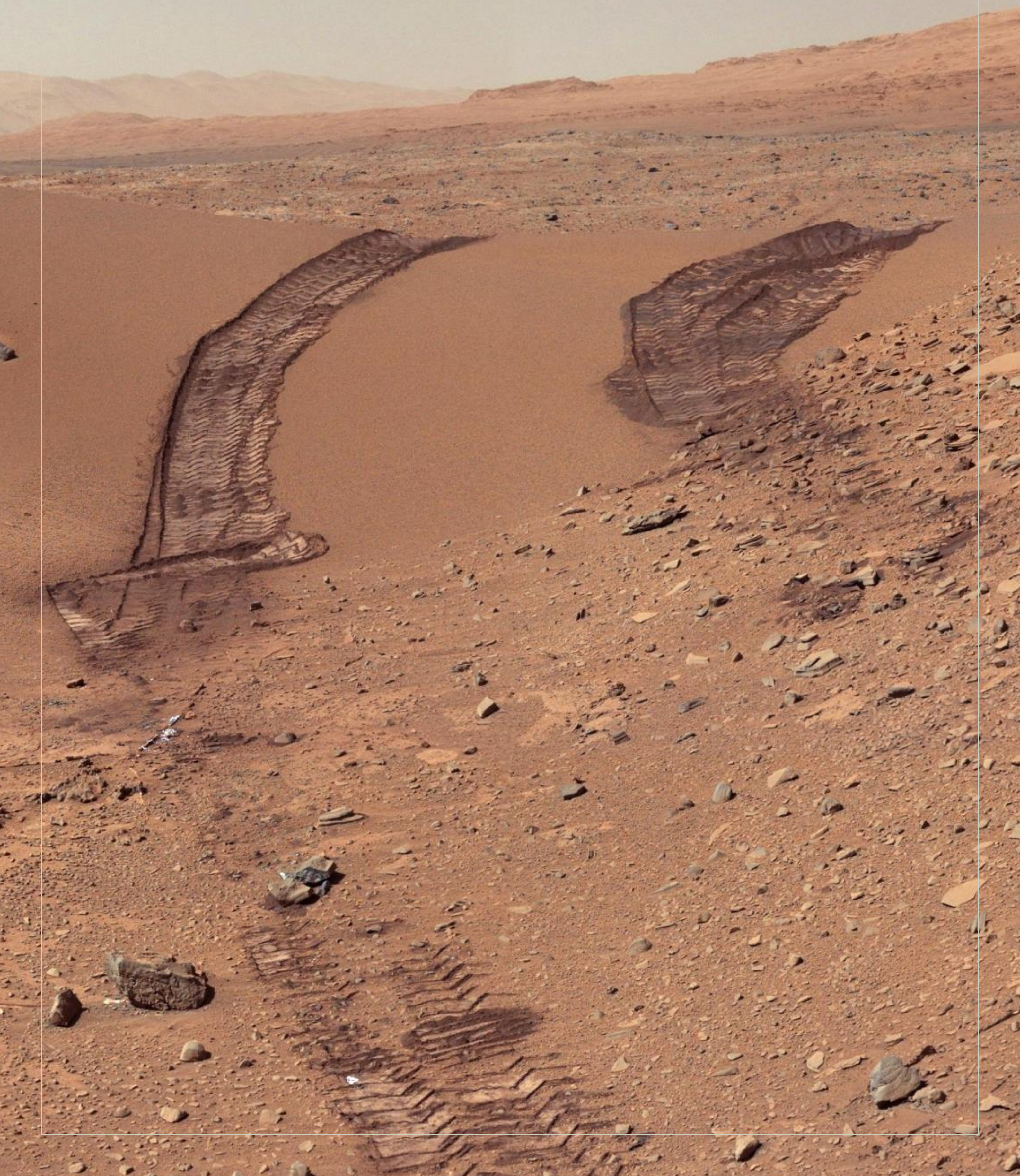
Building with Martian regolith

EXPERIMENTAL RESEARCH ON THE EFFICIENT AND SUSTAINABLE PRODUCTION PROCESS AND CONSTRUCTION METHOD

AGATA MINTUS, 4745523



GRADUATION REPORT

BUILDING WITH MARTIAN REGOLITH

AGATA MINTUS, 4745523

PERSONAL INFORMATION

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STUDIO/TOPIC

NAME: Sustainable Design Graduation Studio - Material Science & Structural Design

THEME: Experimental research on sustainable production and fabrication of novel material

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GRADUATION PROJECT

TITLE: Building with Martian regolith

TOPIC: Experimental research on the efficient and sustainable production process and construction method

KEYWORDS: Mars | building | ISRU fabrication | sustainability | regolith | efficiency

PREFACE

The main reason for choosing this topic is due to my interest in a hands-on approach and structural design. During my studies, I was developing my skills and knowledge in achieving sustainability in structural design optimization and manufacturing methods. Also, my passion for space architecture pushed me in the direction of experimental research which is possible to perform in the Sustainable Graduation Studio.

I didn't expect at the beginning of thesis studies, that I would be able to propose my own topic for the graduation project, that would be unusual and extreme in terms of the context. The fact, that I was able to focus on my passion and interest towards more scientific aspects like material science during this research made the work enjoyable, challenging and exciting. Therefore I would like to express my gratitude to everyone who helped me accomplish this goal and individual growth.

Firstly, I want to thank all the professors and mentors, who offered their knowledge and experience and helped me with the challenges of the research. Special thanks to Fred Veer for the support throughout the whole graduation, who made the research process less stressful when the scheduled plan was extending and shifting, and more exciting during the experimental part. I had learned, that the scientific and experimental research never goes according to the plan and improvisation and mistakes are common elements of the science. I would like to thank Oguzhan Copuroglu, who offered help and allowed me to extend my research with scientific support in the field of material science. The access to the Microlab allowed me to study and analyse the material on the microscopic level and understand more the microstructure formation. Although I couldn't finish every experiments and analysis within the restricted time, I could experience and learn about the work in a laboratory, which made me understand that this field of studies could be my another passion and hopefully I could develop more in this direction in the future. Also, a big thanks to David Peck, with whom I could discuss very important and challenging aspects of our future life in space – sustainability, and how our approach towards it will influence future issues, politics. This theoretical part of the research showed me how rarely this topic is touched upon and how essential is to implement the sustainable approach within first missions to Mars.

Secondly, I want to show my gratitude towards two supervisors, Layla van Ellen and Fernando França de Mendonça Filho, who helped me with the research and offered their time and contribution in the name of mutual passion and interest towards space. The support from Layla at the beginning of my research, was invaluable, as she had experience with a similar project and could share the knowledge regarding the research process. Special thanks to Fernando, who had the patience to explain every detail of the microscopic experiments and analysis and offered help in investigating the material characteristics.

Furthermore, I would like to thank the companies and institutions who offered the minerals required to prepare the martian simulant: Sibelco (especially Pim Demecheleer), S3-chemicals, Vulkan Europe BV., Gyvlon Gietvloer. Although the futuristic topic and experimental character of the research, they provided the materials and showed interest in the topic and results.

Finally, a great thanks to my beloved Biertje group: Valeria, Alex, Erron and Sofia. Thanks for being my second family in Delft, whom I could always count on to go through tough times and share the best moments of joy.

ABSTRACT

The research is focused on investigating regolith as a building material, while implementing the sustainable approach in terms of energy efficiency and material usage, during production process and construction. The context is located within the first manned missions to Mars, and the requirements, towards testing methods allowing for independence from Earth, are implemented. The requirements for sustainable building on Mars were investigated using a literature review of different aspects regarding manned missions to the Red Planet, as well as of the present understanding of sustainability in space and on Earth.

The studied production process is using compression and thermal treatment as the main processes, as they require relatively simple equipment compared to complex 3D printing or sintering technologies currently researched by scientists. The decision was made based on the fact, that the sustainable approach was the essential factor in the determination of programme of requirements.

The main final product of the research is a novel approach towards the fabrication of martian regolith. The composition of the material is changed in different ways in order to minimize the energy input and required payload for the production process. The compositions with an additional amount of minerals with lower melting point (plagioclase, ferric sulfate), the ones with smaller particle size distribution (amorphous phase elements) or with additional sulfur powder (which could be brought from Earth or extracted in situ in the future) were studied with mechanical tests and microscopic analysis.

The research proved that the change in composition can have a significant impact on the building material characteristics and could be used to optimize the production process. The compressive strength of the produced specimens was ranging between 0,45 – 4,00 MPa. The most promising composition offering relatively good mechanical properties of the material, using 100% in situ resources and allowing for simplification of the production process or decreasing energy demand, is the one with an additional amount of nano-particles od ferric oxide.

The structure built in situ was assumed to be external shell structure protecting inflatable, light habitable modules. The outer shell was analysed in terms of resistance towards wind load, gravity and micrometeorites impacts. The construction method and structure type proposed according to the results from experimental research on the material was based on adobe buildings on Earth. The compressive-only structures built with an interlocking system, which protect the crew against wind, radiation and micrometeorites impacts, were studied and designed.

Content

ACRONYMS LIST

APXS	Alpha Particle X-Ray Spectrometer
AROMA	Automation and Robotics for Human Mars Exploration
CheMin	Chemistry Mineralogy X-Ray Diffraction, an instrument on Curiosity rover
ChemCam	
CNSA	Chinese Space Agency
COPUOS	Committee on the Peaceful Uses of Outer Space
CPFT	Cumulative percentage finer than particles with diameter D
DRP	Dynamic Radioisotope Power
EDL	Entry, Descent, and Landing
ESA	The European Space Agency
e-MMRTG	Enhanced Multi-Mission Radioisotope Thermoelectric Generator
ETFL	Ethylene tetrafluoroethylene, a high-performance plastic
GCRs	Galactic Cosmic Rays
IADC	Inter-Agency Space Debris Coordination Committee
ISRU	in situ resources utilization
JSC Mars-1A	Johnson Space Centre Martian Simulant
KRUSTY	Kilopower Reactor Using Stirling Technology
LEO	Low Earth Orbit
LCA	Life Cycle Assessment (Analysis)
MA	Moon Agreement
MAHLI	Mars Hand Lens Imager
MFA	Material Flow Analysis
MGS	Mars Global Surveyor
MGS-1	
MMRTG	Multi-Mission Radioisotope Thermoelectric Generator

MMS	Mojave Mars Simulant
MMS-1	Mars Garden Simulant
MOLA	
NASA	The National Aeronautics and Space Administration
OST	Outer Space Treaty
PB	Polybutadiene
PE	Polyethylene
PLA	Polylactic Acid
PP	Polypropylene
PVC	Polyvinyl Chloride
RC	Registration Convention
ROSCOSMOS	Russian Space Agency
RPS	
RTG	Radioisotope Thermoelectric Generator
RWGS	Reserve Water Gas Shift
SEP	Solar Energetic Particles
SL	Space Law
SLM	Selective Laser Melting
TBP	Three-bending Test
TiSD	Technology in Sustainable Development
TRL	Technology Readiness Level
UN	United Nations
WT%	Percentage by Weight

INTRODUCTION

1.1. Report structure

This is a report for a master thesis at the Building Technology programme, titled “Building with Martian regolith”. It’s a combination of a literature study and experimental research, presenting broad investigation on conditions having an impact on Martian architecture, as well as a detailed study of sustainable production and fabrication process and the ways to optimize it.

The paper is structured into five parts. The first one, introduction, is explaining the concept of this research, presenting problem statement, objectives, research questions and the plan of the thesis. It also includes a general methodology description, which is further explained in each chapter. Literature review had to be very broad as the topic is still not well explored and the conditions and requirements for the project had to be investigated for different aspects. Additionally, the topic of sustainability on Mars was explored, as no paper about this issue was found during the literature study. The third chapter is presenting pre-experimental decisions, which are based on literature review and possibilities related to conditions of Martian missions. Finally, the experimental and design part of the research is showed at the end of this chapter.

1.2. Context

Since the 20th century, humans have been investigating the universe beyond Earth’s orbit. For the last decades, space agencies were proving, that our civilization is capable of achieving dreams and goals, which at the beginning were just sci-fi stories. The space exploration and planning of colonization became part of our culture and everybody is certain, that it will be part of our everyday life in the future. The reasons, why we want to go beyond our planet, referred first to ambition and curiosity but recently people started to see potential politic and economic benefits. These factors drive us towards new space race and more complex missions (Owens, et al., 2017). Just in 2018, the amount of new discoveries and achievements is enormous, ranging from launching new rocket system – Falcon Heavy designed by SpaceX, which can revolutionize future missions, to sending an advanced lander to Mars – InSight, which will for the first time analyze subterranean conditions and environment (Figure 1).

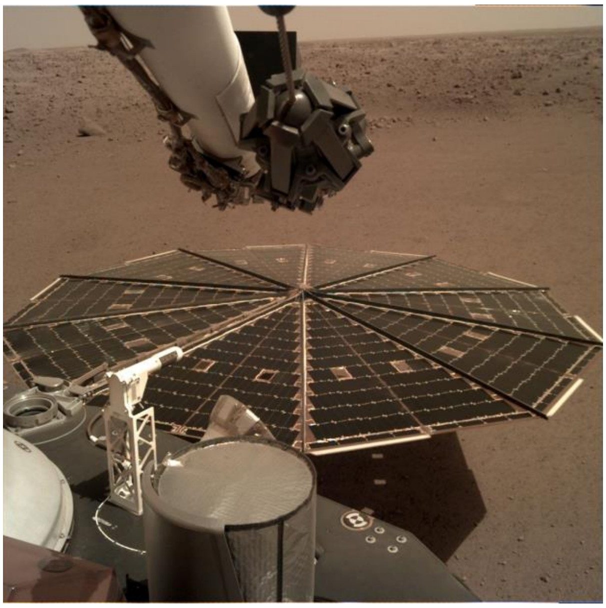


*Figure 1: **Left** - Falcon Heavy launch, 6th February, NASA's Kennedy Space Centre, Source: Walter Scriptunas II / Spaceflight Now, **Right –** InSight lander on Mars, Source: NASA/JPL-Caltech*

Future plans regarding human space exploration are focused on deep space missions. Among these plans is Mars - a destination, which could help us find unknown answers about Earth and develop technologies regarding space colonization. After landing on the Moon, space agencies are building enthusiasm to visit the new planetary object (Croucher, 2006). Buzz Aldrin, Apollo program astronaut says:

> *“Humans need to explore, push beyond current limits just like we did years ago. Apollo was the story of people at their best, working together for a common goal. We started with a dream, and we can do these kinds of things again. I know it. I’m living proof that it can be done.”*

The new destination brings new challenges and requirements (Larson, et al., 2000). The most important aspect of the manned mission to Mars is developing space settlement technologies. In the book "Human spaceflight: mission analysis and design", authors write, that future landing missions would require surface modules for extended surface stay for humans, which later could be developed into a long-term human presence on the planet (Larson, et al., 2000). The book also mentions that the ideal design of building space architecture on the surface of other planet is fully automated and independent from Earth (Figure 2).

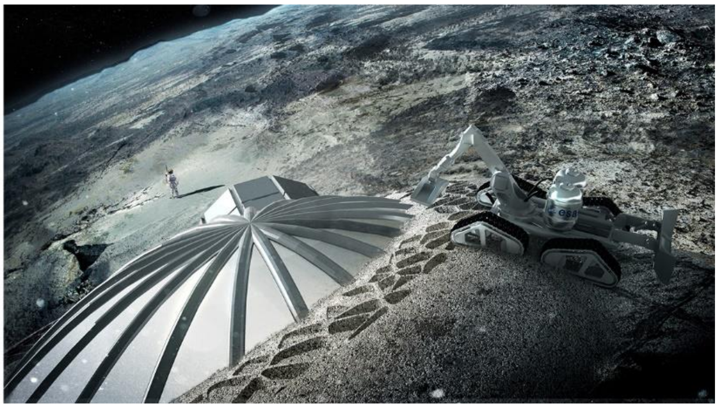


*Figure 2: **Left** - A Contour Crafting robot prints a road in front of a hangar for a lunar lander, Source: Behnaz Farahi/NASA, **Right** – 3D printing concept for lunar based using in situ resources, Source: Foster + Partners*

Space architecture is an interdisciplinary specialization which integrates technical fields like aerospace engineering, architecture, human factors, and medicine, as well as more humanistic specializations like psychology and art. This broad topic is still an emerging idea, because of the diversity of aspects and challenges regarding implementing and testing concepts in outer space (Häuplik-Meusburger, et al., 2016). This research is focused on building technology, including material production, construction method and structure design of Martian habitat, which needs to meet habitation requirements.

Habitability in space context can be understood according to Dr Häuplik-Meusburger *"as the measure of how well the (built) environment supports human health, safety, and well-being to enable productive and reliable mission operation and success."* In this report, the focus is oriented towards creating a structure which could be part of the habitat protecting the potential crew from some hazardous Martian conditions, like micrometeoroids and radiation.

In the near future, the deep space exploration and the dream to step on the surface of another planet will be achievable. Space agencies present each year, more detailed and reasonable plans for these missions. The vision of space colonization is not a science fiction idea anymore but became part of the space program.

Figure 3: SpaceX render illustrating plans for colonizing Mars, Source: SpaceX

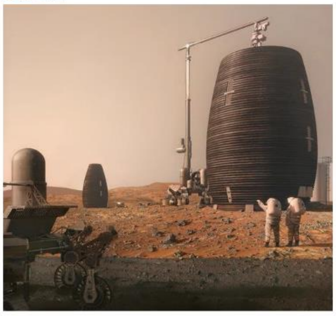
1.3. Problem statement

Importance of the research

EMERGING FIELD

NEED FOR EXPERIMENTAL RESEARCH

PROVOKING DISCUSSION



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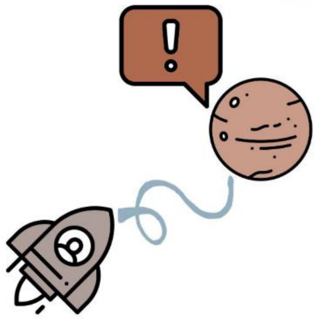
Issues related to the topic



MISSION CONDITIONS

MARTIAN CONDITIONS

COMMON APPROACH

Common approach → Research approach

HIGH-TECH → EFFICIENCY, TRL AVAILABLE

LACK OF SUSTAINABILITY → IMPLEMENTING SUSTAINABILITY

EMERGING FIELD

The emerging space exploration and colonization planning are directing our focus on Mars and Moon for the next few years (Giancarlo Genta, 2017). The need for architects and building engineers is increasing and the research on possible material production and building construction is required. Currently, the government space agencies like NASA and ESA, as well as private companies are conducting studies on building extra-terrestrial habitats for first deep space manned space missions, which are planned for years 2025 – 2035 (Lim, et al., 2017).

MARTIAN CONDITIONS

First manned missions to Mars would be unpredictable, as the data about the Red Planet, that we have, might be incomplete. The effect of long-term isolation or Martian unfamiliar, hazardous conditions' impact on a human is also unexplored. Therefore, first building structures on Mars would need to be reliable and advanced, but also achievable in terms of technology and time. The building possibilities are limited by Martian conditions.

Mars has very hostile environmental conditions, which impose strict requirements for habitation design and production processes. The crucial issues determining the limits and possibilities is the distance and transportation system which would deliver potential equipment, material, and energy source. Due to these limitations, there is an emerging concept for in-situ resources utilization (ISRU) as the source for building materials, energy, fuel or life support systems.

> *"NASA is making long-term investments to advance ISRU technology in multiple areas, including a particular focus on:*
> - *Mars atmosphere-based resource acquisition and processing;*
> - *Regolith-based volatiles resource acquisition and processing;*
> - *Regolith-based in-space manufacturing and construction."*

The available resources for building material on Mars are regolith (in the form of soil and dust), rock, ice -dry ice (carbon dioxide solid phase) or water. In this research, the main focus will be on exploring Martian regolith – its availability, properties, processability. The reason for this choice is the fact that soil is the most abundant resource on the planet and relatively broader data is gained about it compared to other materials mentioned earlier.

SUSTAINABLE AND RESPONSIBLE APPROACH

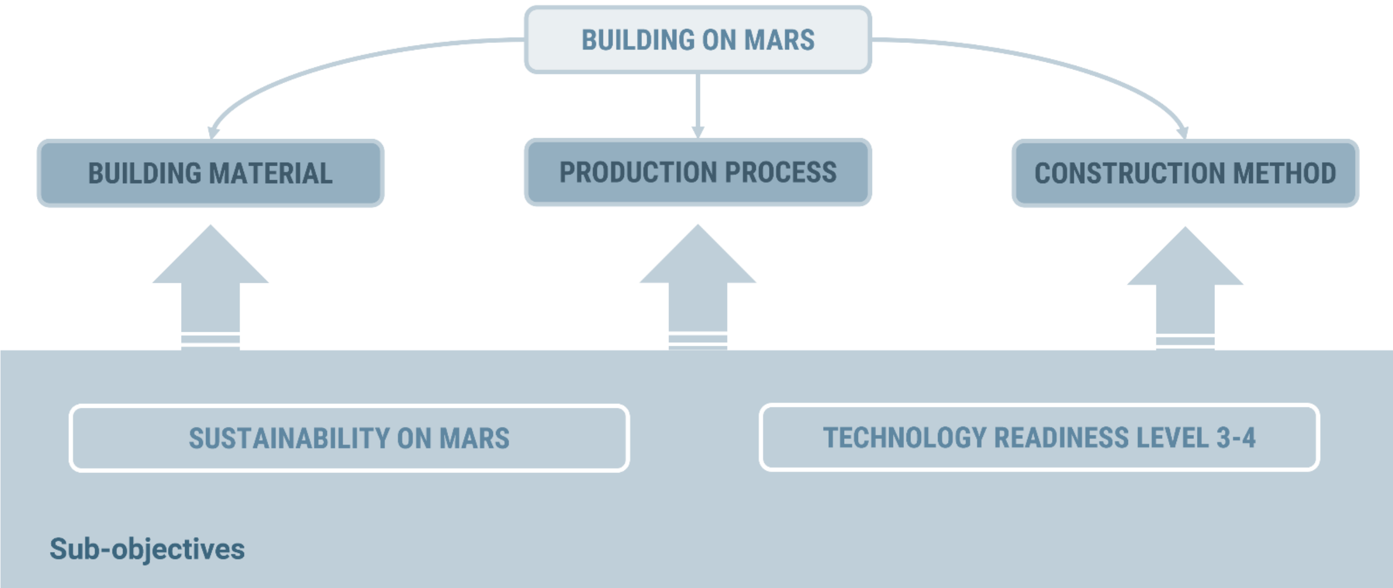
After the literature review, it was noticeable, that sustainability in terms of responsible material management and environmental protection is neglected by the space agencies. Therefore, in this project, the sustainable approach was implemented and the attempt to start a discussion on this topic is one of the research goals. Ongoing researches regarding Martian regolith as a building material and its production processes are oriented towards advanced technologies and exploring the possibilities and limits of the material. Often, the studies don't integrate the sustainable approach into the process, which can lead to inefficient energy and material usage. The advanced technologies and concepts could be more suitable for later phases of Mars colonization, where manufacture and industry are already present on the planet. The focus of this research is building habitat for first manned missions. It means that the planet is still not fully explored and the energy, as well as technology, is limited due to the transportation conditions.

TECHNOLOGY READINESS LEVEL

The ongoing researches regarding building on Mars are focusing usually on high technology and conceptual architecture projects. The technical aspects are the secondary issues and the level of technology readiness is neglected. The fact, that the first missions to Mars are planned for 2025-2030 requires from the technology used for the production and building process to be developed and tested in advance. Therefore, the production process, manufacturing, and construction method will be focusing on already existing technologies.

1.4. OBJECTIVES

Main objectives



GENERAL OBJECTIVE

The general objective of this thesis is to explore and study the possibilities for sustainable building of a habitat on Mars with in-situ resources (regolith) and sustainable production process and construction.

SUB-OBJECTIVES

The sub-objective is:

- Specify and investigate the aspects and parameters determining sustainability regarding building material production process and construction method on Mars
- Specify the technology readiness level of the production process and construction method

FINAL RESULT

The final product of the research is a novel building material and its production process. Additionally, the structure and construction method is proposed and optimized in terms of material and energy usage.

1.5. Research Questions & sub-questions

MAIN RESEARCH QUESTION

How to sustainably build with Martian regolith using energy efficient in-situ production process and construction method?

SUB RESEARCH QUESTIONS

The secondary questions would help determine the program of requirements for each part of the research (material, production process, building component, structure) and find the most suitable option for each.

1. *What is the sustainability on Mars and how it should be implemented in the building aspects?*

It was important to determine what is sustainability on Mars and what is the impact of the sustainable approach on decisions regarding building on Mars. The programme of requirements was extended by the requirements in accordance with defined sustainability.

2. *What are the material requirements and which in situ materials are suitable for that?*
3. *What are the available in situ production processes in terms of efficiency and sustainability?*

These questions are answered using a literature review of conditions on Mars and requirements for the missions as the main research method. Additionally, the conclusions from the research on sustainability are used as a filter to include sustainability in the requirements.

4. *What are the requirements for the structure, and construction and which technologies and building forms meet these requirements?*

This question is answered by the literature review and conclusions from the experiments on the production process.

5. *What is the sustainable construction method for designed building material and structure?*

This question is answered by the literature study and research on sustainability. The answer could be specified after the experimental part of the research and research by design.

1.6. Methodology & Research Design

APPROACH & METHODOLOGY

The project is developed using three research methods: literature study, experimental research, and research by design. Figure 4 presents a schematic relation between these parts, which are explained later.

Research design

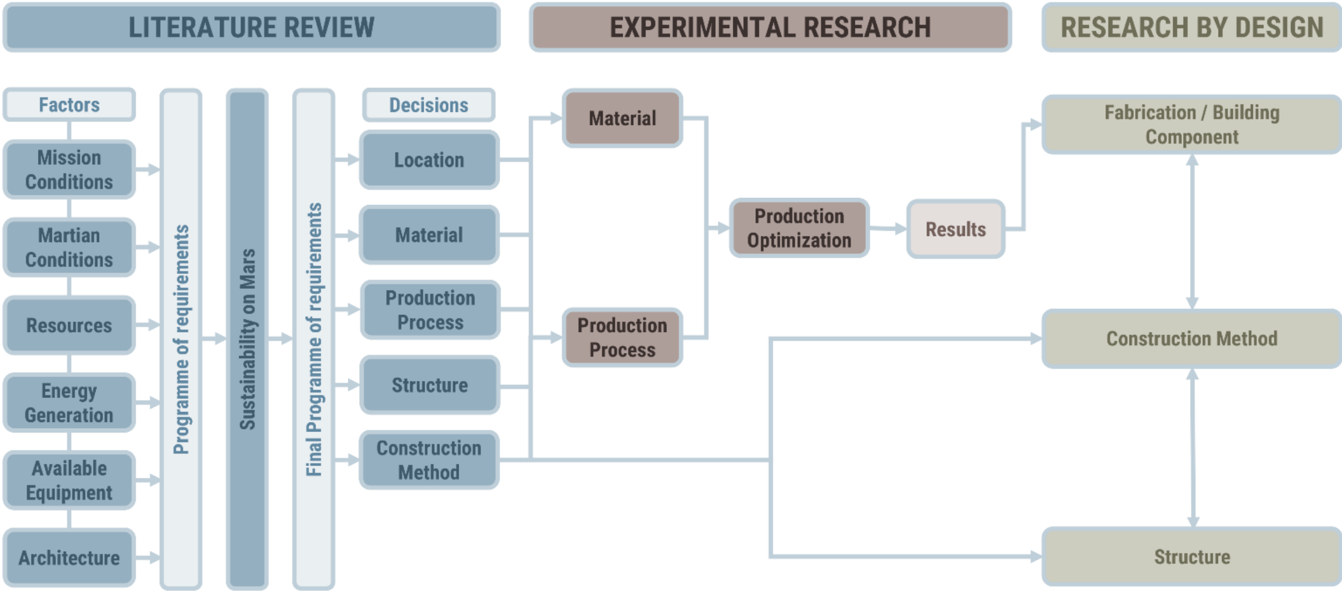


Figure 4: Research methods plan and relation

LITERATURE STUDY:

The first one - literature study focuses on determining Martian conditions and programmes of requirements for three aspects of the project: material, production process, and structure. Each part will be later developed and tested with physical experiments and computational simulations. As the topic of this research is still an emerging idea, the available literature is mostly academic and scientific reports published in magazines or at conferences related to space engineering. The general knowledge about missions plans was investigated by following space agencies programmes like NASA, ESA or SpaceX. Conditions on Mars were gathered using scientific data collected during several missions to Mars. The Literature review is summarized to conclude the approach and design the research. The most important topics investigated are:

- Martian conditions
- Habitats examples
- Technology and equipment availability
- Ongoing researches study and their comparison
- Programmes of requirements
- Sustainability

EXPERIMENTAL RESEARCH:

The second part of the research is experimental and is based on the knowledge gained during the first phase. The experiments concern mainly preparing material composition and testing production methods. The experiments will focus on determining the best processes and required factors like conditions, time, equipment. Next step would be minimizing energy usage during this process with preserving desired product properties. The experimental topics are listed below:

- Mixture/ Material preparation and experimentation
- Production Process preparation and experimentation
- Production process optimization

COMPUTATIONAL MODELING, PHYSICAL MODELS AND SIMULATIONS – RESEARCH BY DESIGN:

The third part would be mostly computational including modelling and simulations. The structure and construction method will be designed for building component, which was the final product of the experimental part. These two elements will be optimized to minimize energy and material usage.

- Fabrication, assembly design
- Habitat's structure concept
- Construction method design
- Habitat design

RESEARCH DESIGN

The experimental and computational part of the thesis is divided into three phases: material composition, production & fabrication and construction method.

First part – **Material Composition**, is performed in a research lab using experimenting and modelling techniques. The material composition is analyzed in terms of production possibilities and binding method. Preliminary production techniques are performed to analyze the structure.

Production & Fabrication part is divided into two phases, depended on each other. The production phase is an optimization phase, where the product properties, energy usage, and simplifying approach are the key factors. The fabrication part is focused on designing and testing the building component. The testing is performed in both research lab and mechanical behaviour lab. Then, the conclusions in terms of the relation between the production process and building material properties are inferred to achieve final building component.

The third phase – **Construction Method** is performed mostly using computational modelling and simulation. The choice of method is based on previous research phases' results and conclusions. The simulations are used to determine achievability (equipment, time, technology) and structural possibilities of the building component.

Timeline of the research is presented in Table 52 – Appendix 1.

LITERATURE STUDY

2.1. Programme of requirements

Aspects

This chapter is structured based on other master thesis research, titled *Building on Mars – Research on In-Situ resources utilization (ISRU) for a sustainable habitat*, written by Layla van Ellen. (Ellen, 2018) The report was oriented to similar building technology aspects, therefore the programme of requirements context was overlapping. Knowledge and study on the material and production process were however extended here due to a different choice of material and research goals.

According to the goals of this research, the programme of requirements will be prepared for material, production process/fabrication and construction method/structure (Figure 5). The aspects that have an impact on a programme of requirements refer to:

- Mission conditions
- Martian conditions
- Resources – Building material
- Energy generation options
- Available equipment
- Architecture

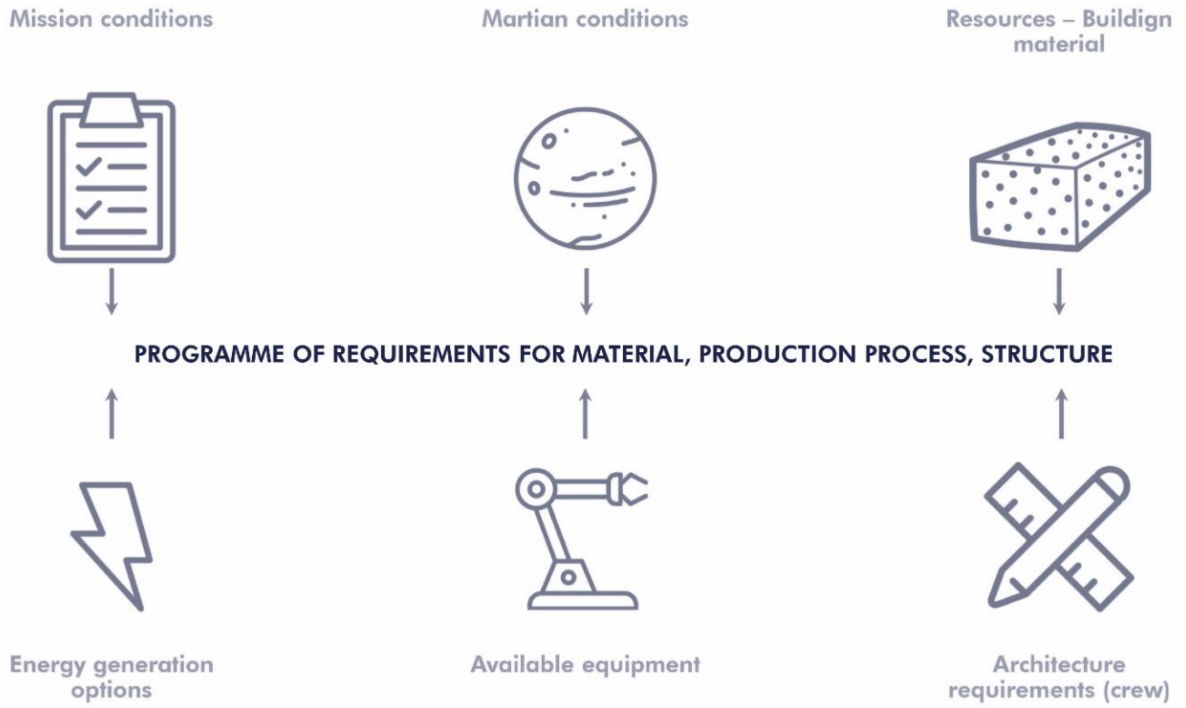


Figure 5: Scheme presenting the aspects influencing the programme of requirements

MISSION CONDITIONS

Mars - the exploration destination, as mentioned in the Introduction chapter is a realistic plan. Future manned missions to Mars has been planned since the 1950s. Current mission models like Zubrin's *Mars Direct*, Aldrin's *Mission to Mars*, NASA's *Journey to Mars* and *SpaceX's Mars Colonization* (Jordan, 2017) are the base approaches, which would be considered as the models for ideal mission's requirements. Most of these mission designs are focused on in situ resources utilization (ISRU). It means, that Mars' local resources should be used as a building material, energy source or material for life support systems to decrease payload mass and volume launched from Earth. First manned missions are planned for 600 days - 3 years (surface stay) and 2 - 6 people crew.

The missions are planned for years 2025-2035, therefore the technology used for the missions should be already under development and possible to achieve until that time. ESA has developed a system determining technology readiness level (TRL), where the equipment that can be sent into space has 8/9 level (flight qualified/flight proven) (TEC-SHS, 2008). Ongoing researches related to space architecture have 3/4 level, which corresponds to a proven concept of technology/technology tested in a laboratory environment.

As mentioned in the introduction chapter, the transportation is complex and problematic, which makes it an essential condition for Martian architecture. The first issue occurs already on Earth – rare launch windows. These windows are the possible dates for launching rockets to Mars. They depend on the orbits of planets and the distance between them. It is calculated, that the best launch window appears every 26 months. Combined with 600 days of shortest travel to the Red Planet, it results with rare transports, deliveries, and most important long-term missions. It has an impact on the fact, that the equipment and resources for building habitat should fit in one rocket. (Loff, 2018) Moreover, the payload (mass and volume) of a rocket is very limited. The biggest rockets – Falcon Heavy and SLS, which are currently under development will hold 16,800kg (SpaceX, 2018) and 40,800kg (Harbaugh, 2018) to Mars respectively. Therefore, it is important to reach most energy and material efficient production and building process. Additionally, the ISRU approach could solve the problem with the limited payload for resources. Another essential issue related to the great distance between planets is communication delay ranging from 4 to 24 minutes. Currently, rovers and landers on the surface of Mars work very slowly, waiting for instructions from Earth and sending back data with delay. Researchers propose that this problem could be solved if the processes would be independent and autonomous.

MISSION CONDITIONS - SUMMARY

Table 1: Mission condition - summary

MISSION CONDITION - SUMMARY		
Factor	**Effect**	**Requirement**
crew size: 2-6 people	habitat's volume designed for 6 people	min habitat volume - 150m³ (data explained in the chapter: Architecture)
min mission duration(surface): either 3 weeks or 600 days	habitat might be used just for 3 weeks	building habitat shouldn't be too demanding
multiple manned missions planned	reusable habitat	habitat's lifespan extended to multiple missions
missions planned for years 2030-35	the technology available and achievable in years 2030-35	TRL of the production process and building system should be already 3/4
rare launch windows	rare transports and deliveries	required resources and equipment fit in one rocket
limited payload	limited Earth resources and equipment	ISRU approach, efficient production, and building process

Martian conditions

GENERAL INFORMATION

This chapter will explain general information about Mars, which will be relevant to the research and further decision making. The Martian conditions will determine the programme of requirements for each aspect of the thesis. In the book about Martian surface and atmosphere (Fran Bagenal, David Jewitt, Carl Murray, et al., 2008), authors create an introduction and perfect background information required for this research.

Mars is the fourth planet from the Sun. The average distance from Earth is 54.6 million kilometres. The day is slightly longer than the terrestrial one and is called “sol”. The Martian year is equal to 687 Earth days or 669 sols. The size and mass of Mars are smaller and is presented in Table 2 with other basic properties. The highlighted rows include the parameters that could have an influence on building on Mars.

Table 2: Basic properties of Martian climate and physical parameters compared to Earth

Parameter	Mars	Earth
Radius (equator)	3,396 km	6,371 km
Mass	6,42 x 10 ^{23}	5,97 x 10 ^{24}
Day	24 hours 40 minutes	23 hours 56 minutes
Pressure	0,4 – 0,87 kPa	101,325 kPa
Gravity	3,71 m/s^2	9,8 m/s^2
Surface Temperature (average)	-46°C	-14°C
Surface Temperature (range)	-143°C - 35°C	-80°C - 60°C
Moons	Phobos and Deimos	Moon

MARS CONDITIONS AND HAZARDS

Mars has no magnetic field, although fossil magnetic field was observed on the surface. The field is not generated continuously, it’s rather in the form of stripes. These remains of the previously existing magnetic field have a huge influence on the upper atmosphere – ionosphere, changing its density. This could affect communication systems between Mars and Earth and on the planet itself. Unfortunately, no rover or lander had investigated stronger fields (Dubinin, et al., 2016). Figure 69 illustrates the crustal magnetism which disappears in the northern hemisphere and in volcanic areas.

The lack of a magnetic field has an impact on some climate conditions essential for building a habitat. Dr Fabio De Blasio, in the book Mysteries of Mars, explains atmospheric conditions on Mars and their influence on climate (De Blasio, 2018). The lack of magnetic field results in a thin atmosphere and low ground pressure of about 600 Pa. However, the atmosphere is able to keep dust particles suspended by the Martian wind. The composition of the atmosphere is presented in Table 3 below. Carbon dioxide is the most abundant component, which is responsible for the absorption of infrared radiation. Due to this process, the temperature decreases constantly up to 100 km. The temperature can differ significantly, with the average range -143°C - 35°C. The contrast between day and night can reach up to 100°C. Usually, the wind is weak, but sometimes a sandstorm occurs, which can last even a few months. The strongest storms occur at the perihelion period when the southern hemisphere surface receives maximum thermal energy from the Sun. During this phenomena, the potential solar energy, which could be used as a source of renewable energy for building process is limited. Other effects of Martian wind are dust devils occurring in the afternoon preferably in the southern hemisphere. They peak up the dust cover leaving a dark path behind. The mentioned phenomena caused by wind are shown in Figure 70.

Another issue related to the thin atmosphere and lack of magnetic field is cosmic radiation. While for the building itself and production process, radiation has a slight impact, then for the manned crew it is a lethal factor. The radiation environment on Mars has two components: a continuous flux of Galactic Cosmic Rays (GCRs) and transient but intense fluxes of solar energetic particles (SEP) (Parnell, et al., 1998). The compared values of radiation dose rates in different locations and situations are showed in Figure 71. For 500 days on Mars (which is less than the shortest planned mission) the value is located near 300 millisieverts (mSv), while the permissible amount, according to NASA is 1000 mSv for an astronaut in a lifetime. This value is associated with a 5% increase in fatal cancer development risk. This research is aiming to design a structure that could be treated as a habitat or part of the shelter. Therefore the insulation against the radiation is required for the habitat.

Table 3: Composition of the Martian atmosphere (by volume), Source: Fran Bagenal, David Jewitt, Carl Murray, et al., 2008

element	name	%
CO_2	Carbon dioxide	95,32
N_2	Nitrogen	2,7
Ar	Argon	1,6
O_2	Oxygen	0,13
CO	Carbon monoxide	0,08
H_2O	Water	210ppm
NO	Nitrogen oxide	100ppm
Ne	Neon	2,5 ppm
HDO	Hydrogen-deuterium-oxygen (semi heavy water)	0,85 ppm
Kr	Krypton	0,3 ppm
Xe	Xenon	0,08 ppm

The surface of Mars is also exposed to micrometeorite strikes because many of these don't melt during the atmospheric entry. According to Dr Robert Dycus, the average velocity of micrometeorite hitting the surface can be 7,0±0,2 km/s (Dycus, 1969). This phenomenon requires the structure to be resistant to direct and dynamic impacts.

There is no evidence of plate tectonics, therefore marsquake can be neglected as a factor affecting a built structure and as a hazardous parameter. Moreover, the other consequence is the conservation of old traces of geological activities like impact craters, which are the source of regolith. The preserved geological forms and structures have been investigated by orbit fly-by and landing missions. The data gained by infrared spectroscopic measurements and X-ray diffraction analysis allows determining the composition of Martian surface.

The topography of Mars is diverse but easy to distinguish in terms of highlands and lowlands. This division is visible in Figure 72, which represents a map of altimetric data made by Mars Global Surveyor (MGS) spacecraft. The legend explaining the colours is below the map. From the image, it is evident, that the northern hemisphere has an altitude below datum and is relatively more smooth (fewer craters and disturbance) compared to the other half. The southern hemisphere is higher and contains more craters and mountains. This division of the planet is called the Martian dichotomy. On the same image, there are selected names of regions and structures important for this research.

Table 4 presents the summary of conditions and their effect on a manned mission to Mars, building, and human.

MARTIAN CONDITIONS - SUMMARY

Table 4: Martian conditions summary

MARTIAN CONDITIONS - SUMMARY		
Factor	**Effect**	**Requirement**
Surface Temperature (-46°C)	the unfavourable temperature for humans	habitat structure should protect against low temperatures, a great difference between interior and outdoor temperature
Surface Temperature Range (-143°C - 35°C)	high-temperature altitude having an impact on the habitat structure	structure resistant to temperature differences
low Pressure (0,4 – 0,87 kPa)	too low pressure for a human to survive without pressurized spaces	habitat should provide and withstand pressure difference, habitat should be sealed - **zero permeability**
Sol length - 24h 40 min	limited solar energy	solar energy shouldn't only source if so there is a need for energy storage
no magnetic field	galactic radiation and solar particles - deadly for human	habitat protecting against radiation
no magnetic field	thin atmosphere - micrometeorites strikes	habitat outer shell resistant to dynamic impacts
dust storm	blocking sunlight and impede communication	solar energy is not the only source

RESOURCES – REGOLITH

The material, chosen for this research is the Martian regolith. This decision was made, to investigate and extend the knowledge about using ISRU approach for building on Mars. There could be also other resources available, like dry ice and water in the form of ice, however, they are less explored and the excavation or processing could be very energy demanding. Moreover, the water might be too precious for a manned mission, as it is essential for human life support systems. Rocky material is also available and well-studied, but considering energy demand for excavation and fractioning, it is not an ideal choice. Martian soil and dust are similarly explored. Additionally, they are in the form of loose material available on the surface. Detailed material characteristics of regolith are described below.

AVAILABILITY

As mentioned earlier, the regolith is a secondary product of impacts. The ejected material can be distributed up to many kilometres around the crater. It can later consolidate as sedimentary rocks with the addition of ice and as a fine powder, free to wander around the surface. Due to the absence of water, the fine-grained surface layer is easy to be carried and transported by wind flows. Small particles can travel incessantly leading to the homogenous composition of the dust on the entire planet. This makes the excavation of the material easier and the availability of the resources broader. Moreover, the fact that the composition of dust is homogenous makes it a better building material as the production process and building technologies could be similar in more than one region.

Regions abundant in fine grains contain dunes. Figure 6 presents the map of dust regions on the surface of Mars. As visible in the image, dust is more available in the northern hemisphere. Due to the localization of material, more detailed data about the composition will be gathered based on surface missions close to the regions rich in dust. The rovers and landers are shown in the same Figure. The most promising data can be gained from the latest missions as they are better equipped and the analyzing technology was improved compared to previous ones. Therefore, the data about the composition of dust gained by Curiosity and Spirit rovers was chosen to be investigated.

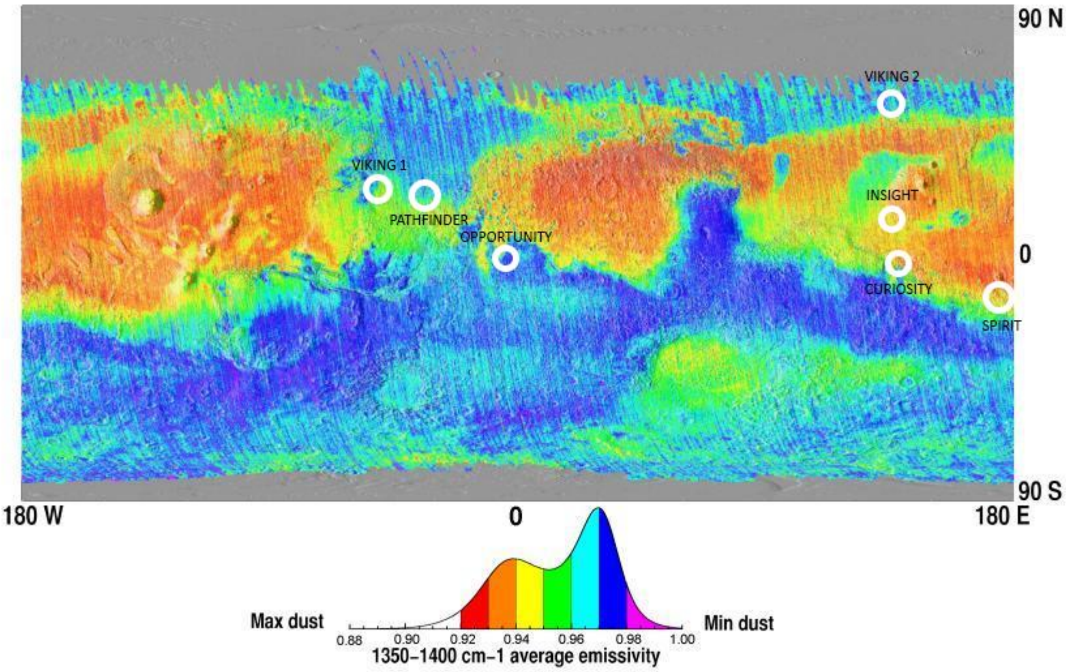


Figure 6: Dust cover map of Mars, Source: Mars Global Data Sets

SAMPLES

Curiosity is a rover designed by NASA which landed on Mars in 2012 in Gale Crater region. Its task is to analyze surface and atmosphere conditions, trying to explain geological processes occurring on the Red Planet. The vehicle is equipped in instruments investigating different properties of the surface material and climate. The image of curiosity is shown in Figure 7. The instruments, that are important for this research are ChemCam, Mars Hand Lens Imager (MAHLI), Alpha Particle X-ray Spectrometer (APXS) and Chemistry Mineralogy X-ray Diffraction (CheMin) (NASA/JPL-MSL, 2019).

