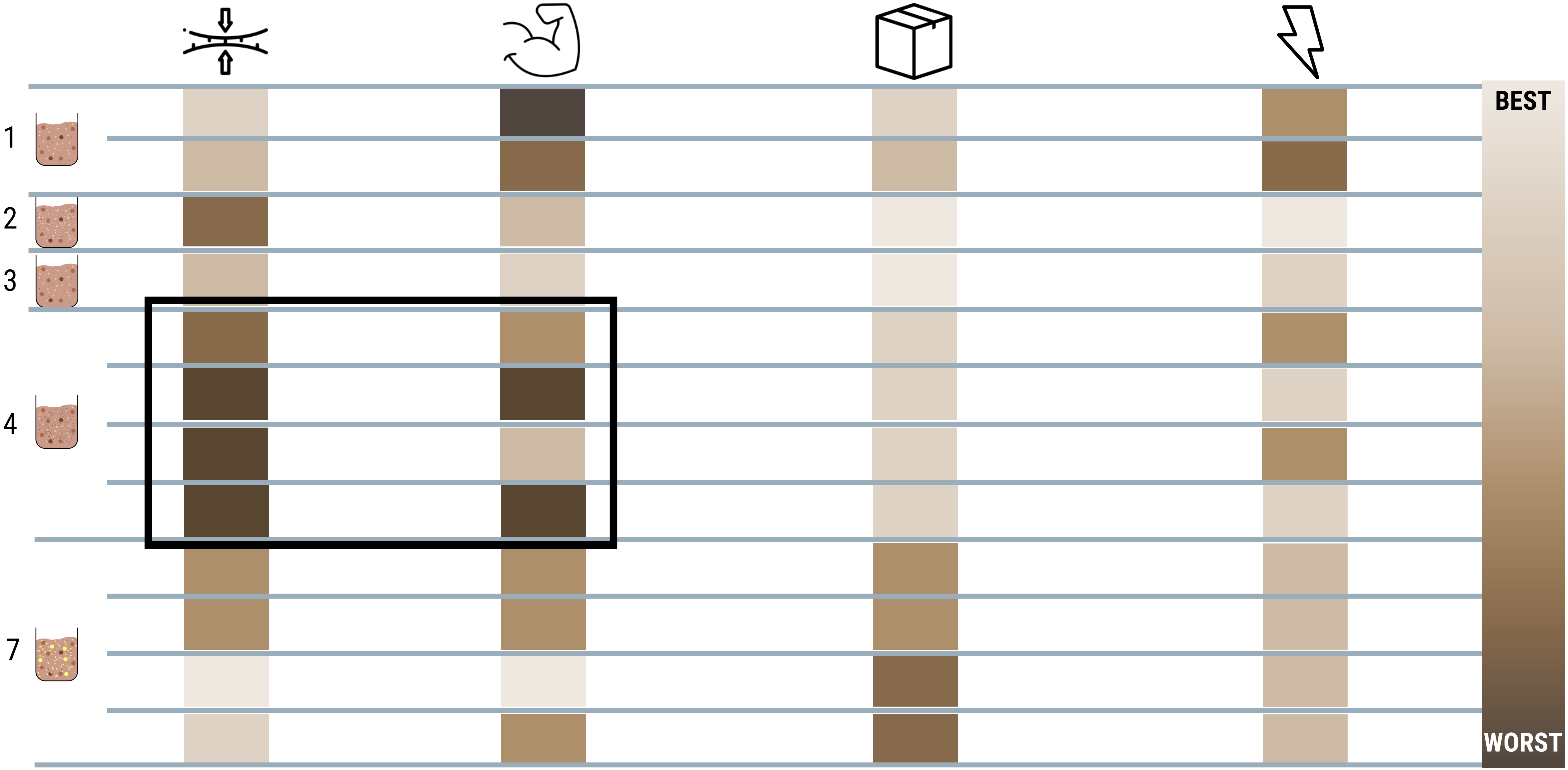


first changes in graph – edges cracked

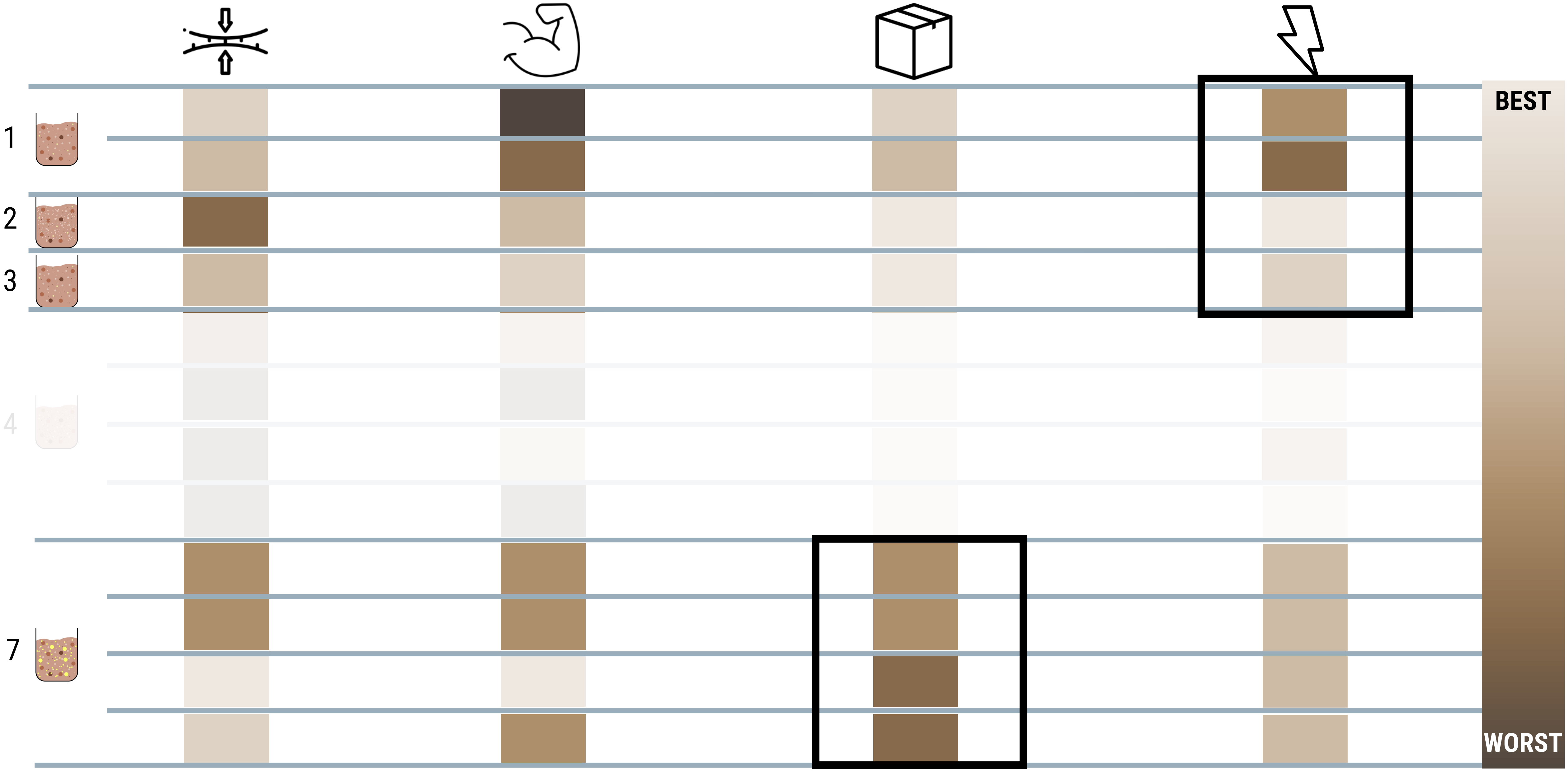


edges cracked central hardened

EXPERIMENTS - DIFFERENT BATCHES

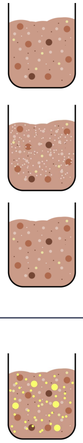


EXPERIMENTS - DIFFERENT BATCHES



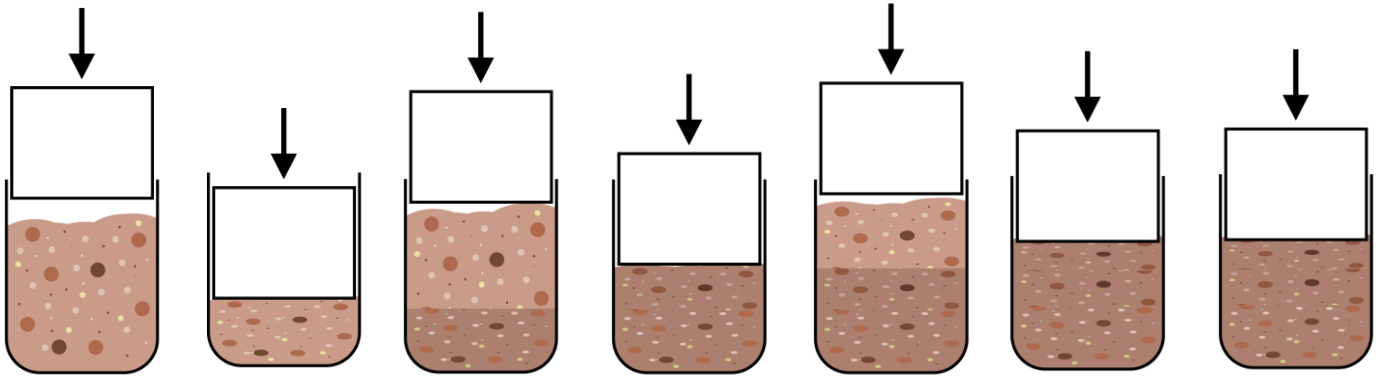
EXPERIMENTS - SCALING UP

SAMPLES



1, 2, 3	0˚C	300˚C	600˚C		
7	5	7	10	30	%

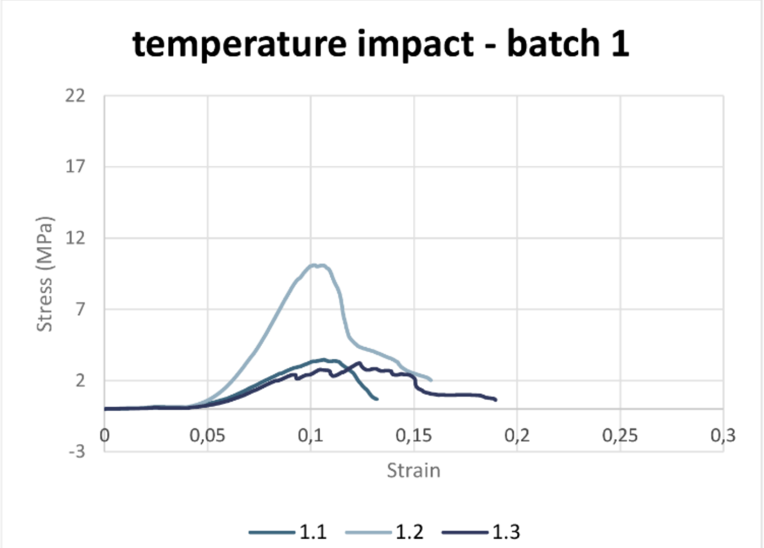
LOADING SETTINGS



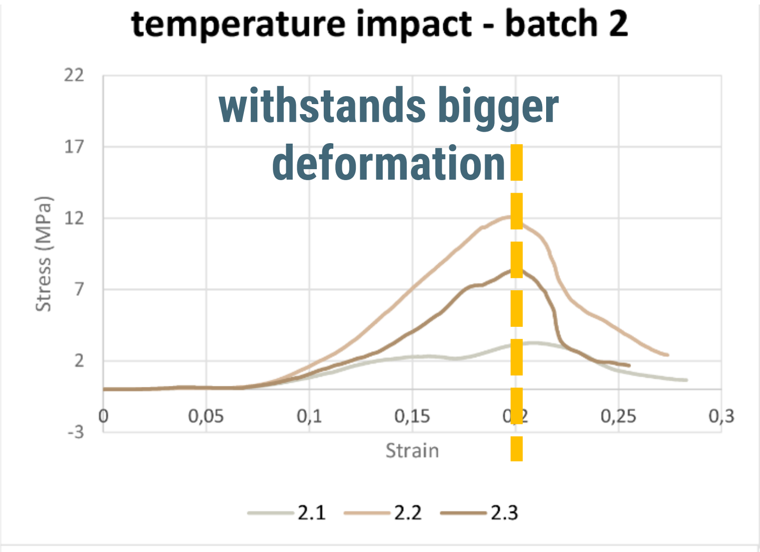
10kN 30s — refill — 10kN 30s — refill — 10kN 30s — 95kN 300s