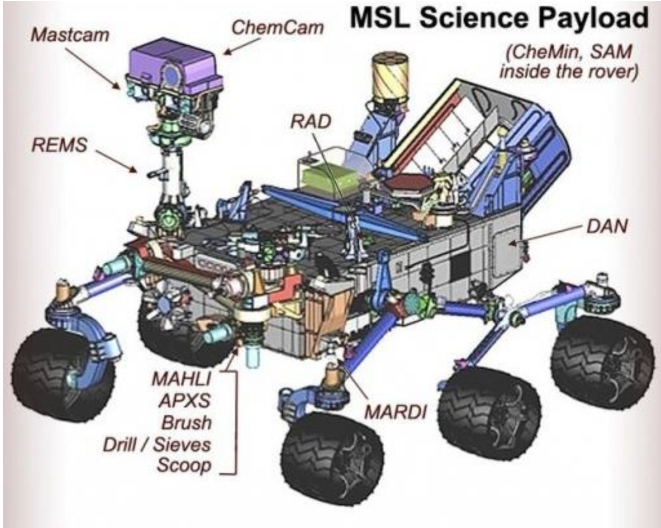


Figure 7: Curiosity rover instruments, Source: NASA, JPL, Caltech

- **ChemCam** – analysis of the chemical composition of rocks and soil
- **MAHLI** – makes microscopic images of minerals, textures, and structures in rocks and soil
- **APXS** – measures the abundance of chemical elements in rocks and soil
- **CheMin** – studies mineralogy and chemical composition of rocks and soil

Curiosity analyzed two types of dunes (soils) – active (Bagnold Dunes) and inactive (Rocknest) visible in Figure 8 (Cousin, et al., 2015). The active regions are the one, where the aeolian processes continuously form and change the surface. The Rocknest bedform is a dust deposit, where the rover could gather information about mineralogy and chemical composition of finest grains – ideal for this research. The scientist assumes, that this composition is the closest one to the global composition. Using average composition in the research could be more beneficial for future missions, where there would be a high possibility of finding global regolith close to different landing locations.

The Bagnold dunes are darker, better sorted and include less slit-sized or smaller grains compared to inactive dunes. However, the analysis of the active region also contains relevant data as grain size distribution, due to the fact, that the instruments analyzed with a diameter smaller than 150µm. Moreover, dust is most abundant in dunes regions, where it would be mixed with soil.

Therefore, these two samples – Rocknest and Bagnold Dunes (Namib) were chosen for further investigation of material.

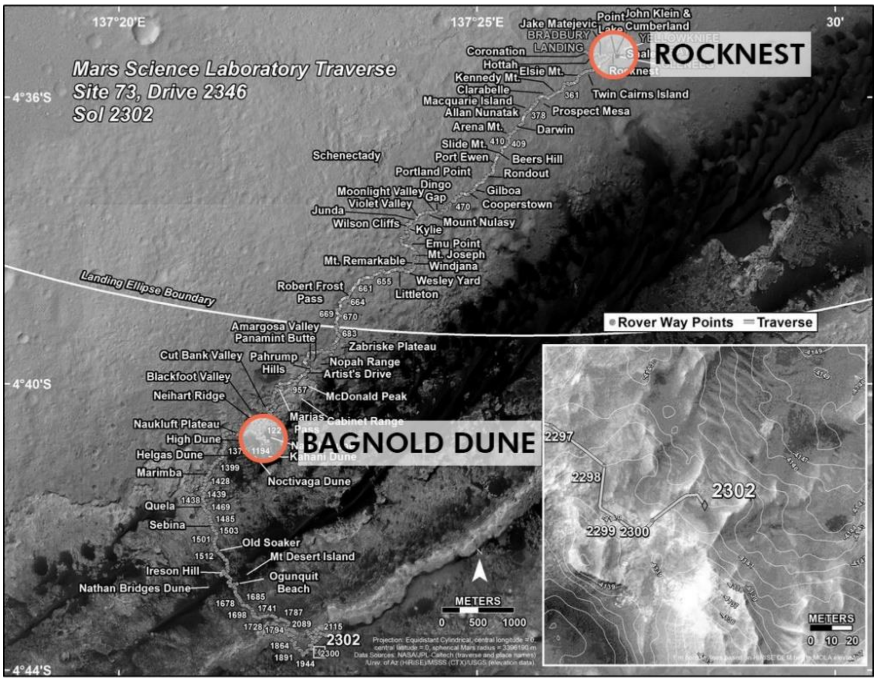


Figure 8: Map of Curiosity exploration with highlighted regolith samples locations, Source: NASA/JPL - Caltech/Univ. of Arizona

MARTIAN SIMULANTS

To study some technologies for Mars exploration, scientists developed simulants on Earth based on data gathered by rovers and landers. These simulants' compositions were prepared based on mineralogy and chemical analysis of real Martian samples. There are three commonly used simulants for research purposes: Johnson Space Center JSC Mars-1(A), Mojave Mars Simulant (MMS) and Mars Garden simulant (MMS-1 and -2). However, in a recent paper, (Cannon, et al., 2019a) researchers from the University of Central Florida developed more accurate simulants (MGS-1) and explained the limitations of previously mentioned ones.

According to authors of the paper, the JSC Mars-1(A) and MMS simulants are no longer available outside of NASA. Additionally, the material from the Johnson Space Centre is extremely hygroscopic and contains organic carbon elements, which was never detected on Mars. The MMS simulant is, on the other hand, consisted of nearly 100% crystalline material, while the real Martian regolith consists of both crystalline and amorphous elements. This composition is explained in next sub-chapter. The designers of MMS-1 and -2 claim to use the same composition as MMS simulant, but the major material in the sample is mined in the different region. The MGS-1 is based on Rocknest mineralogy and chemical composition and uses the most recent discoveries and data to reach the most accurate material. The composition of the simulant is presented in Table 8, in chapter "Composition" to compare it with real Martian samples. The material sources and preparation steps were explained in the same paper, which was the basis for this research.

Martian regolith sample analysis, showed that the material consists of two types of components: crystalline and amorphous. The crystalline part is mostly made of basaltic minerals. The major elements are plagioclase feldspar, Forsterite Olivine, Pyroxenes Augite, and Pyroxenes Pigeonite. Both, Rocknest and Namib samples included these minerals in slightly different formulas (Blake, et al., 2013)(Achilles, et al., 2017) Although it is assumed that there can be some halides, perchlorates, and carbonates present in soil, the Curiosity didn't detect any of these elements in dunes. It is possible, that they are below the detection limits of CheMin – less than 1%. Table 5 presents the crystalline composition of Rocknest and Namib soil.

Table 5: Rocknest and Namib soil mineralogy - a crystalline form

ROCKNEST				NAMIB			
Mineral	**Weight %**	**Formula**	**Grain size (µm)**	**Mineral**	**Weight %**	**Formula**	**Grain size (µm)**
Plagioclase Feldspar (more Ca than Na)	40.8	(Ca0.50(4)Na0.50)(Al1.50Si2.50)O8 Or (Ca0.57(13)Na0.43)(Al1.57Si2.43)O8	90% < 150	Plagioclase Feldspar	37	(Ca0.63(5)Na0.37) (Al1.63Si2.37)O8	Mainly coarsest material (>150 µm), but Olivine is more present in coarse fraction
Forsterite Olivine (more Mg than Fe) Fo58	22.4	(Mg1.15(5)Fe0.85)SiO4 Or (Mg1.24(6)Fe0.76)SiO4		Forsterite Olivine (Fo56)	26	(Mg1.11(6)Fe0.89)SiO4	
Pyroxenes Augite (High-Ca)	14.6	(Mg1.01(15)Ca0.80(11)Fe0.19(19))Si2O6 Or (Mg0.88(10)Ca0.75(4)Fe0.37(12))Si2O6		Pyroxenes Augite (High-Ca)	22	(Mg1.03(15)Ca0.81(11) Fe0.16(19))Si2O6	
Pyroxenes Pigeonite (Low-Ca)	13.8	(Mg1.02(16)Fe0.88(18)Ca0.10(9))Si2O6 Or (Mg1.13(12)Fe0.68(12)Ca0.19(5))Si2O6		Pyroxenes Pigeonite (Low-Ca)	11	(Mg1.03(23)Fe0.79(25) Ca0.18(11))Si2O6	
Magnetite	2.1			Magnetite	2,1		
Anhydrite	1.5	$CaSO_4$		Anhydrite	0,8	$CaSO_4$	
Quartz	1.4			Quartz	1,3		
Hematite	1.1	Fe_2O_3		Hematite	0,9	Fe_2O_3	
Ilmenite	0.9	$TiFeO_3$					

Another part of regolith is amorphous phases. There is no accurate data regarding these elements, but the scientist was able to make some estimations (Morris, et al., 2013) It constitutes 36-45 wt% of analyzed soil samples. The instruments on Curiosity rover were able to detect only a few elements like Fe, S, Cl, Si, which could be part of amorphous elements. Most abundant and often detected are nanophase iron oxides (npOx like ferrihydrite) and phases enriched in Si, like maskelynite, allophane, amorphous silica (opal) and basaltic glass. The second group is a combination of phases. Unfortunately, the percentage composition is not known yet. It is assumed that there are also some amorphous sulfate and carbonate, but usually, they are present below detection limits. This is proved by the fact, that the Curiosity also detected volatiles like H_2O/Oh or SO_3 (Leshin, et al., 2013). The approximate compositions of mentioned amorphous elements are presented in Table 6**.**

Table 6: Chemical composition of Gobabeb soil sample, Source: Achilles, et al., 2017

Composition Element	Amorphous[1]	Amorphous[2]
SiO2	20.54	49,53
TiO2	0.88	2,12
Al2O3	3.26	7,86
FeOT	8.22	19,82
MnO	0.37	0,89
MgO	0.00	0,00
CaO	1.27	3,06
Na2O	1.85	4,46
K2O	0.49	1,18
P2O5	0.79	1,91
Cr2O3	0.39	0,94
Cl	0.50	1,21
SO3	2.91	7,02
Total	41.47	100

SIZE DISTRIBUTION

According to Ming, et al., 2017, the soil is made of 15-25% clay particles and 75-85% silt and sand. The common dust particles have an average diameter of 2µm. The particle types and sizes present on Mars are presented in Table 7.

Table 7: Grain sizes present in Martian soil samples

Diameter (mm)	Particle	Elements abundant
<0,004	Clay	Mostly dust and amorphous phases
0,004-0,00625	Slit	Hematite, anhydrite, magnetite, ilmenite
0,00625-0,125	Very fine sand	
0,125-0,25	Fine sand	Quartz,
0,25-0,5	Medium sand	plagioclase
0,5-1,0	Coarse sand	Mostly olivine, pyroxene minerals

In the samples collected at Rocknest and Namib bedforms, the instrument analyzed only grains smaller than 0,15mm. The grain size distribution of these soils is presented in Table 9. Interestingly, vibration analysis performed by rover shows the relation between grain size and type of mineral. Figure 9 presents a graph with minerals detected after direct/indirect vibration test. From this test, it is assumed, that the olivine and pyroxene are more abundant in sand-size grans, while the minor minerals like magnetite, hematite, and anhydrite usually occur as fine-size particles

Table 8: Mineralogy of Rocknest, Namib and MGS-1 regolith samples

ROCKNEST		NAMIB		SIMULANT, MGS-1	
Mineral	Weight %	Mineral	Weight %	Mineral	Weight %
CRYSTALLINE					
65%		65%		70%	
Plagioclase Feldspar (more Ca than Na)	40.8	Plagioclase Feldspar	37	Albite	41,6
Forsterite Olivine (more Mg than Fe) Fo58	22.4	Forsterite Olivine (Fo56)	26	Highly Forsteritic Olivine	21
Pyroxenes Augite (High-Ca)	14.6	Pyroxenes Augite (High-Ca)	22	single bronzite-variety pyroxene	31
Pyroxenes Pigeonite (Low-Ca)	13.8	Pyroxenes Pigeonite (Low-Ca)	11		
Magnetite	2.1	Magnetite	2,1	Magnetite (as black iron oxide)	2,9
Anhydrite	1.5	Anhydrite	0,8	Anhydrite	1,3
Quartz	1.4	Quartz	1,3		
Hematite	1.1	Hematite	0,9	Hematite (as red iron oxide)	1,7
Ilmenite	0.9				
AMORPHOUS					
35%		35%		30%	
npOx,	19	npOx	23	Ferrihydrite	4
Si-enriched component	35,3	Si-enriched	59	Basaltic Glass	65
				Hydrated Silica (as diatomaceous earth)	14
S - enriched	13,02	SO3	8,5	ferric-sufate (iron (III) sulfate pentahydrate)	20
		Al2O3	8,5		
				Fe-carbonate (siderite)	4

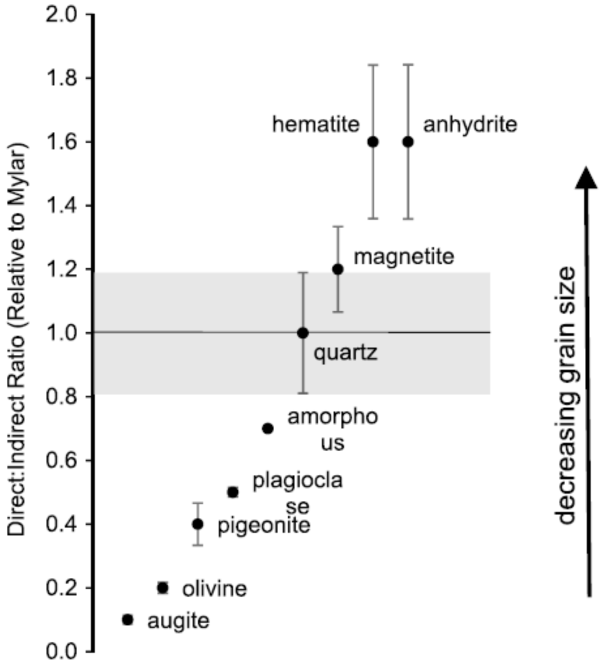


Figure 9: Measured phase abundance ratios for Martian soil sample analyzed via direct and indirect cell vibration. Source: Achilles, et al., 2017

Table 9: grain size distribution in the Namib sample

Wt%	Grain size mm
40-60	0,1 – 0,15
30-50	slit, clay
2	Coarse, 0,3-2

ADDITIVES

To improve properties of the building component additional material is often used in form for example fibres. Researchers are studying different options for those additives which can be mixed with Martian regolith. Usually, spacecraft reusables or organic materials are chosen for this type of researches. Some concepts for habitats on Mars also propose to use additives made out of in-situ resources – like glass or basaltic fibres or produced polymer material from the atmosphere. However, this brings additional production process, therefore taking into account efficiency and reduction for energy demand additives won't be included in the building material.

RESOURCES - SUMMARY

Table 10: Resources requirements - summary

RESOURCES - SUMMARY		
Factor	**Effect**	**Requirement**
dust and fine particles of regolith most abundant and have a global composition	similar building process in more than one region	
perchlorates present on the surface (in soil)	perchlorates harmful for humans	interiors protection layer separating crew from regolith material
dust and sand present on the surface - dunes most abundant		location nearby dunes
grain size distribution varies from clay to cobble size	some particles might be too big for processing	sieving and/or fractioning of regolith required

Energy generation options

REQUIREMENTS FOR AN ENERGY SOURCE

Based on the requirements from previously mentioned factors, it can be assumed, that there are limitations for volume and mass (brought from Earth) of the equipment that will produce energy. Moreover, the mass of the energy resource launched from Earth should be minimized. Therefore, the relation between mass and efficiency of the landed resources is essential. This limitation makes renewable energy more suitable for generating power.

The renewable source, on the other hand, should be easy to utilize and available globally. The fact, that the production and building process would be fully automated allows it to proceed day and night. It brings another requirement for the renewable source – accessibility. Permanent access to this source is ideal, however, if not, there should be an efficient energy storage system. Though, it is associated with additional equipment launched from Earth.

Irrespective of the type of energy generation source, the power system mechanism should be tolerant to surface dust contamination and environmental conditions. Any movable elements should be protected from the dry atmosphere on the surface. Additionally, the technology should be prepared for only robotic handling. Any transportation, deployment, unloading would be performed by rovers or robotic arms. In case of any change of location or building another habitat in a distant place, the power station should be compact and easy to transport. According to NASA's Mars study Capability Team (Rucker, 2016), the Operational Life Limit should be 10 years (in case of continuous generation) or 12 years (in case of intermittent work). It was based on the fact, that although the power system would be launched with the first mission, it would require to support the following missions.

AVAILABLE ENERGY SOURCES

The available energy sources for Mars missions were compared by Simon D. Fraser in a chapter of a book about Prospective Energy and Material Resources on Mars. (Soediono, 2009) In the Automation and Robotics for Human Mars Exploration (AROMA) study made by ESA, the output power requirement for investigated systems ranges between few watts up to tens of kilowatts. Due to the climate conditions on Martian surface, thin atmosphere, there is a broad range of options for power generation. According to the author, the energy generated on the surface on Mars can be achieved by following options (Table 11):

Table 11: Power generation options on the surface of Mars highlighted options are the most likely pathways according to the author, Source: "Mars: Prospective Energy and Material Resources" Soediono, 2009

power generation options	technologies e.g.
Alternative power generation options	geothermal energy, solar power satellites/beamed power from space
Landed energy resources	primary batteries, fuels or feedstock species, nuclear energy resources
Solar-energy-to-electric conversion	photovoltaic, solar dynamic power systems
Landed non-nuclear energy resources	primary batteries, readily-fuelled fuel cells or heat engines
Landed nuclear energy resources	radioisotope generators, fission reactors with static or dynamic conversion systems
ISRU process	the utilization of in-situ resources for propellant and/or oxidant production
Fuels/oxidants	hydrogen/oxygen, methane/oxygen, carbon monoxide/oxygen, methanol/oxygen

The most likely available options are surface solar energy utilization, landed energy resources (where the best one would be nuclear power) and ISRU processes. Other types of power generation systems are less explored or are associated with relatively bigger payload transported from Earth. Therefore, below only solar, nuclear and ISRU energy sources would be investigated.

SOLAR ENERGY

GENERAL INFORMATION

The solar radiation was used in most of the space missions because it is a renewable energy source and there is no need for the extra payload for the resource in the rocket. On Mars, it has been used in several rovers and landers, like Viking, Opportunity, and InSight. It is not considered as the only source, because of its limitations regarding Martian conditions (Delgado-Bonal, et al., 2016).

LIMITATIONS

This renewable source of energy is one of the most obvious choices. However, the limitations due to climate conditions are an issue when we consider a high-performance application such as a complex production process. These limitations are mostly related to atmosphere impurity caused by floating dust. As mentioned earlier, potential dust storms could decrease the energy output to minimal or none for weeks or months. According to NASA's Mars Study Capability Team, the average dust storm can last for 120 days blocking the direct light by 30-40%. Additionally, the average sunlight period is 12 hours, becoming inefficient during the rest of the day. Therefore, even if the solar energy would be considered the main option for power supply, there should be an alternative source, which would be independent of environmental conditions.

The life-span of solar panels is essential for planning energy generation options. On Earth, it ranges between 15 – 20 years. Unfortunately, there is no data for Martian conditions, though scientists assumed that it will be lower than on our planet.

The other limitation is the requirement regarding the location of the habitat and power plant. Solar panels require solar energy, while scientists prefer exploring well-preserved regions of the planet, which comes to be usually dark and cold.

EQUIPMENT

The possible solar energy utilization technologies are photovoltaic, photothermal and solar dynamic systems. They depend on solar irradiance, which can be divided into direct, diffused and global solar radiation. The equipment for direct solar irradiance collection requires expensive and complex tracking mechanism to orient the receiving surface always perpendicular to the Sun's rays. The global solar irradiance is collected by flat plate collectors with one rotation axes continuously adjusted or adjusted from time to time.

The photovoltaic system requires less complex equipment and therefore payload. However, it requires manual orientation of the panels and maintenance to keep the photovoltaic surface clean from dust. The Insight lander is equipped with the lightest deployable circular solar arrays on Mars. According to the producers, the efficiency of cell technology should be 29,5%

ENERGY AMOUNT

According to prof. Viorel Badescu, on Martian surface, the solar global irradiance could range between 400 W/m^2 at the noon of a clear summer day to 80 W/m^2 at midday during a winter dust storm. (Badescu, 1998) The average solar potential for the day-night cycle is assumed to be 100-120 W/m^2 for equator regions (including dust storms possibility but without efficiency factor). It means, that the solar panels would be three times less efficient on Mars than on Earth.

The InSight lander equipped in solar panels produced 4588 watt-hours during first sol (two solar panels, about 2,2m each in diameter) (Brown, et al., 2018). *"On a clear day two panels will provide 600 to 700 watts of power – enough electricity to run a household blender,"* say the panels' designers. However, if the dust suspended in the atmosphere is included in the estimation, then the max value might be 300W. By multiplying the value by 12 hours (daytime on Mars) the result of max 3600 Wh (3,6kWh) can be calculated.

LANDED ENERGY RESOURCES – NUCLEAR POWER

GENERAL INFORMATION

Among the available landing resources is a nuclear power, which will be investigated in this research. There are two types of nuclear power systems present in the space industry.

Radioisotope systems: NASA has the most developed nuclear power generation technology (NASA, 2019). It is favourable for long-term missions and when the power demand is not exceeding a few hundred watts. A developed technology commonly used in space exploration is Multi-Mission Radioisotope Thermoelectric Generator (MMRTG), which is currently working on Mars in Curiosity rover. This power system produces electricity from the natural decay of plutonium-238 dioxide, transforms into uranium 234 which generates heat.

In the future, there is a plan for developing the technology by creating e-MMRTG (Enhanced Multi-Mission Radioisotope Thermoelectric Generator, which offers a significant increase in power compared to the system in Curiosity. This improvement might be even >25% efficiency at the beginning of life and >50% at the end of the 14-year mission. Moreover, this system is planned to be applicable to multiple types of missions.

Another technology assigned to this group is the Dynamic Radioisotope Power (DRP) system. It is not yet developed enough to be used in a space mission, but NASA considers it as a potential solution for harsh, dark and dusty environments. This technology uses a closed thermodynamic cycle such as Stirling or Brayton cycle to produce power.

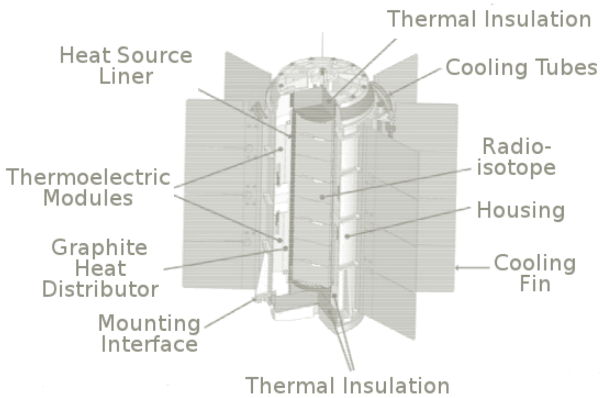


Figure 10: MMRTG model for the power system, source: NASA

Fission Systems: Another system under development is Kilopower Reactor Using Stirling Technology (KRUSTY), which is one of NASA solutions for generating power for Mars colonization (Hall, 2017). The system is based on reactor converting heat produced by uranium-235 into motion, which is later converted to electricity. The conceptual visualization of the system is presented in Figure 11. The surplus heat will be removed by umbrella-like cooling arrays.

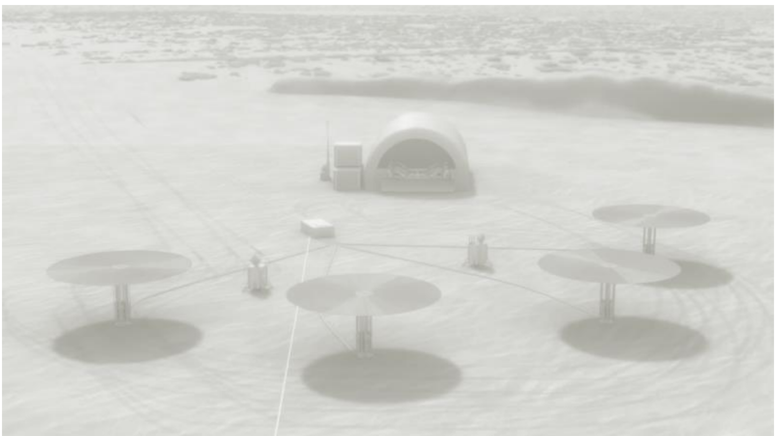


Figure 11: Kilopower conceptual visualization, Source: NASA

Micro-fission nuclear reactor was considered as one of the options, but according to NASA, it might be too heavy for current Entry Descent and Landing (EDL) concepts. Moreover, the contamination risk is too high (Moses, et al., 2016).

LIMITATIONS

Radioisotope systems: Radioactive material creates a risk of radioactive contamination, resulting in health issues and environmental impact. Additionally, the thermoelectric generators are very inefficient – ranging between 3-7%. Although dynamic generators can provide four times higher efficiency.

Fission Systems: The disadvantage of this technology could be the mechanical structure of the system. Stirling technology would require movable elements, which could be unreliable considering repair difficulties.

EQUIPMENT

Radioisotope systems: RTG is equipped in an array of thermocouples placed in the walls of the equipment and sturdy container with radioactive material. Each thermocouple is connected to a heat sink. It doesn't have any movable elements. Dynamic RPS requires thermodynamic cycle engine and the power converter, which is producing electrical power from heat energy (Stirling, Boyton). These convertors have moving parts – pistons and alternator, which convert motion into electricity. Additionally, to prevent friction and impacting the side walls the convertors use a gas bearing system or flexure bearing with springs.

Fission Systems: Kilopower system's most important elements are Stirling engines, radiator - umbrella, sodium heat pipes, reactor core, reflectors, and shielding parts.

ENERGY AMOUNT

Radioisotope systems: Curiosity rover's record for power output is **2806 watt-hours per one sol**. It is equipped with about 5kg nuclear power. In general, the MMRTG is assumed to produce 2,8W/kg, while e-MMRTG would generate >3,6W/kg.

Fission Systems: Whereas KRUSTY system is available to produce **1-10kWe** of electricity. The expected mass for the 10kW output is 226kg. The specific power will reach 6,5 W/kg (Briggs, et al., 2018). The comparison of solar and nuclear energy in NASA projects is presented in Figure 12. Between Curiosity and InSight mission is only 6 years and the energy produced by solar panels is impressively higher than the nuclear one. It can be possible, that by the time of first manned missions to Mars, the technology for generating energy from renewable resources would reach similar or better results as fission power.

Figure 12: Comparison of NASA energy generation technology

In the same chapter, the author Simon D. Fraser compared these two options: solar and nuclear resources, in Table 13 below. Although it's clear from the table, that the nuclear power has more potential, the plans for future missions assume, that there would be at least two sources of energy. Solar energy advantage is related to its sustainable aspects, while future nuclear systems can produce much more energy.

IN-SITU RESOURCES UTILIZATION

GENERAL INFORMATION

There are few concepts for the production of propellants from the Martian atmosphere or soil (Moses, et al., 2016). Using fuel cell it is possible to convert fuel into electricity through an electrochemical reaction. The required resources are fuel and oxidant. There are a few types of fuel cell systems, which are listed below – Table 12. Three most important fuels for Mars are hydrogen, carbon monoxide and methane.

Table 12: Fuel cell options for Mars

option	Operating temperature °C	Fuel
Polymer Electrolyte Membrane Fuel Cell (PEMFC)	50-95	$H_2(CH_3OH)$
Phosphoric Acid Fuel Cell (PAFC)	160-220	H_2
Molten Carbonate Fuel Cell (MCFC)	620-660	H_2, CH_4, CO
Solid Oxide Fuel Cell (SOFC)	800-1000	H_2, CH_4, CO

The required elements for this process are hydrogen fuel with oxygen or another oxidizing agent. Hydrogen and CO can be extracted from the atmosphere. The fuel cell can produce electricity continuously, as long as oxygen and fuel are provided. The basic elements of a fuel cell are presented in Figure 73.

Sabatier reaction has the potential for fuel production. In the case of Mars, the essential compound required for this process is CO_2 from the atmosphere. With the addition of H_2 brought from Earth or from H_2O extracted from near-surface regolith, methane and oxygen can be produced. This reaction produces also heat in the form of steam. The Sabatier reaction is written as:

Equation 1

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O + \text{energy (heat)}$$

This reaction is exothermic, which means that there is no need for external energy to drive it. Additionally, the water can be pumped into an electrolysis cell to split it with electrolysis reaction into hydrogen and oxygen. Hydrogen can be then recycled back to the Sabatier reaction (Equation 1), while oxygen can be stored for crew or other purposes.

The reserve water gas shift (RWGS) reaction can produce oxygen and carbon monoxide (either vented or utilized as fuel) using electrolysis on water produced by the Sabatier reactor (Equation 2). The basic scheme of the Sabatier/RWGS reactor is presented in Figure 74.

Equation 2

$$CO_2 + H_2 \rightarrow CO + 2H_2O$$

Combining both reactions, the Equation 3 can be written as:

Equation 3

$$3CO_2 + 6H_2 \rightarrow CH_4 + 2CO + 4H_2O$$

To produce hydrogen the pyrolysis reactor could be used (Equation 4) using methane as a reactant.

Equation 4

$$CH_4 \rightarrow C + 2H_2$$

Summary of all possible processes of ISRU fuel production is presented in Figure 13 below.

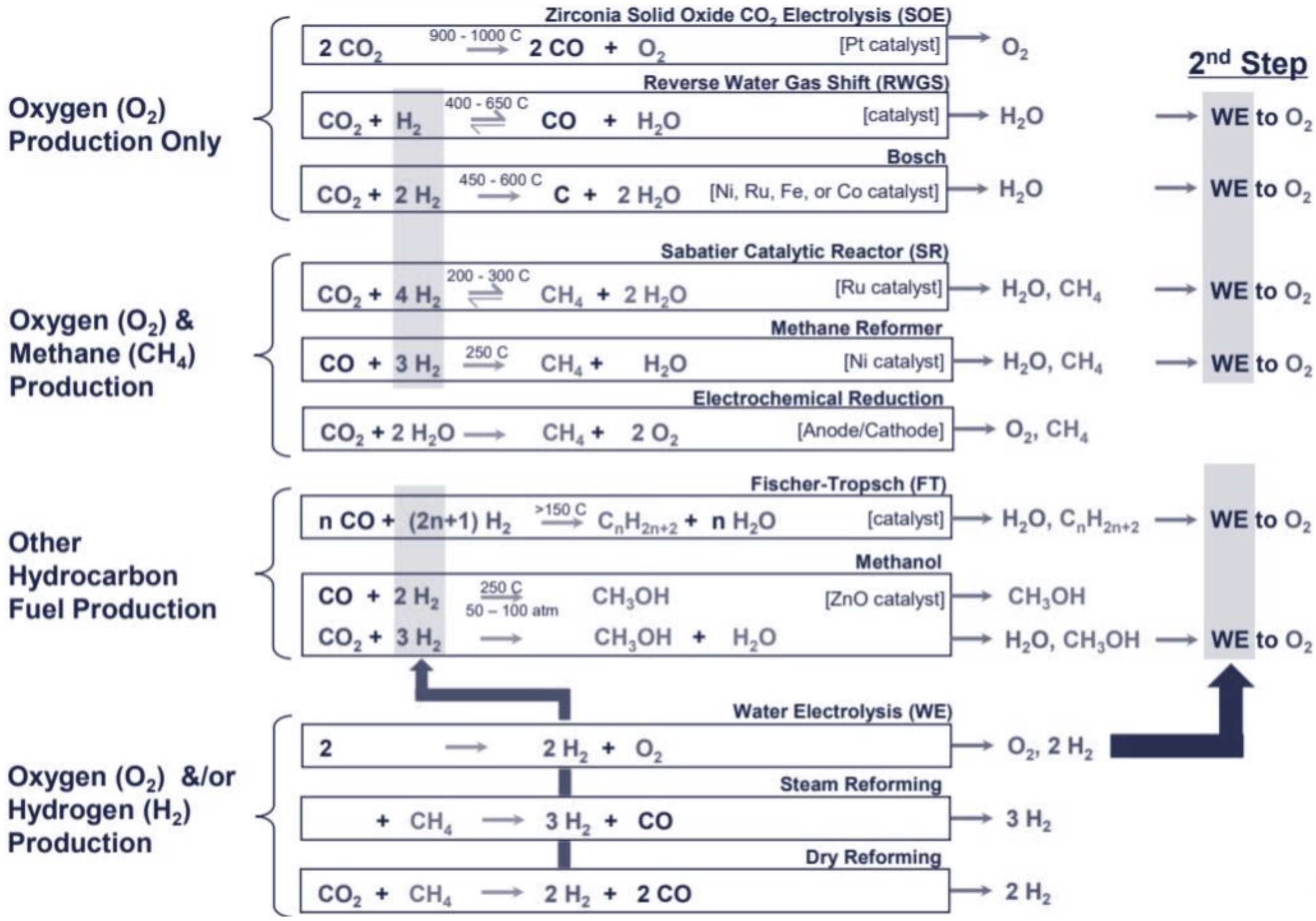


Figure 13: Fuel production processes available on Mars. Source: Aeronautics, 2017

LIMITATIONS

Storing hydrogen with cryogenic storage is considered inefficient and problematic. The fuel cell provides not a fully efficient process, therefore there is by-product chemicals and heat with the electricity. Additionally, the operation temperatures are very high. In the case of using CO in the process, there is a risk of poisoning the noble metal catalysts. To control and minimize it there is a complex gas clean-up required.

Sabatier process requires moving hydrogen, oxygen, and methane in liquid form from the tank to tank. This might be problematic considering additional pumping elements and thermal control. Otherwise, the freezing of water can destroy the system. Favourable equilibrium at a temperature ranging between 200-300°C.

ISRU utilization systems can't be the only energy source. They require power to control, support or start reactions. Additionally, the compound needs to be stored in specific conditions which also require power input.

EQUIPMENT

As visible on the schemes presenting reaction models, there would be few instruments required. The final amount of payload would be based on the reactor choice. Additionally, the tanks would be required for produced fuel and another element.

From the book *Mars – prospective energy and material resources* (Soediono, 2009) the authors estimated that a tank for storing 30kg of hydrogen would have 200kg, while a tank for storing energy-equivalent 72 kg of methane would require 60kg payload.

ENERGY AMOUNT

In the mentioned book, Soediono compared different fuels storage system masses and their specific energy. Based on this table, it was assumed, that from the fuels available on Mars, the best option is methane, with the specific energy 1851 Wh/kg.

CONCLUSION

The energy generation options were compared based on the issues related to the maintenance and access to the energy (Table 13). The decision, of which source to choose, was made after research on sustainability.

Table 13: Surface solar energy utilization versus nuclear power generation, Source: "Mars: Prospective Energy and Material Resources" Soediono, 2009

Issue	Surface solar energy utilization	Landing nuclear resources	ISRU processes
specific energy with respect to the Earth launch mass	?	?	?
system lifetime	very long, but depends on the maintenance	very long	-
continuous power output	not available, intermittent storage system necessary	available	available, dependent on resources
reliably	very high, but depends on installation, location, and operation	very high	-
maintenance	required	not required with RTG	-
operation in harsh environmental conditions	problematic	no problem	no problem
output power predictability	limited	very high	-
dependence on orientation	limited	no problem	no problem
cost	lower	high development	-
portability	lower	higher (compact) (diameter-64cm x height-66cm)	-
renewable	yes	no	Depends on the fuel?

AVAILABLE EQUIPMENT

In terms of transportation issues, the available equipment for production and building process was based on the equipment, that was already sent into space. For the first mission, the technology for building structures on Mars needs to be autonomous and tested. Therefore, the technology used in rovers and landers as well as in building industry would be considered (Figure 14).

To collect the samples for analysis, rovers are equipped with multiple elements collecting, preparing and analysing material. The method for collecting samples depends on the kind of material. Due to the focus on Martian regolith and dust as the source of building material, the options are narrowed to extraction using a shovel, sieving meshes and grain size reduction technology. Additionally, the equipment for determining the composition and grain size distribution would be included. The elements collecting and analysing the material would help prepare the right material for the chosen production.

The production processes available on Mars would need to be developed and reliable, therefore the complexity plays a key role in choosing the technology. Most of the designs for buildings on Mars are focusing on 3D printing as the best option, however, it requires complex equipment and the isolation of the material from Martian pressure and temperature during extrusion (Figure 21). The potential production process could use a combination of compression and thermal treatment as these processes are the most common and developed on Earth.

The final production process was chosen after reviewing ongoing research studies and research on sustainability and material (PRE-EXPERIMENTAL DECISION-MAKING).

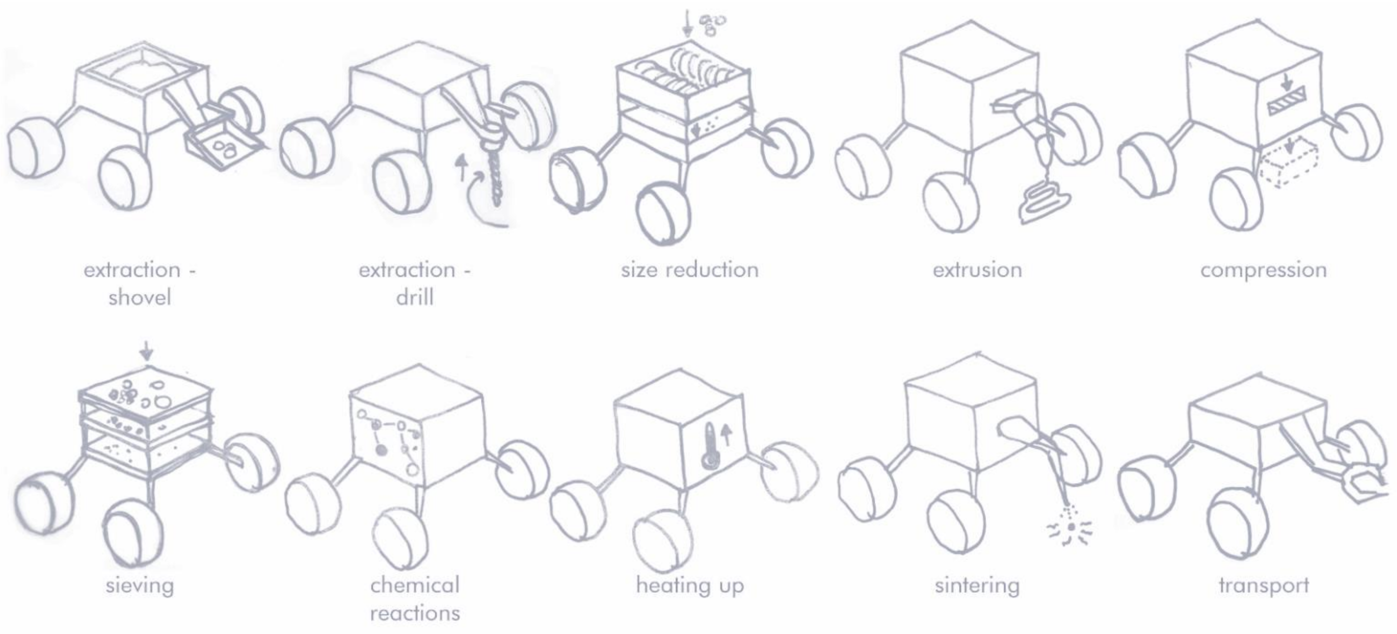


Figure 14: Potential production processes on Mars

ARCHITECTURE

There are several factors influencing the design of a Martian habitat. They are mostly human and mission oriented. These factors are listed below. In this report, the self-sufficiency will not be investigated as it's mostly connected to life-support systems and installations, which are not related to building material and structure itself.

Figure 15: Factors influencing architecture and structure of the habitat

CONFIGURATION – PROGRAM AND PLAN

The suggested volume depends mostly on mission duration, crew size, and mission type. For the first missions to Mars, the volume for the 6-person crew should be at least 150m^3. The interior should include spaces for several activities:

- Sleeping, private activities (quarters)
- Hygiene
- Dining
- Working
- Exercising
- Translation portals or pass-through
- Storage
- Docking ports

All these activities should be easily accessible, but also, the relation between them dictates the functional plan. For example, the private quarters should be the safest and most protected spaces, close to hygiene modules. However, the connection between exercise and working space should be limited due to safety, noises, smell, etc. Therefore the ideal concept for habitat is a modular configuration, where some functions are separated in another module. The functional adjacency is presented in Figure 16.

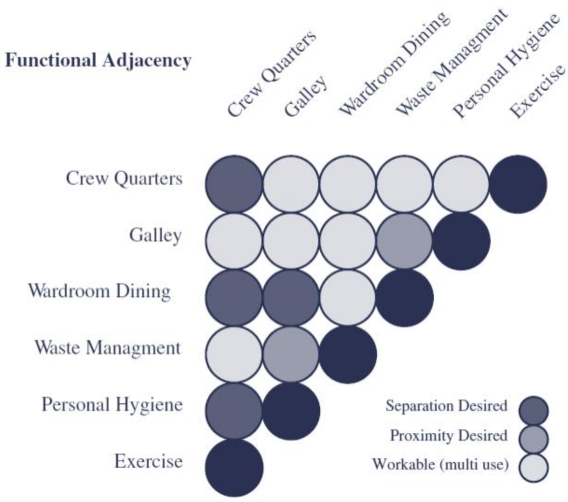


Figure 16: Functional adjacency of habitat spaces Häuplik-Meusburger, et al., 2016

Another important factor is zoning – both, regarding the separation of private and group spaces as well as the graduation of indoor and outdoor. There are some design examples, where the authors proposed spaces which were semi-outside, where the crew didn't need space suits, just breathing masks.

More detailed characteristics of habitat configurations are presented in O.Bannova book (Häuplik-Meusburger, et al., 2016).

CREW WELL-BEING AND SAFETY

Habitation design requirements for human missions mostly regard the safety and wellbeing of the crew. The ones important for this research were collected from the book "Space Architecture – Education for Architects and Engineers" (Häuplik-Meusburger, et al., 2016). Due to hazardous conditions on the surface of Mars, the interior of the habitat should support the isolated habitable environment and the building systems should be self-sufficient and sustainable. The factors regarding the indoor climate are the atmosphere, temperature, humidity, pressure, and light. However, these conditions are significant for habitable space, for the purpose of this research they are considered as secondary. This decision was made because the factors of indoor climate are solved mostly by life-support systems and installations. As this thesis is focusing on the production of the building material and construction method the most important requirements concerns safety against the hazards like micrometeoroids, outdoor temperature, and cosmic radiation.

ADAPTABILITY AND FUNCTION

NASA has implemented in XXI century a mission planning system called Capability-Driven Approach. Together with international partners, they developed Global Exploration Strategies including Habitability and Destination Capabilities (National Aeronautics and Space Administration, 2011b). Among these fundamental systems to investigate are long-duration habitation, mobile exploration module, EVA systems, Human-robotic interface, and destination systems. The authors emphasize, that it is ideal to leverage each mission, i.e. prepare technology so it can be reused for multiple mission scenarios and operations. In the architecture context, it could reveal as modular habitat structure, flexible configuration, and adjustable interior function.

REFERENCE PROJECTS

Projects from 3D printed Habitat Challenge Phase 1 - the Design Competition required teams to submit architectural renderings and was completed in 2015.

1. **ICE House**

Although this project uses different resource material than regolith I decided to keep it as a reference regarding the space design. This project in a concept of a Martian habitat proposed by winning team formed by SEArch (Space Exploration Architecture) and Clouds AO (Clouds Architecture Office). The group designed a 3D printed structure made of Ice. Despite the fact, that this material brings precious light inside the habitat, it has an important advantage in the fact that water is better as radiation insulation than regolith. Another potentially good part of the design is the idea of creating a gradient transition between safe interior and hazardous outdoor environment.

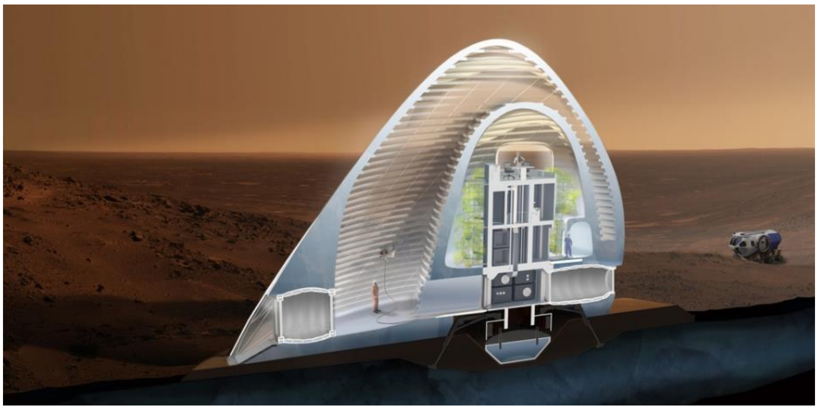


Figure 17: Section of the ICE HABITAT, Source: SEArch+, et al., 2015

The core of the habitat is a vertically oriented lander which contains all the mechanical services and life supports systems. Two layers of the ice structure visible in Figure 17 create intermediate zones acting as thermal and radiation insulation. This allows a crew to exit the main habitat without an EVA (extravehicular activity) suit. The middle space – between the lander and first layer of ice is pressurized at the same level as the interior of the hab. It is allowed by an ETFE membrane stretched on the surface of the ice structure. In the production process, the team uses the physics of phase change of water.

2. **LavaHive project**

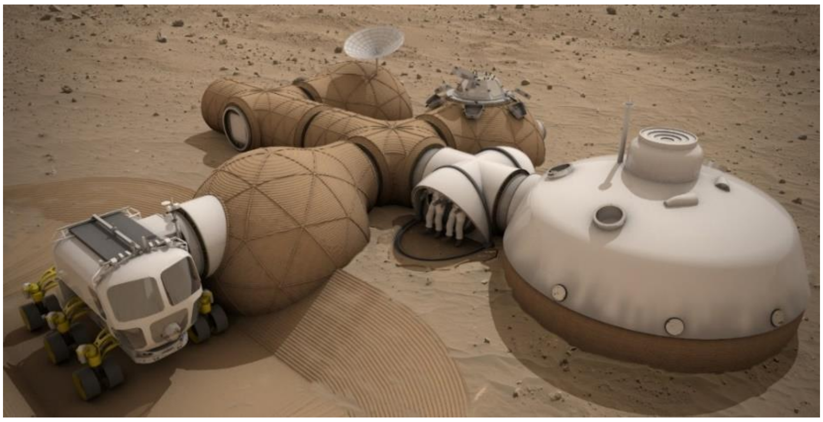


Figure 18: LavaHive conceptual visualisation, Source: Liquifer System Group

This is a project designed by European Space Agency's European Astronaut Centre and LIQUIFER Systems Group, which won the 3rd place in the NASA 3D Printed Habitat Challenge. It's a modular habitat using novel construction method – lava casting. According to authors: *"A linear configuration of modules was decided to be the safest, most effective, and most flexible option when considering this larger scale structure. Extending the configuration in the future is foreseen for including additional docking ports or other working areas."*

The building process is performed by 2 rovers – one to sinter, second to melt regolith. The core of the habitat is inflatable and the 3D printed structure is layered on its surface. The inside of the regolith structure is covered with epoxy which will seal the habitat. The potential of this design is the incorporation of components that are part of a spacecraft, which would bring rovers and landers to Mars. The reuse of these elements can be an advantage of sustainable design.

Projects from 3D Printed Habitat Challenge Phase 3 - the On-Site Habitat Competition, challenges competitors to fabricate sub-scale habitats and has five levels of competition – three construction levels and two virtual levels. For the virtual levels, teams must use Building Information Modeling software to design a habitat that combines allowances for both the structure and systems it must contain. The construction levels challenge the teams to autonomously 3D-print elements of the habitat, culminating with a one-third-scale printed habitat for the final level.

1. **SEArch+/Apis Cor's project – Mars X House**

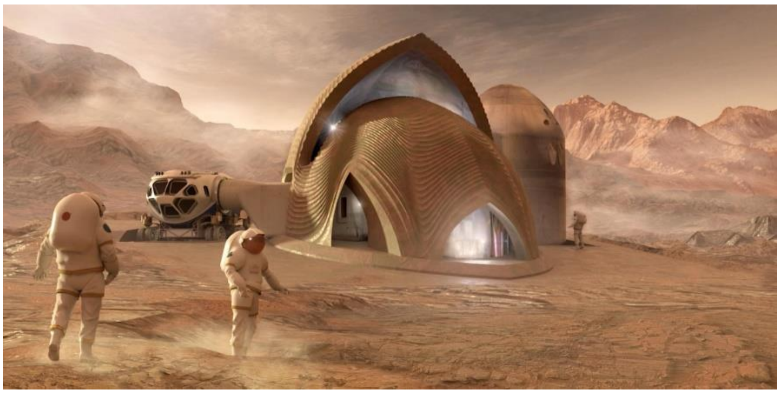


Figure 19: Mars X House visualization, Source: SEArch+, et al., 2018

This project is another interesting design of the habitat, where the team tried to combine two Martian resources – ice and regolith. Valuable research on radiation protection as a factor for structure design might be important information for this research. According to the authors, *"the density of Martian atmosphere along the horizon allows solar transmission up to 30° above the horizon"*. The design takes into account the orientation and location (northern hemisphere) of the habitat. The opening in the shell structure made of regolith are oriented towards the north and let a diffused light to the interior up a 30° angle.

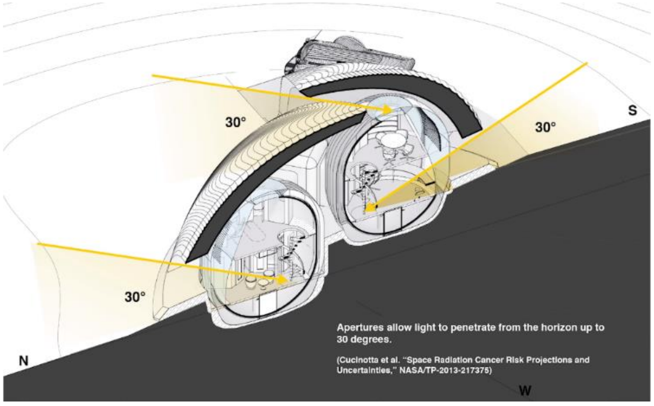


Figure 20: Scheme section of the design explaining the implementation of radiation shielding research to the design, Source: SEArch+, et al., 2018

2. Team Zopherus – Rogers, Arkansas

Modular design, where the lander is the equipment and printing place at the same time. The lander creates a printing chamber sealed to the ground and creates hexagonal structures in its pressurized interior space.

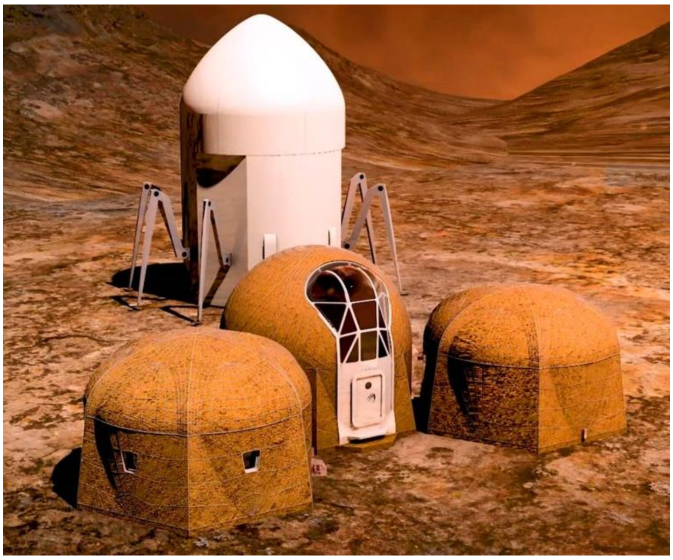


Figure 21: Zopherus habitat concept visualization presenting three 3d printed modules and the spider-lander, Source: NASA

ARCHITECTURE - SUMMARY

Table 14: Architectural requirements - summary

ARCHITECTURE - SUMMARY		
Factor	**Effect**	**Requirement**
Configuration	Accessibility, zoning	Modular plan
Functional programme	Volumes and sizes determined for each activity	Dimensions of spaces
Crew wellbeing	Zoning	Modular plan
Crew safety	The structure is resistant and insulates	Structure of mechanical properties and insulation characteristics specified
Adaptability	Multi-mission planned for one habitat	Easy to adapt habitat structure to new mission planned or extend the existing plan

PROGRAMME OF REQUIREMENTS SUMMARY

The previous part of this chapter presented the conditions regarding the Martian climate and mission. Below will be presented a programme of requirements ensuing from these conditions. Based on these requirements the ongoing researches were chosen to study and compare – see chapter 4.

Material requirements:

- ISRU material, available on the surface – the preferably entire planet
- Easy excavation and collecting process
- Preferably ready for usage after collecting – no extra processes required (mechanical grinding, milling, sieving)

Mixture and production requirements:

- Minimize water consumption – ideal water-less production
- Be adjustable to slightly different compositions of regolith
- Easy and fast to prepare
- A minimal amount of processing and energy efficient
- Minimum resources required from Earth – fit in one rocket
- Limited volume, mass, and complexity of the equipment required from Earth – fit in one rocket
- TRL of the production process should be already 3/4

Building product/structure requirements:

- Easy to construct, maintain, repair, safe
- Withstand extreme temperature differences
- Withstand damage due to radiation or micrometeorites
- Possible to construct volumes and dimensions required for habitable space
- Thermal and radiation insulation
- Habitat should provide and withstand the pressure difference
- Sealed structure - Zero permeability
- Fast building – energy available whole day
- Not flammable, not decompose
- Interiors protection layer separating crew from regolith material
- Preferably last longer than one mission (1-3 years)
- Adaptation to mission, flexibility, expansion possibility
- Modular structure
- TRL of the building system should be already 3/4

CONCLUSION

Investigating the reality and conditions related to building on Mars, one aspect turned out to be essential, however missing in the plans and concepts for missions to Mars. This factor is sustainability. On Earth, it is an existing approach in the field of building industry. Therefore it was decided to investigate the sustainability on Mars, regarding the building and production processes.

The habitat would require specific equipment, which needs to be transported from Earth. The complexity of the systems that need to be implemented in the structure of a habitat Is challenging to build on site. Moreover, it would require more time and energy input during the construction phase. Therefore, it was decided, that the built structure on Mars would be only the outer shell protecting against radiation, wind (dust) and micrometeorites. The habitable part would be inflatable and would be brought in the rocket with the crew.

2.2. Sustainability on Mars

New chance

Sometimes, the exploration of space is compared to colonialism which began in the 15th century. Back then, it all started with a similar approach driven by ambition and curiosity, which evolved later into much greater movement. The phenomenon of conquering new lands and excavation of their resources for self-growth doesn't seem to be much different from what space explorers are planning. Besides, the space agencies are considering also the possibility of the permanent presence of a human on other planets or just in outer space. The term "Mars colonization" is used in public media and by some scientists without any reflection on the issues it might bring. The past provides evidence of the harmful impact the colonization can cause. Despite the ruthless influence and induction of extinction of many native civilizations, it brought overexploitation of land and resources. The effects of these doings are visible in our modern times, where we still continue to satisfy our needs by exploiting distant terrains. This time, the intact world we are going to "explore" is Mars. Although there is still no evidence of any life form on this planet, we should ask ourselves how should we treat the land. It is a chance to avoid mistakes from the past and responsibly perform this space colonization by predicting the impact and back-casting for a sustainable future.

To ensure, that the research is following a sustainable approach, an additional study on sustainability on Mars was executed. First, the sustainability on Mars had to be defined and investigated. How would the definition of sustainability differ for other planet compared to the one determined for Earth? The sustainability on Earth has several definitions, but the most known one is the one stated by the Brundtland Commission in 1987 (Doan, et al., 2017). According to this, *"sustainable development is a development which meets the needs of the present without compromising the ability of future generations to meet their own needs"*. This definition was selected to be a starting point of this part of the research because it is strongly connected to the responsible management of resources and environmental protection, which would already be the issues of the first missions. Although space was not considered in this definition, it could be extended to determine and supervise planetary resources utilization (Tan, 2000).

To establish sustainability on Mars, the following methodology and gap analysis were implemented. First, the existing tools and measures regarding sustainability on Earth will be analyzed, with the focus on building industry application. Relevance and potential application regarding building on Mars are determined for each chosen example of the approach. Then, the existing regulations regarding space environment protection and resources excavation in space law were investigated, in the global/international scale like treaties, and smaller scale like private companies. The understanding of space sustainability must be determined to be able to create the right measures for this field. The conditions and therefore approach towards sustainability might be different beyond our planet. Finally, the preliminary methodology for establishing sustainability on Mars is created and presented. It will start with the conclusions collected from the analysis part, as well as the first attempt to determine sustainability on Mars. The methodology process, which is based on the gap analysis is presented in Figure 22.

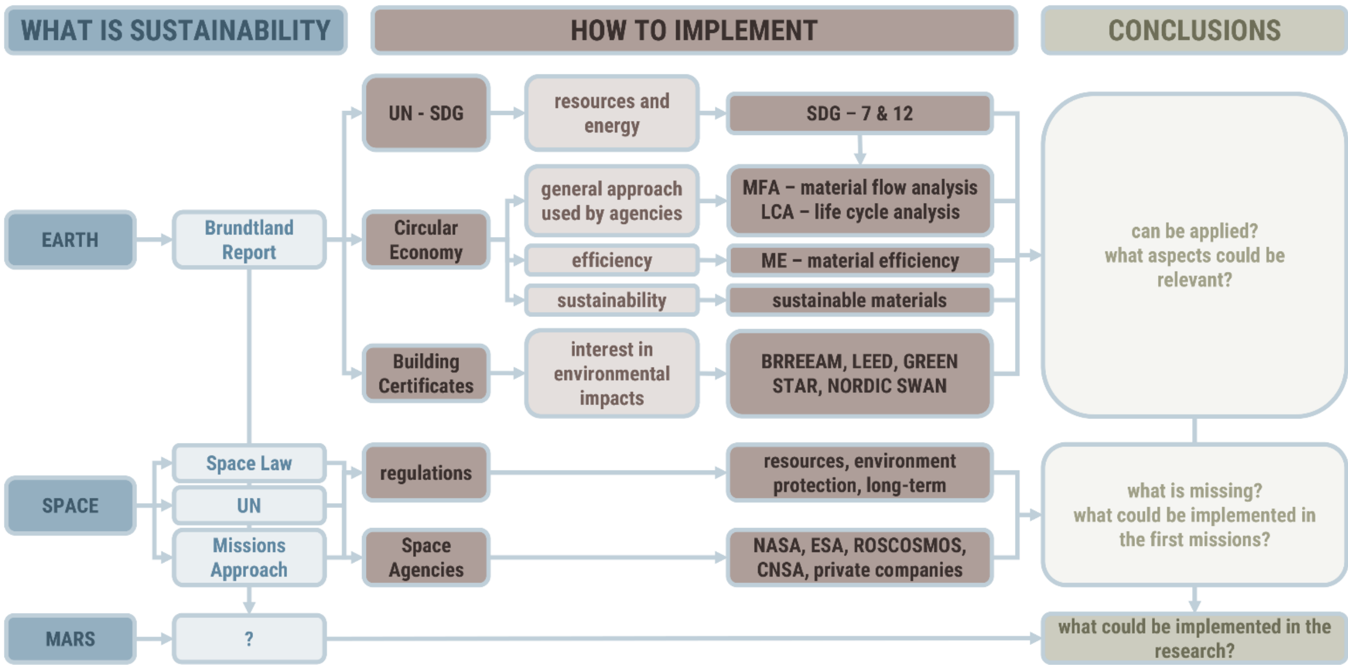


Figure 22: Scheme of the research on sustainability

Sustainable development on Earth

On Earth, the sustainability approach is already broadly discussed and established in many countries as the development factor for industry and economy. As mentioned at the beginning of this chapter, there are multiple definitions of sustainability, but a most common one is focusing on preventing environment and resources for future generations while providing the existing demands equally and responsibly to the present generation (The Brundtland Commission report).

There are multiple programmes trying to implement sustainability on a global scale. In this report, the aspects related to the building industry will be investigated, as the sustainable building and production process are the goals of the research. This study was performed by starting with a big – global scale approach for tackling the issues, which later was narrowed down to only building related measures. First, the approach of the main institution globally monitoring and supporting sustainable development – the United Nations will be presented. It presents global and general issues and how they could be solved or controlled. Then, the Circular Economy frameworks will be investigated, looking for a potential application in Space or on Mars. They have a more economic approach and could help determine the essential aspects of sustainability in the field of economy. Although during the first missions there won't be any independent economic system on Mars, it is important to start the discussion about how the future martian colonization could tackle the circularity. Finally, the certification system created especially for the building industry will be analyzed, as it largely overlaps with the field of the thesis.

17 SUSTAINABLE DEVELOPMENT GOALS (SDG)

United Nations established 17 goals for sustainable development, which should be achieved by the year 2030, which overlaps partially with the plans of manned missions to Mars. They are related to issues of environmental impacts and human rights. The fact, that they are planned on a global scale, will bring public awareness among society, which might start to demand sustainable solutions from the companies and governments. Therefore, the investigation of the SDG would be a good background for the research, as they are very general. Although there are 17 goals, only two will be analysed. They are related to the topic of resources and energy management, which would be the key aspects of building first habitations. The goals related to the building industry are Goal 7 – Affordable and Clean Energy and Goal 12 – Responsible Consumption and Production (United Nations, 2019).

AFFORDABLE AND CLEAN ENERGY

Regarding the energy, efficiency and renewability are emphasized as the sustainable development goals (Inter-Agency and Expert Group on SDG Indicators, 2016). Although these aspects are strongly related to nowadays issue of poverty, climate change and overpopulation on Earth, which are not going to be the issues on Mars for the first century, the importance of these goals is overlapping with the requirements for Martian missions. The renewable energy would increase the independence from Earth, while combined with the improvement of the efficiency it would decrease the payload demand. In the case of Mars, the most developed renewable energy is solar energy. Its efficiency had increased recently, which is clearly visible when comparing the values of power peaks of rovers, landers, and satellites built today and at the beginning of the century.

The essential goal for sustainable energy is also international cooperation and exchange of research and technology as well as the promotion of investments in the projects and infrastructure. However, this goal doesn't have any influence on the research. Moreover, space exploration is already an international undertaking and equipment is usually provided by several companies and countries for one mission.

Finally, the usage of sustainable energy is needed to achieve all goals. The fact, that nuclear power is commonly used and planned for space missions, raises a question which energy source would be more sustainable in case of deep space exploration or long-term settlement. On Earth, nuclear power is considered as unsustainable and Recent extraction and processing methods for nuclear energy are limited and controlled according to the sustainable development concept. It's minimizing the impact on people and the environment (Nuclear Energy Agency, 2016). However, the accident risk and radioactive waste, for which, the safest option is long-term storage, are still a major problem.

RESPONSIBLE CONSUMPTION AND PRODUCTION

This Goal is more relevant to the research, as the main goal is to propose a sustainable production process and building method (United Nations, 2018). Research is focusing on regolith and dust utilization, therefore the Goal's target to achieve sustainable management and efficient use of natural resources seems essential. It is also included as a target for this goal, to minimize the waste generation of the production through prevention, reduction, recycling, and reuse.

On Earth, this approach is supported by building a network between multiple stakeholders to ease the exchange of wastes or by-products, which can be used by others. However, there is no market present on Mars, it is possible, that in the future, the colony would need an independent from Earth market and closed-loop system for exchanging resources. For the first missions, it would be important to determine the waste and by-products of production and building processes, which could be in the future reused or recycled and brought back to the system.

CIRCULAR ECONOMY FRAMEWORKS

To support sustainable development, several approaches, as a circular economy, had been designed to implement sustainability in the existing economy (Blomsma, 2018). The circular economy is focusing on minimizing waste, increasing the value of products by controlling the flow of material, its manufacturing, design, and use. In this research, only a few examples will be investigated, as most of these approaches are strongly related to industrial collaboration, market, and consumers. In case of missions to Mars, the collaboration will be very limited until large settlements will be established. The relevant frameworks were chosen based on Blomsma, 2018, which is comparing some approaches based on their main focus, target groups, principles, etc. All presented below strategies differ between each other with main objectives and the relevance for Martian missions.

MATERIAL FLOW ANALYSIS

Material Flow Analysis (MFA) is a method to quantify flows and stocks of resources from the defined system by mass balance (HBrunner, et al., 2005). Usually, it is treated as the first step and necessary base for each circular approach. It gives a detailed understanding of systems, processes, and flows. It was chosen for this research because it is strongly related to resources management and give a great overview of the system.

Objectives

- Determine and reduce the complexity (for the analysis and presentation purposes) of a system of material flows
- Asses the flows and stocks in a quantitative way, determining mass balance

Application

Below is a list of potential applications of MFA and its main purpose in these aspects.

- Environmental Management and Engineering - study contamination and substance flows in the environment to keep them at a reasonable level,
- Industrial Ecology – optimize the total material flow and cycle, information about input and output
- Resource Management – analysis and planning of resources, forecasting scarcity, identify accumulation and depletion of materials
- Waste Management – information about the composition of waste, control of recycling facilities, design for recycling

Limitations

- Preparing the MFA model requires a lot of work and investigation
- The MFA results are based on a simplified version of the system, which might lead to errors

Relevance for building on Mars

The material flow analysis could be helpful in choosing the best option of the production process and construction method. The comparison of flows and total mass balance of Martian resources (material and energy), material brought from Earth in form of equipment and materials can help to determine which option could provide best results in usage and management. It would be important to avoid waste of material, energy or equipment potential. With the MFA it would be possible to investigate which flows could be improved or minimized. Additionally, the contamination of the Martian environment because of preparation of detailed flow for the production can be estimated using this tool.

LIFE CYCLE ANALYSIS

Life Cycle Analysis (or Life Cycle Assessment – LCA) is a tool to help the decision-making process within the life cycle approach (Hauschild, et al., 2018). It was chosen for the study because it’s already implemented in the space industry mission planning and design. This method includes four steps: determination of goals and system boundaries, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA) and a conclusion. Products which will be compared to each other are chosen based on the function instead of physical characteristics. LCI step includes detailed investigation and data collecting. LCIA part is resulting in quantified environmental impacts and used resources. ESA has already implemented the LCA method in their research and mission planning. However, it concerns only the terrestrial and orbital case (ESA, 2015).

Objectives

- Implement Life Cycle perspective in the field of industry and economy
- Quantitative analysis of products (resources, energy, waste, etc.) Life Cycle systems, monitoring and controlling each stage of the cycle in terms of environmental impact and simplification of the system

Application

Below is a list of potential fields of application of LCA and its main purpose in these aspects.

- Governmental management – supporting policy formulation, implementation, and regulation
- Industry Perspective – according to prof. Hauschild, LCA's application can be classified into five categories, out of which, the one relevant to this research is supported in product and process development.

Limitations

- Simplification of the systems might lead to errors. As well as uses of different methods for LCA steps can assign different importance to properties or impacts
- LCA models are based on the average performance of the processes
- Do not include risks analysis of rare events (for example nuclear power appears as an environmentally friendly option for energy generation)
- LCA is used for comparing different processes, therefore it can only help determine which option is the best, but not if it's actually environmentally sustainable
- Cannot investigate local impacts, as environmental damage is calculated on a global scale

Relevance for building on Mars

To use LCA as a tool for sustainable building on Mars, the relevant environmental impacts need to be determined. They might differ from the terrestrial ones, as the conditions are unlike. Additionally, the required lifespan of habitat is not known, therefore estimation would be needed. According to the article about *Life cycle assessment in the construction sector* (Buyle, et al., 2013) is complex because of: different lifespans for the entire building and some components, use of different resources and processes and change in the function of the building. Some of these aspects require another assumption leading to uncertain results.

MATERIAL EFFICIENCY

Material efficiency strategy is focusing on the reduction of material production and processing demand by material efficiency (Allwood, et al., 2011). These could be categorized to extending the lifespan of product, modularisation and remanufacturing components re-use and optimizing products design in order to use less material. The efficiency is already present in the space industry as one of the main goals for minimizing costs and time of the mission, therefore it was decided to include this approach in the study.

Objectives

- Reduce total demand for material production and processing by material, energy efficiency
- Reduce 50% of CO_2 emissions, whilst assuming doubling of material demand (other environmental concerns are also included, like contamination, fossil fuel use, impact on species)

Application

- Building industry
- Engineering
- Aerospace
- Design

Limitations

- Emerging strategy, therefore still limited technology and study supporting material efficiency in the design
- The strategy is strongly against the existing economy system

Relevance for building on Mars

Material Efficiency strategy could be one of the main approaches for building on Mars, as it could decrease the payload and therefore costs of the mission. Moreover, an efficient strategy is also focusing on extending the lifespan of a product. It could support the space agency's capability-driven approach for habitation in space, where the habitat could be used for multiple missions.

SUSTAINABLE MATERIALS ECONOMY

Sustainable Materials Economy is mostly promoting designing and using ecological and less hazardous materials (Geiser, 2005). The author of this strategy, Ken Geiser, claims that by using sustainable materials there could be less concern and attention to the impact on people and the environment. Additionally, he proposes a cyclic system of sustainably managed material flows to conserve the most important resources for future generations. This approach was selected for the study because it brings important discussion about which materials could be considered sustainable on Mars.

Objectives

- Exchange common toxic, hazardous materials with more sustainable materials: renewable, degradable, non-toxic
- Conserve high-quality natural materials for future generations

Application

- Main application the author mentions is industrial production

Limitations

- Technology and sustainable materials are still not developed and studied on a bigger scale, therefore the properties of industrial materials are in most cases more efficient and suitable

Relevance for building on Mars

To implement a sustainable materials economy strategy on Mars, the sustainable materials on the Red planet need to be determined. Although on Earth, some natural materials are considered sustainable, on Mars they might bring organic contamination of the Martian environment to the surface. There is still no evidence of life there, but the concept of bringing terrestrial life-form to Mars is controversial among the experts. Building structures or mixing in-situ resources with materials grown on other planets might make the settlement even less dependent on Earth's supplies, however, these also contain the potential risk of contamination in outer space.

SUSTAINABLE BUILDING CERTIFICATIONS

Due to a growing trend for sustainability and developing regulations regarding the environmental impact of products and production processes, a certification system emerged in the building industry, to promote sustainable building by distinguishing projects, that are designed and built according to this approach. Currently, the certifications are also used to ensure a high level of quality during design and a building process. The certification systems, with a set of quantifiable criteria, help to measure and compare the sustainable performance of a building. However, there is a large discussion about the true importance of certification systems, investigating criteria and guidelines prepared specially for the building industry can support and influence the design of the sustainable Martian habitat.

There was an increase in certification systems around the world, therefore to be able to compare existing certification types and find the most relevant for the project, the Guide to Sustainable Building Certifications was used (Guldager Jensen, et al., 2018). The author is comparing the systems by highlighting and assigning guidelines to three aspects of the sustainability: environmental, economic and social. For the purpose of this research, the certification systems with higher environmental concern are considered most valuable, as the social and economic factors are not the main factors for this project. Systems, as BREEAM, LEED, Green Star, and Nordic Swan are chosen to this research, as they have the highest percentage of environmental aspects included. Please note, that the characteristics of the systems are selective based on the relevancy to the thesis.

BREEAM – UK 1990

BREEAM was the first certification system for buildings, established in the UK in 1990. The aspects of environmental sustainability, are mostly crediting design strategies for energy and water demand reduction, management or efficiency within the building. The environmental impact of building elements is suggested to be tackled with LCA, which can be used rather for choosing less harmful and more efficient option than determining if the product is truly sustainable. The other strategy for sustainable design mentioned in BREEAM is using measures to optimize material and energy efficiency for the design and construction phase. Moreover, it is encouraged to reduce construction waste.

The process of calculating points and evaluating the final score is complicated and differs for each category (Khoraskani, 2012). It also has attention to regional standards and regulations and includes them in the process.

LEED – LEADERSHIP IN ENERGY AND ENVIRONMENTAL DESIGN, USA 1998

The LEED system is mostly focusing on environmental aspects with resources as a major one. It has a direct influence of BREEAM. To reduce demand and optimize the use of material, LCA is promoted as a measurement strategy. According to the system, the raw source for the resources should be responsible. Regarding energy, the usage should be optimized, while the source of energy should be local and renewable or green. Additionally, the pollution of the site and the atmosphere should be prevented during construction and usage phase. Recycling of waste or recyclables is also mentioned in the system.

LEED is claimed to be more simple than most of the other systems, with its easy calculation method, which is using a checklist providing the final list of point (Khoraskani, 2012). The system has a very adaptable weighting process, as it is differentiating environmentally importance of some factors based on regions.

GREEN STAR – AUSTRALIA, 2003

Green Star is a certification system focusing on mostly resources and environmental impact aspects. It’s suggesting to use LCA to compare the design and achieve a lower impact than a reference building, as well as to improve material choices throughout a design and a construction phase. Controlling and reducing the impact of energy and transport is also mentioned as a design factor. The demand for energy should be reduced by design and good installations. Regarding the building material, Green Star is promoting using responsibly sourced resources and reused products with recycled content. Waste from construction, demolition, and operational waste should be minimized and planned according to end-of-life strategy.

Social sustainability is mostly oriented towards health and safety issues, however, these are concerned about more terrestrial conditions like climate change and outdoor-indoor relation.

NORDIC SWAN – THE NORDICS, 2005

Key principals of Nordic Swan are related to resources, energy, and toxicity. It is important to control and make the performance of the building efficient, in order to minimize energy usage and demand. The reduction of environmental impact is mostly related to toxicity recycling. The waste from all phases should be documented and planned for reuse of recycling. The toxicity in the form of chemicals in products should be avoided with a great focus on nanoparticles realizing. Health and safety are narrowed to providing good indoor climate (temperature, ventilation, humidity, noise, daylight) and avoidance of toxicity.

RELEVANCE FOR BUILDING ON MARS

In general, the main factors influencing structure and aspects included in each Certification system, are the determined environmental impacts and regional regulations. Therefore, to create any kind of certification systems or just guidelines for sustainable building on Mars, the environmental impacts which should be reduced or avoided have to be established. Therefore, it is hard to choose relevant factors for sustainable building design if the impact of processes and materials wasn’t tested and quantified in Martian conditions. The understanding of environmental impact in space by space law and agencies will be presented in the next sub-chapter.

Moreover, most of the social sustainability aspects are already required and implemented in the missions, as they support a human presence in space. Human well-being and health is nowadays researched in many space agencies. The economic dimension is also one of the major factors for space missions, as the payload or rocket is almost 90% of mission expenses. The efficiency of energy generation and usage, as well as material efficiency, are currently, driven by only economic factors.

Space Law

EXISTING TREATIES

To perform the space colonization there would need to be international agreement determining environmental regulation and rules for any activity on Mars. This Space Law (SL) is already an existing discussion. Although, until now, these agreements concerned only national space agencies. Currently, with more private space companies, commercialized mission plans and long-term future human presence in space, SL would need to be reinvestigated.

The first treaty, Outer Space Treaty (OST), established in 1967, with 5 additional agreements like Agreement on the Rescue of Astronauts, Registration Convention (RC) (Schoen, 2016), were ratified by USA and Soviet Union and many other nations both active and inactive in space. Another treaty, which wasn't ratified by leading space exploring nations, is Moon Agreement (MA). These treaties were mostly focusing on the peaceful exploration of different nations for the benefit of all humanity. Until now, the SL was creating vague principles to enable flexible exploration and execute scientific experiments in outer space. Regarding Mars colonization, which is associated with long-term or permanent settlements and activity on another planet, the SL is incomplete (Harris, 2018).

For the purpose of this research, only issues related to resources and the environment protection would be investigated.

RESOURCES

The regulations regarding resources mining and excavation are still determined in the context of exploration and not a permanent settlement. According to Philip Harris, they are agreed as:

> *" 1. Space is reserved for the benefit and is the province of all mankind,*
> *2. Every nation shall have equal access to outer space,*
> *3. Nations cannot appropriate space under any claim of national sovereignty,*
> *4. Nations are free to explore and "use" outer space."*

It means, that the nations can't proclaim the right to territory, but can excavate the resources. Space Law doesn't mention regulations or guidelines regarding commercial utilization of space resources. Although, it is mentioned that there should be an emerging international regime in this field. According to OST, the activities of non-governmental entities should be approved by the appropriate State Party to the Treaty.

Moon Agreement, which wasn't ratified by main space-faring nations, differentiates two types of resource utilization: scientific and non-scientific (commercial). The document mentions that the resources are the Common Heritage of Mankind and they should be governed by an international regime. This regime should establish rules regarding rational management of resources, expansion of opportunities in the use of them.

Moreover, there is still no distinction in regulations regarding different celestial bodies like asteroids or planets. Many scientists claim that the rules are not strict enough and that they should be determined for each context separately. Moon would require a different set of directives regarding surface activities than Mars. The fact, that there is no limit or consideration of excavation in case of permanent settlement and colonization of space can cause great problems in the future.

ENVIRONMENT CONTAMINATION

As nuclear power is considered one of the main energy sources in future space exploration, despite its harmful environmental impact, this issue is also included in the research investigation. According to the United Nations Principles (G. L. Bennett, 1995), negotiated at Committee on the Peaceful Uses of Outer Space (COPUOS) forum, the use of nuclear power brings mostly safety issues. The environment impact on other planets wasn't investigated in the discussions held in the 20th century. Only the aspects of using nuclear power for rocket launching and re-entering as a potential risk for Earth's environment were investigated. However, some articles of OST and MA mentions, that the state parties should avoid harmful contamination of outer space. These principles were taken into consideration only regarding military purposes, while commercial or scientific activities are not regulated. Possibly the nuclear power enabled too many discoveries and developments in the space industry, therefore the threat of an environmental impact is still omitted (Tan, 2000).

Similarly, the space debris is a threat as environmental contamination. However, existing treaties don't include a definition of space debris. The only concern is that it might be a threat to any working technology in low Earth orbit (LEO). The non-binding guidelines concern controlling, mitigation and remediation of space debris (Arsenault, et al., 2011). Currently, space debris concerns rather LEO, than deep space, but soon we will need to consider the impact of technology we send beyond our planet.

Recently, experts are considering the biological contamination of outer space as another threat to the space environment. With every launch from Earth, there is a risk of bringing terrestrial organic forms to the world where life was never discovered. There occurs a question if we have the right to spread life into space. This issue is still just a discussion.

SPACE AGENCIES APPROACH

NASA

NASA associates sustainability with efficiency and economic aspects (National Aeronautics and Space Administration, 2011a). They established a Capability-Driven Approach, which is focusing on reusing technology and systems for multiple destinations and missions. Regarding habitation, these capabilities are efficiency oriented, supporting reusable, flexible and modular structures. As mentioned in the chapter about space architecture, there will be multiple missions planned on Mars before establishing a colony. Some of these missions can have different objectives and operations, therefore the designed habitat should be adjustable to different purposes.

Another capability is related to ISRU systems, which can provide building material, energy in the form of propellant and elements essential for life support systems. NASA believes, that this approach will reduce the need for resupply missions and make the habitat independent from Earth.

ESA

ESA is currently engaged in the problem with debris in LEO and in using satellites observing Earth, to monitor changes related to climate change and human impact on the environment. The agency considers the guidelines from the UN COPUOS document "Guidelines for the long-term sustainability of outer space activities". ESA provides a report each year including space activities, launches, sharing gathered data.

RUSSIAN SPACE AGENCY – ROSCOSMOS

There is no official information about Roscosmos considering or improving sustainability in space. No mentions regarding space environment protection are published. However, there are multiple collaboration missions with ESA and NASA which already implement an approach which is based on sustainability. Similarly to the European Space Agency, the Russian institution is more involved in debris issue, than deep space and further Solar System. Roscosmos ratified principles regarding the protection of Earth's orbital resources from space debris. The guidelines were prepared by the Inter-Agency Space Debris Coordination Committee (IADC), which Russia is part of.

CHINESE SPACE AGENCY – CNSA

CNSA includes in its principles term "sustainability", however, doesn't explain how it's going to implement a sustainable approach in space activities. Interesting is, that China is planning to introduce its own space law by 2020. Unfortunately here as well no information on sustainability is provided and accessible. According to the recent article in the Diploma Journal (Goswami, 2019), the main ambitions of CNSA is focused on growth through a space-based economy. The final deadline for achieving goals is 2049, which overlaps with the pessimistic prediction of economic crisis due to fossil fuels becoming scarce.

Their program is based on the commercial exploitation of the natural resources available in space. The chief of China's lunar exploration program stated in 2002, that *"The moon could serve as a new and tremendous supplier of energy and resources for human beings… This is crucial to the sustainable development of human beings on Earth… Whoever first conquers the moon will benefit first."*

PRIVATE COMPANIES

Although there are no regulations specified for non-governmental entities, it is agreed, that they are under the jurisdiction of appropriate national space law. Currently, the network of collaboration between governmental and non-governmental entities is establishing. For example, a new plan of American government for space exploration includes a *"call for innovative and sustainable collaboration with commercial companies"* with the main goal of returning humanity back to the Moon (Walker, 2017). The same initiative shows ESA which is signing a contract with a private company, scientists, which is designing rovers for lunar missions. Although, on their goal is to "show that it is possible to build a sustainable business in space exploration", there are no reports or data available to investigate this approach.

Some companies talk about sustainability concentrating only on Earth's problems and its environment. Their approach is to utilize and exploit space resources to decrease the scarcity of materials on our planet. The ideal source for this mining business plan is Moon and Near Earth Asteroids. Founder of a private company - Moon Express, Naveen Jain claims, that lunar resources can help our civilization achieve more sustainable future, as it is full of energy and material resources (Osborne, 2017).

SUSTAINABILITY IN SPACE

UNITED NATION (UN)

United Nation, apart from watching after and establishing principles regarding sustainability and human rights, extended the field from Earth to Earth's orbit and deep space. Unfortunately, most of their work are just guidelines or suggestions, except the rules regarding space debris in LEO. The nations involved in the space industry consider the control of this issue important. It is rather driven by the fact, that the orbit is becoming 'crowded', therefore there is a need to control the number of launches and activities.

UN tries to implement other regulations regarding sustainability – Long-term Sustainability of Outer Space Activities (Committee on the Peaceful Uses of, et al., 2019). It's focusing on increasing international access to the data, space applications and technologies to meet the needs of the present generation while preserving and protecting space environment for future generations. To establish objectives and principles, Working Group on the Long-term Sustainability of Outer Space Activities was formed. In 2016 experts agreed to the first set of guidelines, extended them in 2018, however, couldn't reach consensus on the final report. The document explains, that

> *"the long-term sustainability of outer space activities is defined as the ability to maintain the conduct of space activities indefinitely into the future in a manner that realizes the objectives of* ***equitable access to the benefits*** *of the exploration and use of outer space for* ***peaceful purposes****, in order to meet the needs of the present generations while* ***preserving the outer space environment for future generations****."*

According to the guidelines, nations can modify implemented sustainable regulations considering their own objectives and development potentials, but the implementation is voluntary. It is though required, that the States will ensure that non-governmental entities under their jurisdiction will apply the established regulations. Other guidelines are mostly related to space debris, protection of Earth's environment, control and international collaboration in data and information exchange. Some of these guidelines are listed below:

- The practice of registering space objects planned to launch
- Exchange of information regarding space activities and discoveries between space agencies and private companies
- The collection, sharing, and dissemination of space debris monitoring information
- Share operational space weather data and forecasts

The guidelines, that are more related to the research are general and the issues are not specified:

- **Share experience related to the long-term sustainability of outer space activities and develop new procedures, as appropriate, for information exchange**
- **Promote and support capacity-building**
- **Promote and support research into and the development of ways to support sustainable exploration and use of outer space**
  - Include other celestial bodies
  - Social, economic and environmental dimensions of sustainable development on Earth should be taken into account while exploration and use of outer space (with reference to document from UN Conference on sustainable Development - General Assembly resolution 66/288, annexe)
  - The technology that minimizes the environmental impact of manufacturing and launching space assets should be promoted
  - The technology that maximizes the use of renewable resources and reusability of space assets of manufacturing and launching activity
  - Implement safety measures to protect Earth and space environment from harmful contamination

SPACE MISSIONS

Although there are no existing principles for sustainability in space exploration, every mission is requiring systems which claim to be sustainable – closed-loop life support systems. These are also first, main driving factors for the space exploration and extending presence of humans in space. Their aim is to create a closed-loop environment within the spacecraft or habitat, which can provide and recycle materials and elements in order to sustain life far from our planet. It requires technology which can manage waste and gain from its products that can be reused (SustainSpace, 2018). However, resources utilization related to building a habitat on the outer planet is not considered as part of the closed-loop system.

WIDER PERSPECTIVE

First manned missions to Mars might seem irrelevant in terms of global environmental impact on the future of the planet. However, the goals and decisions we set today, are essential factors causing future issues. The first missions are also a chance to test these approaches and technology. The fact, that first manned missions are planned for years 2030 – 35, is important for establishing the sustainable goals, as, on Earth, the possibilities and public opinion about sustainability will be different. It might be possible, that by the year 2030 public opinion will have a significant impact on industrial field exacting sustainable approach. During this research, a question raised, if the society might have an influence on the approach of space agencies, demanding sustainable solutions and technologies. In this scenario, it is important for space companies to investigate the possible approach of the public on sustainability in the close future. This research could be one of the possible development of the thesis.

CONCLUSIONS

CAN ANY OF THE TERRESTRIAL SUSTAINABLE APPROACHES BE APPLIED ON MARS?

None of the mentioned approaches for sustainable development can be applied directly to the Martian conditions. First, the sustainability and goals related to this topic should be determined for the Mars case. Additionally, due to different atmospheric and climate conditions, some impacts might become irrelevant, while new ones, which are not harmful to Earth, can appear. However, some aspects can be already considered as a potential cause of an environmental issue. If the statement about preventing an environment for future generations, while meeting the need of present one, would be applied on Mars, the issue regarding contamination of the soil and atmosphere or abuse of resources can be already treated as potential problems.

Some of the aspects of sustainable design are already considered during mission planning, although the focus is set on economic benefits. This is mostly related to energy and material efficiency, which is the main principal of Material Efficiency Economy. This should be extended to more sustainable factors determined especially for Mars case. This could lead to responsible resource and waste management if supported by design tools similar to LCA and MFA. The circular approach is already known for space missions, however only in case of life-support systems.

The certification systems for sustainable buildings are not the ideal solutions for the first missions. Similar certification system could be more relevant for designing whole missions where more aspects are included, like the launch, travel and descend part of the mission. The habitat structures would have slightly different requirements for each mission and the decisions would be made base on the different hierarchy of importance.

WHAT IS MISSING IN THE PRESENT UNDERSTANDING OF SUSTAINABILITY IN SPACE?

There is a lack of a discussion regarding sustainability beyond Earth in the Space Law or in space institutions. There is a concern about space debris or launching systems, but these issues have a direct impact on our planet. The activities having an impact on other celestial bodies are not regulated by any law. The peaceful exploration and the importance of scientific exploration have a major impact on any regulations. Currently, it is more important to ensure, that space resources are available to everyone equally than how these resources are managed. Due to the emerging phase of commercial usage of space and resource mining and its utilization, there is a large need for regulations about responsible and sustainable resource management. To start working on this, first, we need to extend the understanding of sustainability beyond Earth, where the goals of commercial space exploration can't be neglected.

These regulations regarding space environment protection should be established before any long-term settlements. It would be ideal to test the issues and solutions during the first missions to have data regarding sustainable design in space. Therefore, in this project, some principals regarding sustainability will be presented and implemented in the project.

PRE-EXPERIMENTAL DECISION-MAKING

3.1. Implementing sustainability on Mars

DETERMINING SUSTAINABILITY ON MARS

GENERAL

The definition of sustainability, chosen for this research is based on the one, stated by The Brundtland Commission. It promotes strategies, which are oriented towards protection of the environment, which until we decide what is the approach and future for space, is keeping all options possible.

During the first missions to Mars, the technologies and experiments will concern mostly resource utilization, which partially will be used for building habitats. The equipment and processes will have an impact on the surrounding and some of them might be harmful to the Martian environment. *Therefore, the sustainability on Mars, determined for this research is focusing on the environmental impacts as contamination and consumption of resources. Additionally, international cooperation and social awareness are presented as one of the sustainability goals.*

SUSTAINABILITY ASPECTS

International Cooperation

To establish sustainability on Mars, regulations need to be determined as an international policy supporting sustainable development and environment protection. The first step towards establishing new law would be to update the existing one by including regulations for commercial and business activities in space as well as by acknowledging long-term settlements on other planets. Later, it should be encouraged to create joint programs and activities on Mars and to share relevant information and data between states with advanced space capabilities and the developing ones.

Environment Protection

The environmental impacts are not yet determined for Mars. First missions would be ideal to perform required research to quantify and characterize the potential impacts and test the sustainability approach and technology. Therefore, it is important to specify processes, materials that might have an impact on the Martian environment. These could be further studied and tested as the continuation of the research on sustainability on Mars. To estimate the impact before missions, consumption and waste, the analysis of material flows, as LCA and MFA, can be used.

One of the potential impacts is contamination. Pollution aspect needs some quantifiable measures from tests in Martian conditions because it is not known how harmful are some substances on the planet with lower pressure, gravity, and different atmosphere. Nevertheless, some chemicals and materials can be assumed as harmful. The materials, that are considered hazardous are organic materials because they bring a controversial discussion regarding the question if a human can contaminate outer space with life. Moreover, the usage of polymer additives in building component might have an impact on the environment. To assure, that the organic matter or harmful materials won't be present in the structure, in case of prohibition of biological and chemical contamination of Martian surface in the future, the material used for building a habitat in this research will be 100% in situ.

One of the essential goals regarding environmental protection is to prevent the natural environment and the landscape of Mars. It needs to be determined, what are the Martian heritage and the natural landscape necessary to protect. These terrains shouldn't be touched by any activities like hard landing transportation or building.

Sustainable Energy

The energy generation sources investigated in this research are solar, nuclear and ISRU. The solar one is the only one renewable and the new technologies related to this option are improving fast. The potential future efficiency could provide enough energy for building processes. Nuclear energy, however, promoted by space agencies, should be minimized or avoided if possible as a source for building processes. Its radioactive waste and risks related to usage are strongly criticized by the United Nations and should be replaced by renewable energy like solar one. In terms of using fuel cells combined with ISRU approach, it is still not tested or calculated what and how big would be the impact of this process. Therefore, for the purpose of this research solar energy would be considered as the main source, with limited nuclear power as a backup.

Sustainable ISRU

Resource utilization might be the potential impact because if performed irresponsibly might generate large waste and harmful materials or emissions. Another result could be excessive usage of the resource, which might lead to scarcity in the future. Therefore, responsible resources management and utilization is important and should be implemented in the designs of the missions. The utilization processes should be optimized, in order to minimize energy and material usage, and waste production. To choose the best option for the designs and to estimate, which part of the utilization creates to much waste or could optimize in terms of energy and time efficiency, the LCA and MFA could be used. As the approach for design purpose Material Efficiency strategy could reduce the demand for material and energy.

Waste Management

The production of waste should be minimized for every activity such as construction phase, resource utilization, production processes. The systems should be designed towards zero waste by efficiency strategy or by circular strategy.