EXPERIMENTS - SCALING UP – MECHANICAL TESTS - RESULTS

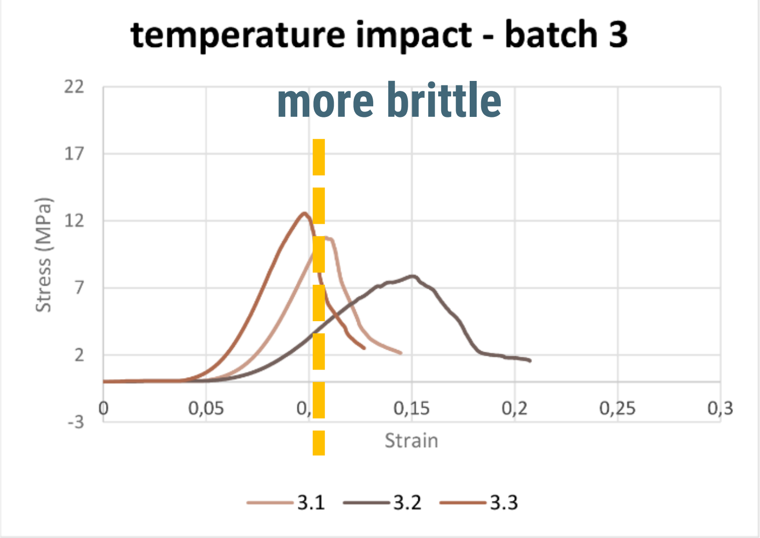
COMPRESSION TEST – STRESS/STRAIN GRAPHS



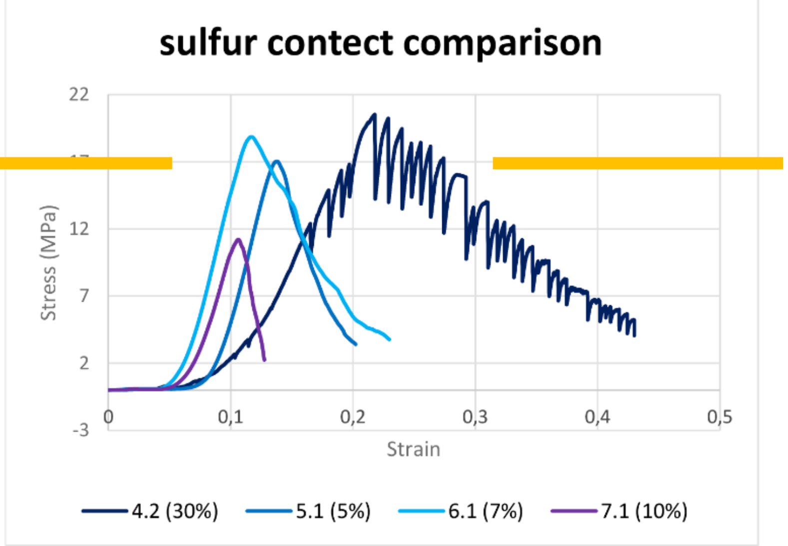
+5% amorphous phase



+5% nano-particle ferric oxide



highest peaks



withstands small cracks

+ sulfur powder (10, 20, 30, 50%)

		MPa	
1	0°C	0,63	✖
	300°C	0,50	✖
	600°C	2,30	
2	0°C	0,45	✖
	300°C	1,75	
	600°C	2,78	
3	0°C	2,53	
	300°C	2,75	
	600°C	1,75	
7	S 5%	4,00	
	S 7%	4,00	
	S 10%	2,50	
	S 30%	3,05	

compressive strength 1,5 – 2 MPa

BEST

WORST

EXPERIMENTS - SCALING UP – MECHANICAL TESTS - RESULTS

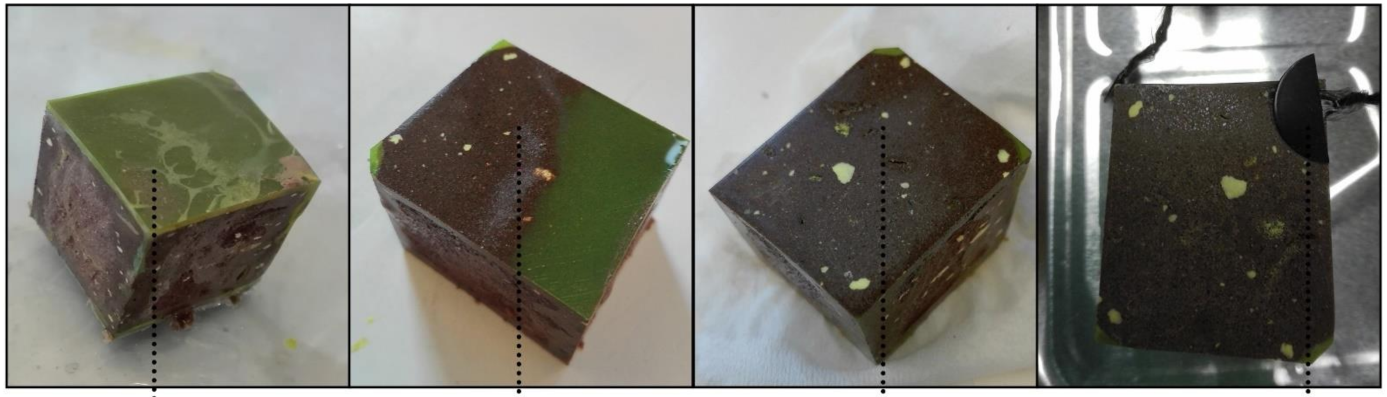
1	0°C	0,63
	300°C	0,50
	600°C	2,30
2	0°C	0,45
	300°C	1,75
	600°C	2,78
3	0°C	2,53
	300°C	2,75
	600°C	1,75
7	S 5%	4,00
	S 7%	4,00
	S 10%	2,50
	S 30%	3,05