BARRIERS IN SUSTAINABILITY IMPLEMENTATION

There are several issues regarding the implementation of sustainability in space missions. They are mostly related to the existing approach of space agencies and the lack of international regulations regarding environmental impact and resource utilization in space. The main problem is, that so far, Earth is defined as the only environment we should take care of. The space agencies are claiming, that space resources should be utilized on a great scale in order to limit the resource consumption on Earth. The land responsibility should be extended beyond our planet, however, it is a complicated political and economic process, which won't be achieved if the territory in space is a condominium, which no one is responsible for.

RESEARCH REQUIREMENTS

Production process

- Material and energy efficiency strategy
- Avoid waste production
- Solar + limited nuclear as an energy generation source

Material

- 100% regolith or in-situ

Building product/Structure

- Material and energy efficiency strategy
- Avoid waste production during construction

3.2. Location

The material chosen for the building – fine regolith and dust is homogenous around the whole planet. The construction method was designed to be applicable in different regions of Mars, due to the requirement for multiple missions to be performed on the surface. However, the choice of the location is important to determine the atmospheric conditions, topography and resources.

For the purpose of this research, the location planned for several missions was chosen – Gale Crater (Hautaluoma, 2018) (Figure 23). The data about the material, used in the research, comes from this region, therefore it would be relatively easier to make the first habitat in the explored area. The location of the design is the region with dark dunes visible at the image. It's close to the area explored by the Curiosity rover and the peak of the crater (Mount Sharp) won't create shadow there as it's in the north-east direction.

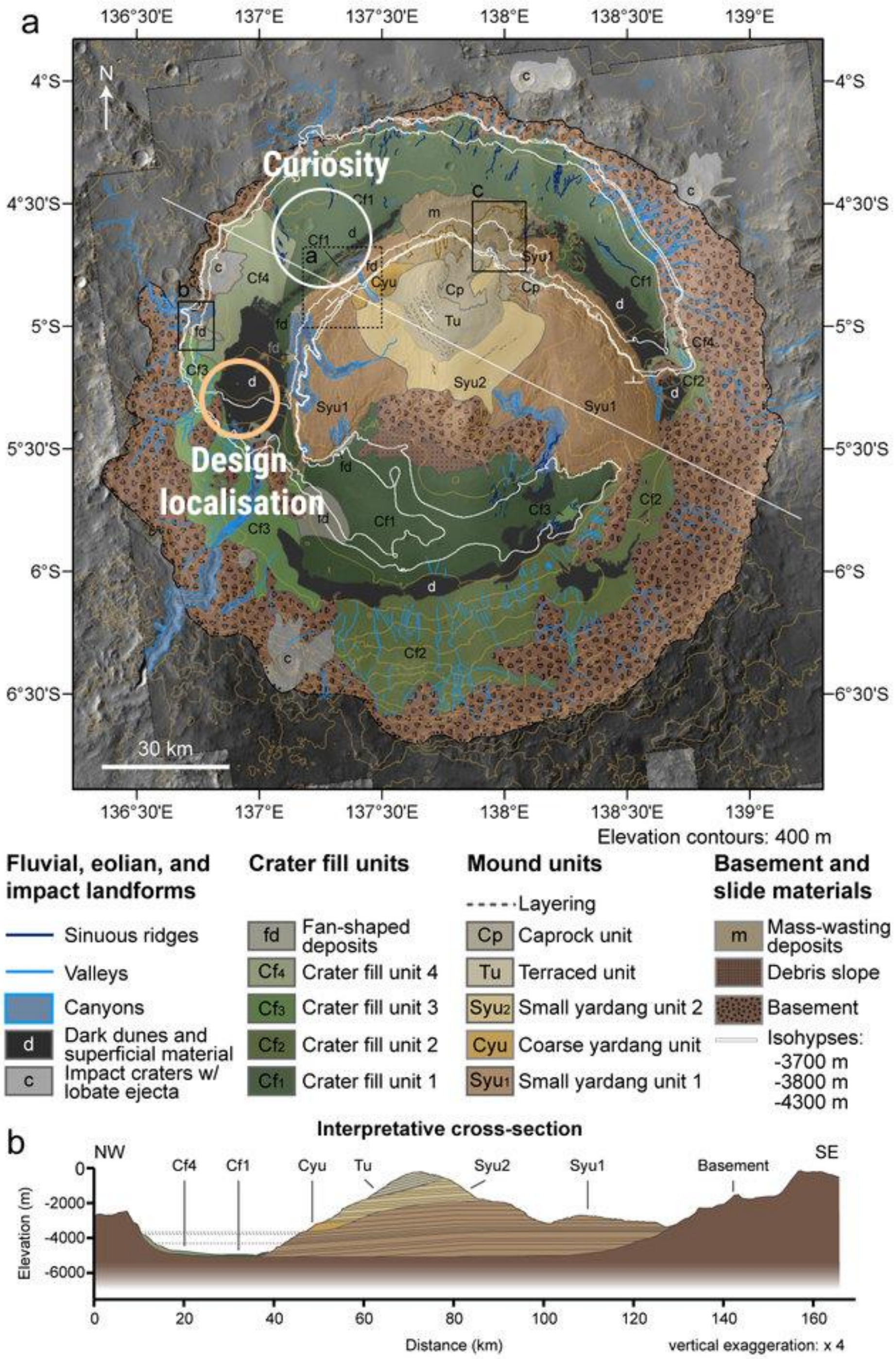


Figure 23: Gale Crater map, surface characteristics and topography, Source: (Deit, et al., 2011)

The Crater is located near the equator and the potential solar energy in this region can reach up to 200 W/m^2 (Delgado-Bonal, et al., 2016). In Figure 24, the author showed the daily dose of solar energy for different orbital positions. However, taking into account the efficiency of the solar power generator and conditions, the exergy of daily power can decrease significantly. In the mentioned paper, the daily solar power was calculated for Gale region (Table 15). The lowest value occurring for the chosen location is 1034 W per sol. This should be the limit for the production process energy requirement, in order to limit the payload and use a sustainable source of energy.

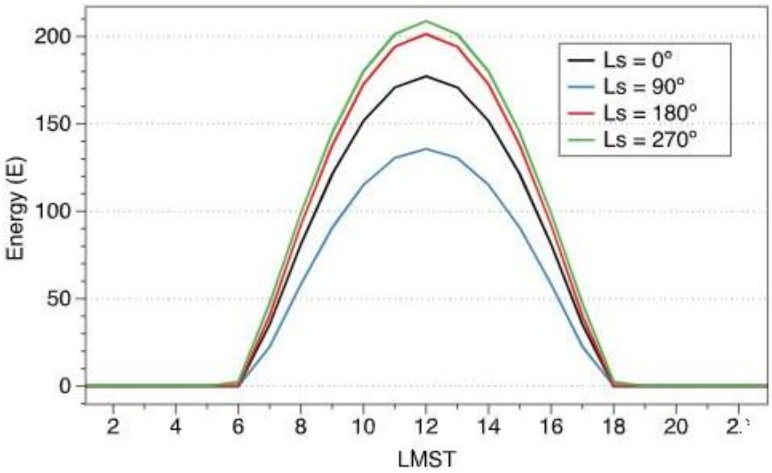
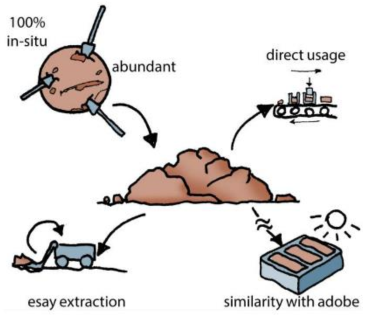


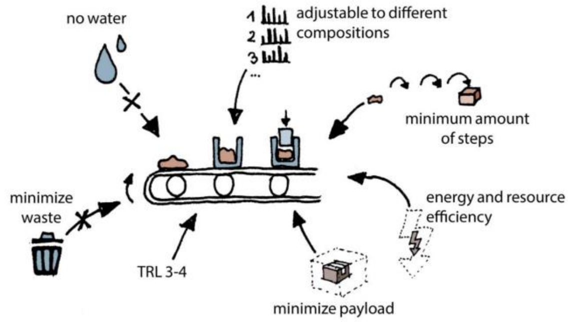
*Figure 24: Obtainable solar energy (E) in crater Gale as a function of Local Mean Solar Time(LMST), and season, Source: (*Delgado-Bonal, et al., 2016*)*

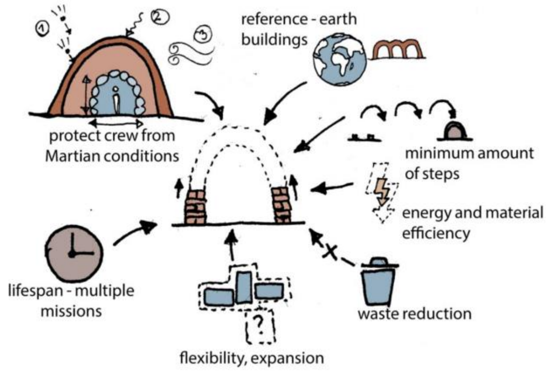
*Table 15: Daily solar power (W) production for a 1m^2 panel for different latitudes and seasons, Source: (*Delgado-Bonal, et al., 2016*)*

	-60˚	-45˚	-30˚	-15˚	0˚	15˚	30˚	45˚	60˚
Ls-0˚	578.3	877.4	1108.0	1253.5	1296.3	1253.5	1108.0	877.4	578.3
Ls-90˚	18.2	221.2	505.9	793.8	1034.0	1220.2	1326.2	1357.8	1335.8
Ls-180˚	657.2	997.0	1259.1	1259.1	1278.3	1424.4	1259.1	997.0	657.2
Ls-270˚	1899.4	1930.5	1885.8	1735.0	1470.2	1128.7	719.3	314.6	25.8

3.3. Final Programme of requirement







3.4. Material

In this sub-chapter, the detailed material mineralogical and chemical composition will be investigated to prepare the best simulant for this research. First, the actual data from Martian samples will be studied, to find the best material type and its properties. Then, the available simulants on Earth will be presented. Based on both, real samples and simulants data, the simulant will be prepared. Finally, the materialization on Mars will be investigated on how this material would need to be extracted and prepared for the production. The requirements from the previous chapters will be included in the decision-making process.

Preparation

ESTIMATION OF THE REQUIRED AMOUNT OF MATERIAL

The required amount of material to be prepared for research was based on the estimation of the needed amount of samples, their size and the density of relevant materials which can be compared to Martian simulant. Table 16 present these calculations. The size of the samples was estimated to be 5x5x5cm, though it is different from the size used in experiments, as it depended on available moulds. The final sample sizes were 4x4x4cm. The amount of samples is based here on the estimated amount of experiments and variables in these experiments. Most ideal is to have the highest amount of samples, which is in this case 50. Though it was further calculated the amount of material for a smaller quantity of samples for comparison.

The chosen comparable materials were: average soil, MGS-1 simulant, and soil from Pathfinder and Viking missions. The simulant has the highest value of density, almost twice as high as the other materials. However, MGS-1 is the most accurate sample of comparison, as the material used for this research is based on this simulant. Based on the results from the table, the final total amount of required material to prepare is 15kg. It covers almost all cases of samples amount and probable density.

ORDERING

Due to time limits planned for this thesis, the material was ordered from local sources, therefore the composition of the used material is slightly different than the MGS-1 simulant. It should be considered in the final conclusions of the report. The plagioclase and pyroxene were added to simulant in the form of basaltic powder, as both of these minerals occur there. The basaltic glass was substituted with basalt fibres, which were ground and milled before adding to simulant mixture. The ferric-carbonate also differs from the one used in MGS-1, while the rest of the minerals are similar to the ones used in pilot research. The final list of materials ordered for the research is listed in Table 16.

PREPARATION STEPS

Before mixing minerals together, some of them would need to be ground to reduce the size of particles. It would make the production more accurate, as the material used on Mars would be dust mixed with soil, with the sizes of grains ranging from clay size to coarse (0,004 – 1mm) – see Table 7 and Table 9 presented above. Table 17 presents the grain sizes planned for each mineral used in the research. Based on this table and the characteristics of ordered material, the decision was made to include basaltic fibres, the high capacity granular ferric oxide in this pre-treatment.

Assessment of The material

MATERIAL RELEVANCE CHECK

To assure, that the self-prepared material is accurate enough to make the research relevant and useful in this field of study, the final production process would be used on both original compositions made by the author of this research and the regolith simulant MGS-1.

REQUIREMENTS:

- ISRU 100%
- Sustainable (no impact on surrounding when abandoned)
- Compressive strength – at least 1,5-2MPa, which is an average compressive strength of an adobe brick

Table 16: Amount and minerals substitutes found on Earth (Europe)

SIMULANT, MGS-1				Material ordered	comment
Mineral	Weight %	total kg	required amount		
Plagioclase	29,12	15	4,368	Albite - sodium feldspar	Due to limitations in pyroxene availability, plagioclase was also added as a basaltic powder
Olivine	14,7	15	2,205	Olivine	
Pyroxene	21,7	15	3,255	Basaltic powder	Difficult to find and order relevant in Europe
Magnetite	2,03	15	0,3045	Black iron oxide	To include magnetic properties of regolith
Anhydrite	0,91	15	0,1365	Anhydrite	
Hematite	1,19	15	0,1785	Red iron oxide	To include the colour
Ferrihydrite	1,2	15	0,18	High capacity granular ferric oxide	
Basaltic Glass	19,5	15	2,925	Basaltic fibres	Difficult to find and order relevant in Europe
Hydrated Silica (Opal)	4,2	15	0,63	Diatomaceous earth	
ferric-sufate	6	15	0,9	Iron (III) sulfate pentahydrate	
Fe-carbonate	1,2	15	0,18	Ferric carbonate	

Table 17: Minerals grain sizes characterization

mineral	Ideal grain size (mm)	Require milling	Wt%	Wt% of grain sizes
Albite	0,1 – 0,5	-	50,82	65,52
olivine	0,1 – 0,5	-	14,7	
Black iron oxide	0,04 - 0,125	-	2,03	4,13
anhydrite	0,04 - 0,125	-	0,91	
Red iron oxide	0,04 - 0,125	-	1,19	
High capacity granular ferric oxide	<0,004	**YES**	1,2	32,1
Basaltic fibers	<0,004	**YES**	19,5	
Diatomaceous earth	<0,004	-	4,2	
iron (II) sulfate heptahydrate	<0,004	-	6	
Ferric carbonate	<0,004	-	1,2	

-

3.5. Production process

Ongoing researches

GENERAL OVERVIEW AND CONDITIONS

The researches relevant to this graduation project will be presented here as a literature review of scientific reports and concepts for building on Mars. The requirements determining the importance of research, based on which the papers were chosen, are water-less (or water-minimized) production processes and regolith/dust as the building material. These concepts were later compared to each other regarding energy consumption and complexity (equipment) of the process, product mechanical (or other if performed) properties, production duration, and potential of the idea.

Production processes are available on Mars concern three stages: extraction, material preparation/selection, and final production process. This chapter is focused on final production processes, while the first two stages will be determined and investigated after choosing the last one.

The most important aspect of the production is how to bind dry and loose material into the building component. The melting point of regolith is about 1100°C, which requires too much energy. Therefore most important part is to find an element that could act as a binder connecting regolith together.

The comparison of chosen researches is presented in Table 18 below. The ones highlighted with orange colour are the most promising in terms of chosen requirements and present four different production processes, which could be compared together to find the most efficient and sustainable option.

Table 18: Ongoing researches used in literature study - comparison

Research	Number of research	Production	Tests	Strength, compression-c, tensile - t, flexural - f,	Conclusions	Comment
regolith mixed with molten sulfur (Wan, et al., 2016)	1	sulfur extracted through chemical or physical reactions, the mixture heated up to 120°C, cool down at room t - 20°C, apply pressure during casting, LDPM simulating	three-point bending, unconfined compression, splitting test	c- 50 MPa	aggregates with small size grains, best ratio 1:1 (sulfur: regolith), rich metal elements in Martian soil reacting with sulfur during hot mixing - better results, fast curing	shrinking, not fire resistant, smell, sulfur extraction
The atomic bond between iron oxide and oxyhydroxide particles (Chow, et al., 2017)	2	samples compressed using 1quasi-static and 2-impact compaction, in 3 different boundary conditions (x-rigid, y-flexible, z-free)	unconfined compression, notched and unnotched three-bending test, splitting	10 - 50 MPa flexural strength		requires binding for building application
Phosphate-based binder (Buchner, et al., 2018)	3	phosphorous pentoxide mixed with martian regolith - tested only case with water addition and dry	Compression tests, Bending tests	10-20MPa	curing time - 2 months,	melting instead of adding water might be problematic, phosphate not abundant
Synthesis with polyethylene (PE) (Sen, et al., 2010)	4	PE produced from Martian atmosphere, mixed with martian regolith and heated up to 140°C, 240MPa pressure applied	Compression test, micrometeoroid ballistic test, radiation test, flexural test	max 41.1MPa	complex PE production - extra complexity	not sustainable
3D microwave printing (Barmatz, et al., 2014)	5	microwave volumetric heating, powder regolith placed in feedstock hopper, heated up to 600°C-700°C surface temperature			700°C was enough to melt core and sinter surface	gradient properties of the samples - powdery outer surface, sintered outer rind, melted interior
Powder Bed Fusion (PBF) (Goulas, et al., 2017)	6	selective laser melting machine (SLM)	Microscopic analysis, hardness test, thermal analysis			production time
Geopolymers from lunar and Martian soil simulants (Alexiadis, et al., 2017)	7	Geopolymerization, aluminosilicate minerals in regolith + potassium hydroxide as an alkaline solution to activate the process	Compression and flexural strength tests	c- max. 2,5 f – 3,6		Requires water – extraction process required
Lunar regolith geopolymer with near-zero water consumption (Wang, et al., 2017)	8	Geopolymerization				Proposed recycling of water in the system

CHOSEN PRODUCTION PROCESSES

Based on the study of the ongoing researches the compression and thermal treatment were chosen as the potential production processes (Figure 25). Different options will be compared with each other regarding the mission and sustainability requirements.

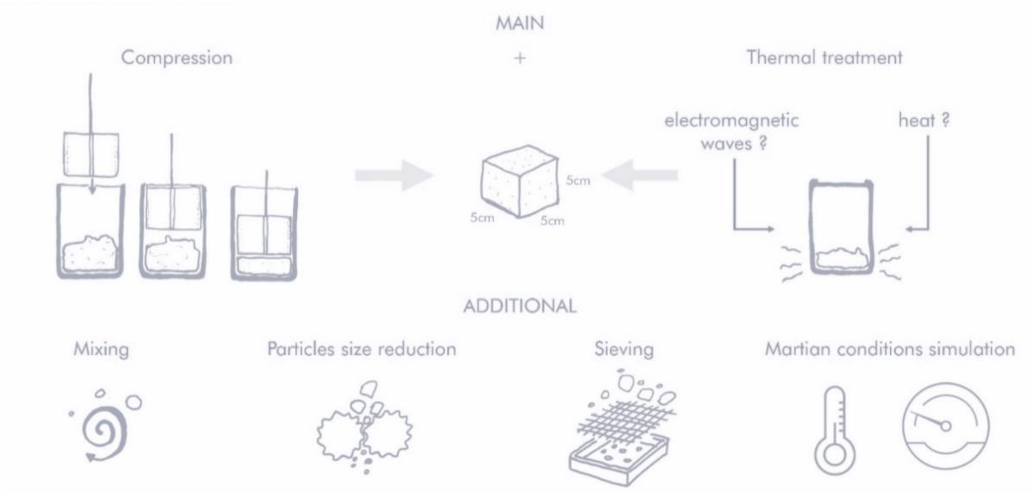


Figure 25: Chosen production process

BINDING OPTIONS

IN-SITU MATERIAL WITH A LOWEST MELTING POINT

The possible minerals used as a binder in the regolith are presented in Table 19 below.

Table 19: Potential binding minerals with the lowest melting point

MINERAL	WT%	MELTING POINT (˚C)	MINERAL FOR SIMULANT	COMMENT
Plagioclase	29,12	Na-,K- 600 Ca/Na - 800	sodic plagioclase (albite)	The albite used in this research have a higher melting point
ferric-sulfate	6	480	iron (III) sulfate pentahydrate	The weight percentage in the composition is limited

The minerals on Mars can have a different melting point than the substitutes used for the simulant. The results of this process might be not very accurate. Additionally, the ferric-sulfate instead of melting is decomposing, which might not bind the regolith.

IN-SITU ALKALINE-ACTIVATED PROCESS - Alexiadis, et al., 2017; Hua, et al., 2002

The materials required for geopolymerization are aluminosilicate elements and alkaline activator, which in case of Mars could be plagioclase and potassium hydroxide respectively (KOH) (Table 20). According to (Hua, et al., 2002) KOH is one of the most commonly used brines for producing geopolymers. KOH properties required to determine, if it might be present on the Red Planet is presented below (Table 21). The drawback of this process is the usage of water. Even if there is a possibility of recycling water in the system, it was decided to not use it in the first place. This could be a potential research development.

Table 20: Potential materials available on Mars used for the geopolymerization production process

MINERAL	ROLE	COMMENT
Plagioclase	Alumino Silicate Material	Most abundant mineral in the regolith and dust composition
Potassium hydroxide	Alkaline Activator	According to Layla van Ellen's report (Ellen, 2018) the Potassium hydroxide might be present in water as brines (salt solutions)

Table 21: Potassium hydroxide properties

Salt	T_e (°C)	DRH (%)	*Χeut* (wt%)
KOH	-63,15	50	32

- T_e is the minimum temperature at which a solution can be liquid,
- the eutectic concentration – *χeut* is the concentration at Te temperature,
- the DRH, threshold relative humidity at which the salt can deliquesce – this can be reached on the surface only poleward of ±60°, during spring

MOLTEN SULFUR - Wan, et al., 2016; King, et al., 2010

The sulfur is present on Mars in the form of sulfides and sulfates. It can be extracted by several chemical and physical processes, for example by heating up the sulfur compounds. The localization of the habitat is not limited by choosing this process. According to the researches – the best amount of sulfur in the composition is between 35 and 50% of the mass.

RELEVANT PROPERTIES TO DETERMINE FOR THE FINAL PRODUCTS FROM THIS RESEARCH

- Mechanical tests for the building material determining:
  - Compressive strength – at least 1,5-2MPa, which is an average compressive strength of an adobe brick
  - Fracture toughness
  - Tensile strength
- Mechanical test for the structure:
  - Simulation of the structure resistance to Martian conditions and loads
    - Micrometeorites
    - Wind
    - Mars quakes

REQUIREMENTS

- Material and energy efficiency strategy
- Avoid waste production
- Solar + limited nuclear as an energy generation source
- No water consumption
- Be adjustable to slightly different compositions of regolith. Possible to build in different locations
- Easy and fast to prepare
- A minimal amount of processing and energy efficient
- Minimum resources required from Earth – fit in one rocket
- Limited volume, mass, and complexity of the equipment required from Earth – fit in one rocket
- TRL of the production process should be already 3/4

3.6. Construction Method and Structure

Structure Type

The structure made out of the regolith can be compared to the adobe buildings made out of the soil constructed on Earth. They can be made out of the similar material - earth building blocks dry-stacked or connected by a binding material. The earth material is very brittle and works only under compression. Tension stress needs to be avoided in the structure. The form of the compression-only structure is usually close to the upside-down catenary shape, which is the ideal shape for this issue. The common compression-only structures are vaults, domes and free form shell structures (Figure 26).

Figure 26: Examples of adobe structures, a) vault, b) dome, c) shell structure, source: Pinterest, Fabrizio Carola, Droneport Shell

Construction system

The main requirement for the construction system is that it needs to be autonomous. The structure would be self-standing after it's finished, but during the building phase, there can different stresses occur. It is important to plan the construction in order to avoid the unstable structures and protect it against the external loads.

The system to connect regolith adobe can be, as mentioned earlier: dry-stacked interlocking or binding. The second one would require another study on the material and more processing on Mars. It would increase energy usage and production time. Therefore, for this research, it was decided, that the interlocking system included in the building block shape would be chosen. The other advantage of the interlocking system is that it allows for recycling of whole structure, as there is no need for using a permanent binder. The assembly is flexible and the construction eased. The definition of the interlocking system was determined in the report "Topological interlocking as a material design concept" (Dyskin, et al., 2019):

> *"Materials assembled from identical blocks whose geometrical shape and mutual arrangement provide kinematic constraints arresting each block within the assembly."*

The mechanical properties of the structure can be improved and controlled by the shape of the block. The design of interlocking is dictated by the need for transferring shear stress in the structure. Additionally, when it comes to brittle material like soil, crack propagation is a frequent issue. However, according to Dyskin, et al., the interlocking system makes the structure more segmented, which decreases the risk of the whole structure to crack. The design of the interlocking system can be described as a function z(x,y) (Figure 27). According to the authors, this method allows to optimise a shape to allow the load to be transferred from all directions while holding the block in position.

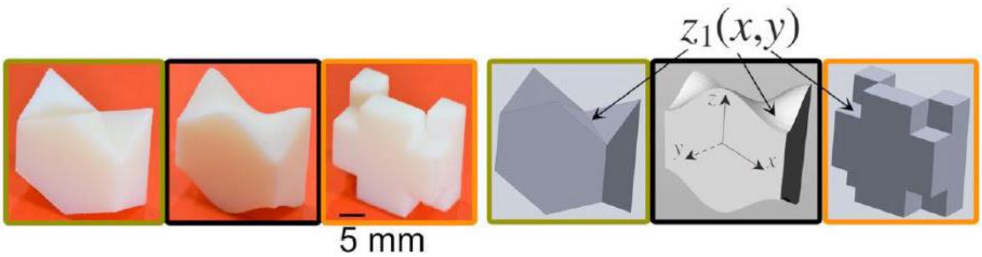


Figure 27: Various shapes of the contrast surface, Source: Dyskin, et al., 2019

The authors presented systems, that could create a stereotomic form in a shape of flat vault structures (Figure 28).

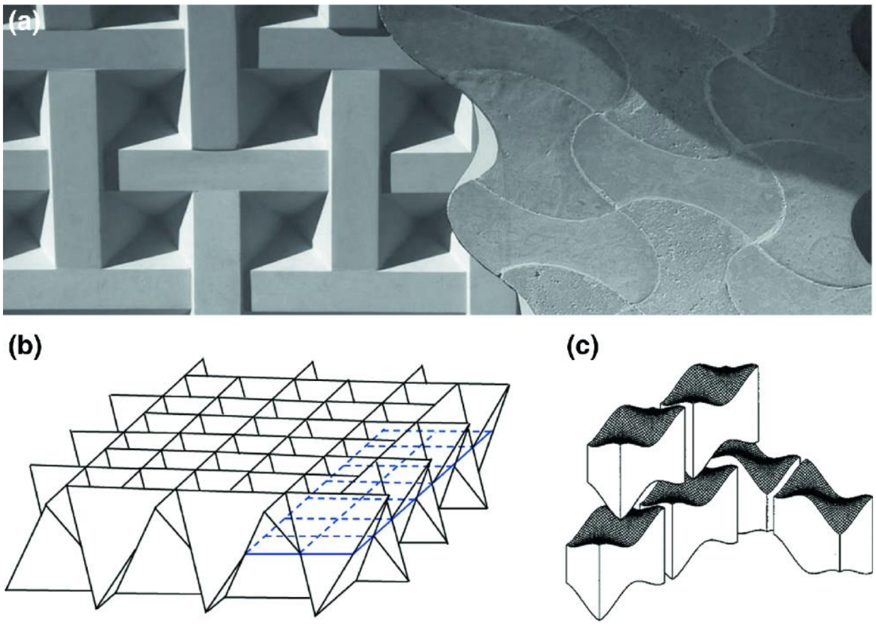


Figure 28: Interlocking systems based on tetrahedra and osteomorphic blocks. The top picture presents a design from the 17th century (Joseph Abeille and Truchet) and the two bottom ones are the topological analogues., Source: Dyskin, et al., 2019

Out of these shapes, the one that can form solid structures and can be produced with just compression was chosen (Figure 28c). However, the shape of the brick is asymmetric and a special production process would be required.

The production process, that could provide complex shape, needs to allow for equal compression in every direction in order to compress asymmetric block. It could be possible with the flexible die as used in rubber forming and hydroforming. This brings extra complexity to the production but allows for building with an interlocking system, which is beneficial in terms of energy and material. These methods use fluids or volatile substances to create three-dimensional pressure (Figure 29). However currently these techniques are used mostly for flat sheet materials, there is a possibility of using it for adobe-like asymmetric blocks, similar to the one used by HYDRAFORM company. In terms of different environmental conditions like pressure and temperature, the choice of fluid or gas needs to be further studied as the difficulty of keeping the material in the required state in these conditions is essential.

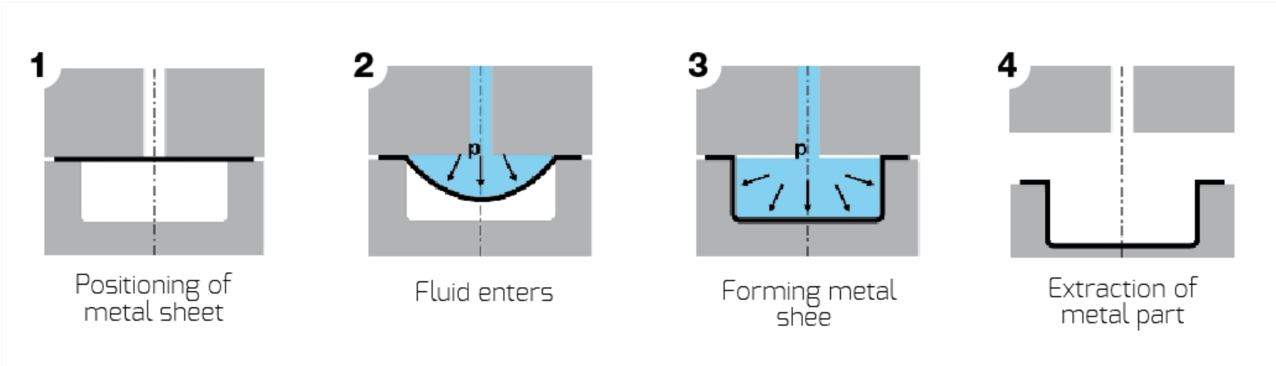


Figure 29: Hydroforming process diagram, Source: Inoxveneta

Assembly of the structures using interlocking system requires to hold the blocks in place until the necessary form is self-locked. It can be done using extra frame and scaffolds or tension cables as suggested by the authors of the book *Architectured materials in Nature and Engineering* (Estrin, et al., 2019). The fully automated construction method on Mars requires very accurate precision of robotic assembly. The right positioning of blocks would be essential for the structural performance of the shell.

Loads on Mars

WIND LOAD

To estimate the wind load it needs to be compared with the values determined for Earth. The average wind speed on Mars ranges between 10m/s and 4m/s, while on Earth the average wind speed is 50m/s. The maximum wind speed during storms and rare dust devils reaches 25m/s with an average 12m/s (Delgado-Bonal, et al., 2016).

To determine the wind pressure, the following formula was used:

Equation 5

$$q = 0.5\ x\ \rho\ x\ v^2$$

Where q is the pressure, ρ is the density of the atmosphere and v is the velocity of the wind.

The density of the atmosphere at the surface of Mars is around 0,020 kg/m^3 (Williams, 2018). The maximum wind pressure on Mars is therefore 6,25 Pa.

MICROMETEORITES

In one of the research papers about building on Mars (Sen, et al., 2010), the authors assumed that the impact velocity of a micrometeorite is 7km/s. The mass can be very slight, 1mg – 1g and the diameter equal to maximum 3mm. The impact force can be calculated with a formula:

Equation 6

$$F = \frac{2mv}{t}$$

Where m is the mass, v is the speed and t is the impact time.

The maximum impact force for micrometeorites is 14000N taking 1millisecond as impact time.

MARSQUAKES

The current mission – InSight is trying to measure the marsquakes in the region of Gale Crater. The lander detected vibrations, but there is no value published. The scientists claim, that the value of the marsquakes is small and therefore in this report, it is neglected.

Comparison – Mars vs. Earth

To understand the relation between the loads and require material mechanical properties, the calculated values were compared to the conditions of the adobe buildings on Earth (Figure 30). The comparison was done using hand calculations and Karamba simulation plug-in software. The Material properties were chosen to be the same for the purpose of the analysis. Table 22 presents the boundary conditions and limit states for the structural model.

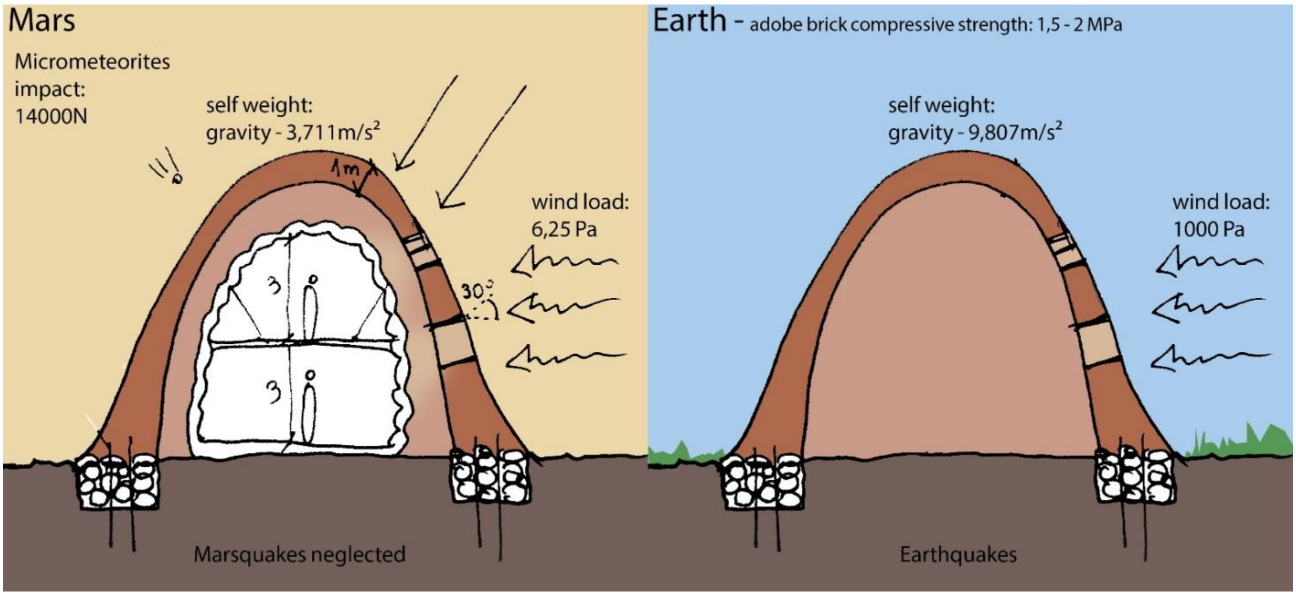


Figure 30: Comparison of loads conditions on Mars and on Earth for earth buildings

Table 22: Boundary conditions and limit states for the structural model

				Earth	Mars
Load Case n°	**Name**	**Type**	**Unit**	**Value**	**Value**
1	dead load	uniformly distributed			
2	wind load	uniformly distributed	kN/m²	1	0,625
3	micrometeorites impacts	point load	kN	_	14

Structure	Comment	Unit	Thickness	Thickness
Cross Section	rectangle	cm	100	100
Span		m	8	8

Safety Limits	Type	Comment	Unit	Value	Value
1	compressive stress		MPa	0,6	0,6
2	tensile stress	1/20 - 1/50 of compressive	MPa	0,03	0,03
3	deformation	L/240	m	0,033	0,033

Material	Parameter	Unit	Value	Value
1	Young's Modulus	MPa	100	100
2	Compressive Strength	MPa	0,6	0,6
3	Shear Strength	MPa	40	40
4	Density	kg/m³	1700	1700
5	Tensile Strength	MPa	0,03-0,012	0,03-0,012
6	Specific weight	kN/m³	16,7	6,3

The cross section for both cases was decided to be 100cm as this is the minimum required thickness of regolith to block hazardous radiation on Mars. The maximum span of the structure was estimated to be equal to 8m. It was done based on the literature review of the studied project examples. The safety limits were estimated based on a literature review of standard structural calculations in the building industry. The material properties were based on the report from the Conference about adobe buildings (Vicente, et al., 2014).

The results from the analysis showed that the requirements for the building material on Mars are lower than those on Earth. The load values are significantly lower, therefore the maximum stresses and deflections are a few times smaller (Table 23). Stress in the structures varies between the two cases (Figure 31). Compressive stress is present in different parts of the structures, which is suggesting a big impact of lower gravity force on structural behaviour. Typically, on Earth, the highest values for compressive stress appear low, while in the case of Martian structure, it concentrated on top of the model. On Mars, more important would be the impact from wind and micrometeorites than the dead load related to a specific weight.

The wind load, oriented upwards, is creating higher tensile strength on the sides of the structure, than the compressive strength generated by gravity. It should be considered during the structure design.

Table 23: Structural analysis comparison between Earth and Mars

			Earth	Mars
Parameter	**Unit**	**Safety Limit**	**Value**	**Value**
Compressive stress	MPa	0,6	0,013	0,0014
Tensile Stress	MPa	0,03	0,003	0,0003
Deformation	m	0,033	0,818	0,17

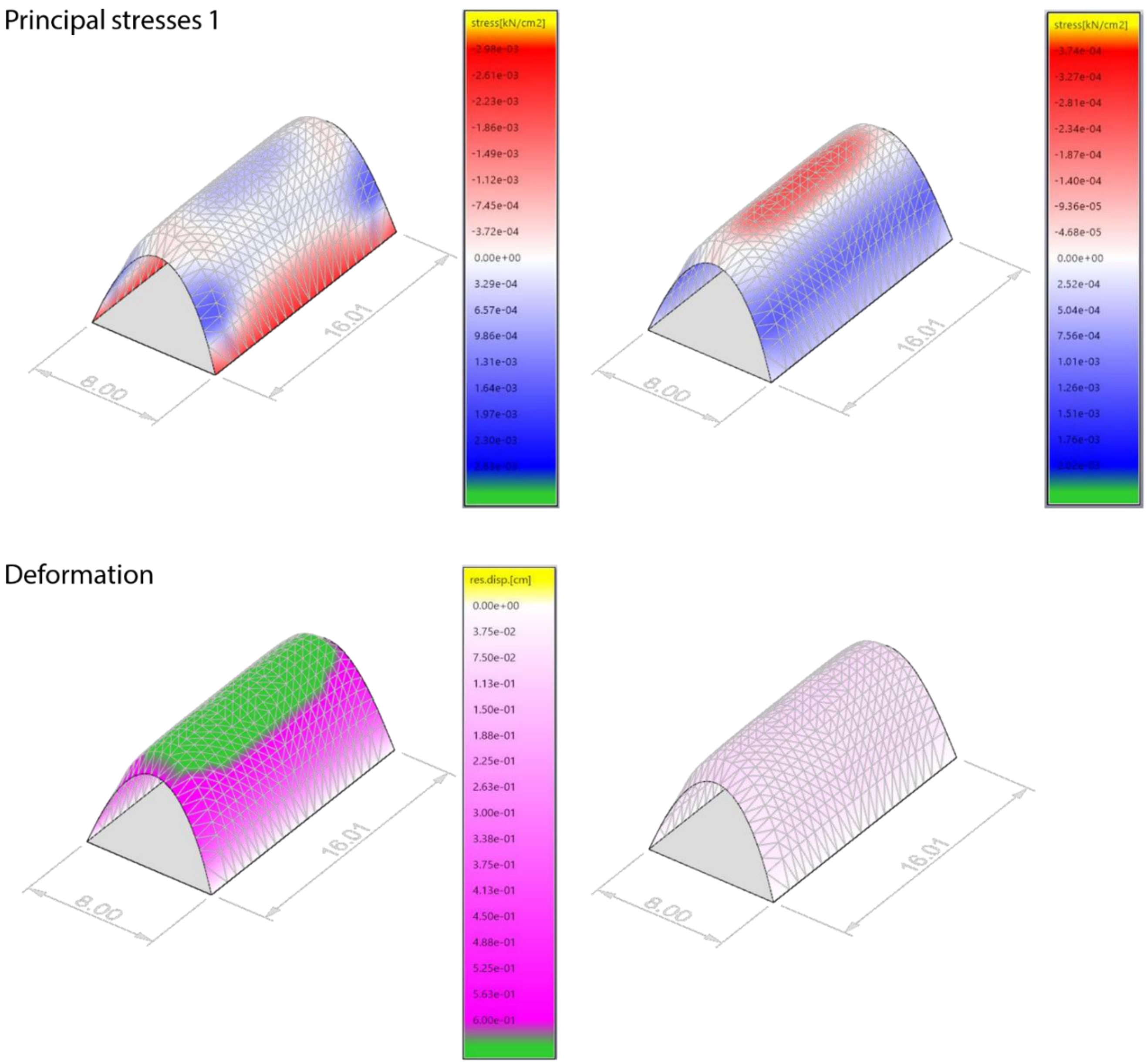


Figure 31: Comparison of Earth and Mars case - Principal stress 1 and deformation

Assessment of The Structure

MECHANICAL REQUIREMENTS

- Withstand extreme temperature differences
- Withstand damage due to radiation or micrometeorites
- Possible to construct volumes and dimensions required for habitable space
- Thermal and radiation insulation
- Not flammable, not decompose
- Wind load: 6,25Pa
- Micrometeorites: 14000N

ARCHITECTURAL REQUIREMENTS

- Easy to construct, maintain, repair, safe
- Fast building – 24/7 hours building
- Interiors protection layer separating crew from regolith material
- Preferably last longer than one mission (1-3 years)
- Adaptation to mission, flexibility, expansion possibility

- Modular structure
- TRL of the building system should be already 3/4

SUSTAINABILITY REQUIREMENTS

- Material and energy efficiency strategy
- Avoid waste production during construction

EXPERIMENTS

4.1. Methodology

The experiments are based on the research papers mentioned in the "Ongoing researches" chapter. They are mostly focusing on comparing three production processes: compression, thermal treatment and molten sulfur as a binder.

This part of the research is divided into 4 steps: preparation, pilot tests, optimisation and construction. The first three, are focusing on the material and production process, while the last one concerns construction method (Table 24). The methodology of the experiments is presented in Figure 32.

The experiments preparation and conclusions are based on the trial and error method, as the compositions of the material, is self-made and there is no research paper to follow directly. If possible, the material was recycled during the experiments.

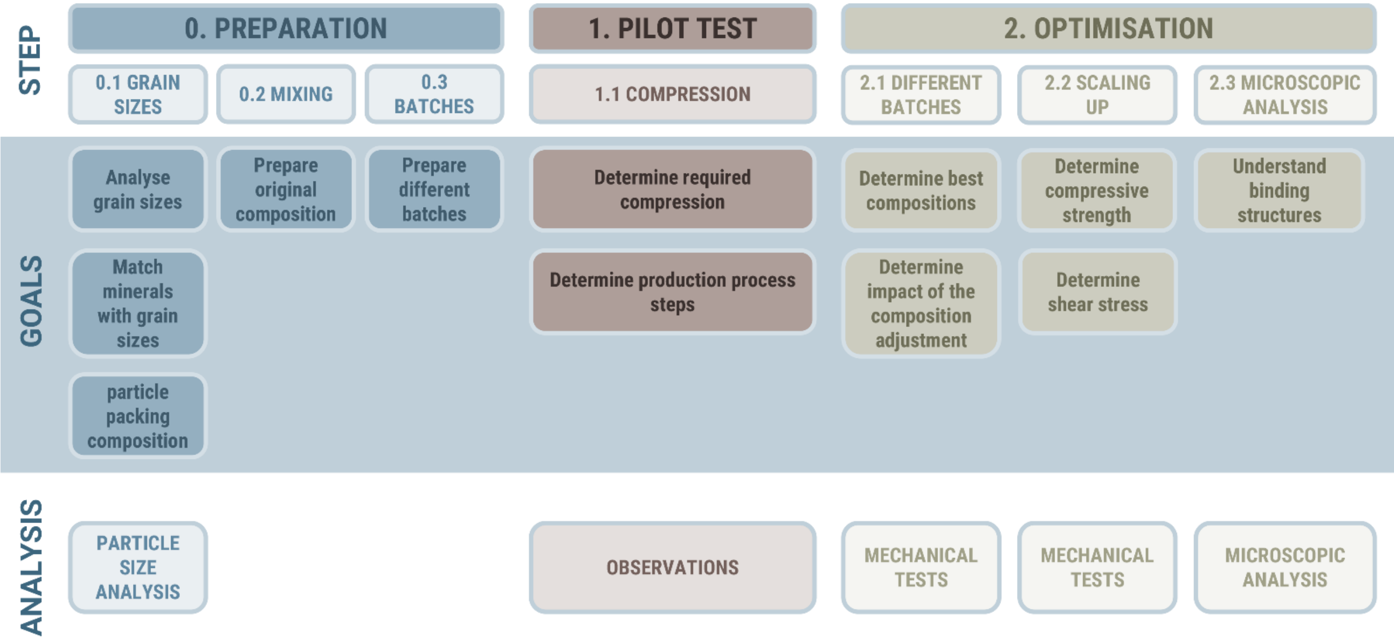


Figure 32: Experiments methodology scheme

Table 24: Experiments list

Experiment name	Objective	Tests + Analysis	Comment
Experiment 0 - Material Preparation and characterization	Prepare simulant and different batches	Analyze chemical composition, preheat material to remove water, size distribution analysis	
Experiment 1 – pilot test	Compression pilot production, compare energy, time and product's binding properties	Surface observation, physical properties observation,	Based on the comparison, the best compression value is chosen, the material can be recycled for further experiments
Experiment 2 - optimisation	production optimization, test different composition options, compare product's properties of compressed and thermally treated samples	Analyze binding properties, physical properties, compressive strength	
Experiment 3 – final optimisation	Combination of different optimisations to check further improvement	Physical properties observation, binding structure, compression strength, microscopy analysis	
Experiment 4 - Construction	Test construction method and bricks connection	Physical model, compression test	

0. PREPARATION

The original material was prepared based on the research paper about the MGS-1 simulant (Cannon, et al., 2019b). Likewise to this research the ordered minerals had to be mixed based on the mineral composition of Rocknest sample from Mars. The grain size distribution was analysed and some minerals had to be milled according to the data.

In the experiments, there would be a different composition of the material tested as a way of optimization. Therefore, different batches should be prepared before the experiments The required Batches differ with the percentage of some minerals or by grain size distribution (Table 25).

Table 25: Batch types and their characteristics

MINERAL	BATCH 1 WT%	BATCH 2 WT%	BATCH 3 WT%	BATCH 4 WT%	BATCH 5 WT%	BATCH 6 WT%	BATCH 7.1. - 7.6. WT%	BATCH 8
TYPE OF BATCH	Original	Amorphous phase + 5%	ferric oxide + 5%	Plagioclase + 5%	Ferric sulfate + 5%	Particle Packing	Sulfur addition	Addition of KOH and water
USAGE IN EXPERIMENTS	Comparison of all experiments	Potential optimization for compression and thermal treatment	Potential optimization for compression	Potential optimization for thermal treatment	Potential optimization for thermal treatment	More compact composition	Molten sulfur as a binder	Geopolymer sample

The original composition will be used to pilot tests and to compare optimizations. It is based on the literature review. Batch 2 was made by increasing the amount of amorphous phase by 5 %, which on Mars would be achieved by only sieving the samples. Batch 3 was prepared based on the research on compacting regolith in order to form building blocks (Chow, et al., 2017). The authors concluded, that the fine grains of ferric oxide created binding formation with other minerals. It was achieved by compaction only, which would require less amount of energy as the production process than thermal treatment. Batch 4 and 5 were prepared for the production process using thermal treatment as the production process. It was done based on the comparison of melting points of the minerals in the regolith. Batch 6 was prepared based on the particle packing idea – which is changing the composition of the material in order to make it more compact. Batch 7 is prepared based on the researches where the authors used molten sulfur as the binder. Both, Batch 6 is proposing and optimized composition regarding grain size distribution, in order to make the mixture more compact. However, due to the fact, that in this research it was decided to use dust and fine grains only, the results of this method might not change the composition much. Batch 7 will be prepared to test the addition of sulfur as a binder. Based on the research paper about sulfur Martian concrete (Wan, et al., 2016) four different ratios of regolith to sulfur will be analysed. Batch 8 is a composition prepared for the geopolymerization production process.

Each Batch (except Batch 7) was put into the oven heated up to 200°C for 6 hours. The temperature and time were determined based on the studied researches. The Batch 7 was prepared by mixing the sulfur powder with an original composition from which water content was removed earlier.

1. PILOT TESTS

The required conditions and settings for equipment used in the process were determined during the pilot test.

2. OPTIMISATION

During the first optimisation, different Batches and production processes were compared and analysed. Later, the best results from the first optimisation experiment were used in the scaled-up experiment to check the properties and behaviour of the bigger samples. The compressive strength is an essential property, therefore it was determined for every experiment.

The secondary properties like tensile strength and fracture toughness were calculated for the final production process and building material.

All the tests and production processes were performed in the earth-like environment due to technical limitations. Different atmosphere conditions – earth-like and argon, were tested in one of the research papers (Barmatz, et al., 2014). The authors claimed, that the impact of the atmosphere is slight.

3. CONSTRUCTION

For the final step, the size and shape of the brick were determined based on the structure requirements and properties of the material produced during the previous experiments.

4.3. Experiments

0.1. Material Preparation and characterization – Milling

AIM AND OBJECTIVES

Two of the ordered materials didn't have fine grain form, therefore they had to be milled and sieved before mixing with other minerals. These materials are basaltic fibre – which had to be transformed into basaltic powder (to simulate basaltic glass), and high capacity granular ferric oxide – which should have grain size <4µm.

EQUIPMENT

To mill the basaltic fibres and granular ferric oxide the vibrating cup mill was used which consists of vibrating machine and a steel container with rings of different sizes which crush the material inside into smaller particles. Depending on milling time the material can be transformed into silt-sized or dust-sized grains.

In order to ensure, that the grains reached the required size the milled material was put into vibrating sieve shaker machine. For this process sieves with mesh size, 0,04mm and 0,06mm were used, for ferric oxide and basaltic fibres respectively.

The granular ferric oxide was put for 12 hours in the oven heated up to 60°C before milling to remove water content.

SET UP AND RESULTS

Before milling, the materials were first put in the steel cup. Due to the size of the cup, the batches of material were about 100g per one round of milling. The milling was set to 90 seconds. The material was later transferred into the sieve and placed in the vibrating machine for 3 minutes. The sieved material was later placed in the plastic containers. The material, that had too big particles to go through the mesh was replaced in the steel cup and milled to reach the required grain size.

CONCLUSION

The ideal material's grain size is not achieved due to equipment limitations, although the final conclusion about the particle size will be presented after particle size analysis.

0.2. Material Preparation and Characterisation – Mixing

AIM AND OBJECTIVES

The preparation of the original composition was done first. Later different batches would be prepared by using the original composition as the basis.

EQUIPMENT

The mixing was done using a laboratory mixer equipped with steel bowl with 10 litres capacity, whisk and selective agitator transmission with 3 speeds settings, from 106 to 358 RPM (revolutions per minute). The mixing was set to speed 1, due to powder and a loose form of all of the materials.

SET UP

Due to the fact, that all minerals have a dust form, the material fitted in the mixer had to be below 1kg. Otherwise, the rotation of the agitator was scattering the material. The material had to be additionally mixed manually with a spoon because there were unmixed concentrations of iron sulfate and iron oxide visible. Later the material was organized in the plastic containers.

RESULTS & CONCLUSION

The material was mixed in the earth's conditions, which might lead to contamination of the regolith and presence of water in the batches. This could have an effect on the results of the experiments. Therefore, the material was put into the oven heated up to 200°C for 12 hours before any experiments in order to remove water content.

0.3. Material Preparation and Characterisation – Preparing Batches 1

AIM AND OBJECTIVES

Before experiments, minerals had to be mixed into batches with different compositions. The types of batches were presented in the previous chapter – *Pre-experimental decision-making* (Table 25). To prepare particle packing batches, the particle sizes had to be analyzed and determined.

EQUIPMENT

For the preparation of the batches, 1-5 and 7 only spoon and the containers were used. However, to prepare the particle packing composition, particle size and shape analyzer – EyeTech Ankersmid was used. The equipment collects data about the particle sizes using Liquid Flow Controller – LFC-101 and the lenses A with the range 0.1 – 300 µm and B with the range 10-3600 µm. Later the data was prepared using the DIPA 2000 software. Finally, the batches were prepared using a sieving machine and placed in the plastic containers. The meshes sizes for sieving were 1, 45, 63, 90 µm.

SET UP

FIRST ROUND BATCHES

The original composition was used to prepare the batches. The additional amount of some material was calculated and later added to the mixture. The amount of additions per 100g is presented in Table 26.

Table 26: Additional mass of minerals per 100g for each Batch

Mineral	BATCH 1 required an additional amount per 100g	BATCH 2 required an additional amount per 100g	BATCH 3 required an additional amount per 100g	BATCH 4 required an additional amount per 100g	BATCH 5 required an additional amount per 100g
ALBITE	29			10	
OLIVINE	15				
BALASTIC POWDER	22				
MAGNETITE	2				
ANHYDRITE	1				
HEMATITE	1				
HIGH CAPACITY FERRIC OXIDE	1	0,5	10,2		
BASALTIC POWDER	20	5,3			
DIATOMACEOUS EARTH	4	5,2			
FERRIC-SULFATE	6	2			10
FERRIC-CARBONATE	1	0,2			

Mineral	BATCH 7.1 required an additional amount per 100g	BATCH 7.2 required an additional amount per 100g	BATCH 7.3 required an additional amount per 100g	BATCH 7.4 required an additional amount per 100g	BATCH 7.5 required an additional amount per 100g	BATCH 7.6 required an additional amount per 100g
ALBITE					9,1	
OLIVINE						
BALASTIC POWDER						
MAGNETITE						
ANHYDRITE						
HEMATITE						
HIGH CAPACITY FERRIC OXIDE						7,07
BASALTIC POWDER						
DIATOMACEOUS EARTH						
FERRIC-SULFATE						
FERRIC-CARBONATE						
SULFUR	10	20	30	50	30	30

PARTICLE PACKING

The analysis of particle sizes was done for each material separately. Each mineral was analyzed in 3 cycles to receive the most accurate results. The material, that the particle sizes were given by suppliers were neglected in the analysis.

Later, the data was gathered and using Particle Packing Method the composition for BATCH 6 was prepared. The theoretical method of Funk and Dinger (Ding, et al., 2018) was implemented (Equation 7).

Equation 7

$$CPFT = \frac{d^q - d_0^q}{D^q - d_0^q}$$

where, CPFT - cumulative percent finer than, d – particle size, d_0 – the minimum size of the particle, D – the maximum size of the particle, q – distribution coefficient (0,25-0,37)

The result of this equation is the percentage of the particles in the composition, that are smaller than the chosen particle size (d). The composition of the Batch 6 was estimated by using q equal to 0,37, which theoretically gives the most compact option. This value was chosen because almost all of the minerals have dust form and differences between particle size are slight. To prepare the compact sample, the original material was sieved through four different meshes. Later, the sieved material was again mixed together in the required percentage. It was decided to sieve original composition, instead of each mineral separately, because on the Martian surface it would be also more convenient to sieve the directly collected material instead of first separating minerals.

RESULTS AND ANALYSIS

FIRST ROUND BATCHES

The batches were organized into plastic containers, with the 7 and 15 g weight of the material. It was estimated, that this amount would fit into the steel mould. Two values were chosen to compare the influence of the amount of material on final specimens properties. The final compositions of batches are presented in Table 27.

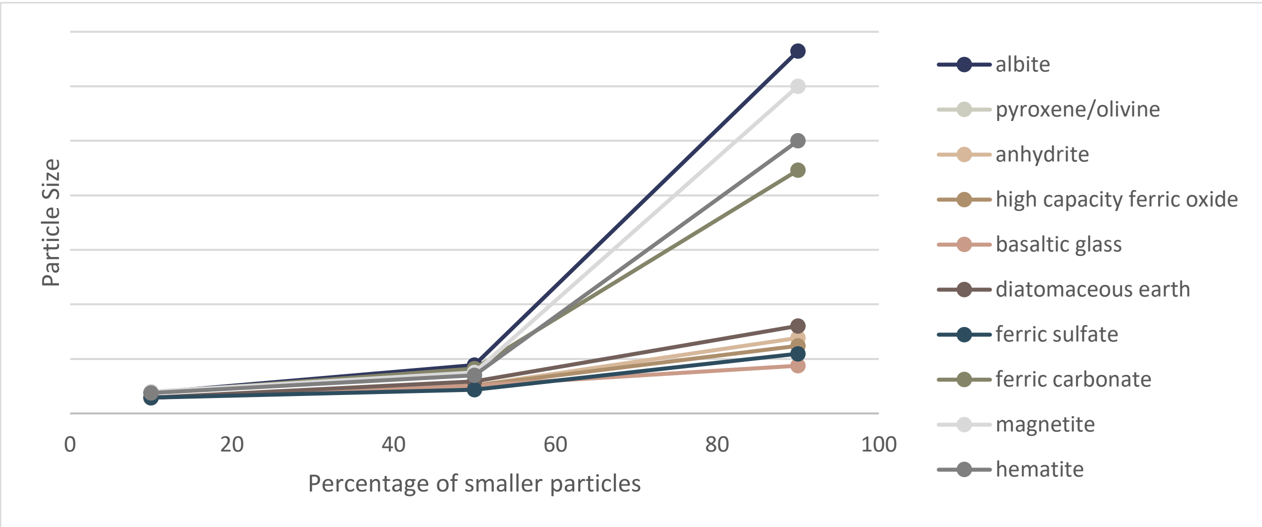
Table 27: The batches composition

MINERAL	BATCH 1 WT%	BATCH 2 WT%	BATCH 3 WT%	BATCH 4 WT%	BATCH 5 WT%	BATCH 7.1. WT%	BATCH 7.2. WT%	BATCH 7.3. WT%	BATCH 7.4. WT%	BATCH 7.5. WT%	BATCH 7.6. WT%
ALBITE	29	24,7	25,9	39	26	23,4	20,8	18,2	13	27,3	18,13
OLIVINE	14,4	12,3	12,9	12,5	12,5	11,25	10	8,75	6,25	8,75	9,03
BASALTIC POWDER 1	21,5	18,3	19,2	18,5	19,3	17,37	15,44	13,51	9,65	12,95	13,51
BLACK IRON OXIDE	2	1,8	1,9	1,6	1,8	1,62	1,44	1,26	0,9	1,12	1,33
ANHYDRITE	0,9	0,8	0,9	0,8	0,8	0,72	0,64	0,56	0,4	0,56	0,63
RED IRON OXIDE	1	0,9	0,9	0,9	0,9	0,81	0,72	0,63	0,45	0,63	0,63
HIGH CAPACITY GRANULAR FERRIC OXIDE	1,2	1,5	11,2	0,9	1,1	0,99	0,88	0,77	0,55	0,63	7,84
BASALTIC POWDER 2	19	25,3	17,1	16,5	17	15,3	13,6	11,9	8,5	11,55	11,97
DIATOMACEOUS EARTH	4	5,2	3,6	3,5	3,6	3,24	2,88	2,52	1,8	2,45	2,52
IRON (II) SULFATE HEPTAHYDRATE	6	8	5,4	5	16	14,4	12,8	11,2	8	3,5	3,78
FERRIC CARBONATE	1	1,2	0,9	0,8	1	0,9	0,8	0,7	1,5	0,56	0,63
SULFUR	-	-	-	-	-	10	20	30	50	30	30

Figure 33: Batches organized in the plastic containers

PARTICLE PACKING

The results of particle packing analysis are presented in Table 29. The smallest and the largest values of particle sizes were determined for each material to find the range of grains for the regolith. The smallest and largest particles are presented at the bottom of the Table. The particle sizes of the missing minerals, magnetite, and hematite, which are 100 µm, had been given by the producers. There is a noticeable relation between minerals and their particles size. Graph 1 presents the grains size distribution for measured materials. The smallest particles sizes are similar for all minerals. A significant change occurs with the highest values, where albite, ferric sulfate, hematite, and magnetite stand out. This relation would be used as a reference to determine the composition after the sieving process.



Graph 1: Particle size distribution based on analysis

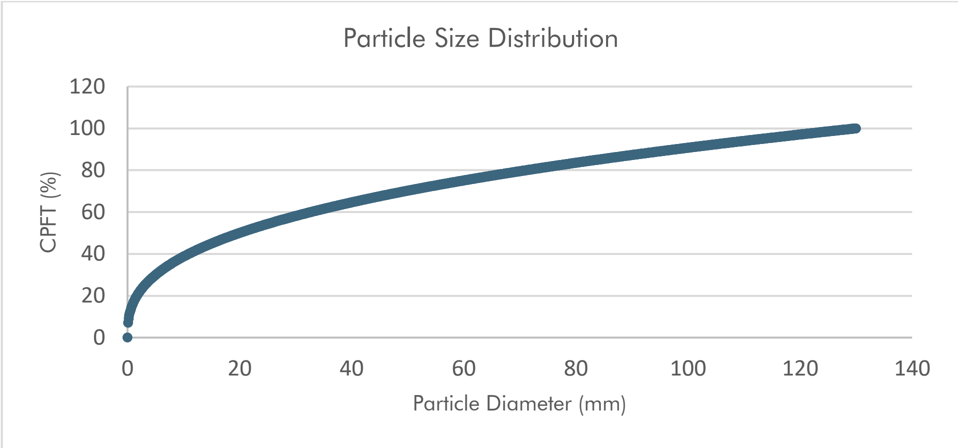
Next, the smallest and highest value of particle sizes were chosen to calculate the particle size distribution of the whole mixture. Graph 2 presents the relation between particles for compact composition. According to this calculation, the percentage of mass ranges was determined (Table 28).

Table 28: Percentage of material divided by grain size ranges in the particle packing composition, Batch 6

Size range	d<1 µm	1<d<45 µm	45<d<63 µm	63<d<90 µm	90<d µm
Mass Percentage (wt%)	16	51	9	11	13
Mass per 200g (g)	32	102	18	22	26

Table 29: Particle sizes for each mineral in 3 cycles

Material	smallest	largest	mean	most often	percentage of most often	D10	D50	D90	comment
albite 1	0,47	74,34	1,14	1,06	15	0,76	1,78	13,29	
albite 2	0,47	69,82	3,05	1,06	15	0,62	1,35	6,16	
albite 3	0,44	33,36	1,14	0,58	23	0,44	0,73	1,6	
Basaltic powder 1	0,58	25,93	1,48	0,73	18	0,58	1,02	2,77	
Basaltic powder 1	0,58	23,75	1,37	0,58	20	0,58	0,87	2,62	
Basaltic powder 1	0,58	19,52	1,29	0,58	21	0,58	0,87	2,48	
anhydrite 1	0,00	130	1,37	0,58	19	0,58	1,02	2,48	are smaller but the laser didn't determine value
anhydrite 2	0,00	126,81	1,38	0,58	18	0,58	1,02	2,48	
anhydrite 3	0,00	124	1,35	0,58	19	0,58	1,02	2,48	
High capacity ferric oxide 1	0,00	22,87	1,09	0,58	23	0,58	1,02	1,75	
High capacity ferric oxide 2	0,00	26,37	1,07	0,58	23	0,58	0,87	1,75	
High capacity ferric oxide 3	0,00	17,77	1,03	0,58	23	0,58	0,73	1,6	
basaltic powder 2	0,00	32,2	1,63	0,58	17	0,58	1,17	3,21	
basaltic powder 2	0,00	21,85	1,44	0,58	17	0,58	1,17	2,77	
basaltic powder 2	0,00	19,52	1,3	0,58	21	0,58	0,87	2,48	
Diatomaceous earth 1	0,00	12,82	1,2	0,58	20	0,58	0,87	2,19	
Diatomaceous earth 2	0,00	13,4	1,18	0,58	21	0,58	0,87	2,04	
Diatomaceous earth 3	0,00	10,2	1,17	0,58	21	0,58	0,87	2,04	
ferric sulfate 1	0,47	100	4,25	1,06	14	0,76	1,64	8,92	
ferric sulfate 2	0,47	110	3,32	1,06	16	0,62	1,49	7,47	
ferric sulfate 3	0,47	108	3,11	1,06	17	0,62	1,49	6,59	
ferric carbonate 1	0,00	32,2	1,08	0,6	23	0,58	0,87	1,75	
ferric carbonate 2	0,00	16,46	1	0,6	23	0,58	0,73	1,6	
ferric carbonate 3	0,00	22,4	1,01	0,6	24	0,58	0,73	1,6	
largest	0,58	130	4,25	1,06	24	0,76	1,78	13,29	
smallest	0	10,2	1	0,58	14	0,44	0,73	1,6	



Graph 2: Particle packing composition size distribution

Sieving process showed, that the mixture of particles with different range of grain sizes have different colours as visible in Figure 34. It corresponds to the relation between minerals and particle sizes, determined by the grain sizes analysis. The layer with the biggest particles (90 µm <d) is more red and coarse, while the two layers with the smallest particle sizes are grey-brown.

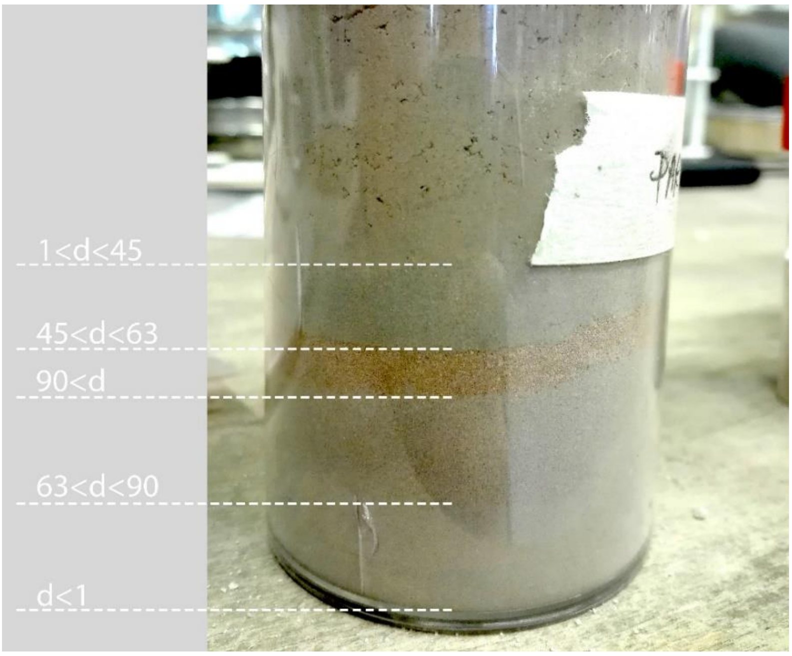


Figure 34: Particle packing composition, visible layers of different grain size ranges.

CONCLUSION

The particle's sizes are very similar for all of the minerals. Only the exceptional maximal sizes differ significantly, however, these are less than 10 percent of the size distribution (Table 29).

There is a noticeable change in colour of the Batch 6 material, which shows the change in the mineral composition. Although it's making the material more compact, the change in composition might lead to differences in thermal treatment results. The mineral with the lowest melting point – ferric-sulfate and albite have, on average, the highest grain sizes. The amount of the biggest particles is volumetrically the smallest one in the composition (Figure 34).

1.1. Experiment– Production Process – Pilot Tests

AIM AND OBJECTIVES

The main objective of the pilot tests was to determine the minimum required force to achieve solidity of the material due to compression. Based on the research done in the University of California (Chow, et al., 2017), the compression pick they used was ranging between 360 and 800 MPa. The pilot tests for this research were performed using 10kN pressing machine, which would result in max 100 MPa when compressing the chosen size of the samples.

The compressed samples were later compared in terms of binding properties by simple observation and physical test. It would help determine the force required for production optimization of the next samples.

EQUIPMENT

The compression bench Zwick (LF7M10) with a maximum of 100 kN load was used. During the compression, the displacement versus time was measured. Each sample was placed in the steel mould with the dimensions presented in Figure 35.

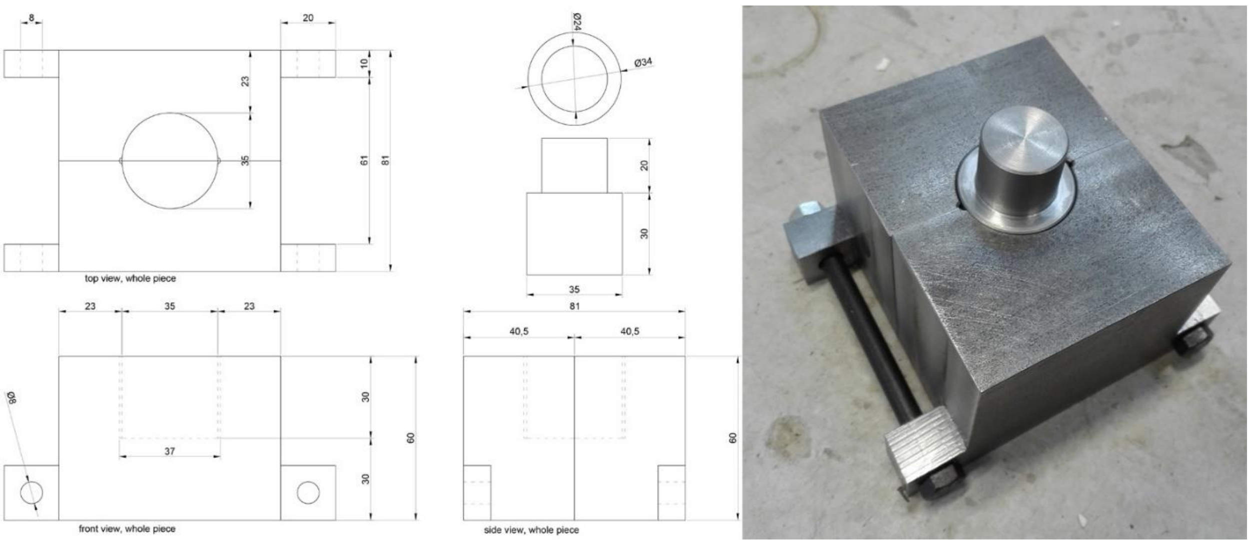


Figure 35: Technical drawing of the mould and the picture of it.

SET UP

The preparation process is the same for each sample. First, the material is placed in the mould using a spoon. Later the material is slightly compressed by hand, with the weighting cylinder visible at the mould picture above (Figure 35). The material fills half of the mould's height – 17,5mm. The picture of the prepared sample is visible below (Figure 36). The mould was later transferred to the compressing machine where the load with different rates and the peak values is tested. Slight amount of material was coming out of the two holes while compressing (Figure 36c).

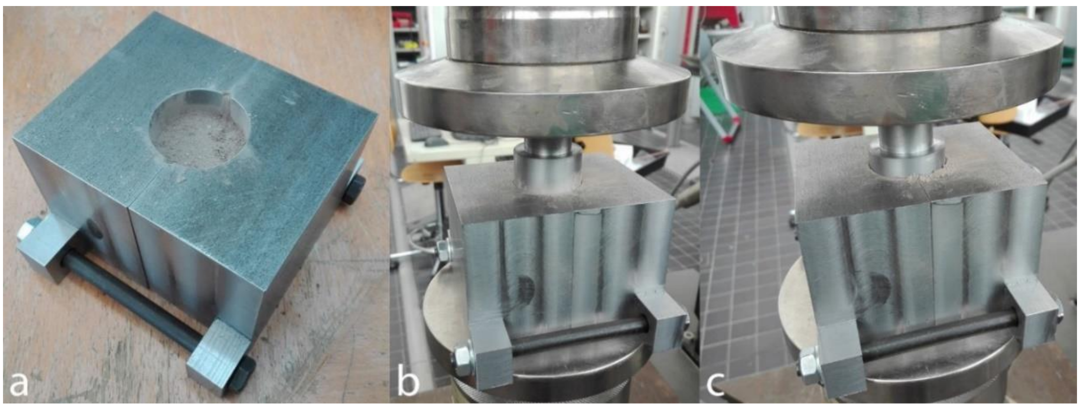


Figure 36: Compression pilot test steps. 1 - material placed in the mould and compacted with the hand; 2- mould placed in the loading machine; 3- due to the loading process material gets out of the holes at the side of the mould.

The first sample was tested in 5 cycles changed every 5 minutes, starting with 10 kN and finishing with 50 kN load. The second sample was loaded in 5 cycles lasting 5 minutes each, with the first load value – 16 kN and the last one – 80kN. The last sample was compressed with 95 kN for 10 minutes. Later the samples were transported to the table were the cylindrical weight was removed and the first observation of the samples was performed. Then, the screws were untightened to open the mould and to remove the sample. The removed samples were also analysed in order to determine the solidity and physical properties of the material. Table 30 presents the loading process for 3 samples.

Table 30: Pilot test loading cycles

PILOT TEST										
No.	Batch type	Mass (g)	Volume (mm^3)	Contact Area (mm^2)	Compression rate (kN/min)	force 1 (N)	force 2 (N)	force 3 (N)	force 4 (N)	force 5 (N)
1.11	1	15	28848,75	961,625	10 kN per 5 minutes, up to 50 kN	10000	20000	30000	400000	50000
1.12	1	15	28848,75	961,625	16kN per 5 minutes up to 98 kN	16000	32000	48000	64000	80000
1.13	1	15	28848,75	961,625	95 kN for 10 minutes	_	_	_	_	95000

VARIABLES AND CONSTANTS

- Variables:
  - 3 compression values and loading rates
- Constants:
  - Samples size
  - Equipment
  - Tests conditions

RESULTS AND ANALYSIS

SAMPLE 1

The results and analysis are divided into two categories: observation and data gathered from the compression bench.

The observations are supported by the pictures of the sample visible in Figure 37. The material reduced the volume twice compared to before the compression process. When the cylindrical weight was removed, the dust material collected in the air holes, covered the top surface of the compacted sample creating a loose layer. When scratched with the spoon, the material shows hardness beneath the loose layer (Figure 37 a). The sample broke into two pieces when the screws were untightened (Figure 37b). In the broken edge, the ferric sulfate (white spots) and hematite (red spots) concentrations were visible (Figure 37 c). The material broke into smaller pieces when tried to be removed from the mould.

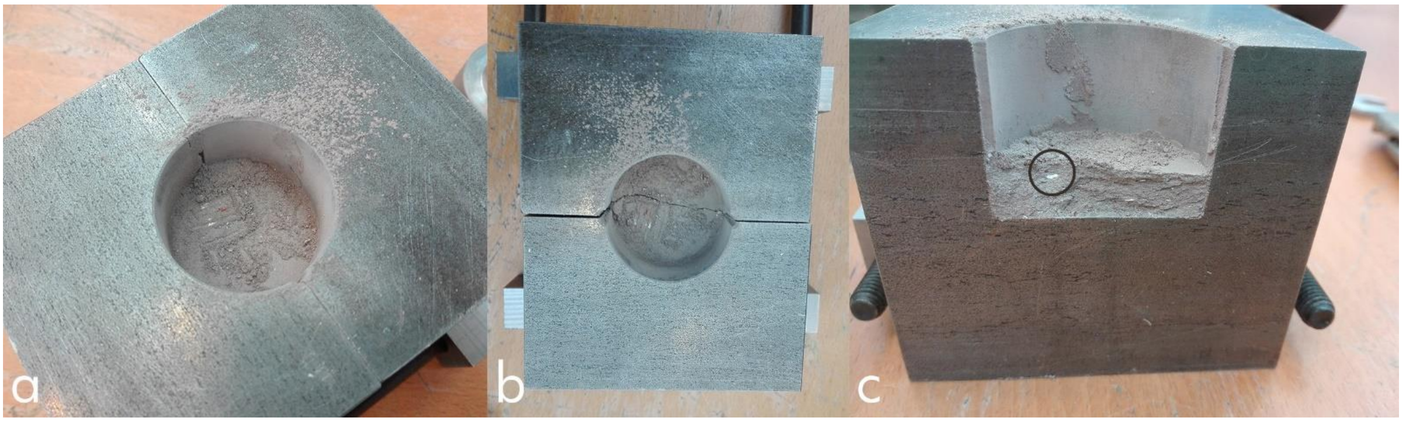


Figure 37: Sample 1 results of the compression process, observation pictures

The analysis of data gathered by compressing equipment is presented in Table 31. The deformation of the samples has the highest values during the first step – increasing the load to 10000N. Later, the compression doesn't change more than 0,64mm at each step. The bigger changes occur during the increasing of load, which takes 10-12 seconds, compared to the constant load steps lasting 5 minutes. The total deformation without the first steps was also calculated, due to different compaction of the material at the beginning.

Table 31: Sample 1 data gathered from loading equipment

SAMPLE 1					
CYCLE	TIME (s)	FORCE (N)	DEFORMATION DIFFERENCE (mm)	DEFORMATION TOTAL (mm)	COMPRESSION (MPa)
	0-12	0-10000	2,1797	2,1797	
1	12-312	10000,00	0,17	2,3501	10,40
	312-323	10000-20000	0,64	2,9928	
2	323-623	20000,00	0,14	3,1315	20,80
	623-635	20000-30000	0,39	3,5198	
3	635-935	30000,00	0,12	3,6435	31,20
	935-946	30000-40000	0,29	3,9288	
4	946-1246	40000,00	0,11	4,0414	41,60
	1246-1256	40000-50000	0,21	4,2496	
5	1256-1556	50000,00	0,12	4,3683	52,00
TOTAL	1556		4,37		
Total deformation without the first step			2,19		

SAMPLE 2

The observations are supported by the pictures of the sample visible in Figure 38. The material showed a similar characterization as in sample 1. However, the pieces it broke into were lightly bigger compared to the first one.

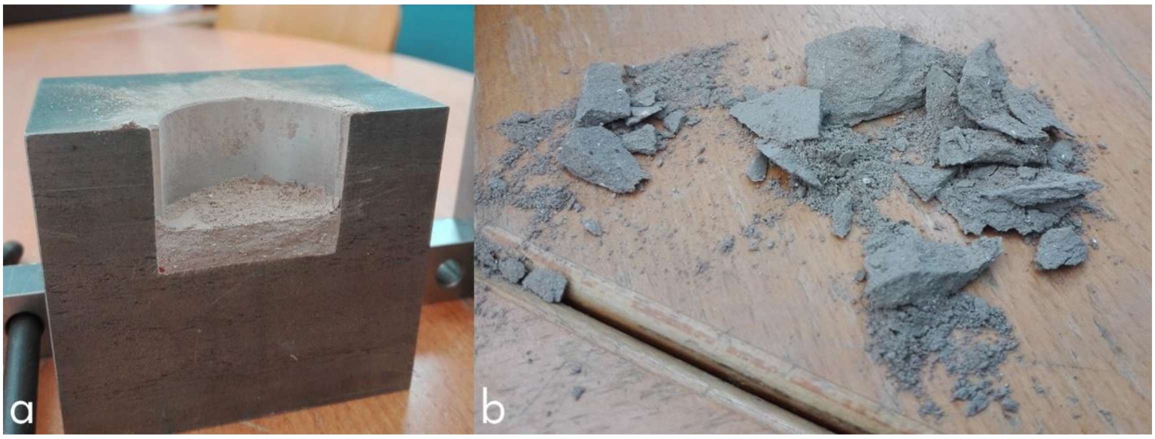


Figure 38: Sample 2 compression process results, observation pictures

The analysis of data gathered by loading equipment is presented in Table 32. The relation between the deformation, load and step number are similar as for the first sample. The first deformation is 4 times bigger, although it might be due to the fact, that the material was less compressed before. The total deformation without the first step is slightly higher, which might be the effect of weak compression done by hand.

Table 32: Sample 2 - data gathered from the loading equipment

SAMPLE 2					
CYCLE	TIME (s)	FORCE (N)	DEFORMATION DIFFERENCE (mm)	DEFORMATION TOTAL (mm)	COMPRESSION (MPa)
	0-17	0-16000	8,77	8,7700	
1	17-317	16000,00	0,17	8,9371	16,64
	317-335	16000-32000	0,78	9,7178	
2	335-635	32000,00	0,14	9,8581	33,28
	635-652	32000-48000	0,46	10,3149	
3	652-952	48000,00	0,15	10,4643	49,92
	935-968	48000-64000	0,35	10,8099	
4	968-1268	64000,00	0,13	10,9410	66,55
	1268-1284	64000-80000	0,29	11,2354	
5	1284-1584	80000,00	0,12	11,3547	83,19
TOTAL	1556		11,35		
Total deformation without the first step			2,58		

SAMPLE 3

The final sample achieved similar results, however, there was less loose material and more solid pieces (Figure 39). The total compression is smaller compared to other samples, which might be the result of strong compaction before the process. It also shows that the time, which was in this case 10 minutes didn't increase the deformation that much. It can be also visible in Graph 3 and Graph 4, where the deformation of the three samples is compared.

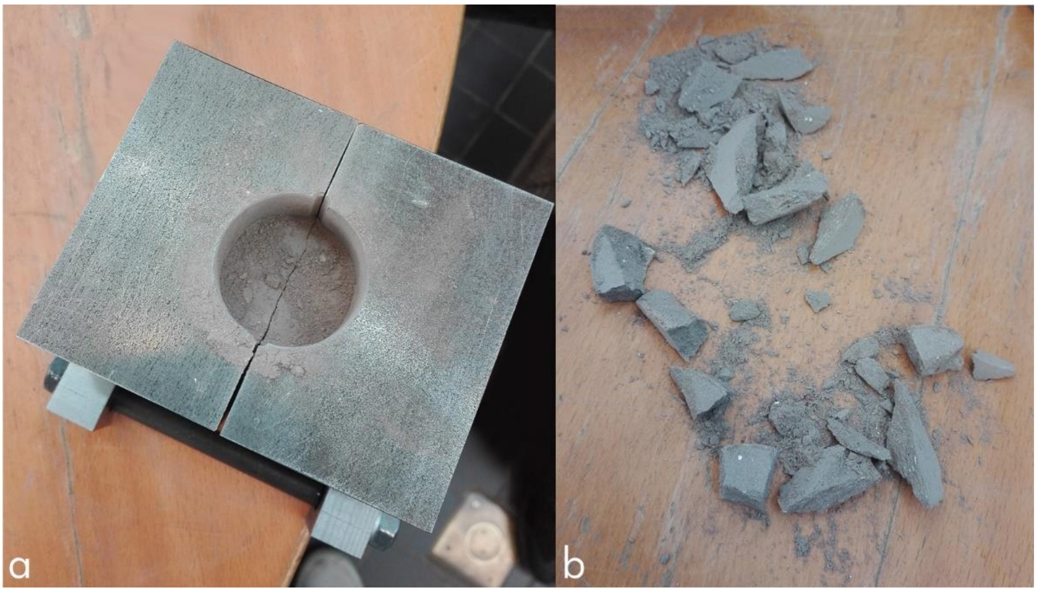
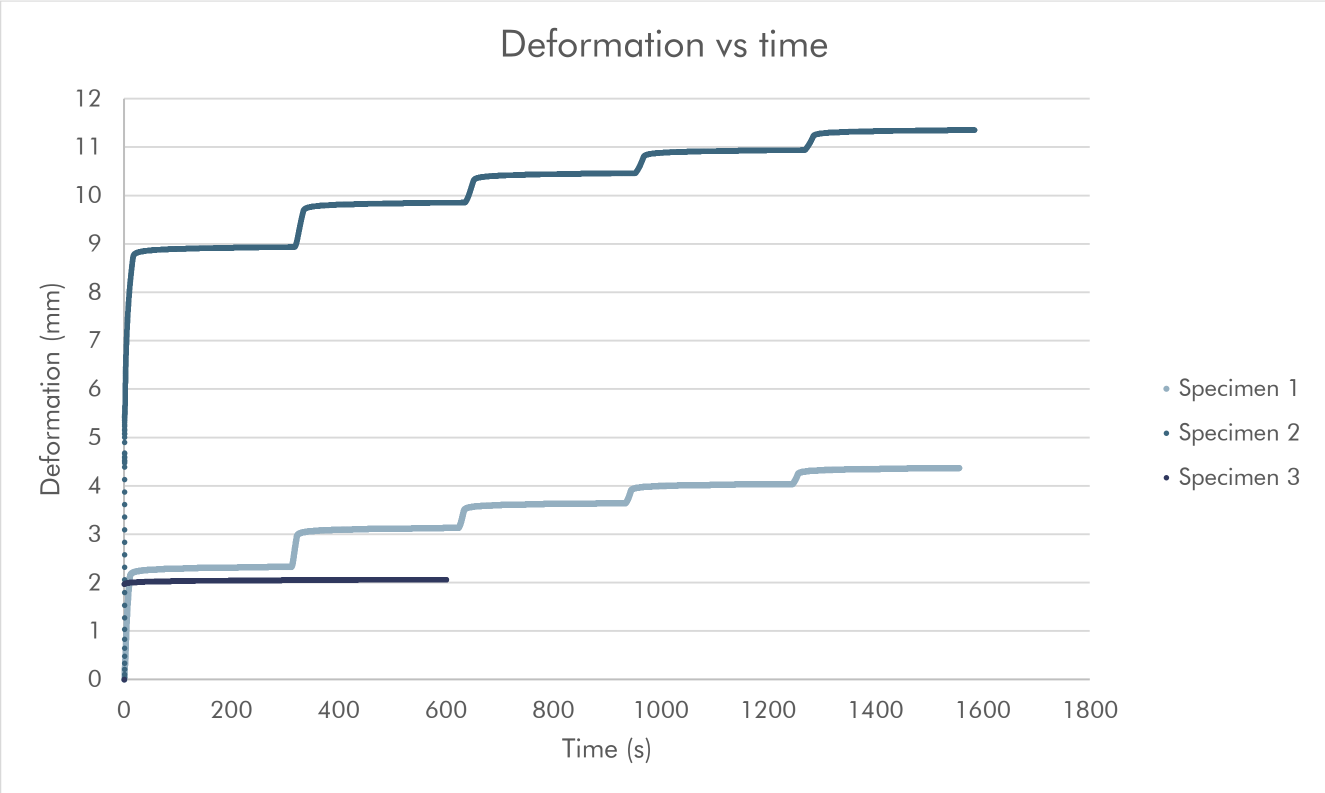


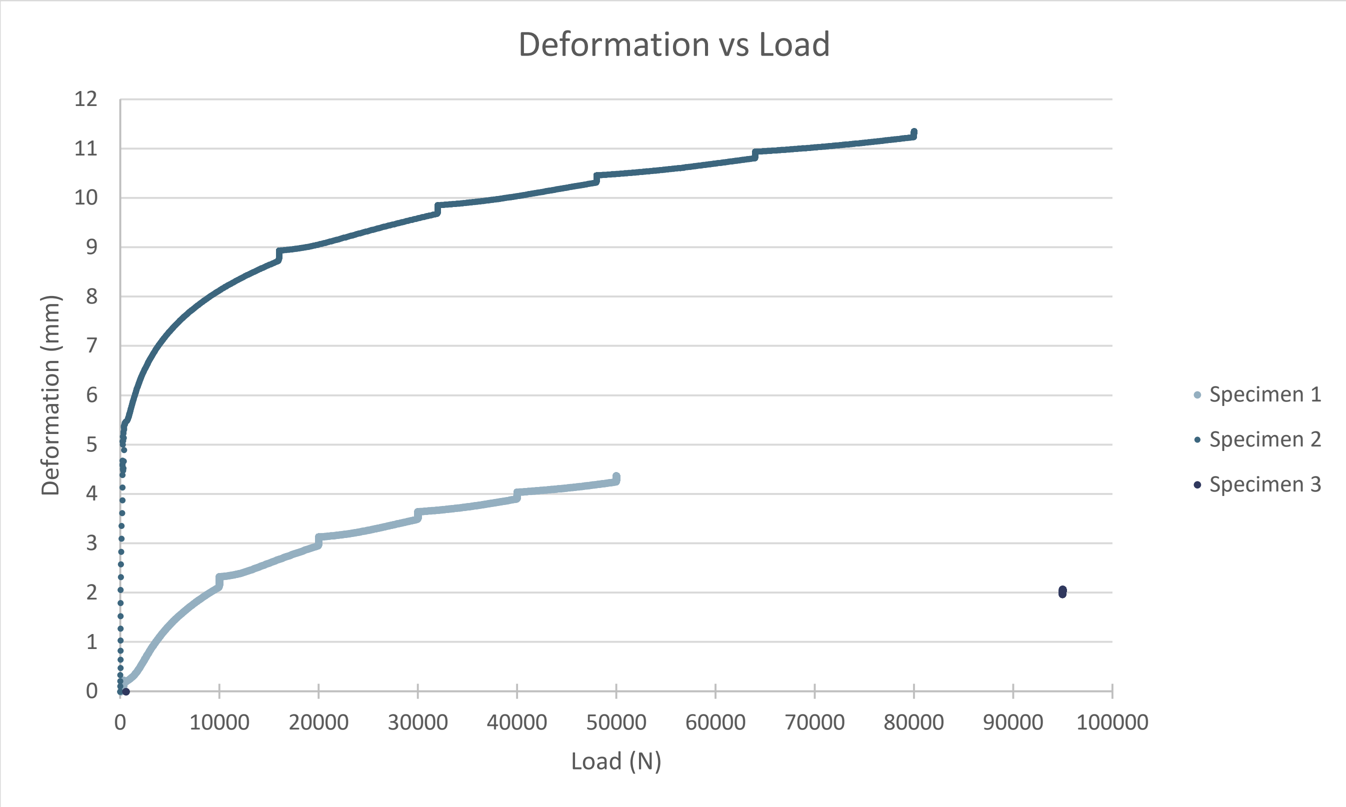
Figure 39: Sample 3 compression process results, observation pictures

Table 33: Sample 3 - data gathered from loading equipment

SAMPLE 3					
CYCLE	TIME (s)	FORCE (N)	DEFORMATION DIFFERENCE (mm)	DEFORMATION TOTAL (mm)	COMPRESSION (MPa)
	0	0-95000	1,97	1,9678	
1	0-600	95000,00	0,09	2,0628	98,79



Graph 3: Deformation versus time, comparison of samples from the pilot test



Graph 4: Deformation versus Load, Comparison of the samples from the pilot test

CONCLUSION

The main conclusion from the pilot tests is the fact, that just the compression is not enough to form bricks. The specimens were very hard but brittle, therefore the binder and binding process are required. Elongation of the loading time is not changing the deformation significantly. The graphs show different deformation due to the various manual compaction pressure at the beginning. It wasn't controlled, therefore the first compression and deformation done by the machine differ significantly per each specimen. In order to be able to compare the values the first compression increase step was neglected.

Later, the increase of the load value has a higher impact on the final deformation and compaction than the step where the values are constant. The physical properties observed were similar for all the specimens, therefore for further research, the value of 9,5kN as the load and 10 (later 5) minutes time was chosen.

Due to the samples' breaking, it was decided to put an extra layer of kitchen foil between mould and material to ease the removal of specimens.

2.1. Experiment– Production Process Optimisation –Different Batches

AIM AND OBJECTIVES

After the pilot test, the first specimens of various batches could be prepared. The compressive strength is calculated and compared. It is important to determine if the thermal treatment is improving the results and how much. If the production process using only compression is enough to achieve the required properties then the energy, payload and time can be saved. The results of this experiment would help determine which composition types are having a more positive impact on the efficiency of the production process and the quality of the final properties.

EQUIPMENT

To compress the samples, the same equipment as for the pilot test was used. To heat up some of the specimens, two ovens were used with the maximum temperature of 1000˚C. During thermal treatment, the specimens were placed in the stone mould, which has the same dimensions as steel mould used for the compression process (Figure 41). To test the compressive strength, the same equipment was used, which analyses the load and deformation relation.

SET UP

COMPRESSION

First samples were compressed for 10 minutes, which was later shortened to 5 minutes, due to time-saving reasons and the fact, that it didn't change compaction effect. The loading value was set to 9,5kN, same as chosen after the pilot test. Table 34 shows all the samples, batch types, loading properties, and deformation. It was decided, that the mass of the material put into the mould will be 7 and 14g to compare the relation between mass/load and mechanical properties of the product. The additional foil layer was added during this test to ease the removing of the specimens (Figure 40).

Table 34: Set up data for specimens. Determined mass, force, compression

SPECIMEN	BATCH TYPE	MASS (g)	TIME (s)	FORCE (N)	COMPRESSION (MPa)	BROKE
1	1	_	600	95000	98,79	YES (ONLY ONE PIECE USED)
2	1	_	600	95000	98,79	YES (ONLY ONE PIECE USED)
3	1	7	600	95000	98,79	**NO**
4	1	14	600	95000	98,79	YES
5	1	14	300	95000	98,79	**NO**
6	2	7	600	95000	98,79	YES
7	3	7	600	95000	98,79	YES
8	3	14	600	95000	98,79	**NO**
9	4	7	600	95000	98,79	YES
10	4	14	600	95000	98,79	YES
11	5	7	600	95000	98,79	**NO**
12	6	14	300	95000	98,79	**YES, LATER**
13	7.1	14	300	95000	98,79	**NO**
14	7.2	14	300	95000	98,79	**YES, LATER**
15	7.3	14	300	95000	98,79	**NO**
16	7.4	14	300	95000	98,79	**NO**

Figure 40: Production process optimization - foil usage

THERMAL TREATMENT

Before the next treatment process, the specimens' mass was measured using a balance.