BEST

WORST

ESEM – ENVIRONMENTAL SCANNING ELECTRON MICROSCOPE

SAMPLE PREPARATION STEPS



epoxy layer after impregnation

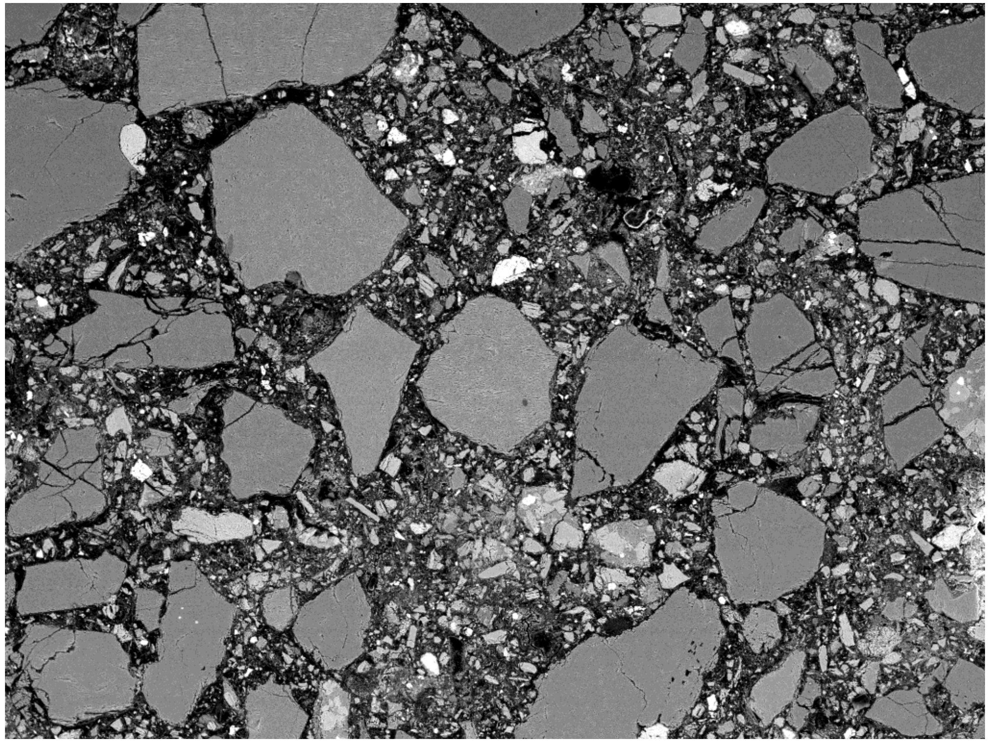
grinding and polishing

placing micro layer of conductive carbon

prepared sample for microscopic analysis, earth connection

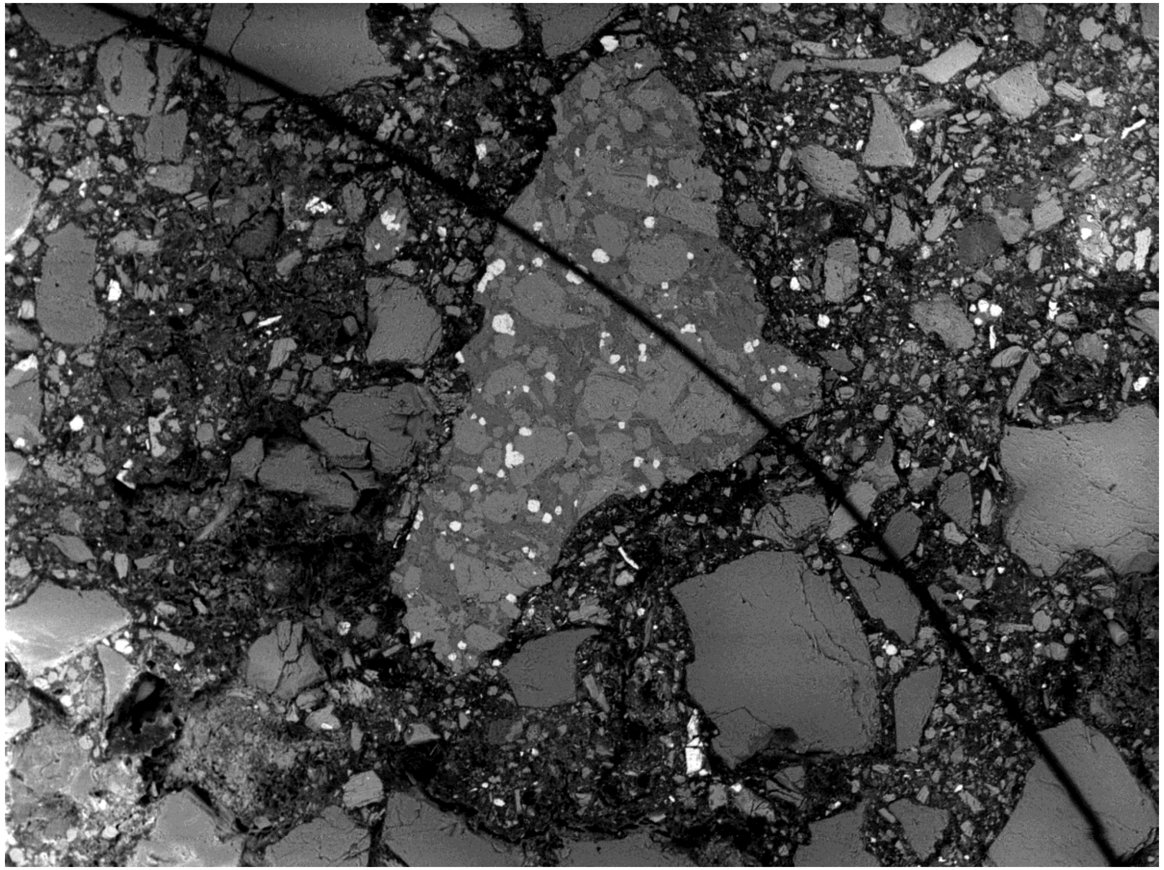
BSE – BACKSCATTERING ELECTRON IMAGING

DENSER MATERIAL = BRIGHTER COLOUR



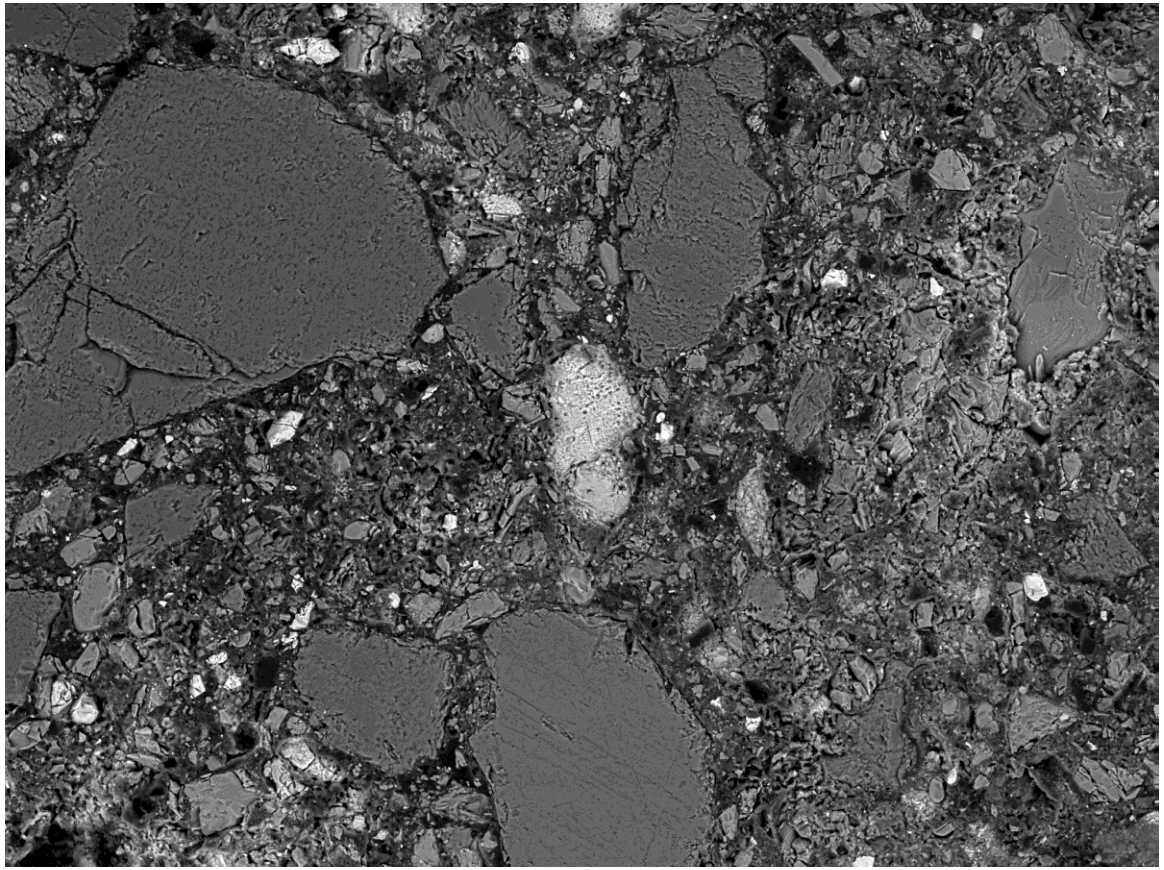
1 NANO-PARTICLE FERRIC OXIDE

HOMOGENOUS COMPOSITION



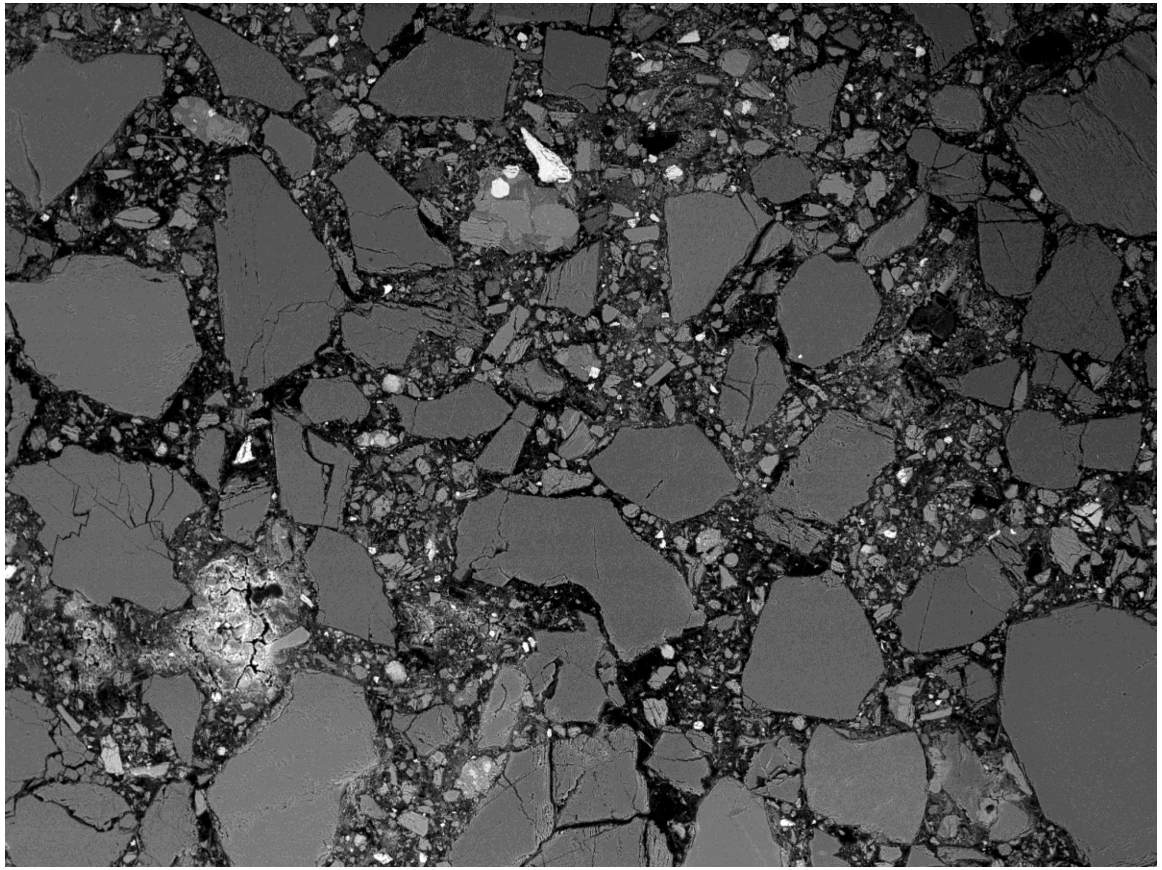
2 5% SULFUR POWDER

HOMOGENOUS COMPOSITION



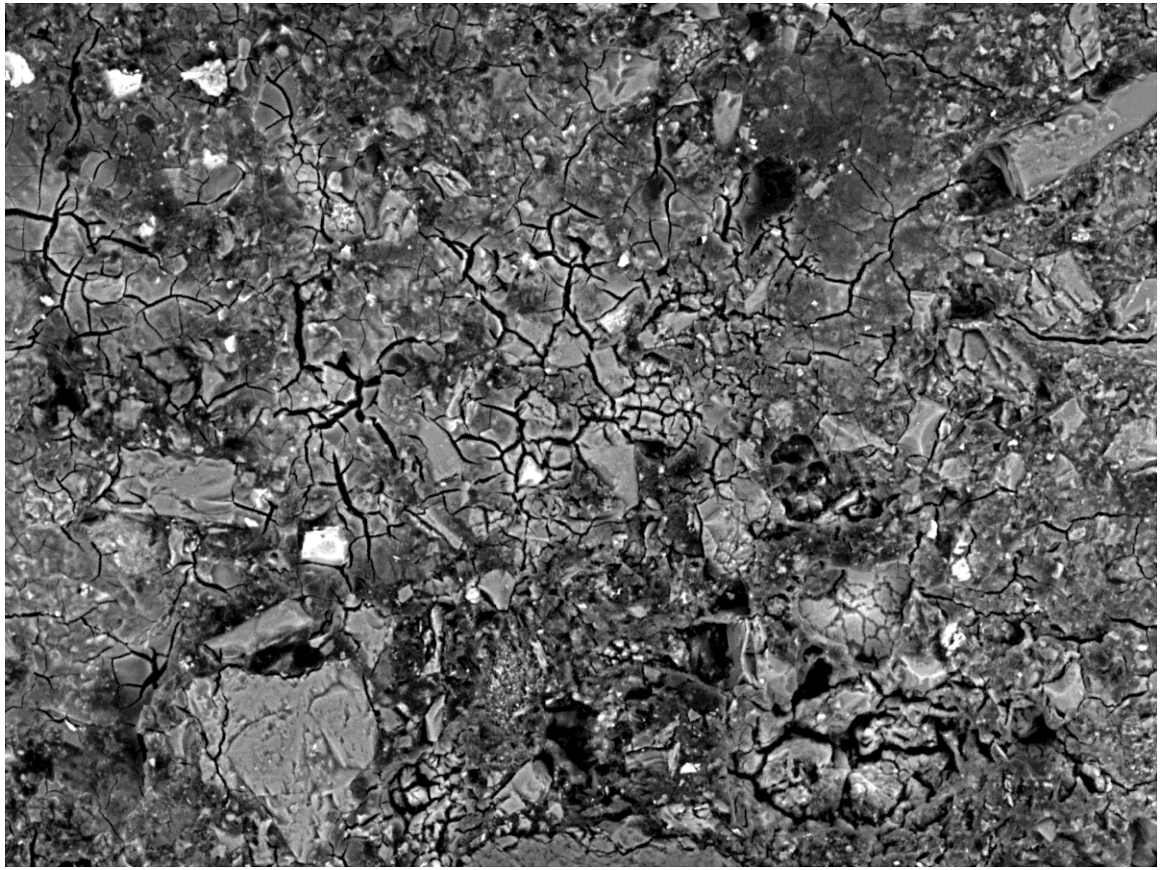
1 NANO-PARTICLE FERRIC OXIDE

CRACKS



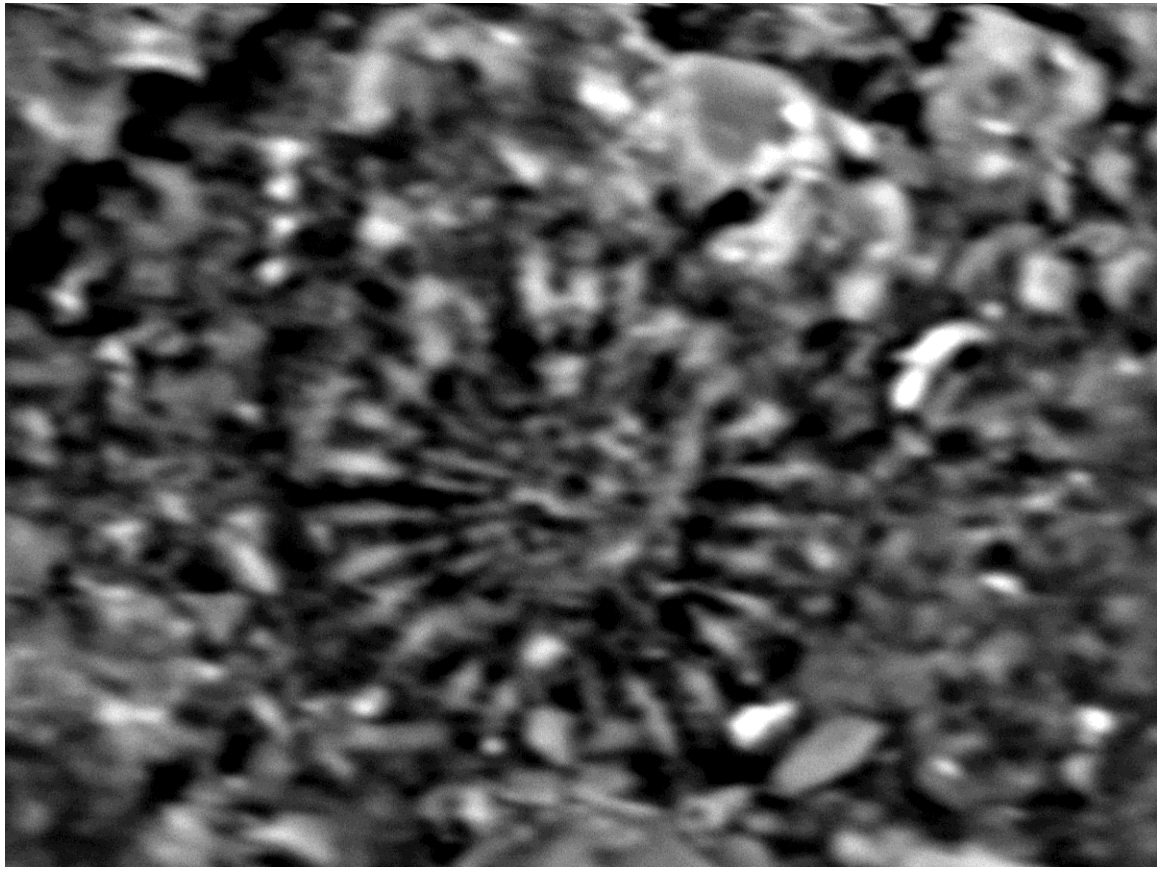
2 5% SULFUR POWDER

CRACKS



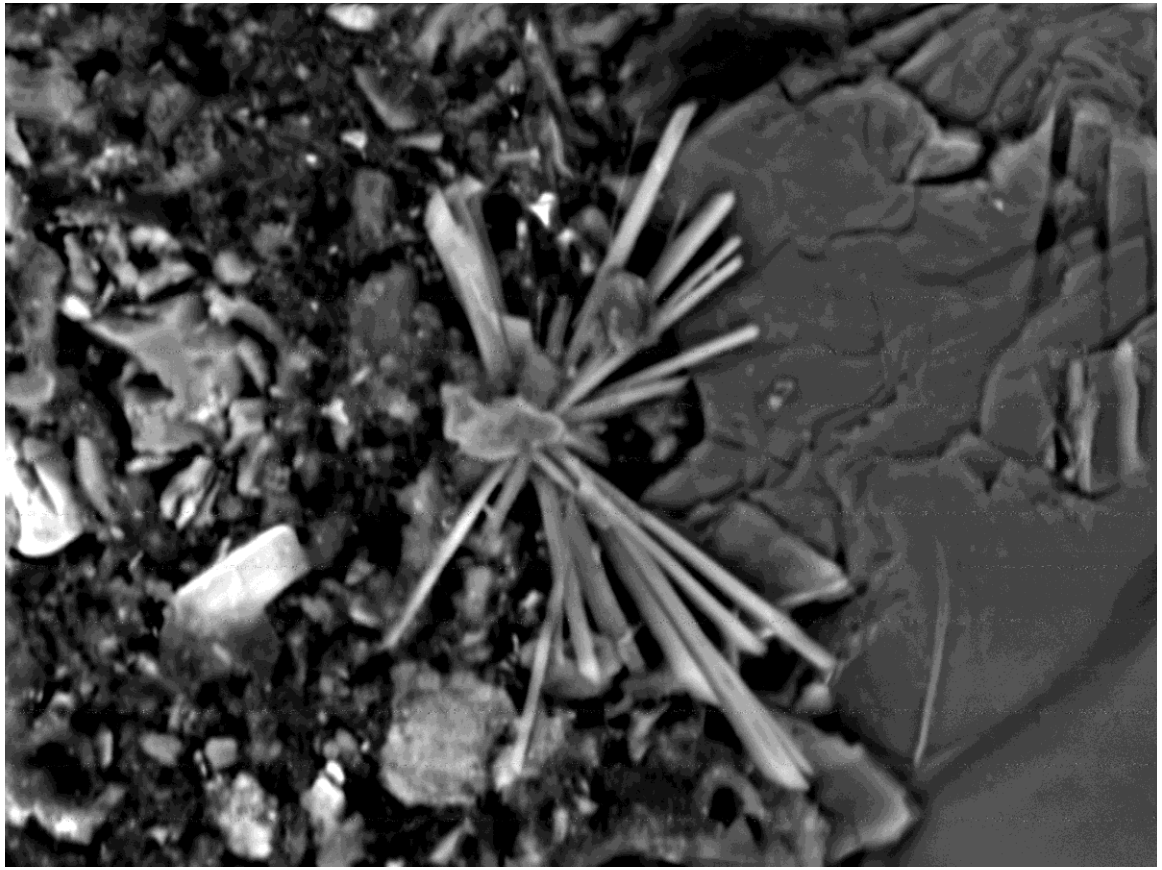
1 NANO-PARTICLE FERRIC OXIDE

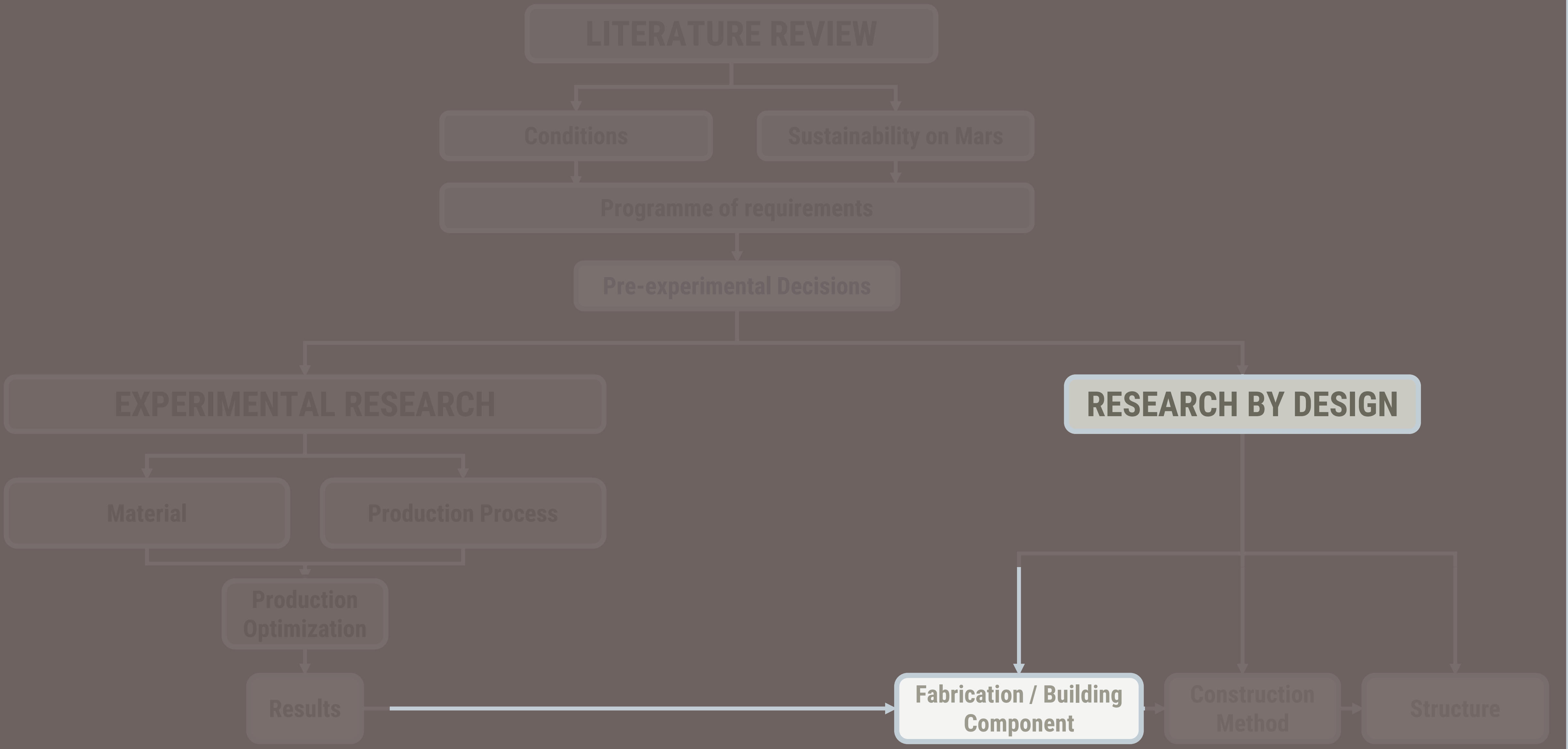
CHARACTERISTIC FORMS



2 5% SULFUR POWDER

CHARACTERISTIC FORMS

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Structure

COMPONENT

- Compressive strength : 1,5 – 2 MPa

CONSTRUCTION METHOD

- Brittle material
- Constructing curved shapes
- Minimized payload, energy demand

STRUCTURE

- Compressive only - vault
- Resistant to loads
- Radiation protection
- Dimensions required for habitable space

OPTIONS

INTERLOCKING

Source: SIAYA Kisumu interlocking bricks

MORTAR

Source: The Constructor. Civil Engineering Home

OPTIONS

ADVANTAGES

Segmentation of the structure	→ Easy construction
Modular, identical shape and size	→ Fast production
No binder or connection required	→ Decomposable structure
Highly tolerant to local failure	→ Structure mechanical resistance