The compressed specimens were put in the oven heated up to different temperatures ranging from 600°C to 1000°C. Although, only the original composition was tested with different temperatures, while the samples with different batches were tested for 600°C to compare all changes in compositions and mass having an impact on thermal treatment and product's final properties. Table 35 presents the data for each specimen regarding thermal treatment settings. This table is extended by the broken pieces, which were used to compare specimens which were just compressed with the ones that were also heated.

Each sample was placed in the stone mould and put to the heated up oven for 4h (Figure 41). After this time, the specimens were taken out and cooled down in room temperature.

Figure 41: Sample placed in the stone mould. At the bottom of the mould, there is a square plate to prevent the melted material from leaking.

Table 35: Specimens data from the thermal treatment process

SPECIMEN No.	BATCH TYPE	HEATING TEMPERATURE (°C)	TIME (h)
1	1	600	4
2	1	0	4
3	1	800	4
4.1	1	600	4
4.2	1	0	4
5	1	1000	4
6.1	2	600	4
6.2	2	0	4
7.1	3	600	4
7.2	3	0	4
8	3	600	4
9.1	4	600	4
9.2	4	0	4
10.1	4	600	4
10.2	4	0	4
11	5	600	4
12.1	6	600	4
12.2	6		
13	7,1	120	4
14.1	7,2	120	4
14.2	7,2		
15	7,3	120	4
16	7,4	120	4

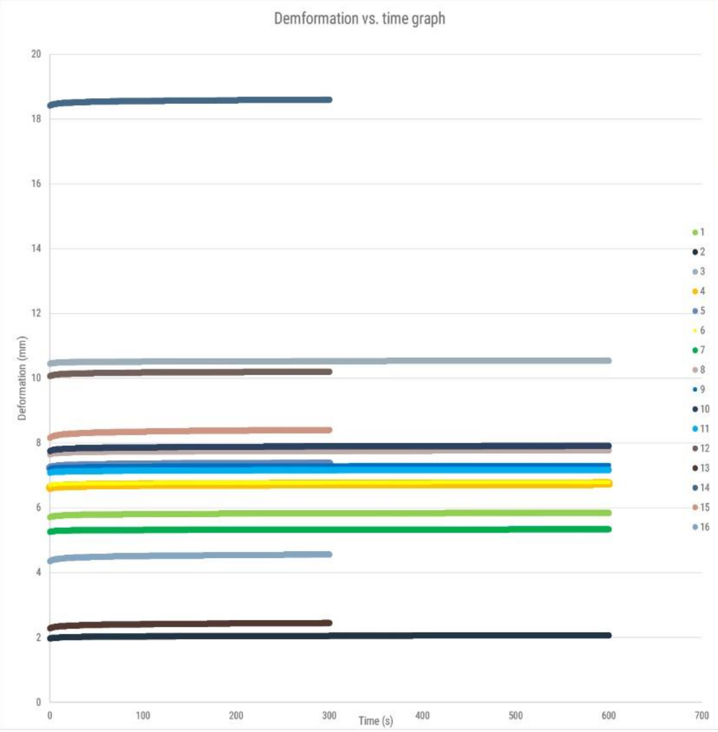
VARIABLES AND CONSTANTS

- Variables:
  - Temperature values
  - Composition
  - Production Process steps
- Constants:
  - Equipment
  - Tests
  - Conditions

RESULTS FROM PRODUCTION PROCESS

COMPRESSION

During the experiment, the compression time was changed from 10 to 5 minutes, because there was no impact on the compaction process. The deformation for each sample is presented in Table 36 and Graph 5. The total deformations differ, but this is due to the distance of equipment pressing the surface to the sample and the fact, that the material could be compacted manually with different force. Therefore, the deformation for constant compression phase was determined and compared. This deformation ranged between 0,08 and 0,25 mm and for the 5 minutes deformation tended to be higher than for the longer compression.



Graph 5: Deformation during compression production process

Table 36: Specimens compression production results

SPECIMEN	BATCH TYPE	MASS (g)	TOTAL DEFORMATION DIFFERENCE (mm)	DEFORMATION DURING CONSTANT COMPRESSION (mm)
1	1	_	5,84	0,14
2	1	_	2,06	0,09
3	1	7	10,54	0,09
4	1	14	6,75	0,13
5	1	14	7,36	0,13
6	2	7	6,79	0,09
7	3	7	5,34	0,08
8	3	14	7,77	0,13
9	4	7	7,31	0,11
10	4	14	7,91	0,16
11	5	7	7,17	0,09
12	6	14	10,20	0,14
13	7.1	14	2,44	0,17
14	7.2	14	18,60	0,18
15	7.3	14	8,41	0,25
16	7.4	14	4,56	0,21

Some specimens broke into two pieces after taking out of the mould, however, some of them were still used in the next step of the production process – thermal treatment in order to have a comparison between compressed and thermally treated samples. Figure 42 presents the specimens after removing from the mould. It was observed, that the specimens with higher mass were less breakable than the thinner samples. The samples with the additional sulfur content were the hardest ones and none of them broke.

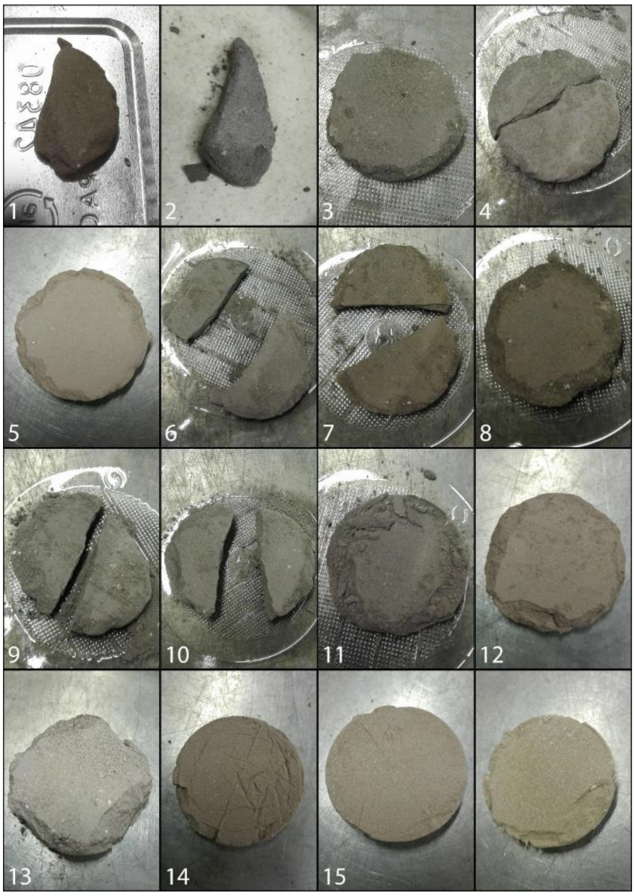


Figure 42: First round of specimens compressed, the first optimisation

THERMAL TREATMENT

After the heating process, the specimens' mass was measured again to determine any loss due to the high temperatures (Table 37). It was observed, that the percentage loss varied between 9 and 1 percent and it tends to depend on the temperature value. The percentage loss increase with the increase of the temperature. However, the highest mass loss was also calculated for temperature 600°C, Batch 6, which might suggest that the particle packing composition had more elements, which evaporate at the temperature of 600°C.

Another result, that was caused by the thermal treatment was a change of the specimens' colour. Figure 43 presents the comparison of specimens which were subjected to heating at different temperatures and the ones that were just compressed. It is visible, that the higher the temperature, the redder the colour becomes.

Due to the heating, in some specimens, there is a noticeable concentration of a red powder, which might be either hematite or red iron oxide. The powder formed spherical shape, which when touched gently, scatters. This might be a weak point in each specimen, because there is a possibility, that these loose forms occur inside the material. In one specimen (5) there was a dark sphere created due to the high temperature, however this time it was solid, harder than the rest of the sample.

Table 37: Experiment 1.2 specimens thermal treatment settings and mass data

SPECIMEN	BATCH TYPE	MASS BEFORE HEATING (g)	MASS AFTER HEATING (g)	MASS LOSS (g)	PERCENTAGE LOSS (%)	HEATING TEMPERATURE (°C)
1	1	5,20	4,90	0,30	6	600
2	1	3,00	3,00	0,00	0	0
3	1	5,80	5,40	0,40	7	800
4.1	1	7,5	7,00	0,50	7	600
4.2	1	7,1	7,1	0,00	0	0
5	1	14,00	12,74	1,26	9	1000
6.1	2	2,50	2,30	0,20	8	600
6.2	2	3,30	3,30	0,00	0	0
7.1	3	3,20	3,00	0,20	6	600
7.2	3	3,40	3,40	0,00	0	0
8	3	12,70	11,90	0,80	6	600
9.1	4	4,50	4,30	0,20	4	600
9.2	4	3,40	3,40	0,00	0	0
10.1	4	7,90	7,50	0,40	5	600
10.2	4	5,00	5,00	0,00	0	0
11	5	6,30	5,90	0,40	6	600
12.1	6	14,10	12,90	1,20	9	600
12.2	6					
13	7.1	14,20	13,10	1,10	8	120
14.1	7.2	14,10	12,82	1,28	9	120
14.2	7.2					
15	7.3	14,40	14,18	0,22	2	120
16	7.4	14,10	13,95	0,15	1	120

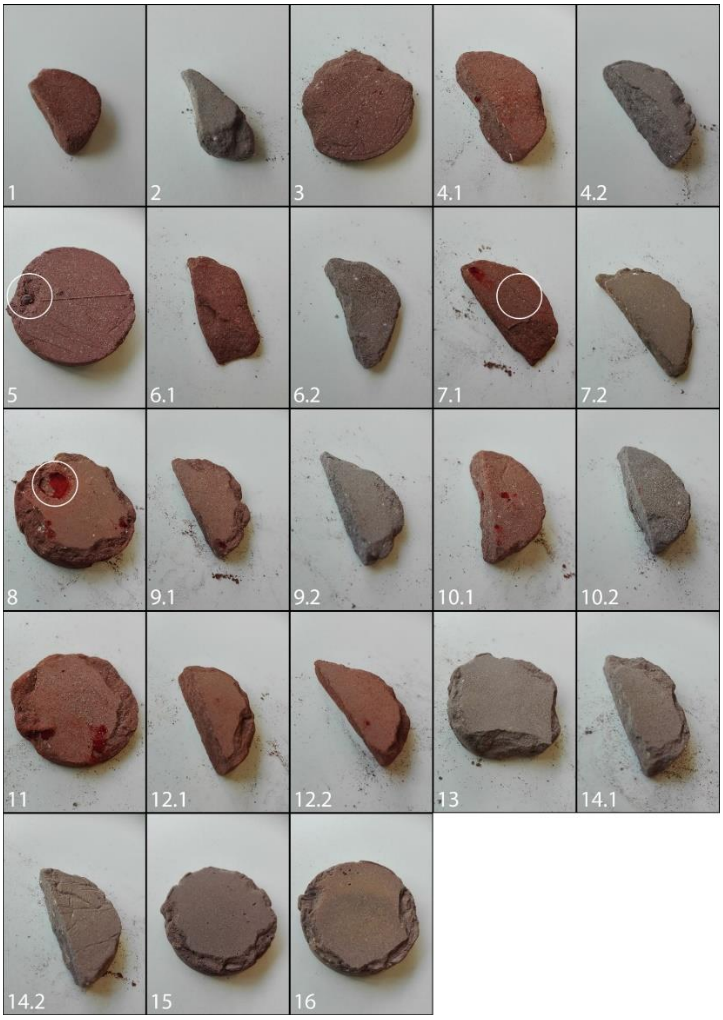


Figure 43: Specimens compressed and heated compared to the specimens that were just compressed

ANALYSIS

MECHANICAL PROPERTIES

All specimens were tested with the compression bench to determine the mechanical properties and the general differences between specimens (Figure 44). This test was used as a method to determine which composition is more The specific results of this test are presented in Table 54 (Appendix 4) and Figure 45. For each specimen, the stress (σ) and strain (ε) were calculated and analysed with a graph. Stress is determined by the ratio of a force and an area the force is applied to (Equation 8), while the strain is expressed as the relation between deformation and the original length (Equation 9). Then, Young's Modulus (E) was determined, using Equation 10. It was later used to compare the specimens.

Equation 8

$$\sigma = \frac{F}{A}$$

where F = force, A = area

Equation 9

$$\varepsilon = \frac{\Delta L}{L_o}$$

where ΔL = deformation, L_o = original length

Equation 10

$$E = \frac{\sigma}{\varepsilon}$$

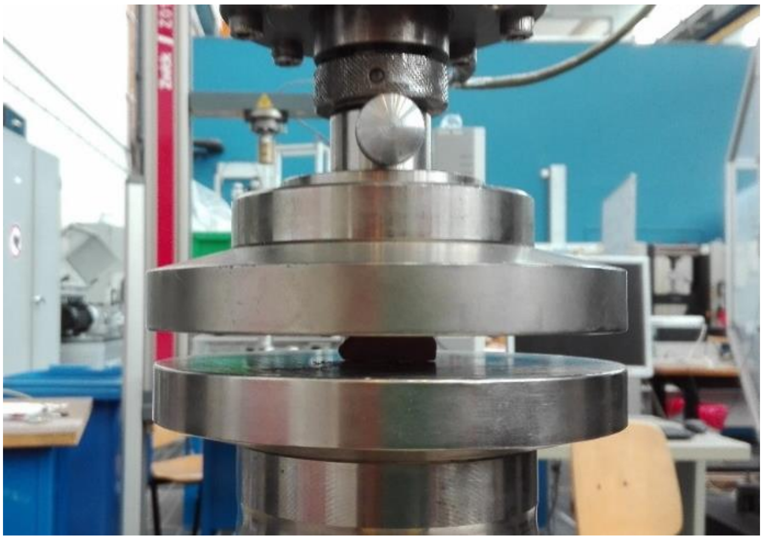


Figure 44: Compression bench - mechanical behaviour testing

The stress-strain graph enables determining the characteristic mechanical behaviour of the material and its mechanical strength.

First specimen (1a_s) was used as a pilot test to determine the required load rate and maximum load. The loading rate used for the first loading was set to 0,1mm/min which reaches 1mm/min in the end. The maximum load acceptable was 1N and the maximum deformation was 1mm, while the sample's height was 7,69mm. It helped determine, that the 1mm/min rate is sufficient enough to analyse the behaviour of the material. The sample didn't break during the pilot test, therefore the maximum load was set to maximum 10000N. The limit for the deformation was set after the pilot test to 1mm.

With the determined load, the specimens which were not heated were tested as the first ones. However, four specimens didn't break during the first compression test, which is visible in the Graphs 6 (specimen 3, 4.1, 6.2, 7.2),. Therefore the limit for the load force was increased to 100kN. The undamaged samples were tested again with the new settings, although the fact, that it was a second compression could have an impact on the results. The centre of the round specimens hardened during the loading and the specimens could resist higher compression later. For the unregular-shaped specimens, the influence was smaller, but it was also taken into account when determining conclusions.

From the results, it is visible, that all the specimens that broke through the whole sample and not only at the edges, were the ones with unregular shape. While the circular ones reached a linear behaviour or slightly concave downwards curves in the graphs. This is due to the disk-form of the specimens and the relatively small height compared to the diameter. This results in inconsiderable shear stress inside the material and the hardening of the central part. Therefore, in the graphs without visible yield drop, the first changes of linear part into curvature with concave downward shape were determined as the possible strength limits for the materials.

To compare the specimens and determine which batches and production processes are promising, the graphs comparing Young's Modulus (E) with area/thickness/batch type were prepared (Graph 7). It is noticeable, that the highest E values have the specimens with the sulfur addition in the composition and the ones, that have a circular shape. The original composition resulted in similar values as three of the 'sulfur specimens'. All of them were thermally treated at different temperatures. The highest E value has the specimen heated up in 800 C˚ (Specimen 3), though this is the result of the second loading. During the first round, Sample 3 reached twice less. The specimen 5, heated in 1000 C˚ has a lower value than the sample produced in 600 C˚, however, it is the value for second loading. When looking at the first loading, it is visible, that the thermal treatment is improving the final properties, though the difference between 600 C˚ and 800 C˚ is slight. There is however a noticeable difference between 0 to 600 C˚ and 800 to 1000 C˚, which proves that the heated ferric-sulfate (melting point 480 C˚) and albite (melting point 800 C˚)act as binders. The addition of ferric-sulfate to the composition (Batch 5), didn't improve the results compared to the samples with an original composition. The addition of albite had a higher impact on the final strength of the material.

The highest improvement on the results has the addition of amorphous phase minerals and high capacity ferric-oxide. This has an impact on the results of the compacted samples. The improvement of the thermal treatment production process is lower in this case. The highest results of the specimens (6, 7) that were just compressed during the production process, exceed some materials, which were thermally treated.

There is no visible general relation between the Young's Modulus and the thickness of the specimen. Although the highest values have thicker samples.

The interesting result had the specimen 12, which had a composition based on Particle Packing method. The compressing strength and Young's Modulus are very low, which might mean, that the difference in grain size distribution resulted in unfavourable composition for production process using compaction and thermal treatment.

The specimens with the addition of sulfur (Batch 7.3 and 7.4) reached the highest stress. The specimens with 10 and 20 % of sulfur didn't improve the results compared to the original composition. The best ratio of regolith to sulfur has the specimen 15 (2:1) which had the highest stress without damage from all the samples.

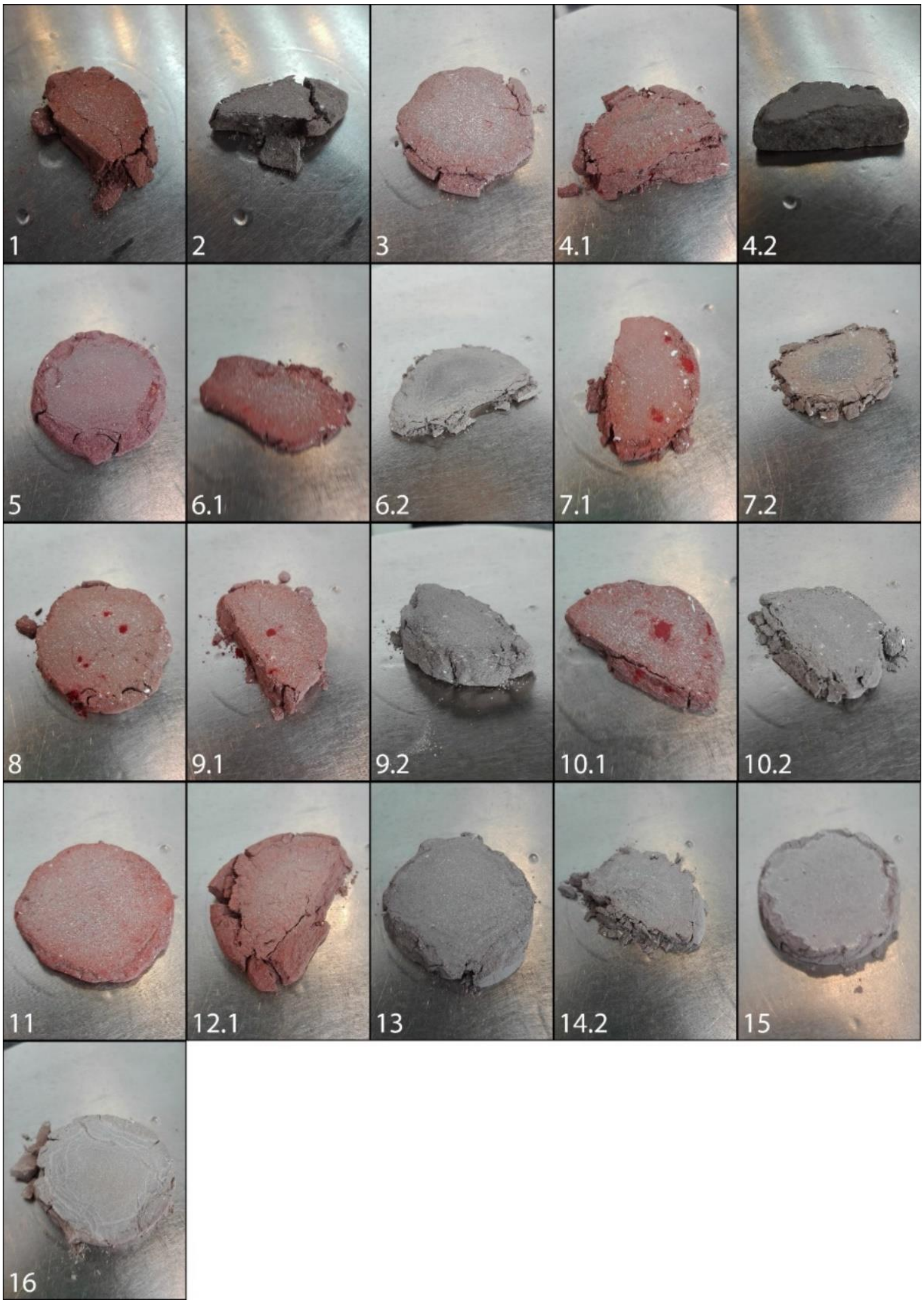
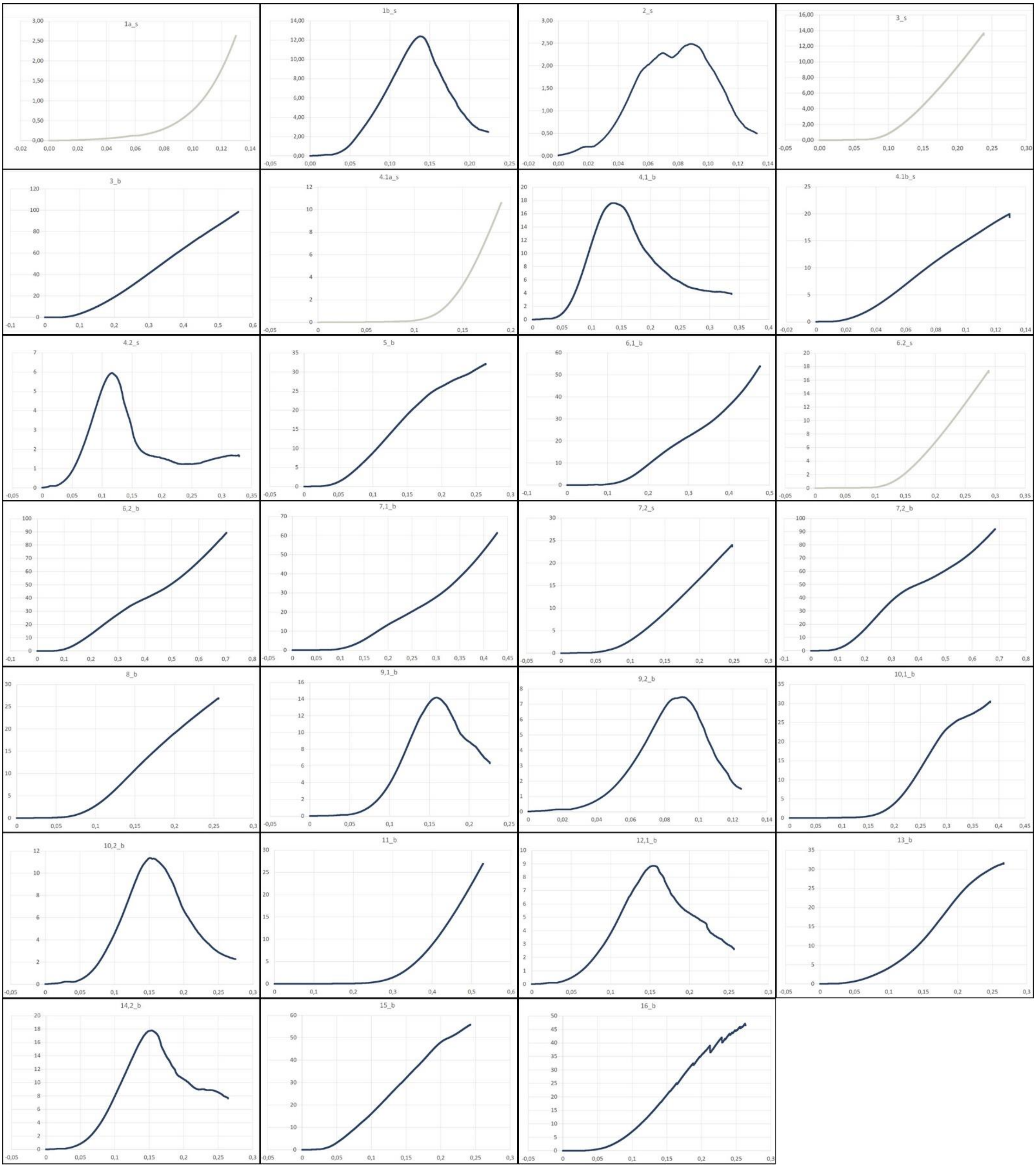
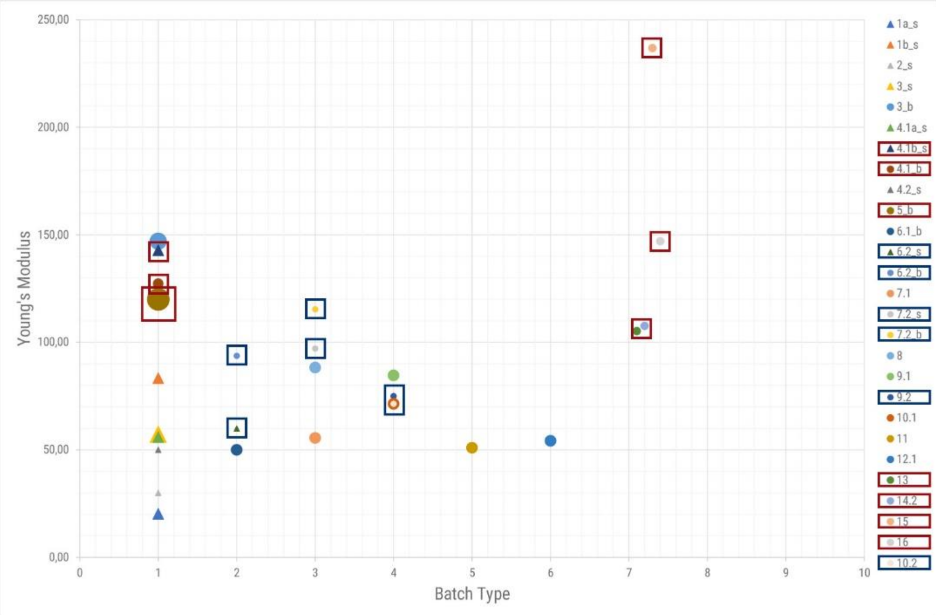


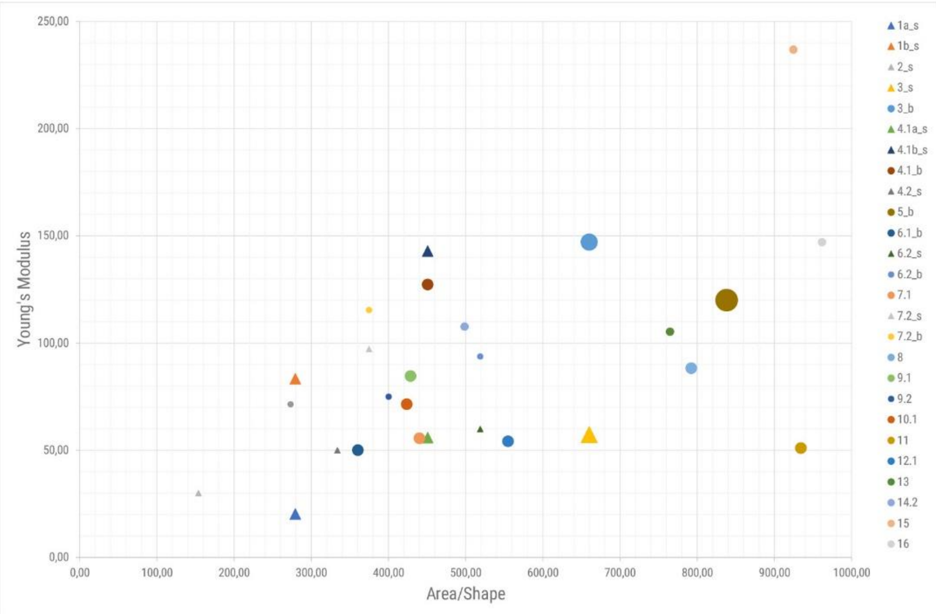
Figure 45: Experiment 1.2 - compression test results, specimens photos



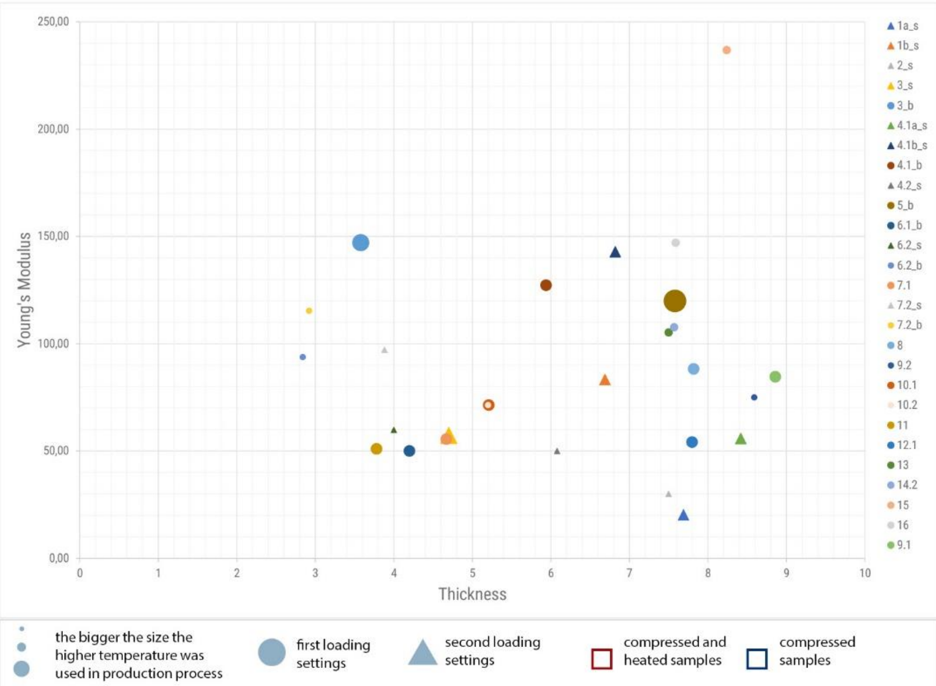
Graphs 6: Specimens Stress-Strain graphs



Young's Modulus
Batch Type
250,00
200,00
150,00
100,00
50,00
0,00
0
1
2
3
4
5
6
7
8
9
10
1a_s
1b_s
2_s
3_s
3_b
4.1a_s
4.1b_s
4.1_b
4.2_s
5_b
6.1_b
6.2_s
6.2_b
7.1
7.2_s
7.2_b
8
9.1
9.2
10.1
11
12.1
13
14.2
15
16
10.2



Young's Modulus
Area/Shape
250,00
200,00
150,00
100,00
50,00
0,00
0,00
100,00
200,00
300,00
400,00
500,00
600,00
700,00
800,00
900,00
1000,00
1a_s
1b_s
2_s
3_s
3_b
4.1a_s
4.1b_s
4.1_b
4.2_s
5_b
6.1_b
6.2_s
6.2_b
7.1
7.2_s
7.2_b
8
9.1
9.2
10.1
11
12.1
13
14.2
15
16



Young's Modulus
Thickness
250,00
200,00
150,00
100,00
50,00
0,00
0
1
2
3
4
5
6
7
8
9
10
1a_s
1b_s
2_s
3_s
3_b
4.1a_s
4.1b_s
4.1_b
4.2_s
5_b
6.1_b
6.2_s
6.2_b
7.1
7.2_s
7.2_b
8
9.2
10.1
10.2
11
12.1
13
14.2
15
16
9.1
the bigger the size the higher temperature was used in production process
first loading settings
second loading settings
compressed and heated samples
compressed samples

Graph 7: Comparison of specimens' strength for Experiment 1.2

PROCESS COMPARISON

From the mechanical properties analysis, the specimens with the highest stress and Young's Modulus values were chosen, as well as the most promising compositions to compare the processes in terms of energy usage, additional payload, complexity and time (Table 38Table 38: Production process comparison). The total values for the aspects weren't calculated, however, the estimation was made for each one. The Equipment aspect was determined based on the steps in the production process requiring different equipment. The general Payload was estimated by looking at the composition of the material and estimating the additional material mass that needs to be launched from Earth to prepare the building material. Process complexity is the number of different steps required to prepare and produce the material. Energy and Time were estimated based on the Process complexity and the Equipment aspect.

It is noticeable, that the best results of mechanical properties have the specimens with the most complex process and the biggest payload requirements. The most efficient production processes reached lower values of E and Stress, however, these values are already selected as the highest ones from the whole experiment.

Table 38: Production process comparison

No.	BATCH TYPE	STRESS	STRAIN	YOUNGS MODULUS (MPa)	EQUIPMENT	MATERIAL PAYLOAD	PROCESS COMPLEXITY	ENERGY USAGE	TIME
4.1b_s	1	10,00	0,07	142,86					
5_b	1	18,00	0,15	120,00					
6.2_b	2	30,00	0,32	93,75					
7.2_b	3	30,00	0,26	115,38					
9.1	4	11,00	0,13	84,62					
9.2	4	6,00	0,08	75,00					
10.1	4	20,00	0,28	71,43					
10.2	4	10,00	0,14	71,43					
13	7,1	20,00	0,19	105,26					
14.2	7,2	14,00	0,13	107,69					
15	7,3	45,00	0,19	236,84					
16	7,4	25,00	0,17	147,06					

WORST BEST

CONCLUSION

The main conclusion from this experiment is that both, thermal treatment and composition change, can have an impact on the product properties. Although, due to high energy usage the specimens requiring higher temperatures (above 600 C˚) for production were not taken into consideration for further optimisation. It concerns the specimens 9 and 10 as Batch 4 was prepared in order to improve the binding properties by adding an extra amount of plagioclase, which has a melting point above 600 C˚. Although the results for the specimen 9.1 were good, they were lower than the results of specimens 6.2 and 7.1 - 7.2 which used significantly less energy.

The compositions 2 and 3 were chosen as one of the options for further development, as they had relatively good results compared to the specimens with high-temperature usage. Although Batch 7 requires bringing additional material – sulfur, the properties of these samples were reaching the best values. Batch 7.3 and 7.1 will be used in the next experiments as a good comparison in terms of good mechanical properties. Additionally, new composition with a smaller amount of sulfur will be prepared, because it requires less energy input for the processing than the samples thermally treated in 600 C˚ and reaches better final mechanical properties. The new batches will have 5 and 7% of sulfur powder.

The other conclusion regarding the experiment is that the size of the samples needs to be increased in order to create shear stress inside and determine the accurate values for compressive strength and mechanical behaviour.

2.2. Experiment– Scaling up

AIM AND OBJECTIVES

In the conclusions from the 2.1. experiment, it was decided that the next step would be to increase the height of the samples. Therefore, the chosen optimisation processes were repeated with the bigger specimens to determine if the results and conclusions from the previous experiment were accurate.

Additionally, smaller temperature (300 C˚) for thermal treatment was tested on one specimen from Batch 1,2 and 3 to check if with the lower temperature can the material reach sufficient compressive strength.

EQUIPMENT

Same equipment as in the 2.1. the experiment was used.

SET UP

The following Batches were prepared: Batch 1, 2, 3, 7.1 and 7.3. The new batches 7.5 and 7.6 were prepared based on the conclusions from the previous experiment. For each Batch, 3 compressed samples were prepared.

The preparation of the samples was changed for this experiment due to the increased height of the specimens. The same mould as previously was used, however, the compression process was divided into three steps. After putting the material into the mould, it was compressed with the loading force of 10kN for 30 seconds. The material was added with a spoon. The small compression was repeated followed by another refill of material. Finally, the sample was compressed with a 95kN load for 5 minutes. The steps of refilling and compression are presented in Figure 46.

Figure 46: Experiment 2.2 production steps (refilling and compression).

The heating process was performed with the same equipment and settings as in the previous experiment. Some samples weren't thermally treated, some were heated in 600, 300 or 120˚C. The table with the specimen number and processing settings is presented below (Table 39).

Table 39: Experiment 2.2 production settings

No.	BATCH TYPE	FORCE 1 (N)	FORCE 2 (N)	σ (MPa)	TEMPERATURE (˚C)	TIME (h)
1.1	1	10000	95000	98,79	0,00	
1.2	1	10000	95000	98,79	600,00	4
1.3	1	10000	95000	98,79	300,00	4
2.1	2	10000	95000	98,79	0,00	
2.2	2	10000	95000	98,79	600,00	4
2.3	2	10000	95000	98,79	300,00	4
3.1	3	10000	95000	98,79	0,00	
3.2	3	10000	95000	98,79	600,00	4
3.3	3	10000	95000	98,79	300,00	4
4.1	7.3	10000	95000	98,79	120,00	4
4.2	7.3	10000	95000	98,79	120,00	4
4.3	7.3	10000	95000	98,79	120,00	4
5.1	7.4	10000	95000	98,79	120,00	4
5.2	7.4	10000	95000	98,79	120,00	4
6.1	7.5	10000	95000	98,79	120,00	4
6.2	7.5	10000	95000	98,79	120,00	4
7.1	7.1	10000	95000	98,79	120,00	4

VARIABLES AND CONSTANTS

- Variables:
    - Batches – compositions
    - Production processes – temperature, amount of processes
- Constants:
    - Tests
    - Conditions
    - Equipment

RESULTS

The compression process resulted in bigger solid samples compared to the previous experiment. All the specimens hardened and kept the brittle character. Due to the refilling steps and the removing of foil after taking out of the mould, there are visible cavities on the sides of the samples (Figure 47). It could have an impact on the results of mechanical tests as it might weaken the specimens' strength in a different way. The horizontal cracks appeared at the height, where the material was refilled, therefore it could decrease the connection between the refilled material and the previous layer. Additionally, at some specimens (4.1-4.3) the remains of foil stayed attached to the surface. They couldn't be removed entirely, as it could break the whole piece.

The heating process affected the samples in various ways (Figure 48). The higher the temperature used, the darker and redder the samples became. Due to 600 ˚C, at the surface of the specimens, the concentrations of red iron powder appeared, which sometimes created cracks in the material. At the samples, that were treated with 300 ˚C, the concentration of ferric sulfate appeared, which could have the same impact as the red iron powder. The specimens with 30% of sulfur addition, resulted in the biggest cracks both, on the side and top/bottom surfaces.

The mass loss was observed and calculated. It was visible, that the mass loss depended on the temperature used, however, it also varies for different batch types. Batch 2 and 3 had the highest temperature loss. This could have an impact on the final mechanical properties of the material.

Table 40: Experiment 2.2 - specimens result after compression and thermal treatment

No.	d_1 (mm)	d_2 (mm)	h (mm)	MASS (g)	AREA (mm^2)	VOLUME (mm^3)	DENSITY (kg/m^3)	T (°C)	MASS 2 (g)	MASS LOSS (g)	COMMENT
1.1	34,00	34,00	19,50	40,00	907,46	17695	2,26	0,00	40,00	0,00	Visible horizontal medium crack in the middle on one side
1.2	35,00	34,00	19,20	39,00	907,46	17423	2,24	600,00	37,50	3,85	red iron concentration, horizontal medium crack
1.3	34,90	35,50	21,00	43,80	989,30	20775	2,11	300,00	42,60	2,74	Yellow concentrations, small cracks on side
2.1	34,00	30,00	15,00	27,50	706,50	10598	2,59	0,00	27,50	0,00	
2.2	35,00	29,00	16,00	30,10	660,19	10563	2,85	600,00	28,40	5,65	red iron concentration, horizontal small cracks
2.3	35,00	32,00	17,20	29,80	803,84	13826	2,16	300,00	29,40	1,34	Yellow concentrations, medium horizontal crack
3.1	35,00	33,00	16,00	29,00	854,87	13678	2,12	0,00	29,00	0,00	
3.2	35,00	32,00	16,00	31,60	803,84	12861	2,46	600,00	30,00	5,06	Small cracks on top
3.3	35,00	34,00	19,00	35,30	907,46	17242	2,05	300,00	34,30	2,83	Small yellow concentration, small cracks on side
4.1	35,00	35,00	19,50	35,10	961,63	18752	1,87	120,00	35,00	0,28	Big horizontal cracks and medium on top and bottom, small holes on the surface
4.2	35,00	33,00	17,50	34,90	854,87	14960	2,33	120,00	34,60	0,86	Big horizontal cracks, small holes on the surface
4.3	35,00	35,00	20,00	39,40	961,63	19233	2,05	120,00	39,00	1,02	Big horizontal cracks, small holes on the surface
5.1	35,00	34,00	18,20	36,10	907,46	16516	2,19	120,00	35,40	1,94	Small cracks on side
5.2	35,00	30,00	18,00	35,60	706,50	12717	2,80	120,00	35,10	1,40	Small cracks on side
6.1	35,00	33,00	18,50	37,80	854,87	15815	2,39	120,00	37,10	1,85	Small cracks on side
6.2	35,00	35,00	19,00	38,80	961,63	18271	2,12	120,00	38,30	1,29	Small cracks on side
7.1	35,00	35,00	19,00	37,20	961,63	18271	2,04	120,00	36,80	1,08	Small cracks on side