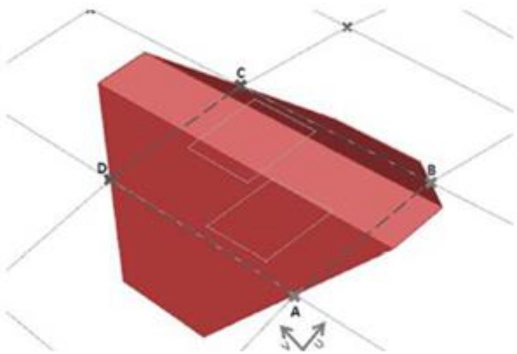
Factors

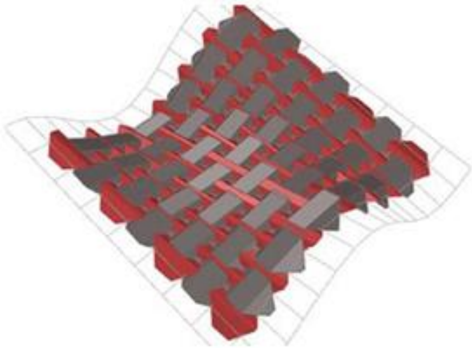
Brittle material

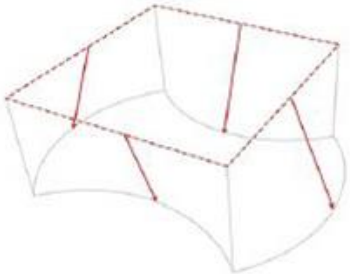
Construct solid forms

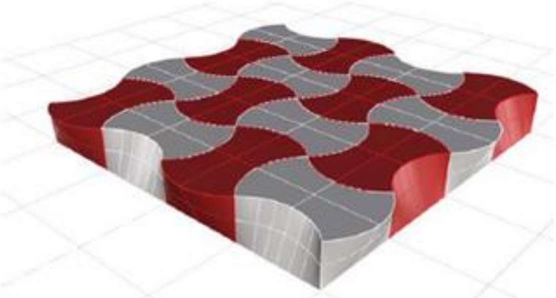
Simple shapes

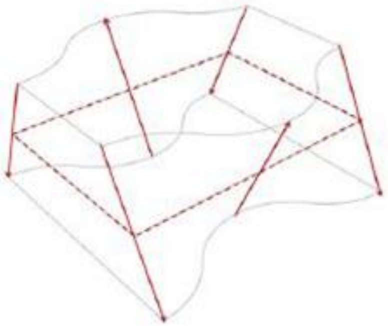
Analysed examples

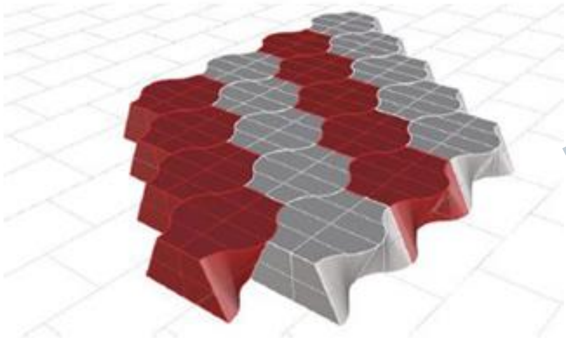


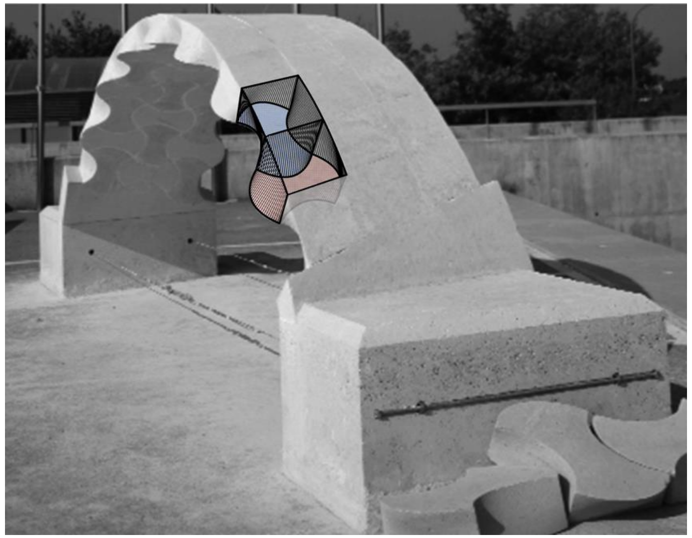








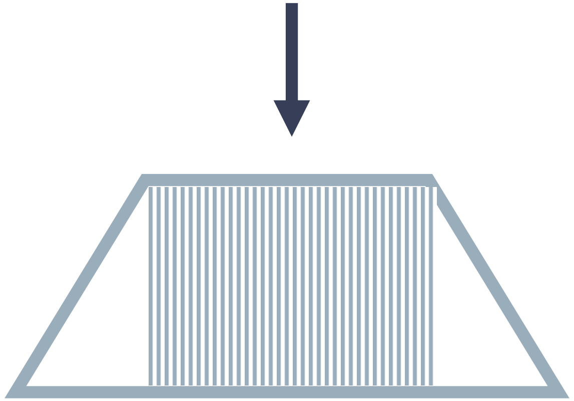


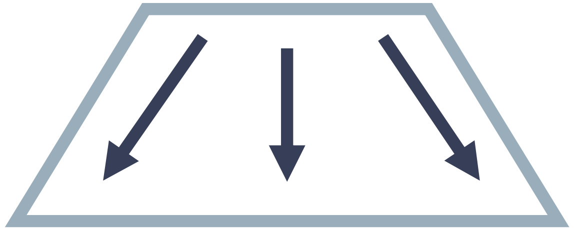


Source: Fallacaras reinterpretation of Truchet vault

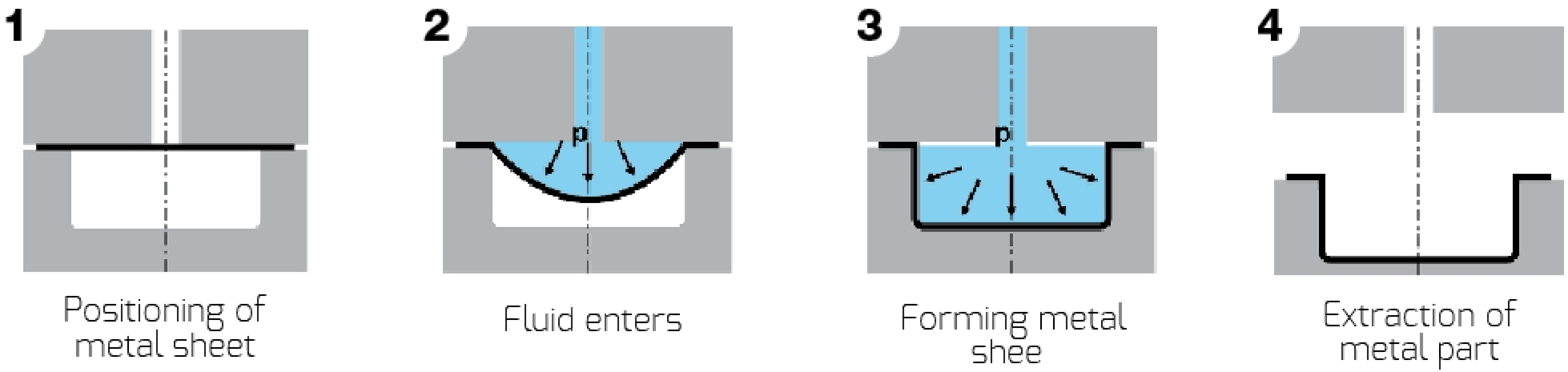
Source: VECO, Marmomacc

FABRICATION PROCESS





ALTERNATIVES FOR FURTHER RESEARCH – RUBBER POD FORMINF, HYDROFORMING

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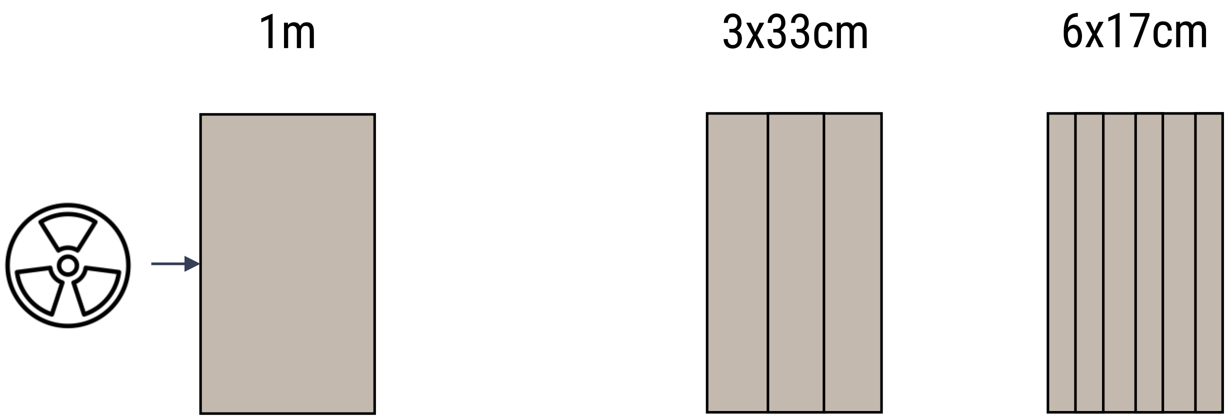
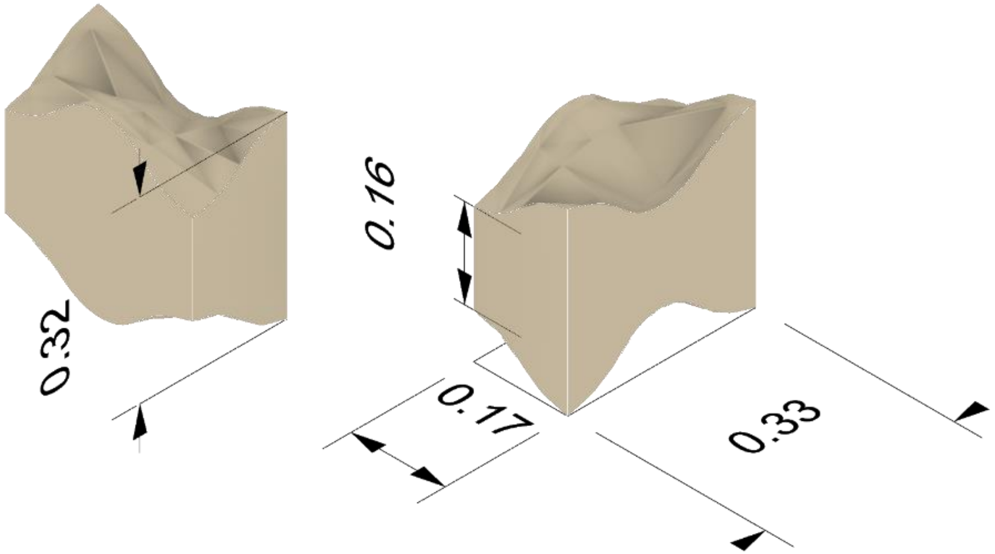
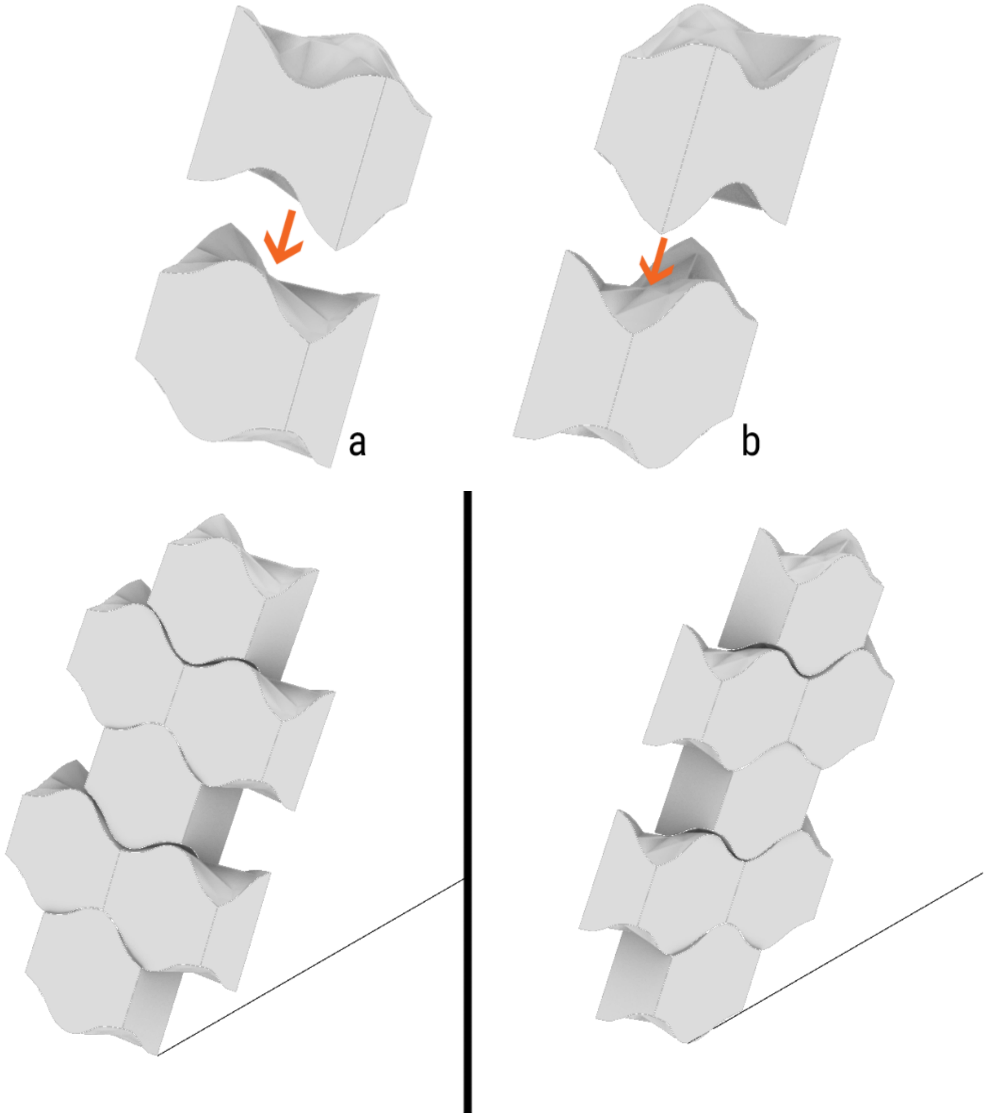
SIZE



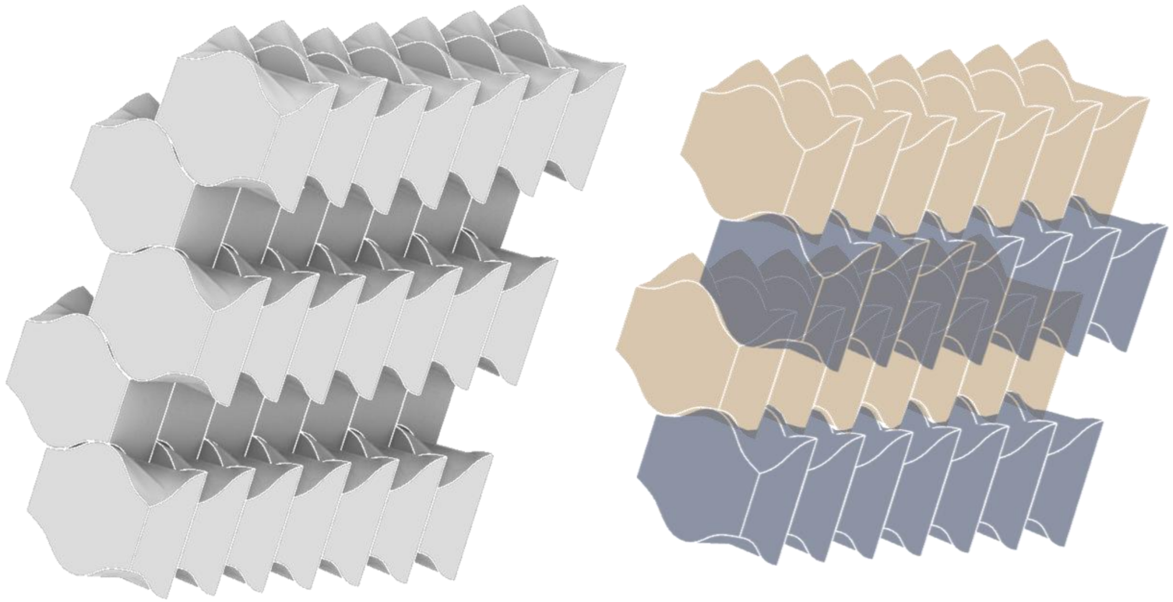


ARCH BUILDING ORIENTATION

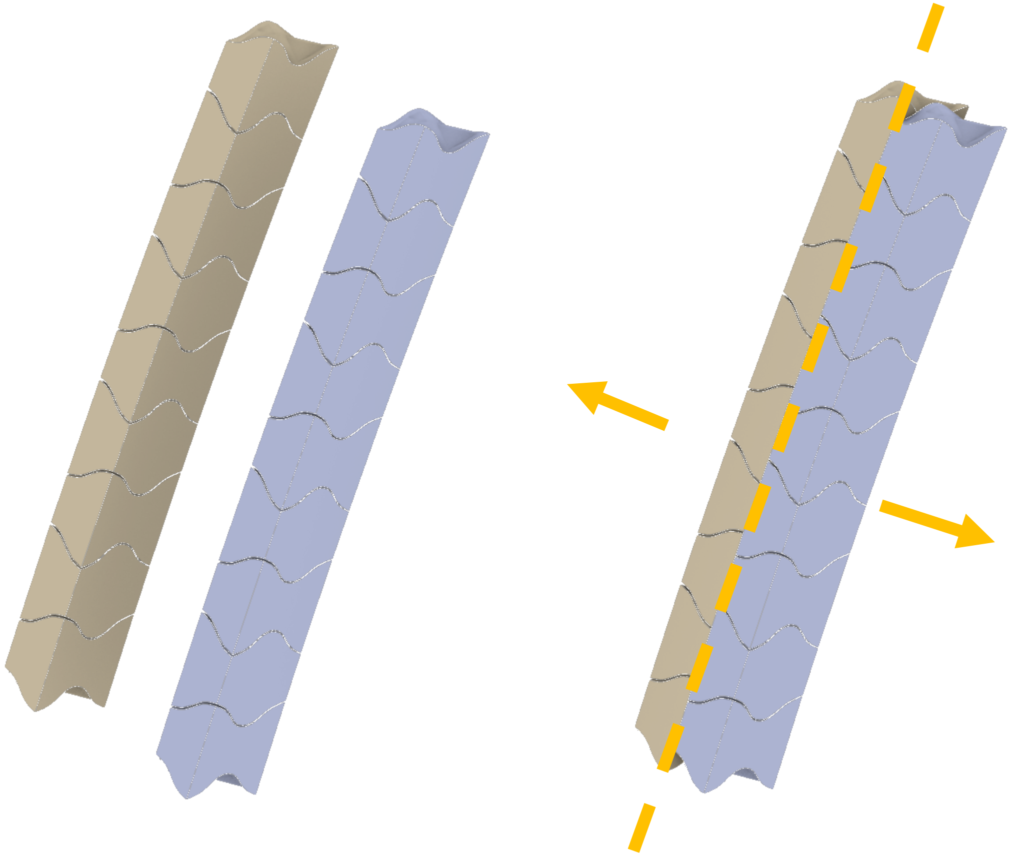


BRICK ORIENTATION OPTIONS

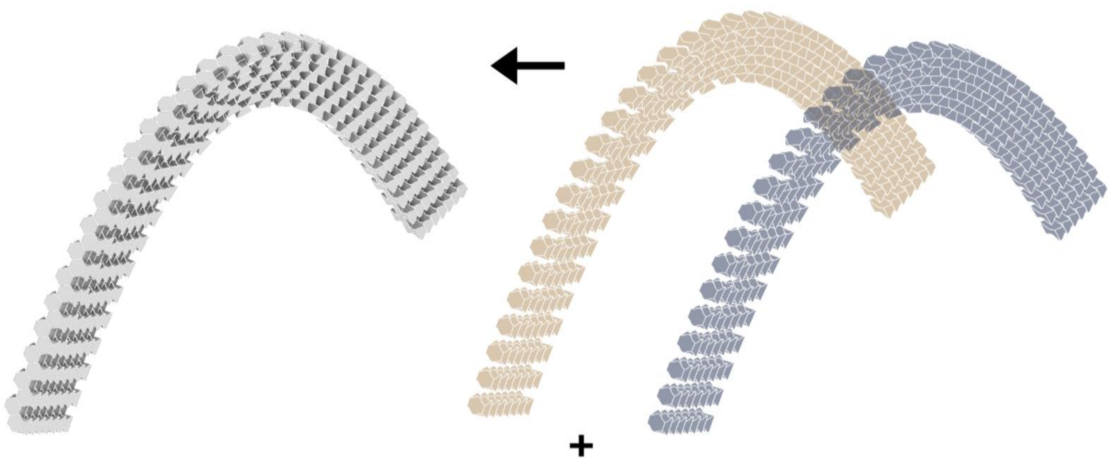
a

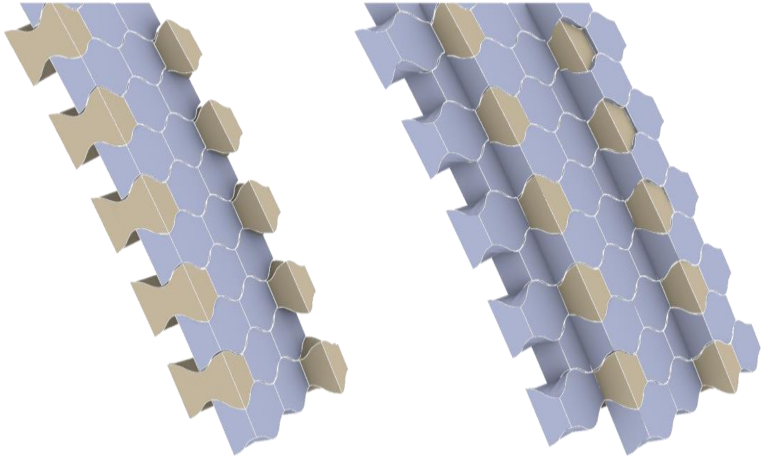


b



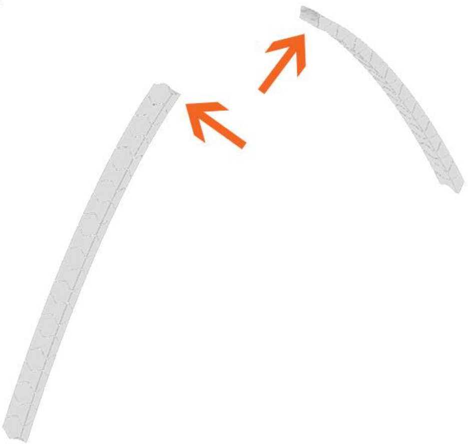
a





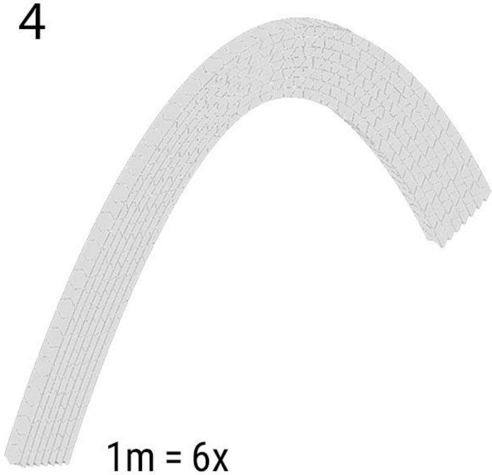
1

2



3

4



1m = 6x

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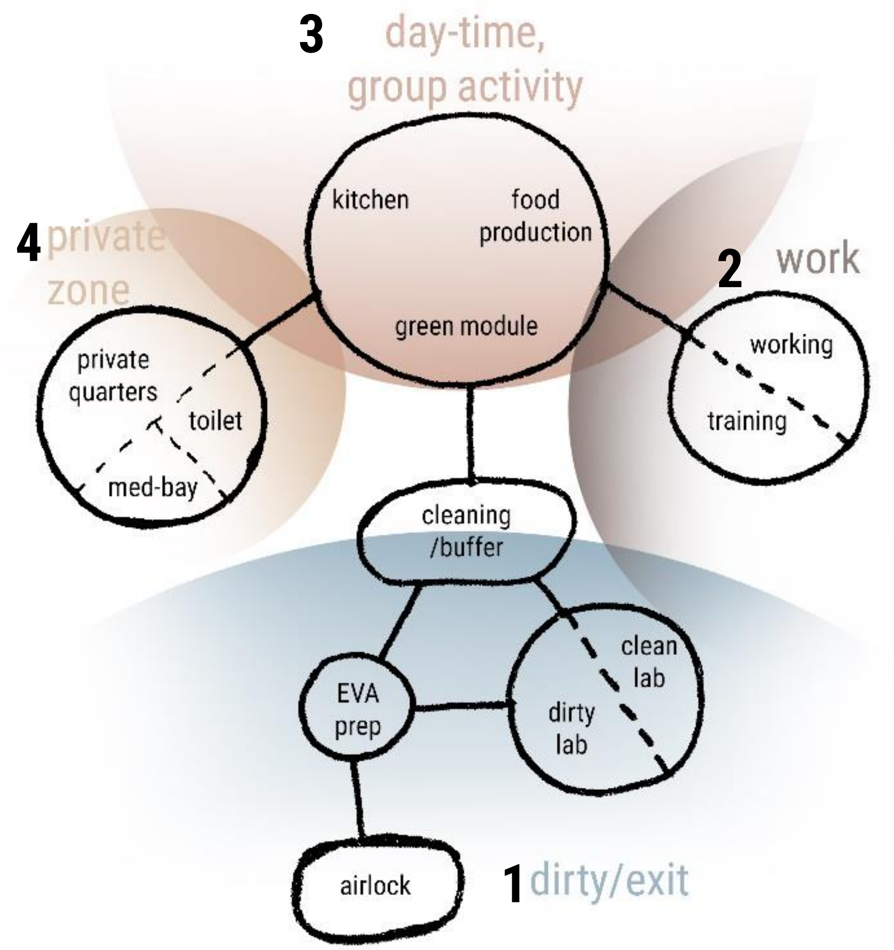
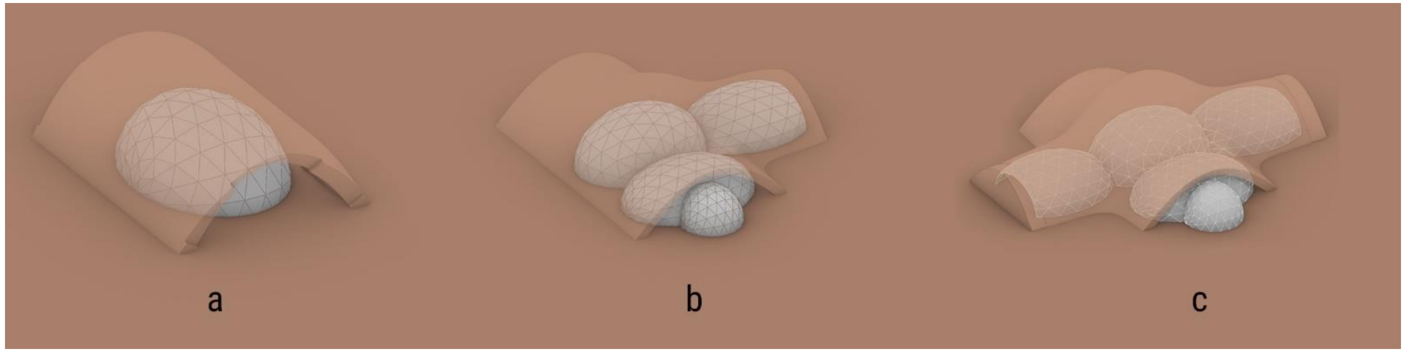
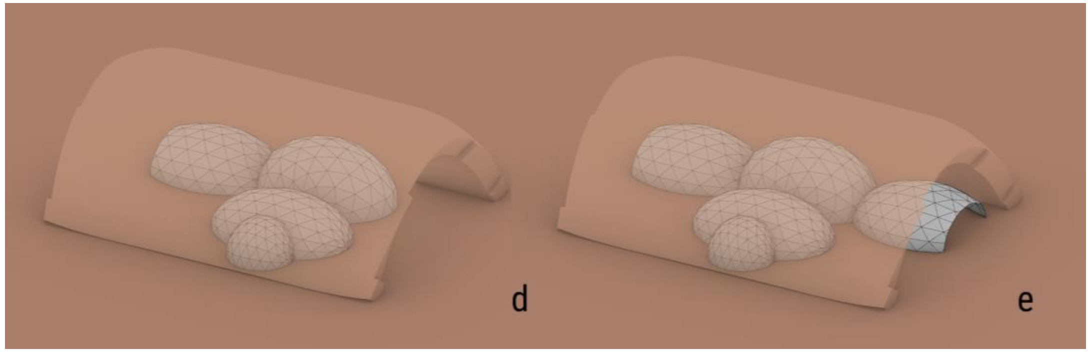
Ideal configuration - zoning