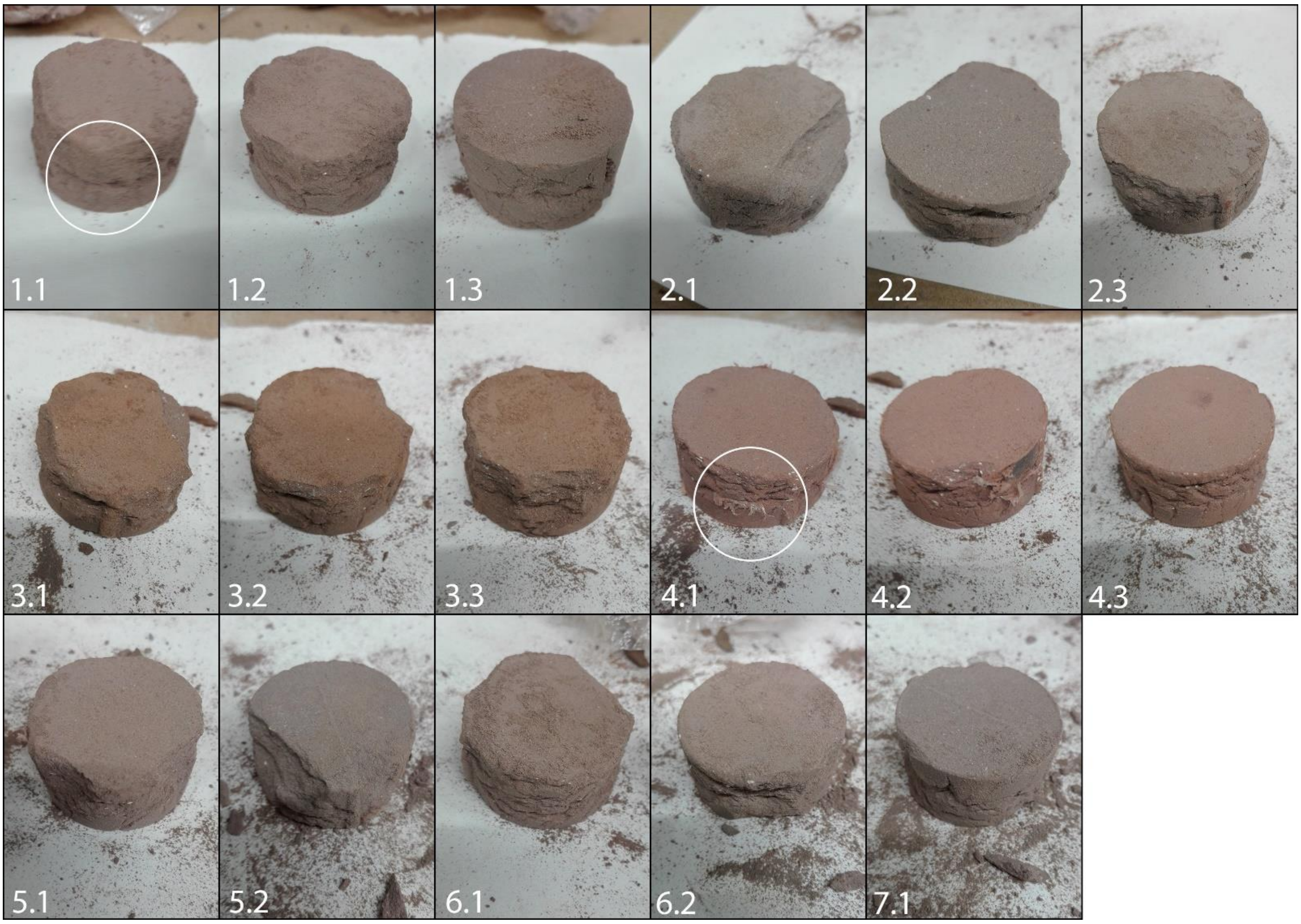


Figure 47: Experiment 2.2 - compressed specimens

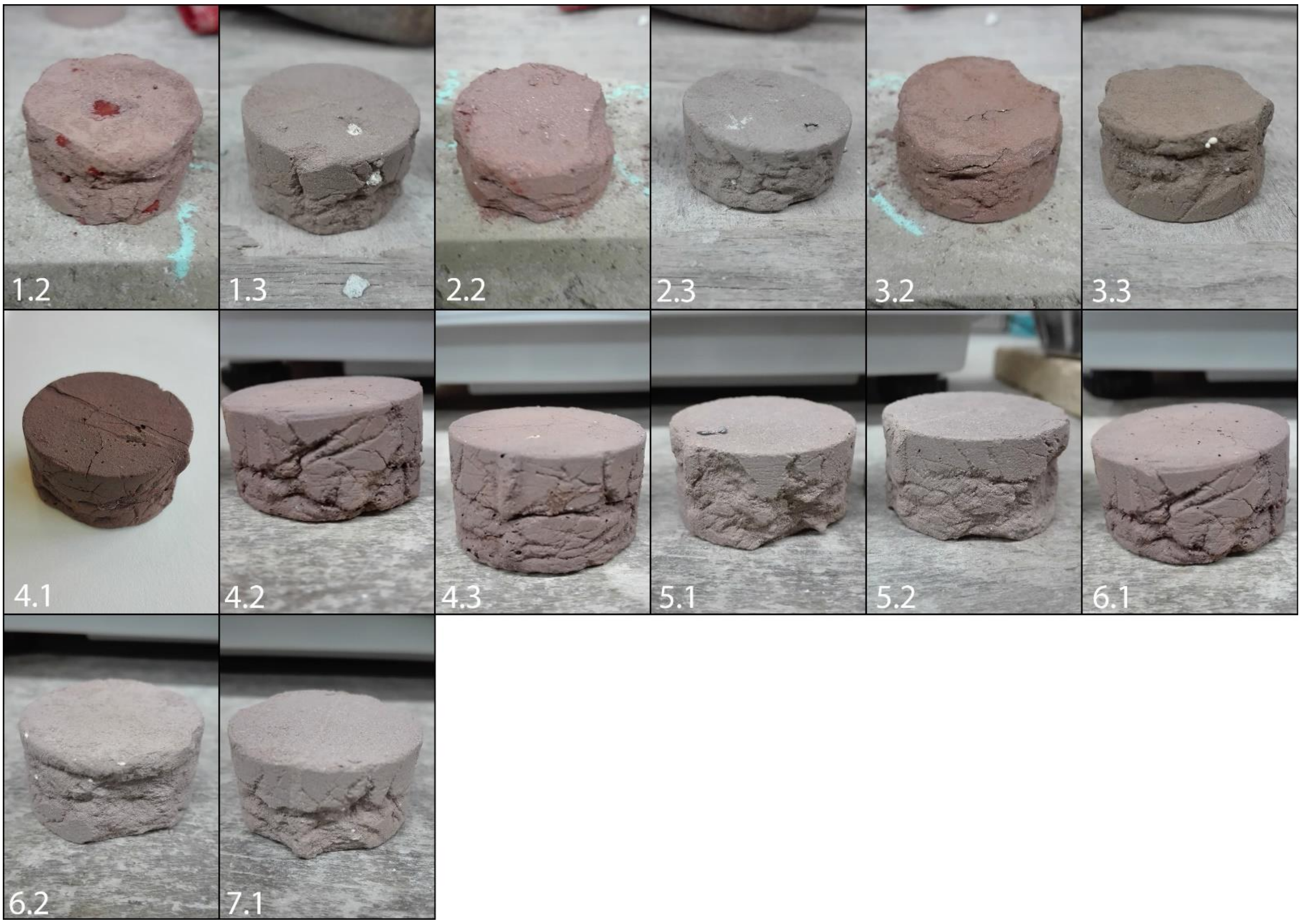


Figure 48: Experiment 2.2 - heated specimens

ANALYSIS

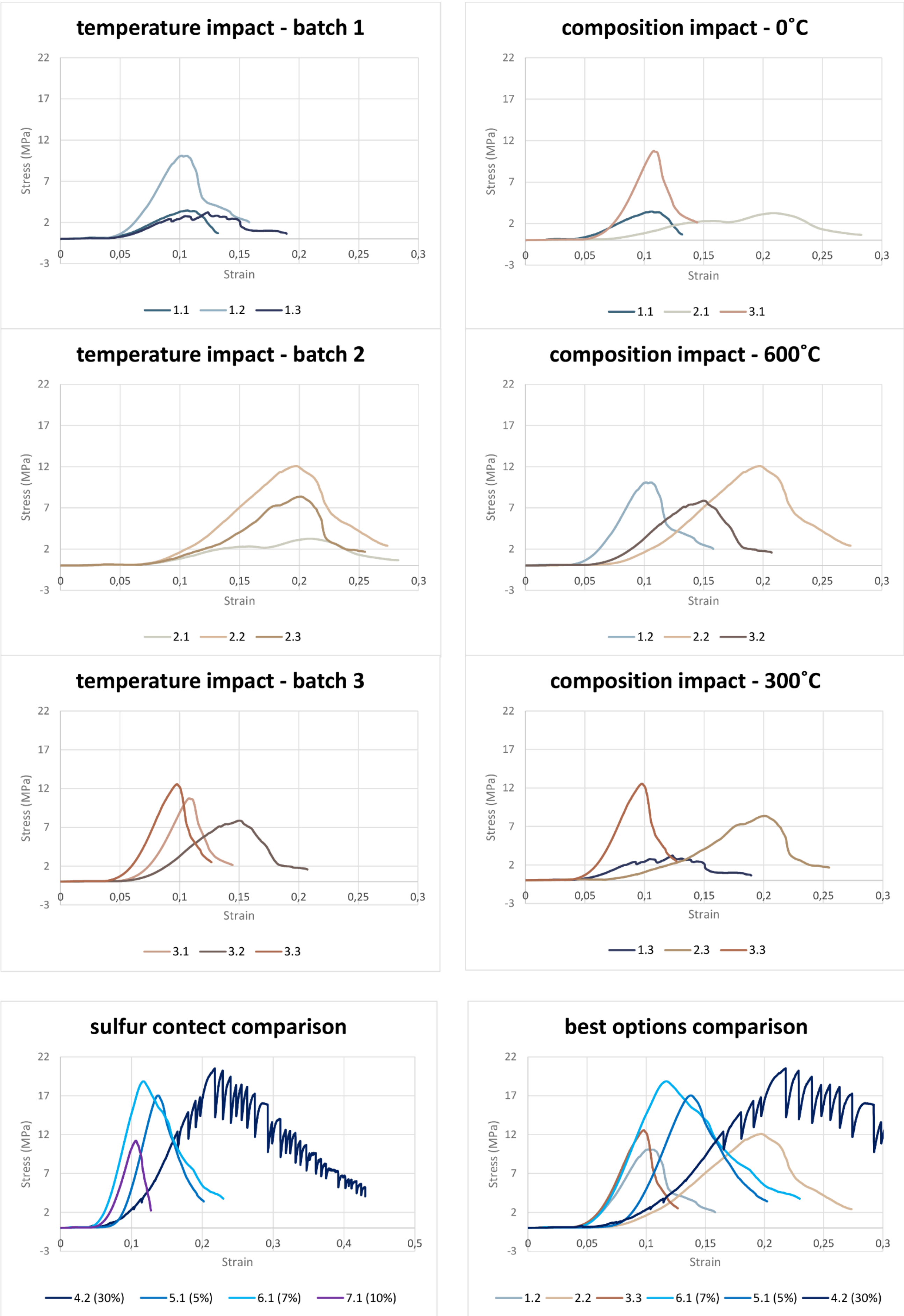
MECHANICAL TESTS

Similarly to Experiment 2.1., the mechanical tests were done using compression bench with the loading rate 2mm/min. The machine's software could generate data regarding force and deformation. Using the formulas (Equation 8, Equation 9, Equation 10) the stress, strain and finally, Young's Modulus was calculated and analysed using graphs (Graph 8). Additionally, the relations of compressive strength and Young's Modulus to batch type and volume of the specimens were studied (Figure 49). The data and analysis were gathered in Table 41. It includes more detailed observations and comments to each specimen.

The mechanical test proved that the change in composition can improve the mechanical properties of the specimens. According to the results, the addition of amorphous phase minerals and nanophase ferric oxide made the material stronger, however, it also changed the impact of the thermal treatment. Composition of batch 2 is in general stronger, can withstand bigger deformation, but also deforms very fast. The addition of nanophase ferric oxide makes the material more brittle, but more resistant to stress up to 12MPa.

The temperature of the heating process is in general proportional to the increase of compressive strength of the material. However, not always the highest temperature resulted in the best properties. In the case of Batch 3, the temperature that produced the strongest material was 300˚C.

The specimens with the addition of sulfur powder had mostly the highest peaks for compression strength. Similarly to Batch 3, this composition made the material more brittle, resistant to lower deformation, however under higher load. The specimen with 30% of sulfur powder addition resulted in material, which can withstand small cracks, which makes it potentially better for resisting micrometeorites impacts. Though the first drop in the graph appears around 12MPa stress, which is congruous to the best results for Batches 1-3. This might be due to the existing cracks in the samples before tests. Specimens with 5 and 7% of sulfur reached 1,5 times higher peak.



Graph 8: Experiment 2.2 – Stress : Strain graphs comparison

Table 41: Experiment 2.2 - Mechanical tests results and comparison

INTERPRETATION	GRAPH COMMENT (Graph 8)	COMMENT	E (MPa)	ε	σ (MPa)	TOTAL DEF.	PEAK FORCE (N)	VOLUME (mm^3)	AREA (mm^2)	t (mm)	d2 (mm	d1 (mm	TYPE	No.
original composition without the heating treatment has one of the worst results	curvature gently increases compared to others, around 10% of deformation the sample breaks	vertical cracks at the side surface	29,37	0,09	2,50	1,66	2268,75	17695,47	907,46	19,5	34	34	1	1.1
the 600˚C heating process increases the results around three times	the sample breaks at the same deformation stage, however, the stress is almost 3 times higher	vertical cracks at the side surface, material crumbled into medium fractures	97,05	0,09	9,18	1,82	8333,85	17423,23	907,46	19,2	34	35	1	1.2
the 300˚C treatment doesn't improve the material's properties, maybe makes it more resistant to cracks	specimen reaches the lowest stress value, multiple drops are visible	vertical cracks at the side surface, material crumbled into small, flat flakes	23,82	0,08	2,00	1,76	1924,35	20194,13	961,63	21	35	34,9	1	1.3
increase of amorphous phase doesn't change the results for just compressed specimen, made the relation between stress and strain even lower	specimen reaches very low stress at the first drop, the graph continues to increase, however, the stress is still low and the deformation has a high rate	vertical cracks at the side surface, material crumbled into small flakes	14,28	0,13	1,80	1,89	1272,10	10597,50	706,50	15	30	34	2	2.1
the rate of deformation is higher, with the same stress the specimen is less resistant, 600˚C treatment increased the results 3-4 times, increased mass loss	specimen withstands biggest deformation percentage, the ration between stress and strain is low compared to others	vertical cracks at the side surface	61,19	0,18	11,12	2,91	7341,80	10562,96	660,19	16	29	35	2	2.2
the rate of deformation is higher, with the same stress the specimen is less resistant, the 300˚C treatment increased the results twice	the specimen has similar curvature as 3.2 with lower stress values, after one drop the stress continued to increase	vertical cracks at the side surface, material crumbled into small, flat flakes	39,90	0,18	7,00	3,02	5628,17	13826,05	803,84	17,2	32	35	2	2.3
the increase of nano ferric oxide increases the compression process results, makes the graph steeper, a material more brittle	the specimen has the highest stress rate among the specimens made with no heating process (4 times more)	vertical cracks at the side surface, material crumbled into few small flakes,	96,76	0,10	10,10	1,67	8638,06	13677,84	854,87	16	33	35	3	3.1
the increase of nano ferric oxide decreases the results of 600˚C treatment, increased the mass loss	the specimen reaches the lowest stress: strain ratio among the ones treated with 600˚C, around the average results	vertical cracks at the side surface, material crumbled into small flakes, circular cracks on top	53,10	0,13	7,00	2,11	5627,10	12861,44	803,84	16	32	35	3	3.2
the increase of nano ferric oxide increased the strength of the material, and 300˚C treatment improved the results, material more brittle	highest stress: strain ratio among the batches with no sulfur addition, stress increasing rate very high	vertical cracks at the side surface, material crumbled into few small flakes,	127,37	0,09	11,00	1,64	9078,70	17241,74	907,46	19	34	35	3	3.3
30% of sulfur content increases material's resistance to cracks,	specimen reaches the highest stress and load, however, the first drop appears early, there are multiple drops after which, the stress still increases rapidly	multiple, random cracks at the side surface, material crumbled into many very small flakes, the test last the longest	74,26	0,16	12,20	2,88	10429,90	14960,14	854,87	17,5	33	35	7,3	4.2
5% of sulfur increased the compressive strength significantly, making the material more brittle	the specimen has a very steep graph, the graph is similar to specimen 6.1, but has lower stress values and higher deformation peak, stress starts increasing after 5% of deformation	few vertical cracks at the side surface, material crumbled into few medium fractures	121,73	0,13	16,00	2,39	14522,00	16515,77	907,46	18,2	34	35	7,5	5.1
5% of sulfur increased the compressive strength significantly, making the material more brittle	the graph is very steep (same as 3.3), the drop is at the highest value compared to others,	many vertical cracks at the side surface, material crumbled into many medium fractures	153,44	0,10	16,00	1,93	13680,37	15815,00	854,87	18,5	33	35	7,6	6.1
10% of sulfur increased the compressive strength and made the material more brittle, however, the peak is comparable to specimens treated with 300 and 600 ˚C	the graph is very steep, the peak is lower than some specimens without sulfur content	few vertical cracks at the side surface, material crumbled into few small flakes, circular cracks on top	100,82	0,10	10,00	1,88	9618,31	18270,88	961,63	19	35	35	7,1	7.1

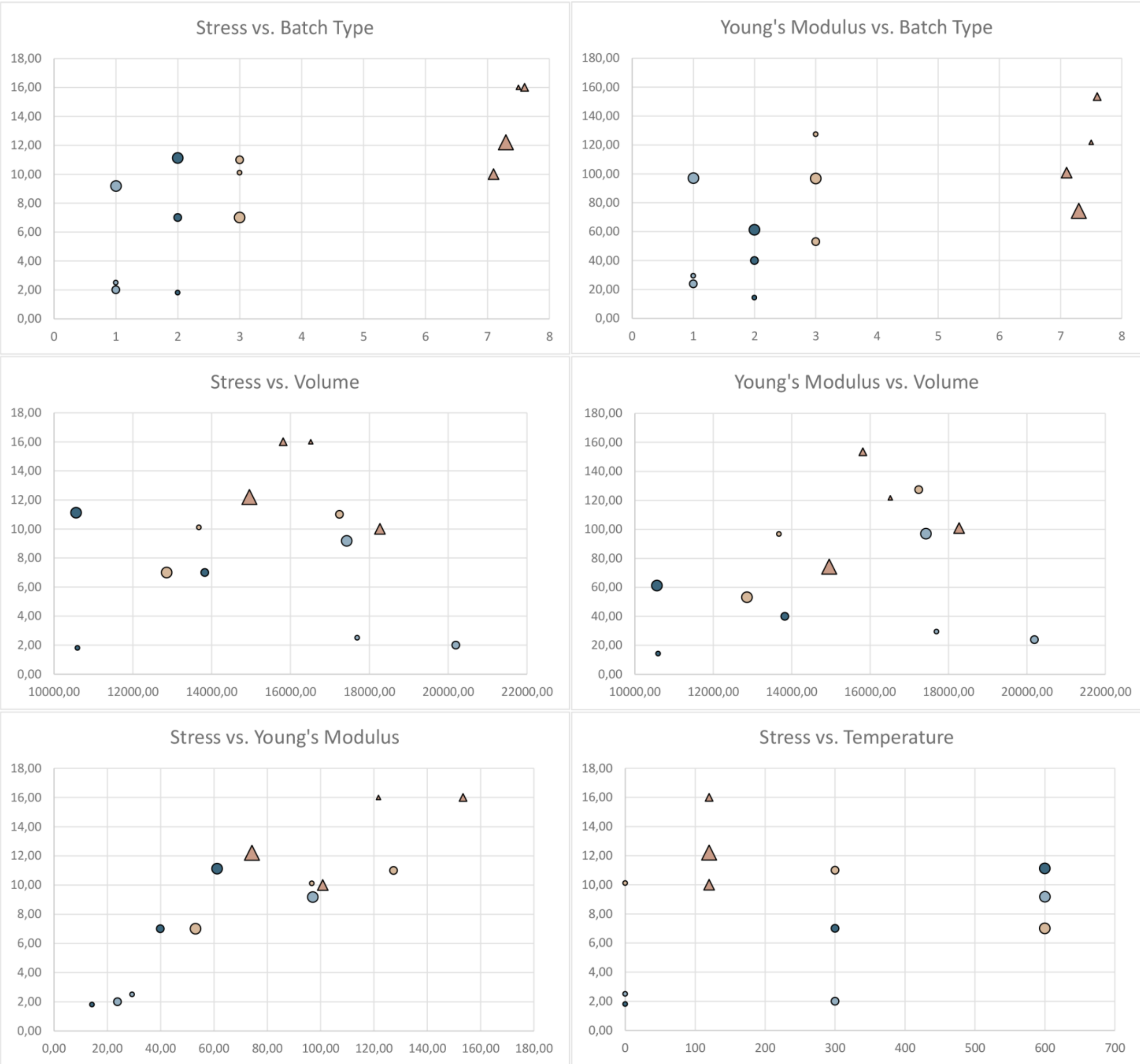


Figure 49: Experiment 2.2 - comparison of stress and Young's modulus to batch type, volume and temperature

The analysis of the relation of volume to stress and Young's Modulus showed that there is no obvious relation between these factors. However, if we neglect the specimens 1.1 and 1.3 it is visible, that the Young's Modulus and stress in general increases with the increase of the volume. According to the temperature, it is visible, that the increase in temperature is giving various results for different compositions. Therefore, it can't be assumed that a higher temperature is always improving material properties.

SAFETY FACTOR

The next step after testing the properties of construction material is estimating the safety factor for the structural design. This estimation takes into account different aspects of a structural design such as safety, failure risks and vulnerability as well as construction cost. For adobe construction in general, estimating the strength of the components always involves a certain level of uncertainty, which will result in the adoption of large safety factors. This is also valid for adobe bricks for which tested mechanical properties can vary considerably from element to element. In this specific case, with the small number of specimens, the estimation of the safety factor should be able to ensure the safety of the structure without limiting the already low mechanical properties of the material. It is also important to underline that, it is hard to ensure the accuracy of the composition. The preparation of material is still conceptual and the method of sieving and grinding needs to be developed and tested on site to provide accurate composition. Therefore, the safety factor chosen for this research is 4. After applying this value to the compressive strength from the results of the experiment this property ranges between 0,45-4,00 MPa (Table 42).

Table 42: Results after applying safety factor

No.	1.1	1.2	1.3	2.1	2.2	2.3	3.1	3.2	3.3	4.2	5.1	6.1	7.1
σ_exp (Mpa)	2,50	9,18	2,00	1,80	11,12	7,00	10,10	7,00	11,00	12,20	16,00	16,00	10,00
ε _exp	0,09	0,09	0,08	0,13	0,18	0,18	0,10	0,13	0,09	0,16	0,13	0,10	0,10
E_exp (MPa)	29,37	97,05	23,82	14,28	61,19	39,90	96,76	53,10	127,37	74,26	121,73	153,44	100,82
σ_design (Mpa)	0,63	2,30	0,50	0,45	2,78	1,75	2,53	1,75	2,75	3,05	4,00	4,00	2,50

ENERGY USE CALCULATIONS

In this analysis, the energy and material efficiency is more detailed studied compared to the previous chapter. The actual and total amount of energy and payload needed is hard to calculate as the design is partially conceptual and not all aspects are researched and included. Additionally, some processes – as compression and basic preparation and collection, are the same for every production method and can be neglected in the comparison. Energy for thermal treatment is defining the most, which process has the highest demand for energy. To calculate the energy input for heating process the formula presented below was used:

Equation 11

$$E = mxc_pxΔT$$

where m is equal to mass, c_p is the material's property called heat capacity and ΔT is the difference in temperature.

For the purpose of this research, the heat capacity was estimated based on the dry adobe, which is around 800 J/kg˚C. The temperature difference was calculated for the average temperature occurring at the surface of Mars: -46˚C (See Martian conditions chapter). In case of material with the addition of sulfur powder, the heat capacity was estimated to be lower based on the sulfur c_p and its amount in the composition. Table 44 presents the values for each production process (per 1 kg of material). According to Newton's Law of thermodynamics, the heat loss is proportional to temperature difference and it can have a significant impact on the energy input increase. It was considered in the conclusions.

The energy and payload requirements are gathered in Table 45. The total energy and payload values were estimated and presented on a gradient scale.

The available payload in the biggest rocket – Falcon Heavy is 16.800kg for the flight to Mars. It needs to be enough for building a habitat. Based on the requirements for sizes – Falcon Heavy payload fairing is 5.2m diameter and 13.1m height, which would be the biggest size of the equipment and the inflatable modules before inflating (SpaceX, 2018) the spans of the structure were estimated to be around 8m. To reach the volume and area of habitat suitable for 6 people, the length of the structure should be 13 m (Figure 50). With these values, the material payload requirement for building material with additions of sulfur was calculated.

The batches payloads were compared, with the estimation of the inflatable module being 1/3 of the final volume. This relation was based on the inflatable module designed by Bigelow ("Bigelow Aerospace," 2019). The material resources and equipment together with energy payload were included. As concluded from Table 44, the energy requirement increases proportionally to the increase of temperature. Additionally, the heat loss would increase the difference even more. By choosing the production process with lower temperature the payload for equipment can increase significantly.

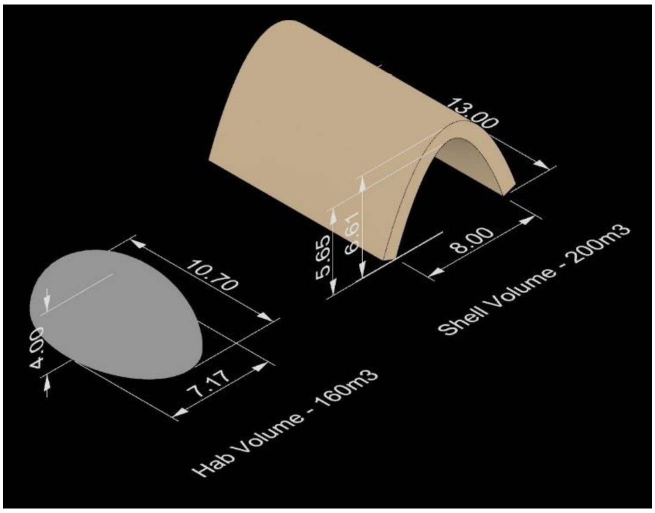


Figure 50: Habitat and structure volumes requirements

Table 43: Sulfur payload calculations

sulfur amount	width (m)	length (m)	volume of building mat (m3)	density (kg/m3)	structure mass req (kg)	sulfur requirement (kg)	sulfur density (kg/m3)	sulfur volume (m3)	hab. volume (m3)	diameter falcon (m)	sulfur payload height required (m)
30% of sulfur	8	10	202	220	44440	13332	2000	6,666	216	5,2	1,281923
10% of sulfur	8	10	202	220	44440	4444	2000	2,222	216	5,2	0,427308
7% of sulfur	8	10	202	220	44440	3110,8	2000	1,5554	216	5,2	0,299115
5% of sulfur	8	10	202	220	44440	2222	2000	1,111	216	5,2	0,213654

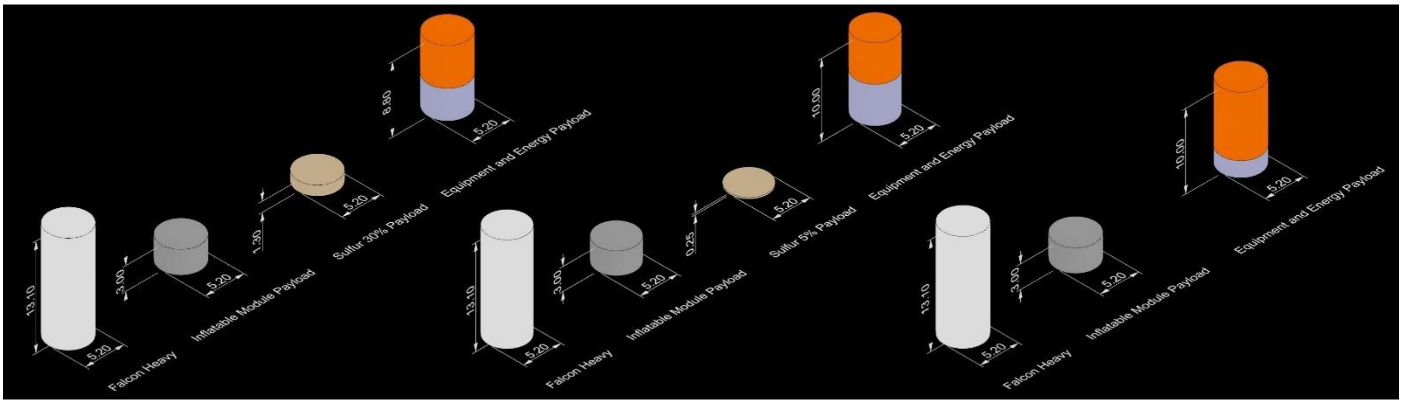


Figure 51: Payload comparison between batches with sulfur and batches treated with high temperature

Table 44: Energy demand for the heating process - estimation.

type	mass (kg)	heat capacity (J/kg˚C)	starting temp	heating temp	ΔT (˚C)	ΔE (J)	heat loss
1.1	1	800	-46	_	0	0	
1.2	1	800	-46	600	646	516800	3
1.3	1	800	-46	300	346	276800	2
2.1	1	800	-46	_	0	0	
2.2	1	800	-46	600	646	516800	3
2.3	1	800	-46	300	346	276800	2
3.1	1	800	-46	_	0	0	
3.2	1	800	-46	600	646	516800	3
3.3	1	800	-46	300	346	276800	2
7,1	1	793	-46	120	166	131638	1
7,3	1	779	-46	120	166	129314	1
7,5	1	796,5	-46	120	166	132219	1
7,6	1	795,1	-46	120	166	131986,6	1

Table 45: Energy input and payload comparison for production processes. Analysis for one brick.

N˚	σ design (Mpa)	E (MPa)	preparation energy (kJ)	energy compression	energy - oven (kJ)	heat loss factor	payload - collecting equipment	payload - compression machine	payload - oven (kg)	payload - resources	total energy	total payload
1.1	0,63	29,37	basic (0)	same for every	0	0	same for every	same for every	0	0	basic	low
1.2	2,30	97,05	2x	same for every	517	3	same for every	same for every	same for every	0	extremely high	low
1.3	0,50	23,82	3x	same for every	277	2	same for every	same for every	same for every	0	high	low
2.1	0,45	14,28	basic (0)	same for every	0	0	same for every	same for every	0	0	basic	low
2.2	2,78	61,19	2x	same for every	517	3	same for every	same for every	same for every	0	extremely high	low
2.3	1,75	39,90	3x	same for every	277	2	same for every	same for every	same for every	0	high	low
3.1	2,53	96,76	basic (0)	same for every	0	0	same for every	same for every	0	0	basic	low
3.2	1,75	53,10	2x	same for every	517	3	same for every	same for every	same for every	0	extremely high	low
3.3	2,75	127,37	3x	same for every	277	2	same for every	same for every	same for every	0	high	low
7,1	2,50	100,82	basic (0)	same for every	132	1	same for every	same for every	same for every	0,1	low	high
7,3	3,05	74,26	basic (0)	same for every	129	1	same for every	same for every	same for every	0,3	low	extremely high
7,5	4,00	121,73	basic (0)	same for every	132	1	same for every	same for every	same for every	0,07	low	high
7,6	4,00	153,44	basic (0)	same for every	132	1	same for every	same for every	same for every	0,05	low	high

CONCLUSION

Based on the analysis of the results in terms of energy input and payload, the specimens, that had sufficient mechanical properties, as well as an efficient production process, were chosen (Table 46). The best option chosen is specimen 3.3, which was produced using 300˚C and has an additional amount of nano ferric oxide. It was decided to be better than the material with sulfur powder because the production of the second would be independent of Earth, as it requires payload of sulfur each time. However, if there would be a possible of extracting sulfur on Mars, the better options would be the building material with 5 – 30 %wt of additional sulfur. For the purpose of this research, the specimen with 5% is considered the second best option.

For the microscopic analysis of the best options, the specimens for comparison were chosen (1,1 - original and 2,2 – amorphous phase, 600˚C). The original composition was chosen to be able to determine what changes occur after processing. The specimen 2.2 would also help study the observed behaviour of specimens with the addition of amorphous phase (makes the material more resistant to deformation).

Table 46: Chosen Specimens for Microscopic Analysis

Specimen	σ design (Mpa)	E (MPa)	Density (kg/m^3)	Tensile Strength (MPa)	Shear Strength (MPa)	Specific Weight (kN/m^3)
3.3	2,75	127,37	1989	0,06	48,85	7,38
7.5	4,00	121,73	2143	0,08	46,92	7,95
7.6	4,00	153,44	2345	0,08	58,85	8,70
7.1	2,50	100,82	2014	0,05	38,46	7,47
7.3	3,05	74,26	2312	0,06	28,56	8,58
1.1	0,63	29,37	2260	0,01	11,30	8,38
2.2	2,78	61,19	2688	0,06	23,53	9,97

4.4. Microscopic Analysis

AIM AND OBJECTIVES

To understand why and which compositions and production processes result in better mechanical properties, the micro structure of the specimens was analysed. It would provide a more detailed characteristic of the properties of the material. The specimens will be analysed under the microscope and compared to the original composition.

EQUIPMENT

For the purpose of this experiment, the Environmental Scanning Electron Microscope (ESEM) was used. The samples were analysed through the use of BSE (backscattered electron) imaging. Due to the malfunction of the equipment, the detector couldn't specify the chemical composition of each particle. The minerals and chemicals were determined by estimation and observation of the scanned images.

SET UP

The two best specimens from the chosen types of compositions from experiment 2.2 were used in the microscopic analysis. First, the samples were vacuum impregnated with epoxy resin and hardener to prepare the specimens for analysis. The epoxy filled the pores, hardened the brittle material and allowed to cut and polish the surface, which would be studied. Later, a thin 10nm layer of carbon was placed in the vacuum chamber onto the surface. This layer of conducting material is enhancing the image contrast and dissipates the accumulated charges on the surface. Finally, the plate was connected to the sample to earth it. The Figure 52 presents the prepared samples and the preparation steps.

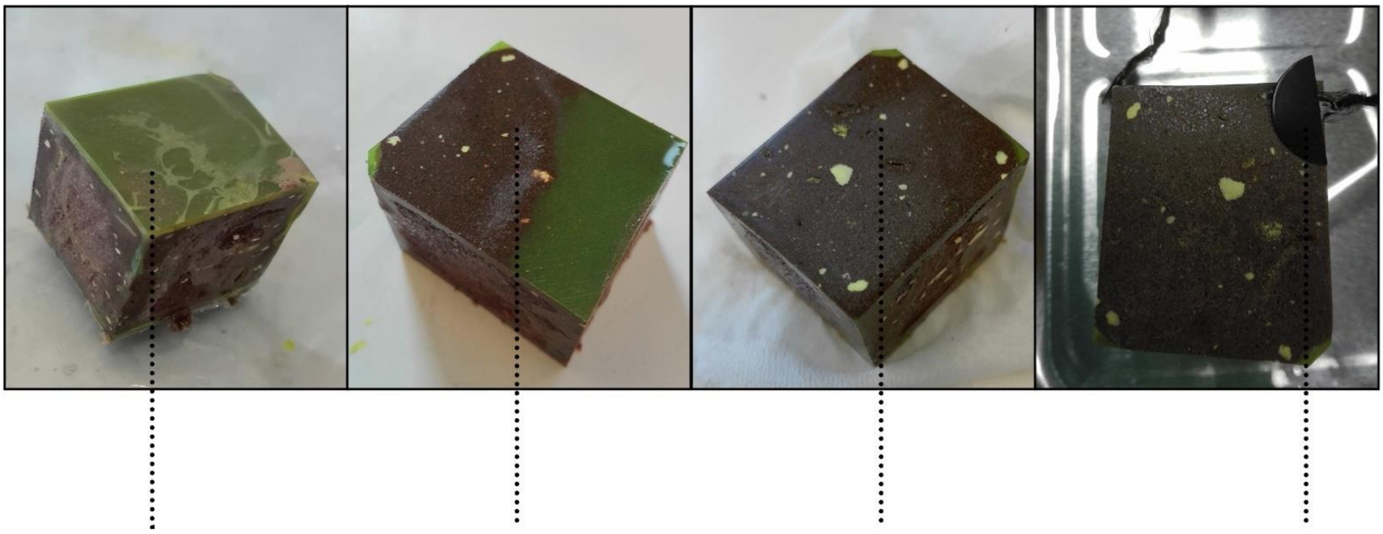


Figure 52: Preparation of the samples for microscopic analysis

To analyse the samples, the density of each mineral and its chemical formula was gathered in Table 47. It allowed determining the particles in the images. Data about the minerals was gathered from the Curiosity Rover Data and Webmineral Database ("Mineralogy Database," 2019). The characteristics of chemical elements were determined with the periodic table. The information about particle size distribution done before the experiments were also used to differentiate the minerals in the images (Table 29).

With the backscattered electrons detector, the scanned images present the particles in a greyscale depending on the density of the minerals, i.e. type of chemical elements and their atomic number. The denser the material, the lighter it appears in the image. In the Table below, the relation in grayscale was estimated based on the average density of the minerals and the number of electrons in the composition. It's not the real gradient scale.

For each specimen, the scanned images were taken with several magnitudes settings to register interesting structures on the microscopic level. The magnitudes were ranging between 100 and 1000. With this range the typical patterns of materials could be analysed, as well as original micro-forms detected.

Table 47: Minerals characteristics for microscopic analysis – batch 3

Mineral	Weight %	density (g/cm^3)	chemical formula	molecular weight (gm)	chemical component	composition element %	Atomic number	
Albite	25,9	2.61 _ 2.63	$NaAlSi_3O_8$	263,02	Sodium (Na)	8,3	11	
					Calcium (Ca)	0,76	20	
					Aluminium (Al.)	10,77	13	
					Silicon (Si)	31,5	14	
					Oxygen (O)	48,66	8	
							10,7679	
Olivine	12,9	3.27_3.37	$(Mg,Fe)2SiO_4$	153,31	Magnesium (Mg)	25,37	12	
					Iron (Fe)	14,57	26	
					Silicon (Si)	18,32	14	
					Oxygen (O)	41,74	8	
							12,7366	
Basalt Powder (pyroxene)	19,2	1,6	_	_	Si	17,26	14	
					Al.	5,51	13	
					Fe	2,65	26	
					Ca	2,51	20	
					Mg	2,37	12	
					Ti	0,59	22	
					Na	1,2	11	
					K	0,08	19	
					0	67,83	8	
							10,3115	
Magnetite	1,9	5.1-5.2	$Fe3O_4$	231.54	Iron (Fe)	72,36	26	
					Oxygen (O)	27,64	8	
							21,0248	
Anhydrite	0,9	2.96-2.98	CaSO4	136,14	Calcium (Ca)	29	20	
					Sulfur (S)	24	16	
					Oxygen (O)	47	8	
							13,4	
Hematite	0,9	5.3	Fe_2O_3	159,69	Iron (Fe)	70	26	
					Oxygen (O)	30	8	
							20,6	
nano ferric oxide	11,2	3.8	$Fe^{3+}{}_2O_3 \cdot 0.5(H_2O)$	168,7	Iron (Fe)	66	26	
					Hydrogen (H)	1	1	
					Oxygen (O)	33	8	
							19,81	
Basaltic Powder (Glass - fiber)	17,1	2,67						
Diatomaceous earth	3,6	2.3	SiO_2		Silicon (Si)	86	14	
					Sodium (Na)	5	11	
							12,59	
iron (III) sulfate pentahydrate	5,4	1,9	Fe2(SO4)3	490	Iron (Fe)	56	26	
					Oxygen (O)	16	8	
					Sulfur (S)	32	16	
							20,96	
siderite	0,9	3.9	$FeCO_3$	116	Iron (Fe)	48	26	
					Carbon (C)	10	6	
					Oxygen (O)	41	8	

Table 48:Minerals characteristics for microscopic analysis – batch 7.5

Mineral	Weight %	density (g/cm^3)	chemical formula	molecular weight (gm)	chemical component	composition element %	Atomic number
Albite	27,7	2.61 _ 2.63	$NaAlSi_3O_8$	263,02	Sodium (Na)	8,3	11
					Calcium (Ca)	0,76	20
					Aluminium (Al.)	10,77	13
					Silicon (Si)	31,5	14
					Oxygen (O)	48,66	8
							10,7679
Olivine	14	3.27_3.37	$(Mg,Fe)2SiO_4$	153,31	Magnesium (Mg)	25,37	12
					Iron (Fe)	14,57	26
					Silicon (Si)	18,32	14
					Oxygen (O)	41,74	8
							12,7366
Basalt Powder (pyroxene)	20,6	1,6	_	_	Si	17,26	14
					Al.	5,51	13
					Fe	2,65	26
					Ca	2,51	20
					Mg	2,37	12
					Ti	0,59	22
					Na	1,2	11
					K	0,08	19
					O	67,83	8
							10,3115
Magnetite	1,9	5.1-5.2	$Fe3O_4$	231.54	Iron (Fe)	72,36	26
					Oxygen (O)	27,64	8
							21,0248
Anhydrite	0,9	2.96-2.98	CaSO4	136,14	Calcium (Ca)	29	20
					Sulfur (S)	24	16
					Oxygen (O)	47	8
							13,4
Hematite	1,1	5.3	Fe_2O_3	159,69	Iron (Fe)	70	26
					Oxygen (O)	30	8
							20,6
nano ferric oxide	1,1	3.8	$Fe^{3+}_2O_3 \cdot 0.5(H_2O)$	168,7	Iron (Fe)	66	26
					Hydrogen (H)	1	1
					Oxygen (O)	33	8
							19,81
Basaltic Powder (Glass - fiber)	18,5	2,67					
Diatomaceous earth	4	2.3	SiO_2		Silicon (Si)	86	14
					Sodium (Na)	5	11
							12,59
iron (III) sulfate pentahydrate	5,7	1,9	Fe2(SO4)3	490	Iron (Fe)	56	26
					Oxygen (O)	16	8
					Sulfur (S)	32	16
							20,96
siderite	1,1	3.9	$FeCO_3$	116	Iron (Fe)	48	26
					Carbon (C)	10	6
					Oxygen (O)	41	8
							16,36
sulfur powder	5	2	S		S	16	16

ANALYSIS

Due to malfunction of one detector, only the general structure of the materials could be analysed. Overall, both of the specimens had homogenous form, where lighter and smaller particles were surrounding bigger and heavier ones. It could be the albite or/and basaltic powder surrounding most of the grains. It could mean, that the manual mixing of the samples is enough to reach good mixture. Sometimes, there are bigger particles occurring, which could be olivine in case of nano ferric oxide sample and ferric sulfate in case of the sample with sulfur (Figure 53).

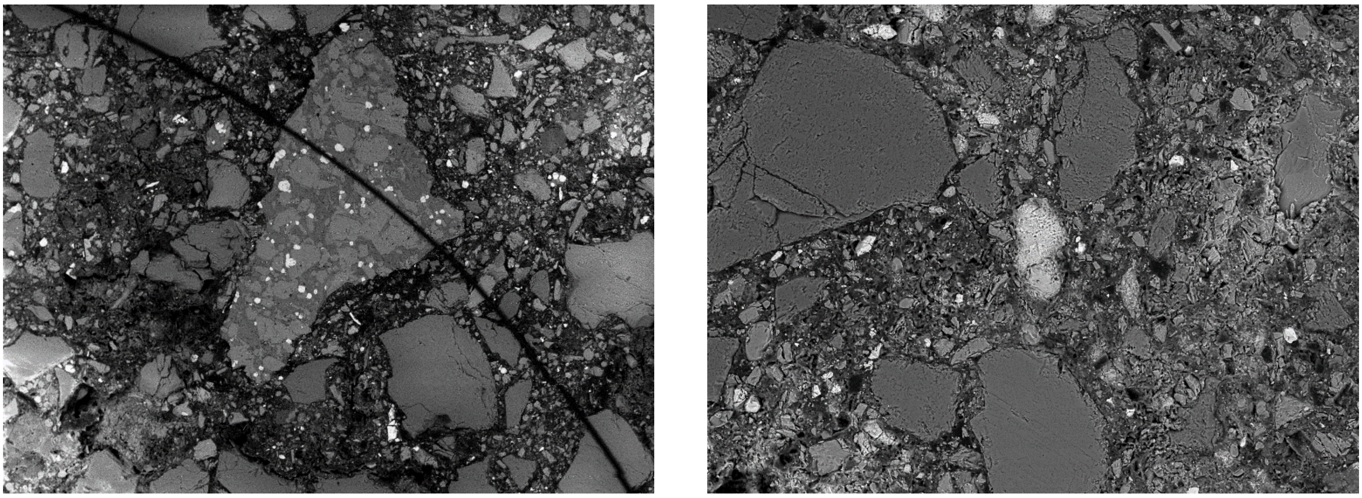


Figure 53: general homogenous form of the mixture. On the left side - nano ferric oxide sample and the right - sulfur powder one

The other aspects, that could be estimated are the characters of cracks. The one with sulfur, had more cracks around the whole specimen. On the other hand, the first sample has smaller amount of cracks and instead there are a lot of voids surrounding the bigger particles (Figure 54).

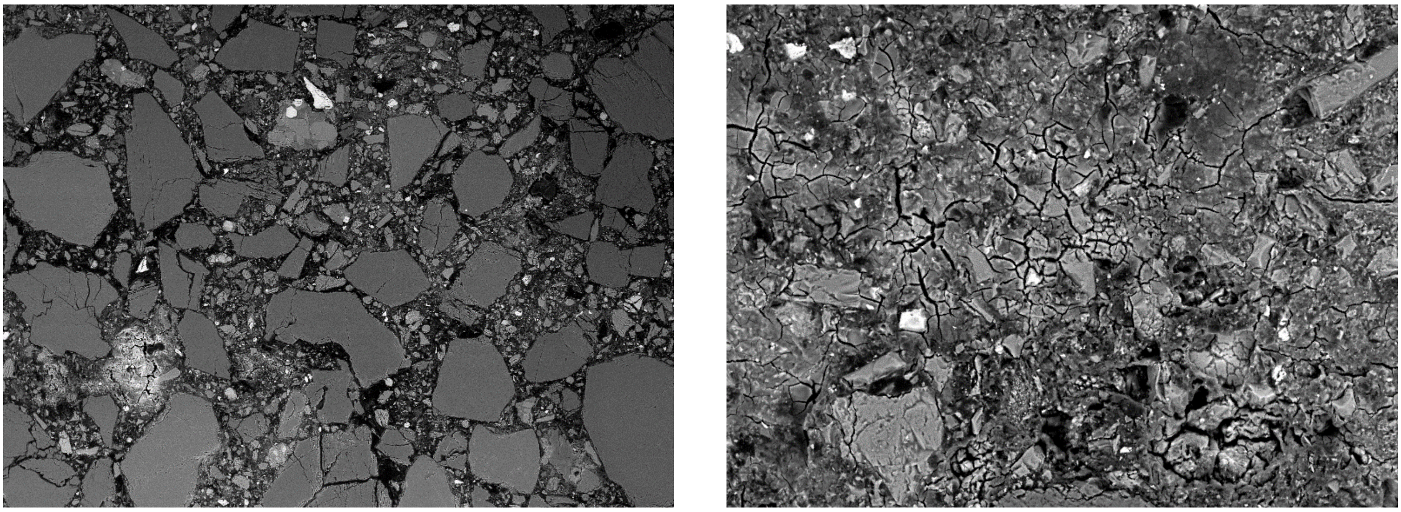


Figure 54: cracks characteristics in the sample.. On the left side - nano ferric oxide sample and the right - sulfur powder one

BUILDING THE STRUCTURE

5.1. Construction Method

As mentioned in chapter 3.6. Construction Method and Structure the proposed interlocking system is based on the research done by A.V. Dyskin et al. It was tested for brittle materials like glass and adobe. It allows for building solid and curved shapes and was proved to be highly resistant to local damage (which could happen in case of micrometeorites).

To build the curved shape like arc, the brick could be oriented into directions (Figure 55). Although the tested option was the one with longer edge perpendicular to arc curvature (Figure 55a), both orientations were considered at the beginning. While dry stacking the blocks to form self-standing structure, there would be a need for support before the last keystone is be placed (Figure 56-2). This could be done by attaching cables to the blocks and holding them in position by tension, or by solid support from the inside of the arc.

The thickness of the structure needs to protect against the radiation, therefore according to NASA, it needs to be at least 1m. To create this with one layer of bricks, the brick would need to be 1m long, which would make the fabricating equipment enormous. Therefore it was decided that the highest value of brick dimension would be 30cm (Figure 54). In this case, the compressing and heating rover could fit in $1m^3$ of payload space. It would allow bringing multiple rovers instead of just one.

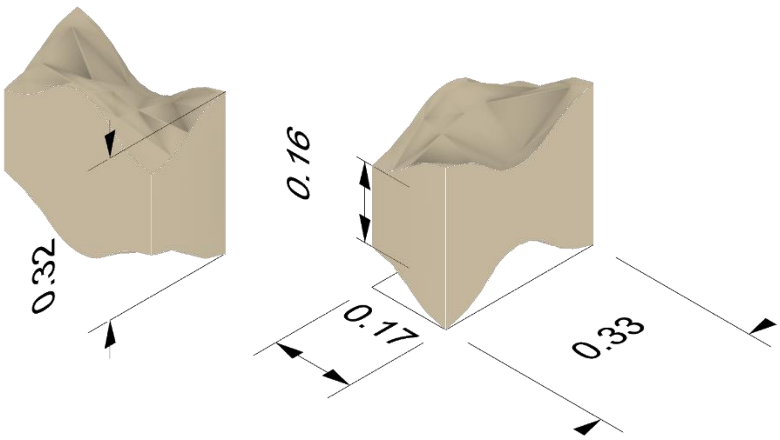


Figure 54: Brick dimensions

To build the 1m-thick arch, there is a need of 3 or 6 layers (Figure 56-4), based on the chosen orientation of the brick.