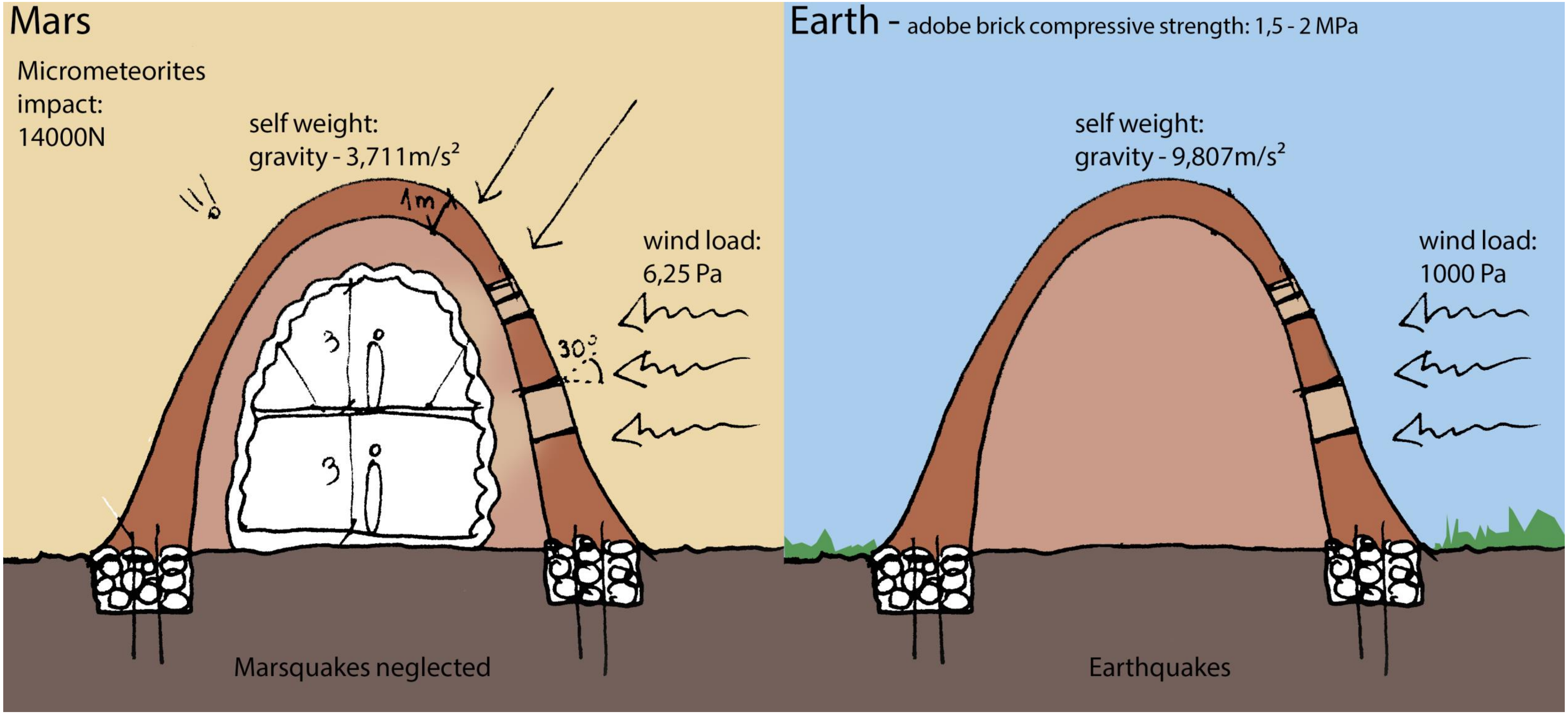


Ideal form – possible to expand and adapt to mission

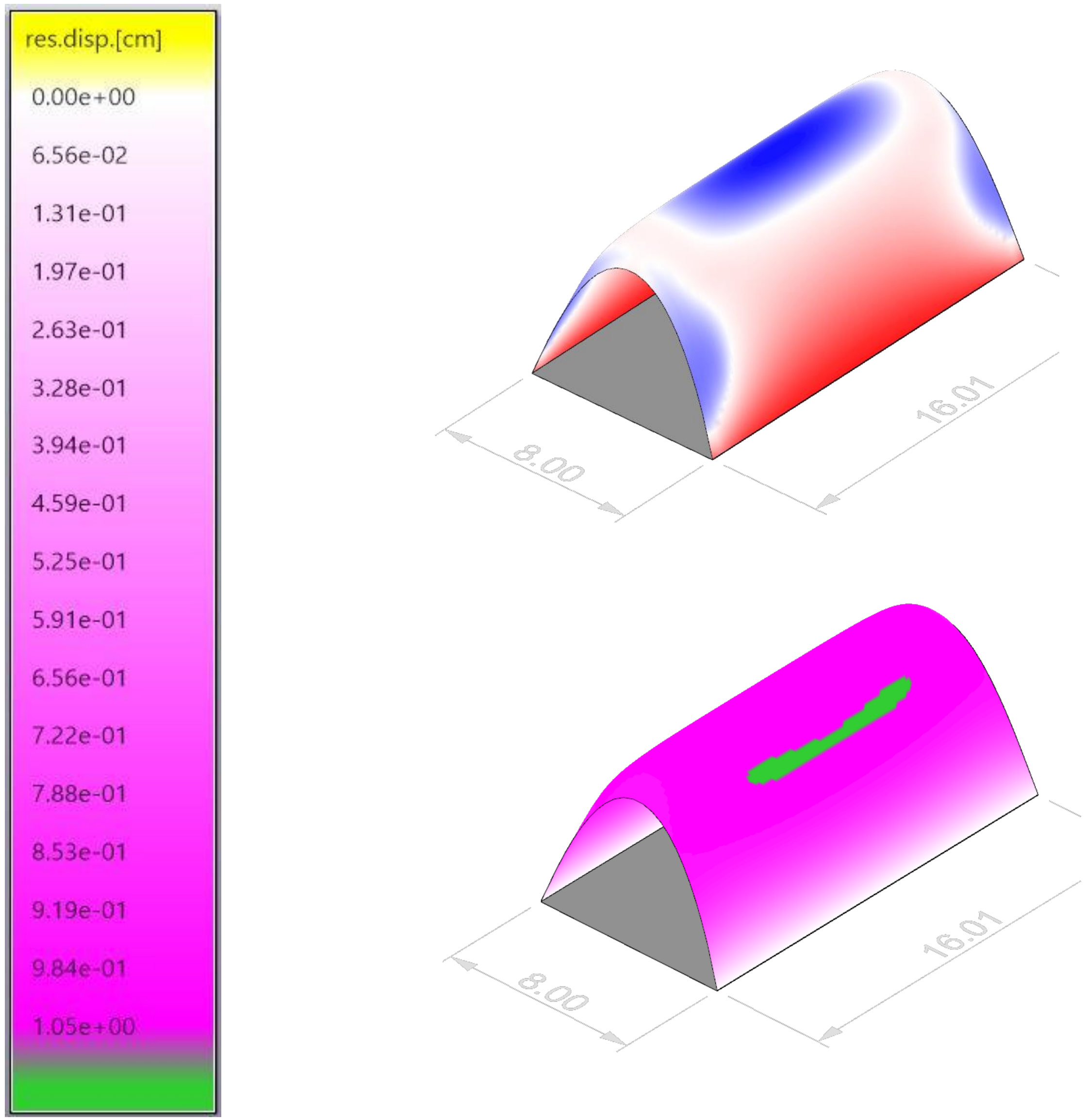




Structure - requirements



EARTH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4.59e-01
5.25e-01
5.91e-01
6.56e-01
7.22e-01
7.88e-01
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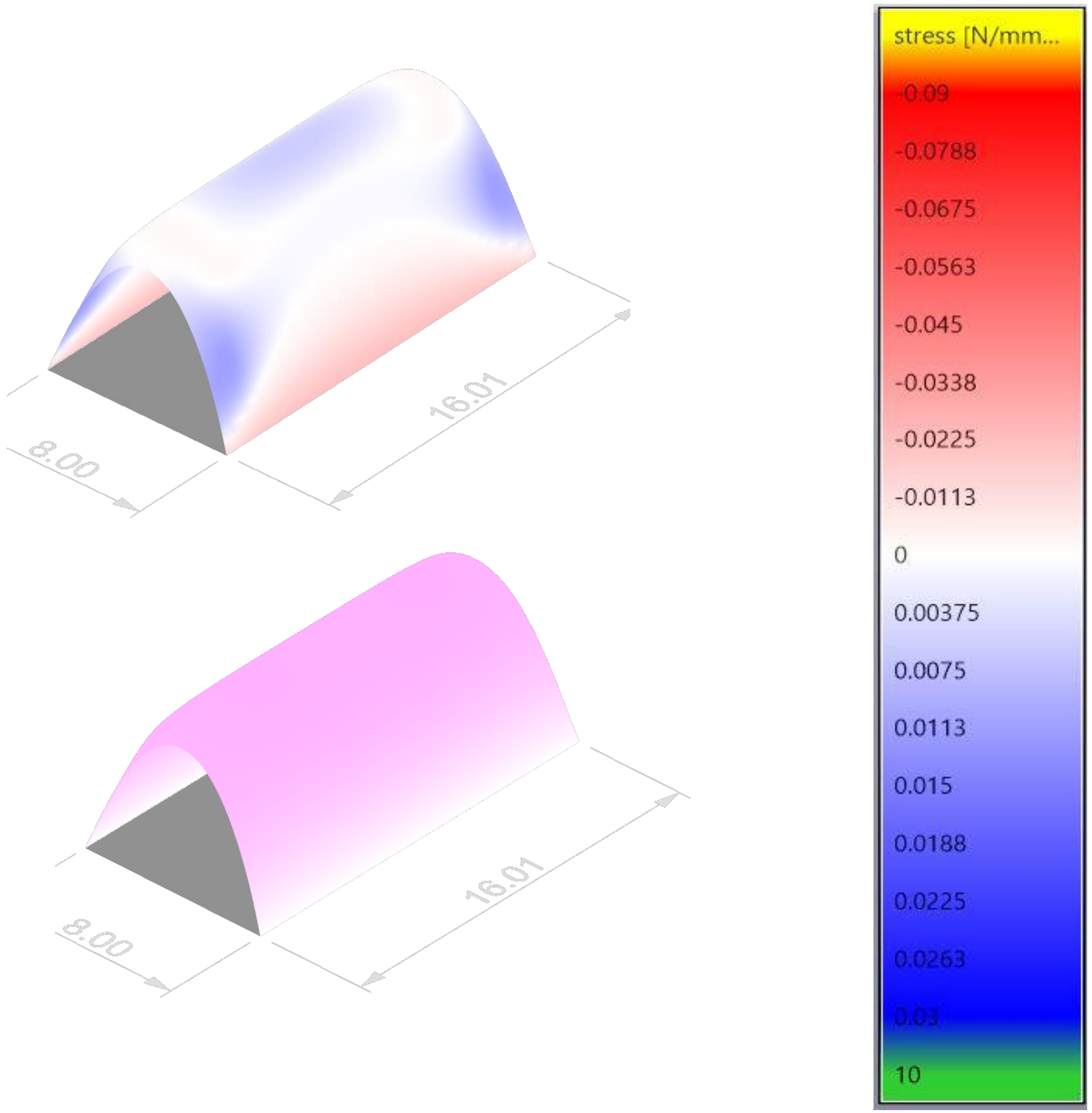
8.00
16.01
8.00
16.01

MARS


stress [N/mm...
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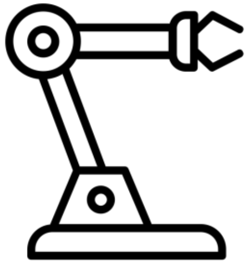
-0.0788
-0.0675
-0.0563
-0.045
-0.0338
-0.0225
-0.0113
0
0.00375
0.0075
0.0113
0.015
0.0188
0.0225
0.0263
0.03
10
8.00
16.01
8.00
16.01

MINIMUM 300 DAYS AVAILABLE

Preparation

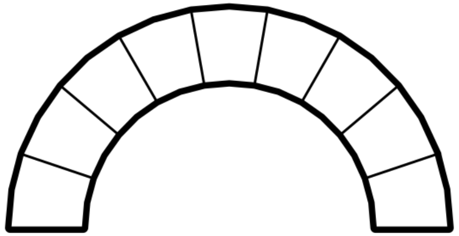
95 DAYS

Production Process



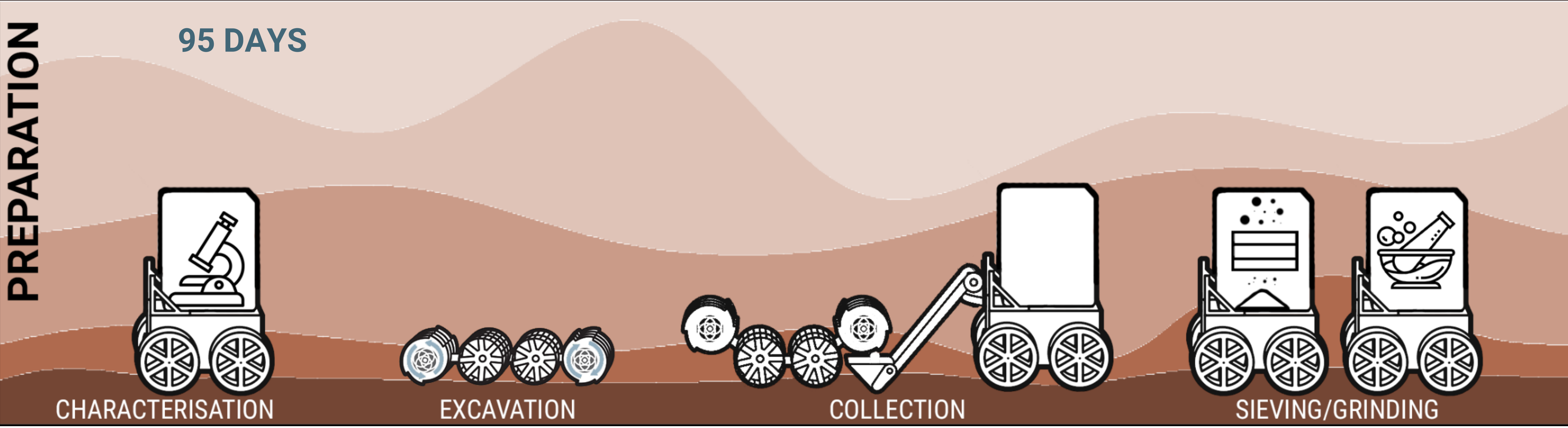
180 DAYS

Construction



35 DAYS

X 12 HOURS



240 HOURS

240 HOURS

540 HOURS

total 180 kW

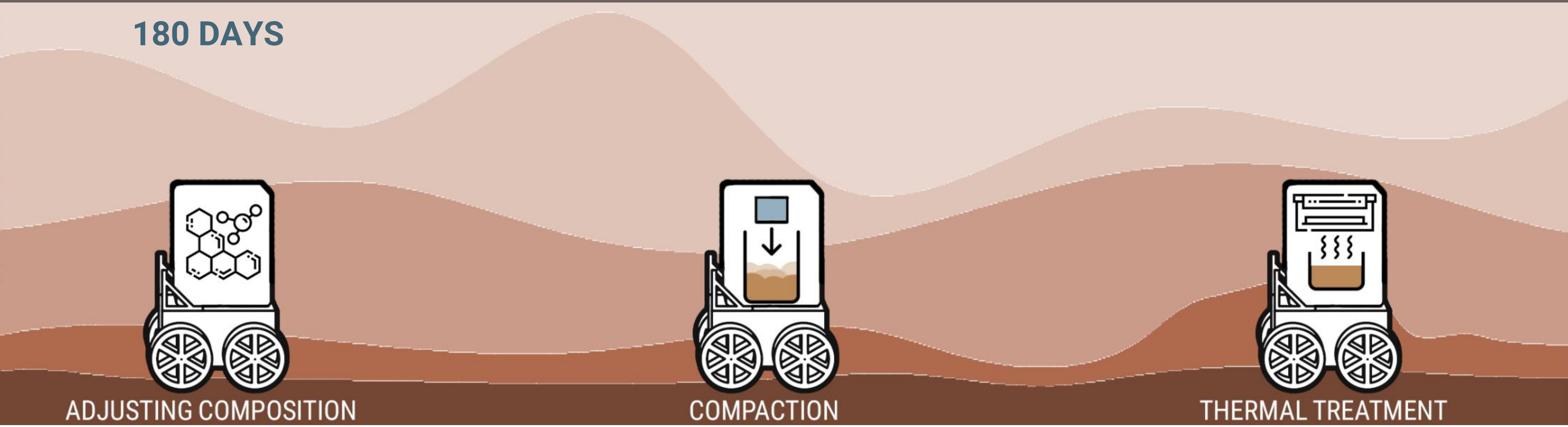
0,6 kW/h

	Unit	Value
Regolith Payload	kg	80
Power usage per kg	W	4
Structure Mass	kg	45000
Regolith volume	m3	~27
Volume per day (min)	m3	2,7

STRUCTURE - BUILDING PHASES & ENERGY DEMAND

FABRICATION

180 DAYS



Batch type 3.3	Unit	Value
Compaction of 1 brick (Work = F x d)	kW	0,7
Number of bricks required		1740
Heating time	h	4
	s	14400
Thermal treatment of one brick (ΔE)	J	276800
	W	19

720 HOURS

total 1195 kW

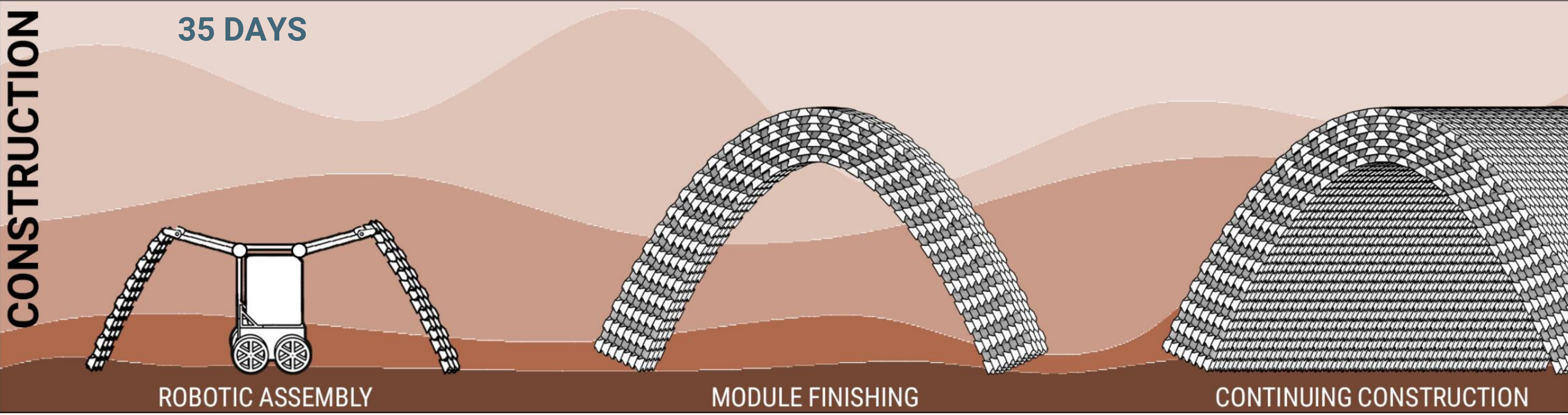
1,63 kW/h

1440 HOURS

total 33447 kW

23 kW/h

STRUCTURE - BUILDING PHASES & ENERGY DEMAND



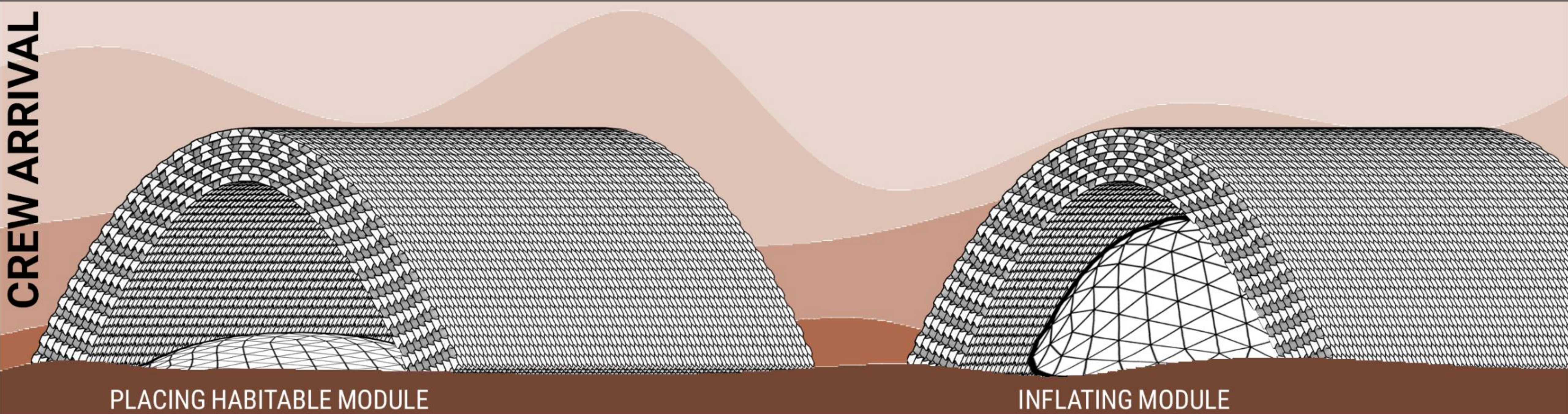
420 HOURS

0,285 1195 kW

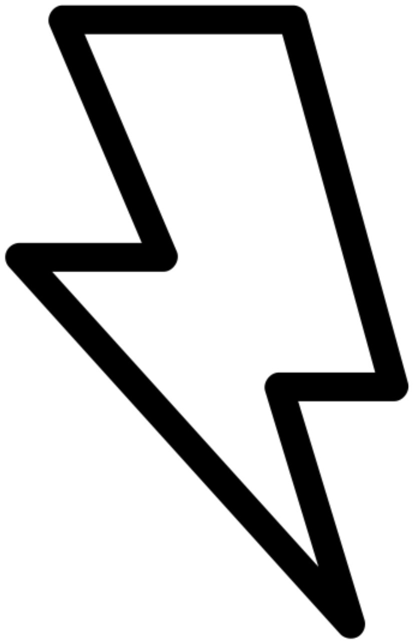
0,00068 kW/h

	Unit	Value
Brick mass	kg	25,86
gravity	m/s2	3,71
Height 1	m	6
Energy 1	J	514
Power 1	W	0,30
Power 1 for all bricks	W	171
Height 2	m	3
Energy 2	J	257
Power 2	W	0,15
Pwer2 for all bricks	W	86
Height 3	m	1
Energy 3	J	86
Power 3	W	0,05
Power 3 for all bricks	W	29

STRUCTURE - BUILDING PHASES & ENERGY DEMAND



STRUCTURE - BUILDING PHASES & ENERGY DEMAND



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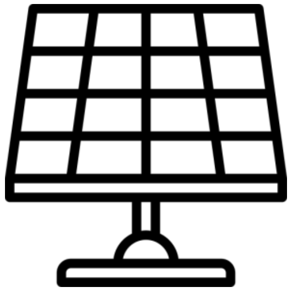
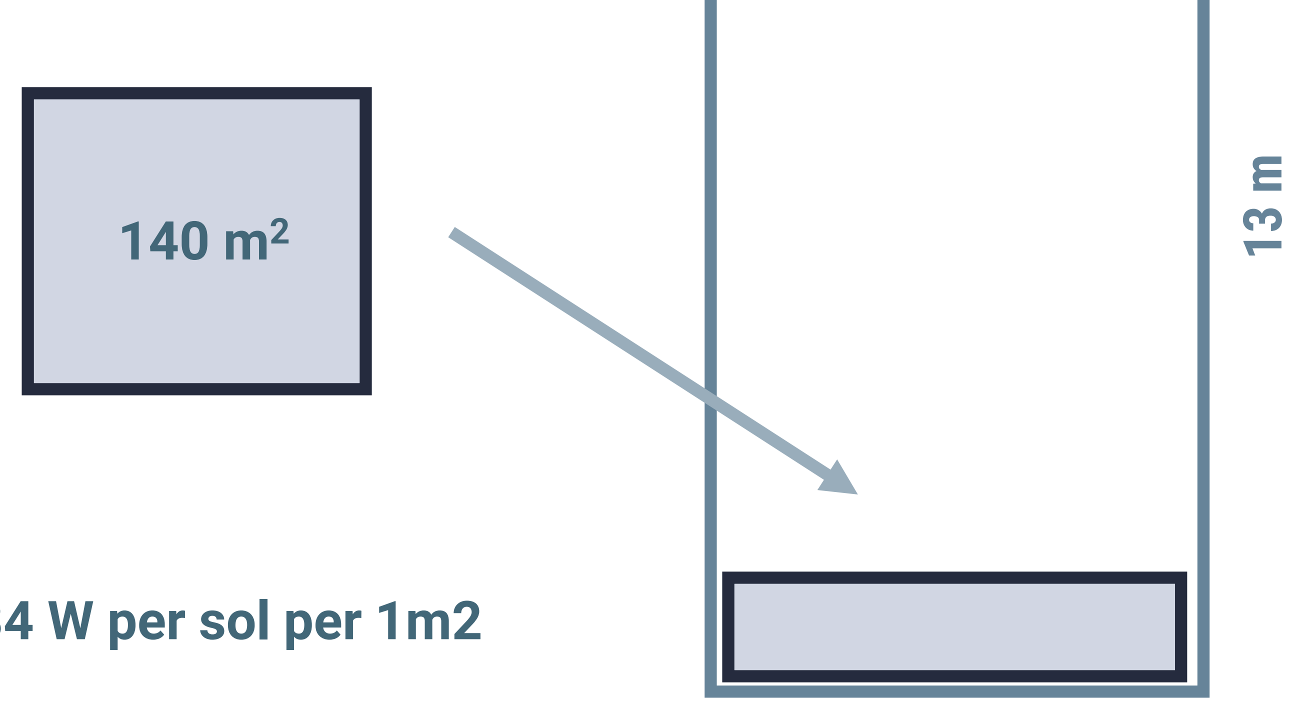




TOTAL ¬ 40MW

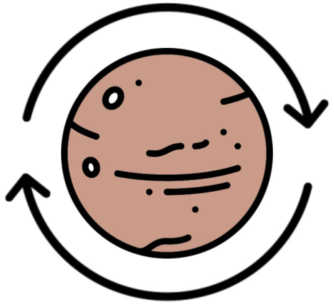
144 kW per sol

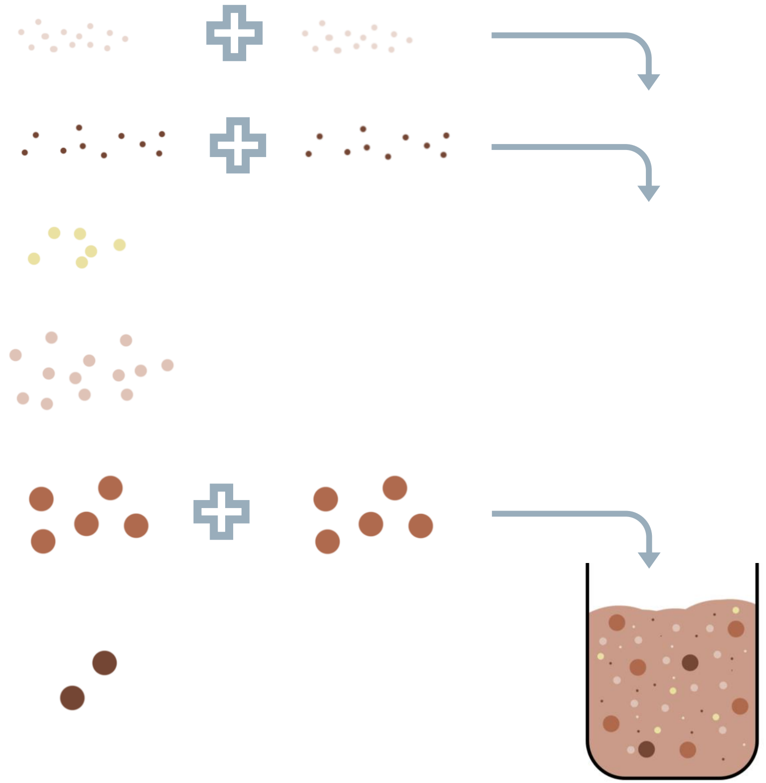
144 000 W per sol

1034 W per sol per 1m2

Falcon Heavy Rocket

CONCLUSIONS





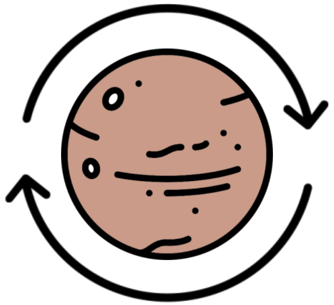
DISCUSSION & TESTING

INNOVATIVE OPTIMISATION

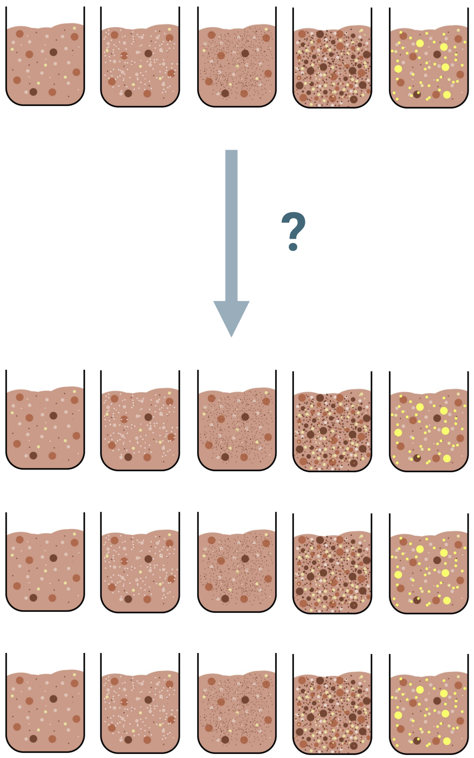
AVAILABLE TECHNOLOGY, EFFICIENCY

Future Research

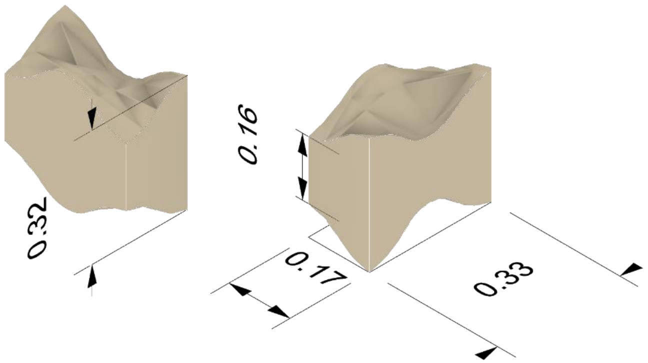
Sustainability on Mars



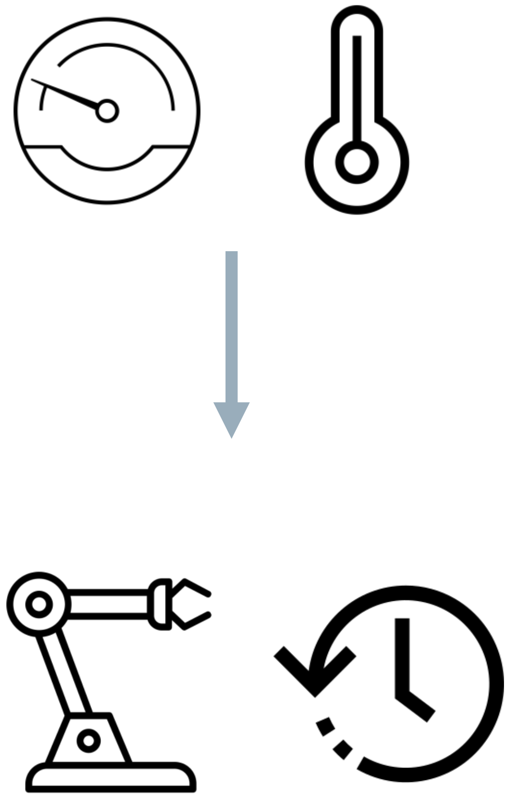
Composition adjustment options study



Construction & Fabrication Method



Conditions Simulation - IMPACT

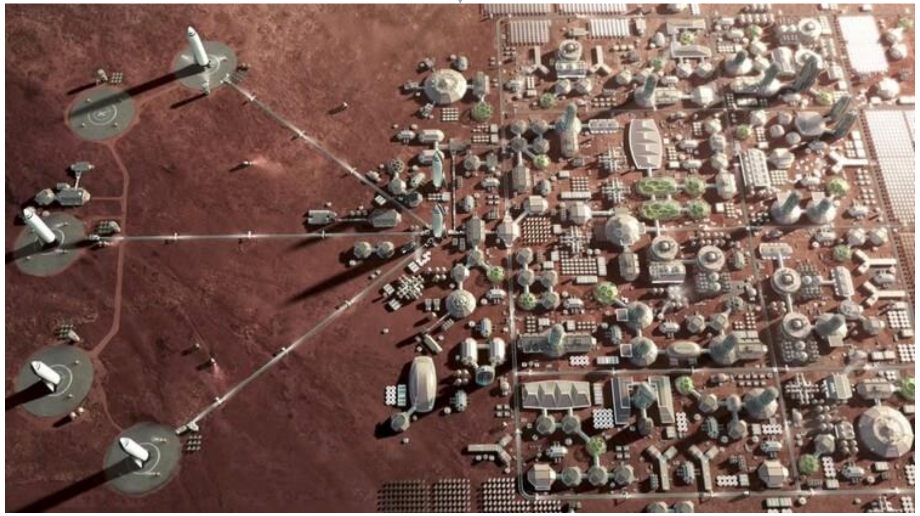


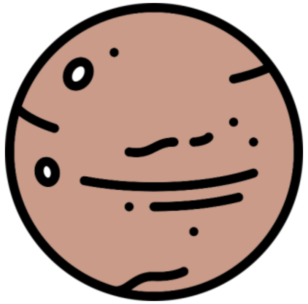
Limitations

- small amount of samples
- often estimations instead of calculations
- limited time for experimental research resulted in inaccuracy
- malfunctions of equipment

REFLECTION

GAP





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THANK YOU!

QUESTIONS / FEEDBACK