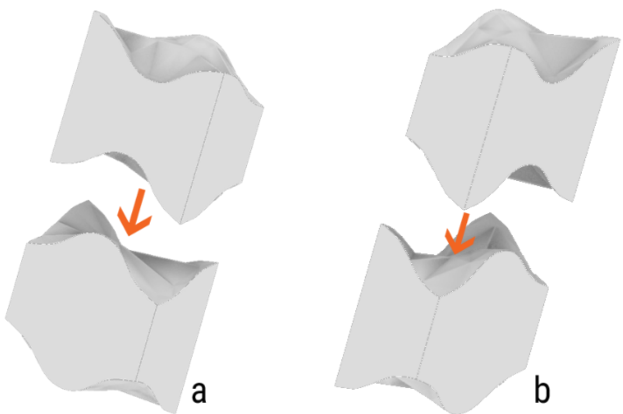


Figure 55: Interlocking system, arc orientation options

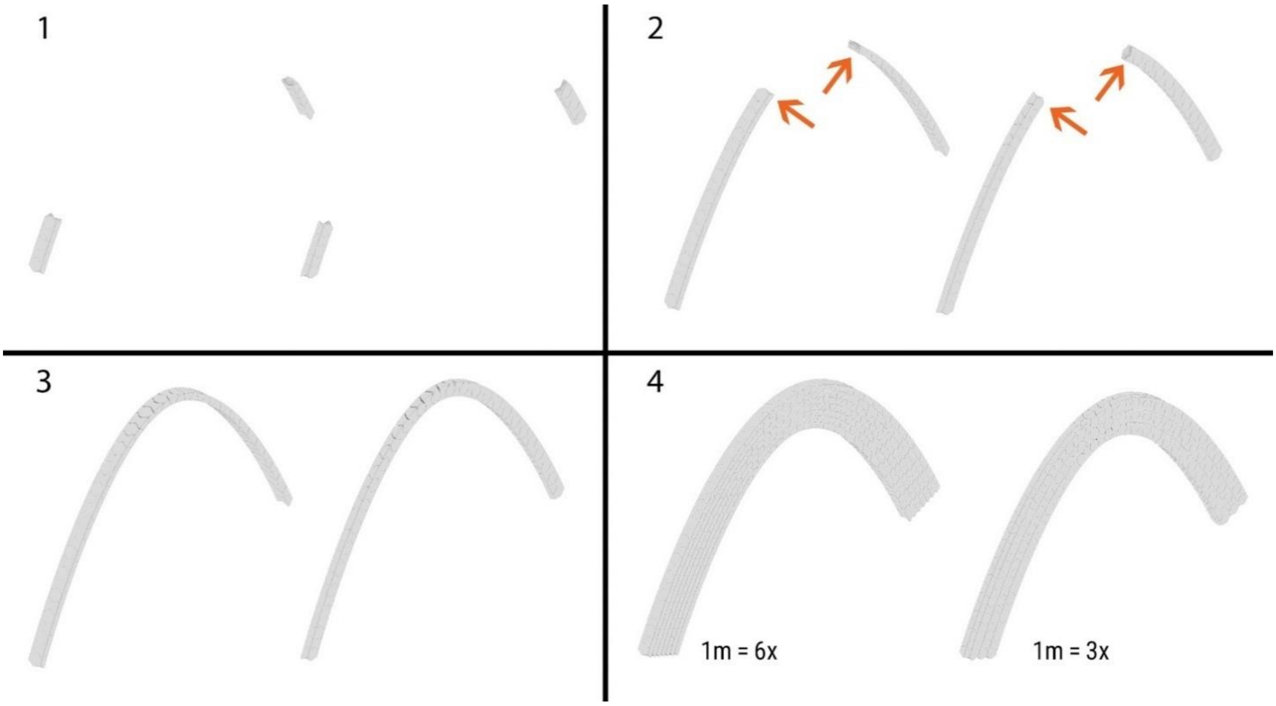


Figure 56: arc construction steps; 1 - base, 2- support needed before completing the arc, 3- completing arc, 4- adding next layers

To interlock the arches along with the vault, the bricks need to be shifted. This requirement disqualified the second option of brick orientation, as it would not allow connecting arches together (Figure 57). Although, using only the first option of interlocking arches, would allow for friction between layers of the brick (Figure 58). To avoid that, the brick would need to interlock with each other in both perpendicular directions (Figure 59). The shape of the brick allows for perpendicular interlocking, however, due to the proposed curved structures, this would need to be investigated and further studied.

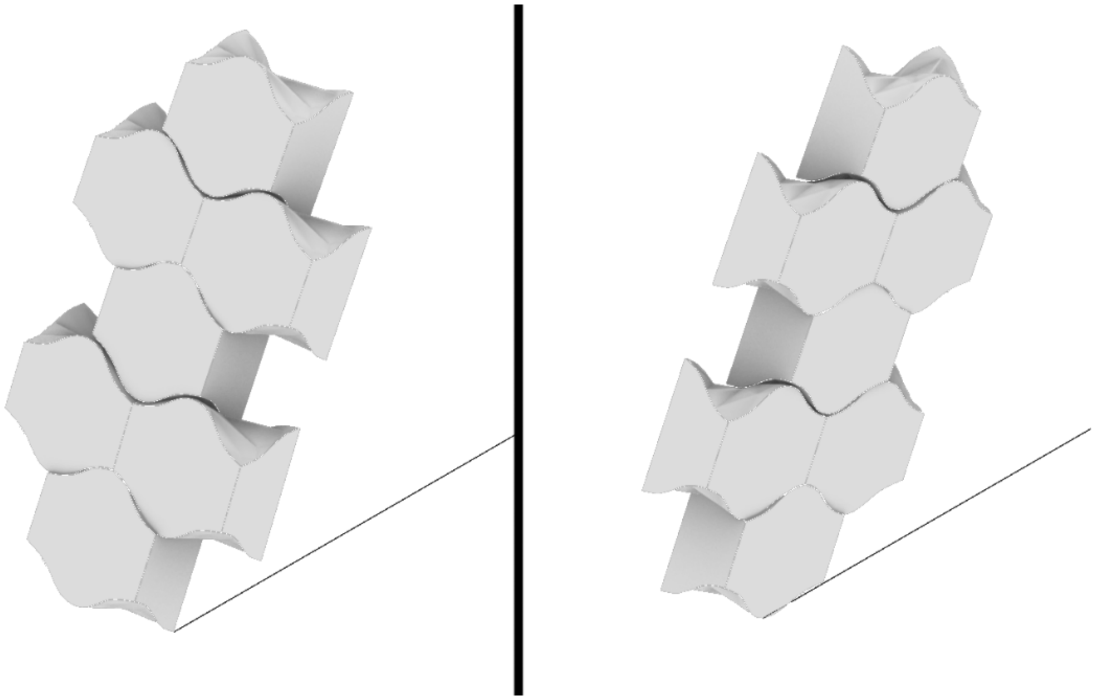


Figure 57: interlocking system, blocks shifting options

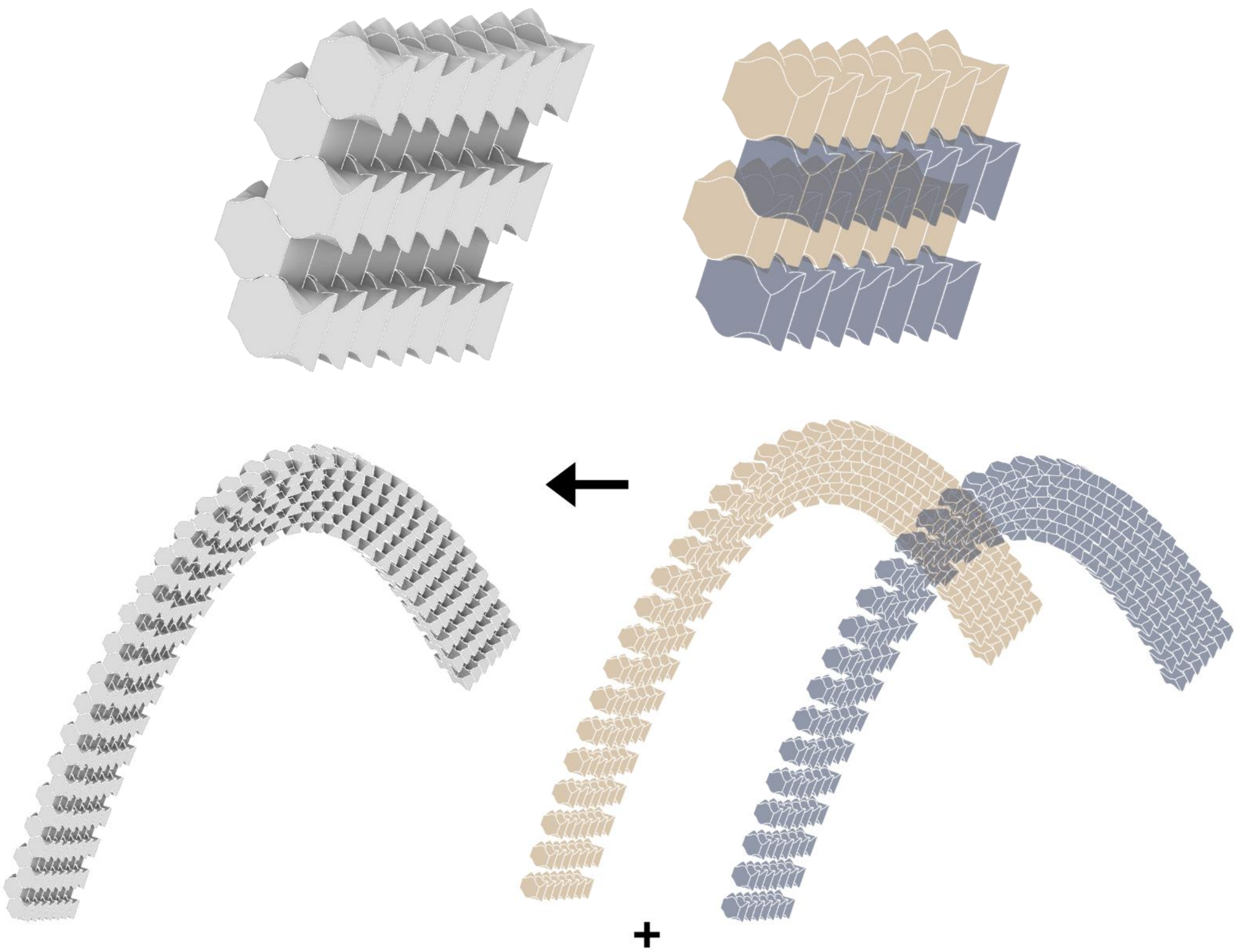


Figure 58: Shifting bricks. The full arc with shifted blocks

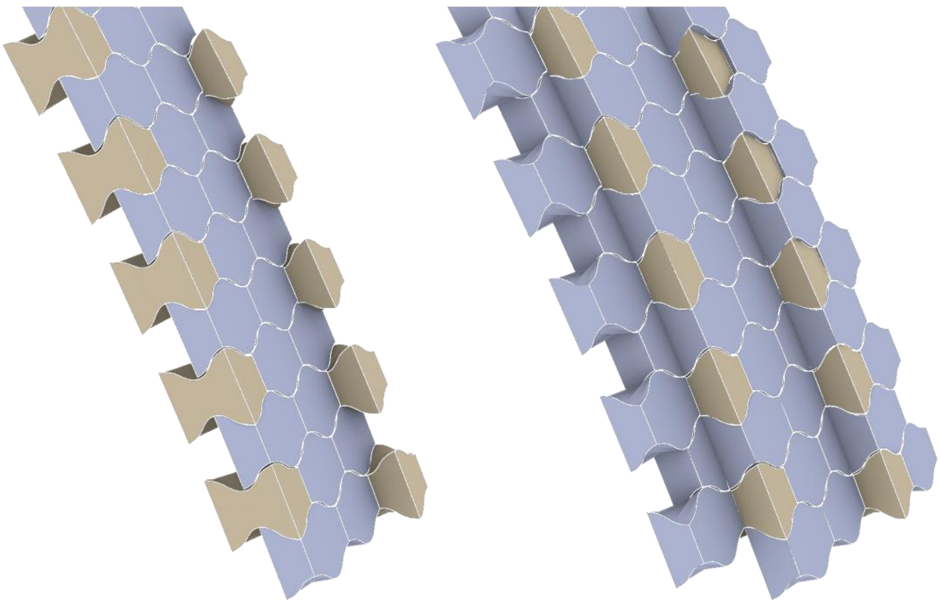


Figure 59: Possibility of perpendicular interlocking

5.2. Building Phases

Based on the conditions for launch windows and travel time, it was estimated, that the structure should be possible to build within 150 days. Although the best launch windows occur every 26 months, it is possible to launch the rocket more often. The travel time in the history of mars missions was ranging between 150 and 300 days. The heavy payload takes more time to reach Mars, therefore it was chosen to accomplish the structure during 300 days. Based on this time, the available time for each building phases was estimated (Table 49). Some of these activities can be done simultaneously. It was decided, that the bricks production process would take most of the time, due to the heating process included. The available hours for each process were divided by 2 as the main energy source would be solar energy available during daytime.

Table 49: Building phases and time

Phase	Activity	Time (days)	Time (hours)
Preparation (some can be done simultaneously)	Material Characterisation	20	240
	Material Collection	45	540
	Surface Preparation (Foundation)	20	240
Fabrication	Bricks Production	180	2160
Construction	Brick Assembly	35	420

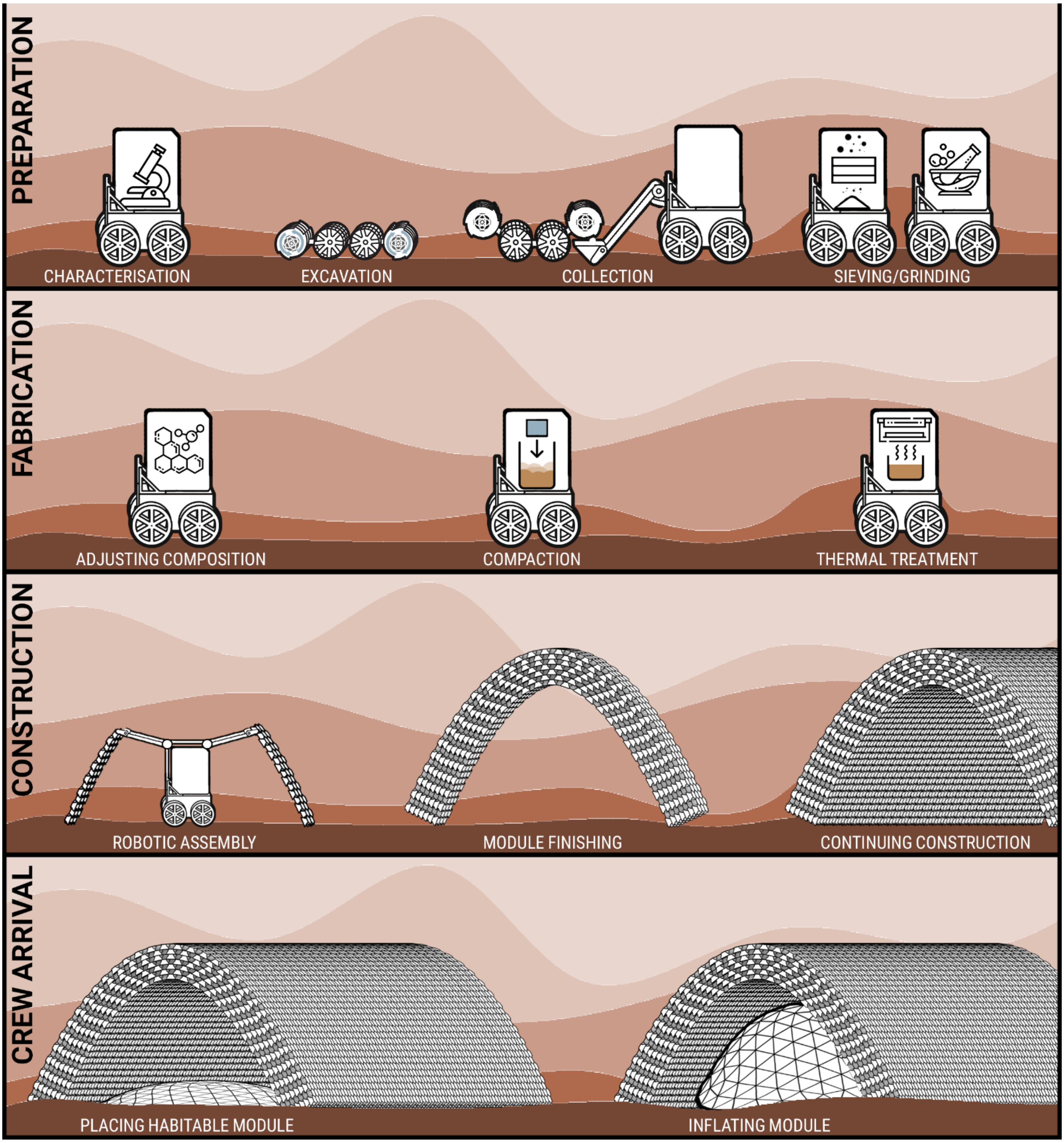


Figure 60: Building phases

PREPARATION

CHARACTERISATION

At the beginning of the building mission, the surrounding material characterisation would need to be done. The particle size distribution analysis and investigation of the mineral composition are required. It would allow for accurate preparation of the material. For the purpose of this phase, the building rovers need to be equipped with the analysing equipment to be able to run the analysis separately and simultaneously. The bigger area is studied, the more efficient the production and building phase can be as the most suitable dust regions will be located.

EXCAVATION/COLLECTION

The currently available rover designed to excavate regolith is the mining robot RASSOR 2.0 (Regolith Advanced Surface Systems Operations Robot Excavator) made by NASA (Mueller, et al., 2016). The power characteristics of this rover are presented in Table 50 . It is powered by to batteries that can be recharged at the lander, where solar panels or other source of energy can be located. The rover needs 4W to extract kg of the material. It was estimated earlier, that the mass of the structure would be around 45000kg, therefore the required power for extracting this amount of material would be 180kW.

Table 50: RASSOR's characteristics and power demand for regolith excavation

	Unit	Value
Mass	kg	60
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
Total power required for structure	**kW**	**180**
Available time	**h**	**300 (rest for sieving, grinding)**
Excavate phase	**kW/h**	**0,,6**

Figure 61: RASSOR 2.0 - mining rover designed by NASA, Source: Townsend, et al., 2017

Before the building phase would start, the surface and foundation for the construction need to be prepared. The surface should be hardened by compaction or with the use of produced bricks. If necessary, the foundations could be reinforced with spacecraft recyclables, however, this would make the structure, not 100% decomposable.

FABRICATION

After the preparation stages, the bricks can be produced and simultaneously assembled by the rovers. The need for the support during construction, makes the modular approach more suitable, as the segments of the structure can be finished separately and later joined together. This could also lead to a decrease of the support structures required to bring from Earth. The energy demand for the chosen brick types (3.3 and 7.5) is presented in (). The time for compaction and thermal treatment was determined as 720 and 1440 respectively.

Batch type 3.3	Unit	Value
Compaction of 1 brick (Work = F x d)	kW	0,7
Number of bricks required		1740
Total Compaction	**kW**	**1195**
Available time	h	720
Compaction phase	**kW/h**	**1,63**
Heating time	h	4
	s	14400
Thermal treatment of one brick (ΔE)	J	276800
	W	19
Total E	**kW**	**33447**
Available time	h	1440
Thermal Treatment	**kW/h**	**23**

CONSTRUCTION

The energy required for robotic assembly was estimated based on simple calculation of work done for lifting the bricks to the required height. The highest point the brick would need to be picked up was estimated to be 6m based on the architectural requirements. This value was used for 1/3 of the required bricks as not all of the blocks would need to reach this height. The second and third 1/3 of the structure would be picked up to the height of 3 and 1 m respectively. Table presents the calculations and values of the assembly phase.

	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
Power in total	**kW**	**0,285**
Available time	h	420
Assembly Power	**kW/h**	**0,00068**

TOTAL ENERGY DEMAND

The total power required for the investigated actions is equal to around 40 MW, however, this value would be higher as not all of the processes were included in the calculations. By dividing it by the available time, the average required power would reach almost 12kW/h. The minimum solar power available on Mars was determined earlier to be 1034W per sol per 1m^2 of panel. Per sol, the power demand would be 144 kW. It means, that the required area of solar panels is 140m^2. It can sound as a lot, however it could easily fit in the rocket.

CREW ARRIVAL

When the structure reached the self-standing and supporting form, the habitat module can be placed under the vault. Then, the module can be inflated to reach the maximum volume. To transport the module under the structure, the access to the inside has to be kept. The dimensions of the openings need to be at least 5,2m wide and 3m high, as it was estimated to be the size of the inflatable module payload.

Finally, the structure can be closed or the size of the openings can be adjusted to the requirements of protection against radiation. From the literature review, it was concluded that there might be openings to let the daylight in, however, the habitable space needs to be receded from the edge of the opening. The angle between the surface and the line connecting furthest point of the module and top part of the opening needs to be below 30˚ (Figure 20).

5.3. STRUCTURE

CONFIGURATION

The configuration of the habitat dictates the ideal plan of the structure. It was based on the literature review of the architectural and mission requirements (Mission conditions, Architecture).

The main requirement is the functionality of the habitat and the safety/wellbeing of the crew. To reach that, some of the activities have to be separated into 4 zones – private, group, work and dirty (Figure 62).

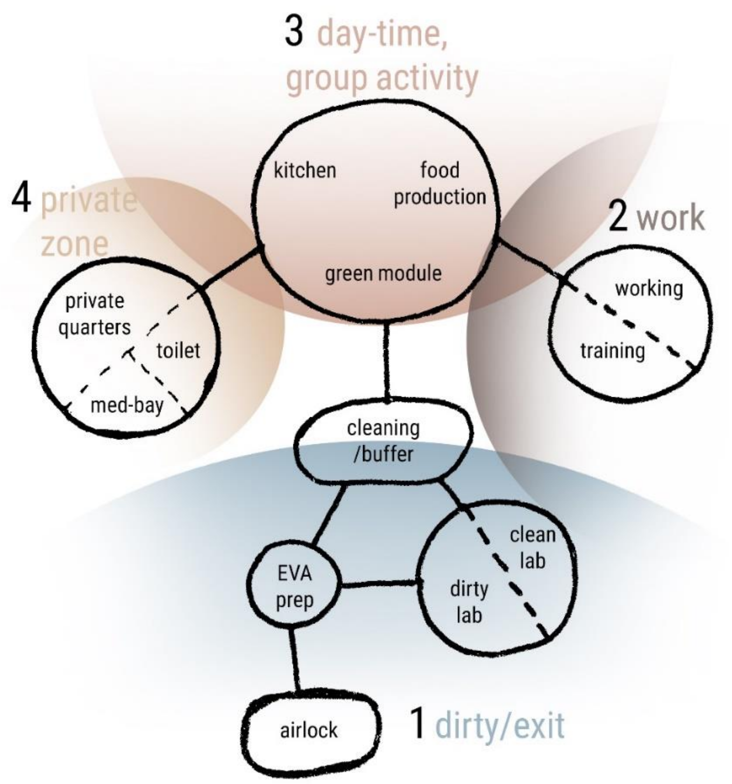


Figure 62: Functional Configuration

The configuration of the habitat ideally would be modular, however as mentioned in the section about the interlocking system, the shape of the brick would need to be slightly adjusted to reach the continuous and solid complex shape. For the purpose of this research, all of the options would be analysed structurally, however, the connection detail is for now possible only for the simple vault shape (Figure 63a). This allows for creating single-curved long and wide structure, where modular habitat volumes need to be connected linearly.

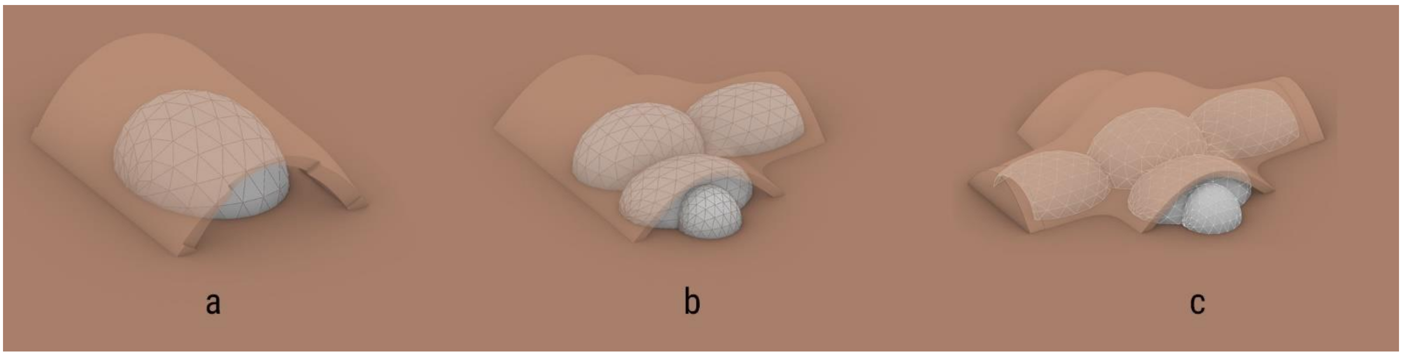


Figure 63: Possible structures analysed in the research

STRUCTURAL ANALYSIS

To understand the possibilities of the material, the comparison between Mars and Earth was repeated, using the characteristics of the specimen 3.3 from Experiment 2.2. Moreover, a different relation between height and span of the vaults were studied. The ratio of the case -1 is 0,5, case -2 is 0,4 and case -3 is 0,3. From the previous structural analysis done before the experiments, it was concluded that due to low gravity force on Mars, the wind load oriented upside down might have a bigger impact, though the value is almost 2 times lower than on Earth. Therefore, the ration between height and span was studied here first.

The simulation showed, that the behaviour of the structure due to the decrease in height is similar on both planets. There is a decrease in deformation between case 1 and 2, but in case 3, although the mass of the structure decreased, the deformation increased compared to the 2nd option (Figure 64). The tensile stresses increased in all cases within the decrease of height, therefore it would be ideal to keep the higher ratios of height and span. The compressive stress, likewise the deformation, decreased from case 1 to 2 and the ratio of case 3 increased again.

The principal stresses, when compared with the same scale of display for every model show more tension in the structures on Mars (Figure 65). The compressed surfaces decline, which is not ideal for brittle material as martian regolith.

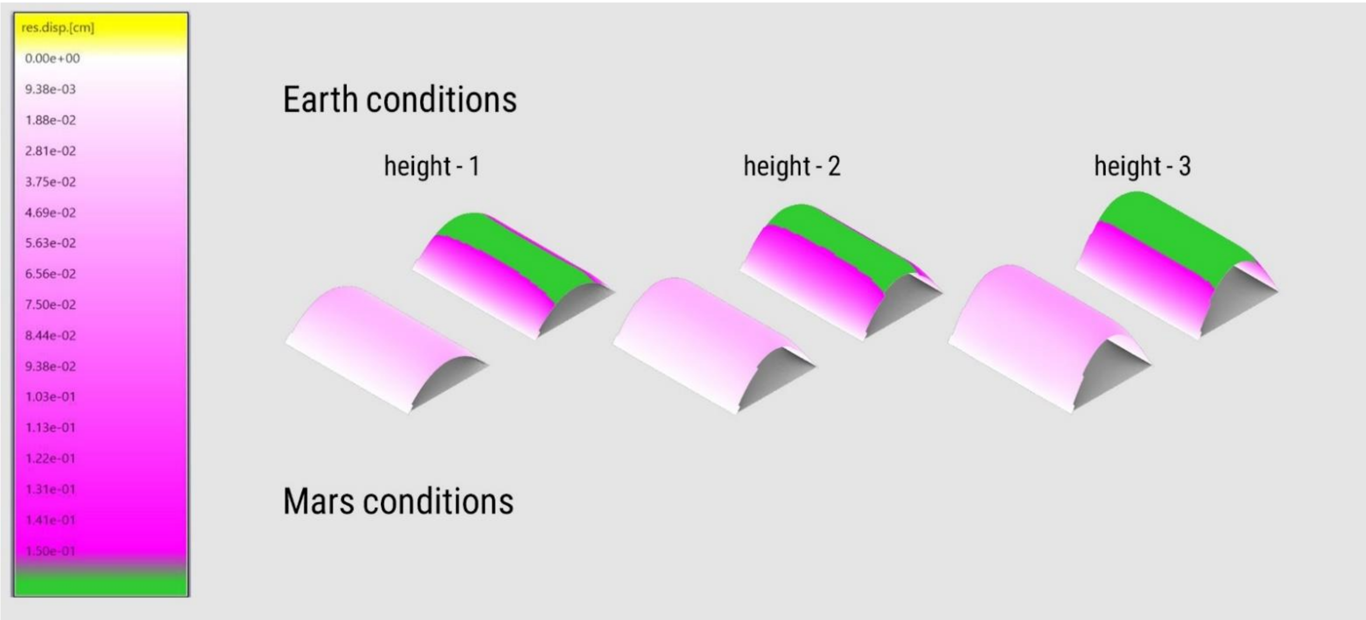


Figure 64:- Earth and Mars deformation comparison. Height-span relation

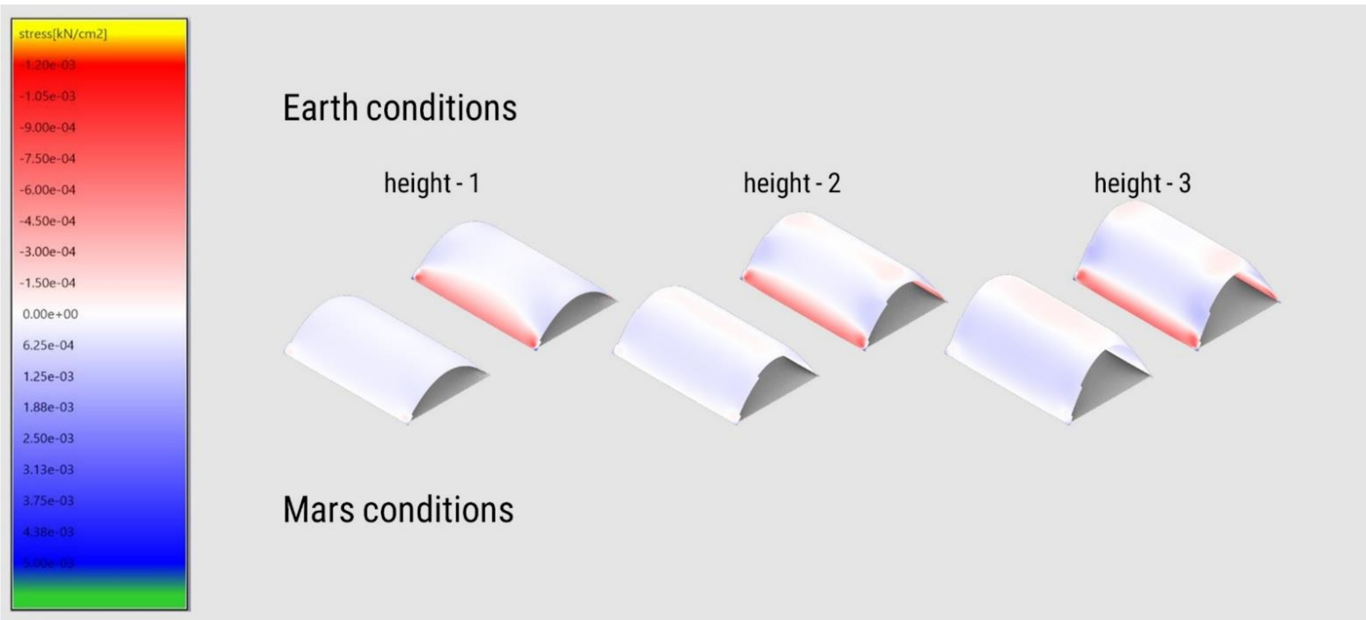


Figure 65: - Earth and Mars principal stresses 1 comparison. Height-span relation

The basic structures of the simple vault and crossed vaults were analysed as the next step to define the best option for a structure. Again, the deformation and principal stresses were investigated to determine compressive form among the available options. Same cases of height-span ratio were considered in this analysis.

The simulations of deformation showed, that the smallest values were reached by the model with the height: span ration of 0,4. Though, with the complexity of the structure and increase of mass, it tends to increase (Figure 66).

The principal stresses, however, showed that adding perpendicular vault increase the stiffness and makes the form more compression-only. Interestingly, the addition of the fourth vault increases the stresses and makes them less homogenous, which can create additional friction inside the structure (Figure 67, Figure 68).

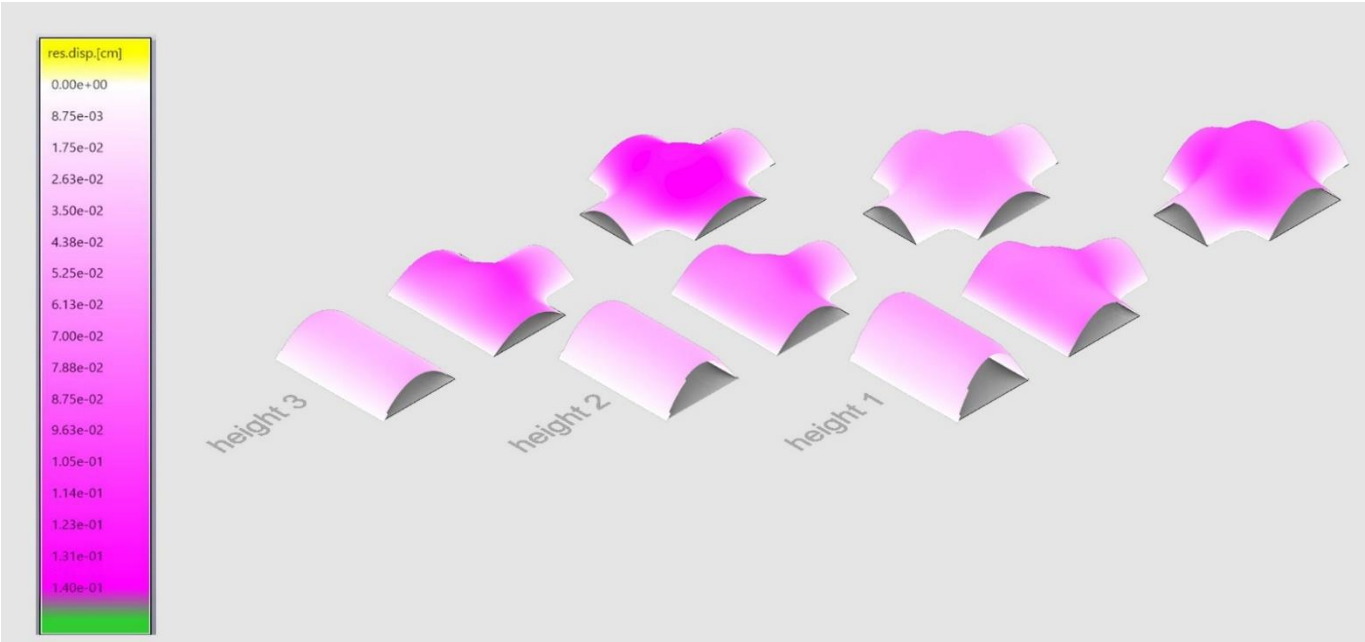


Figure 66: Basic shapes analysis – deformation

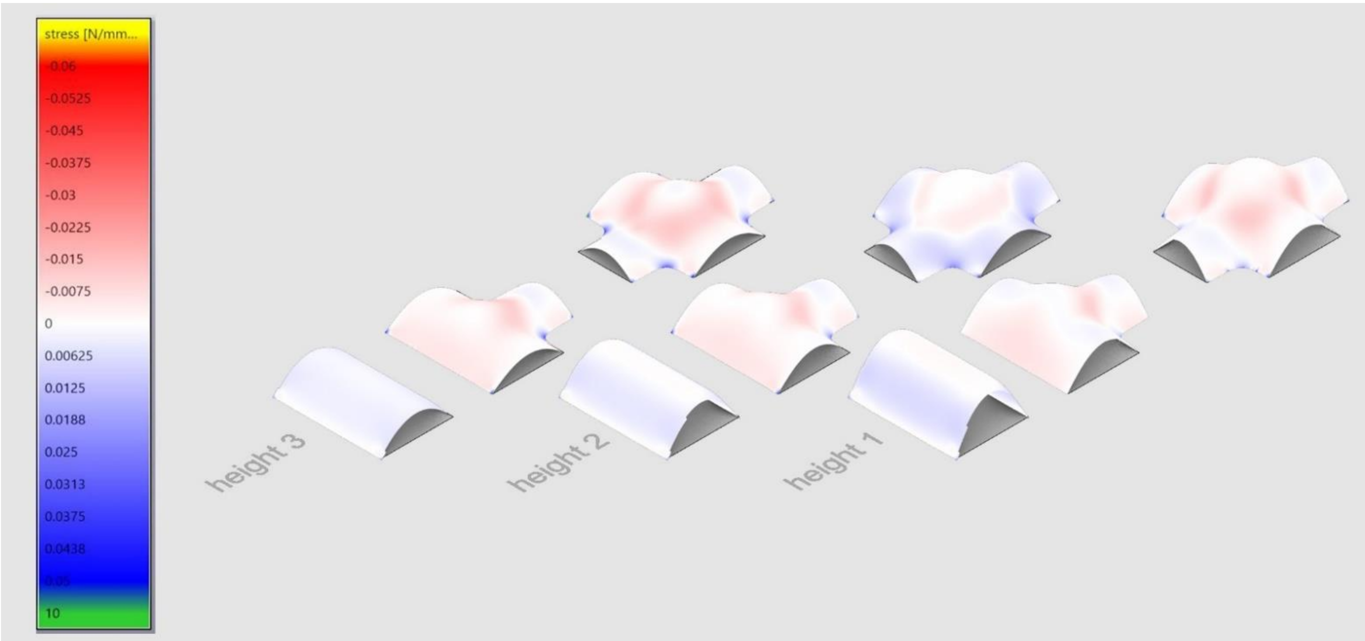


Figure 67: Basic shapes analysis - principal stresses 1

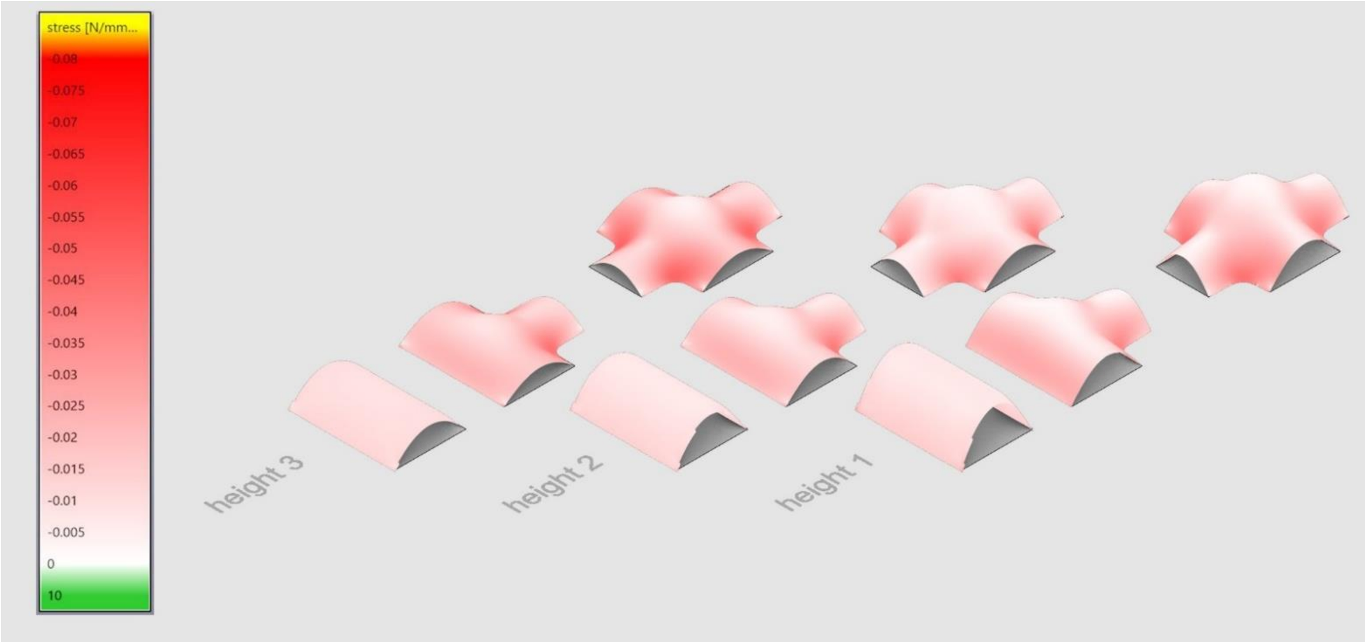


Figure 68: Basic shapes analysis – principal stresses 2

Table 51: Structural analysis results for basic shapes

model	def max	Compressive stress	Tensile stress
	cm	MPa	MPa
1.1	0,054	0,0022	0,000062
1.2	0,044	0,0022	0,000072
1.3	0,046	0,0022	0,000096
2.1	0,10	0,0039	-0,0008
2.2	0,099	0,0048	0,00078
2.3	0,12	0,0047	0,00081
3.1	0,12	0,0042	0,0012
3.2	0,07	0,0034	0,0076
3.3	0,14	0,0047	0,001

CONCLUSIONS

6.1. Answers to research questions

SUB-QUESTIONS

What is the sustainability on Mars and how it should be implemented in the building aspects?

The general definition of sustainability, chosen for this research is based on the one, stated by The Brundtland Commission. It promotes strategies, which are oriented towards protection of the environment, which until we decide what is the approach and future for space, is keeping all options possible. During the first missions to Mars, the technologies and experiments will concern mostly resource utilization, which partially will be used for building habitats. The equipment and processes will have an impact on the surrounding and some of them might be harmful to the Martian environment. Therefore, the sustainability on Mars, determined for this research is focusing on the environmental impacts as contamination and consumption of resources. Additionally, international cooperation and social awareness are presented as one of the sustainability goals.

To establish sustainability on Mars, regulations need to be determined as an international policy supporting sustainable development and environment protection. The first step towards establishing new law would be to update the existing one by including regulations for commercial and business activities in space as well as by acknowledging long-term settlements on other planets. Later, it should be encouraged to create joint programs and activities on Mars and to share relevant information and data between states with advanced space capabilities and the developing ones.

The environmental impacts are not yet determined for Mars. First missions would be ideal to perform required research to quantify and characterize the potential impacts and test the sustainability approach and technology. Therefore, it is important to specify processes, materials that might have an impact on the Martian environment. These could be further studied and tested as the continuation of the research on sustainability on Mars. To estimate the impact before missions, consumption and waste, the analysis of material flows, as LCA and MFA, can be used.

One of the potential impacts is contamination. Pollution aspect needs some quantifiable measures from tests in Martian conditions because it is not known how harmful are some substances on the planet with lower pressure, gravity, and different atmosphere. Nevertheless, some chemicals and materials can be assumed as harmful. The materials, that are considered hazardous are organic materials because they bring a controversial discussion regarding the question if a human can contaminate outer space with life. Moreover, the usage of polymer additives in building component might have an impact on the environment. To assure, that the organic matter or harmful materials won't be present in the structure, in case of prohibition of biological and chemical contamination of Martian surface in the future, the material used for building a habitat in this research will be 100% in situ.

One of the essential goals regarding environmental protection is to prevent the natural environment and the landscape of Mars. It needs to be determined, what are the Martian heritage and the natural landscape necessary to protect. These terrains shouldn't be touched by any activities like hard landing transportation or building.

The energy generation sources investigated in this research are solar, nuclear and ISRU. The solar one is the only one renewable and the new technologies related to this option are improving fast. The potential future efficiency could provide enough energy for building processes. Nuclear energy, however, promoted by space agencies, should be minimized or avoided if possible as a source for building processes. Its radioactive waste and risks related to usage are strongly criticized by the United Nations and should be replaced by renewable energy like solar one. In terms of using fuel cells combined with ISRU approach, it is still not tested or calculated what and how big would be the impact of this process. Therefore, for the purpose of this research solar energy would be considered as the main source, with limited nuclear power as a backup.

Resource utilization might be the potential impact because if performed irresponsibly might generate large waste and harmful materials or emissions. Another result could be excessive usage of the resource, which might lead to scarcity in the future. Therefore, responsible resources management and utilization is important and should be implemented in the designs of the missions. The utilization processes should be optimized, in order to minimize energy and material usage, and waste production. To choose the best option for the designs and to estimate, which part of the utilization creates to much waste or could optimize in terms of energy and time efficiency, the LCA and MFA could be used. As the approach for design purpose Material Efficiency strategy could reduce the demand for material and energy. The production of waste should be minimized for every activity such as construction phase, resource utilization, production processes. The systems should be designed towards zero waste by efficiency strategy or by circular strategy.

There are several issues regarding the implementation of sustainability in space missions. They are mostly related to the existing approach of space agencies and the lack of international regulations regarding environmental impact and resource utilization in space. The main problem is, that so far, Earth is defined as the only environment we should take care of. The space agencies are claiming, that space resources should be utilized on a great scale in order to limit the resource consumption on Earth. The land responsibility should be extended beyond our planet, however, it is a complicated political and economic process, which won't be achieved if the territory in space is a condominium, which no one is responsible for.

What are the material requirements and which in situ materials are suitable for that?

From the literature study, the programme of requirements was determined for the material. The factors determining the limitations and demands regarding the material were related to the conditions on Mars, space missions and sustainability. The most important aspects were the availability and extraction method. The material should be abundant on the planet because there are multiple missions planned for Mars. The production process, as well as construction using the chosen material, should be possible on the majority of the Martian surface.

The material should be relatively easy to processed to minimize energy consumption and increase production and building efficiency. Preferably, the resource should be ready for usage after collecting or with a limited amount of preparation steps. If any extra processing is required it should not be very energy demanding.

Another requirement concerns sustainability. To protect the Martian environment from contamination (both organic and toxic), the material should be 100% in-situ. However, the reusing of space craft recyclables could be considered as a sustainable circular approach, the built structure would have a negative impact on the natural surroundings. Moreover, the less processed material, the easier it can be recycled.

Although it was decided at the beginning to use regolith, the possibilities of using other in-situ materials were taken into consideration. The materials were compared in terms of availability, extraction method and preparation for the production process. Regolith is the most common material on the Martian surface. The fine form of the regolith is homogenous around the whole planet and is available on the surface as a loose dust material. It doesn't require complicated preparation processes and can be directly processed into a building material by compression or thermal treatment.

The choice of the material and it's preparation have an impact on every step of the building process. The material composition was used in this research as an opportunity to optimize the production process in terms of energy usage and improvement of mechanical properties of the building component. The efficient method for regolith composition preparation and adjustment is sieving, which uses the differences in the relation between particle sizes and types of minerals. The data gathered by Curiosity rover shows, that the composition of minerals changes with increase or decrease of grain sizes.

It allows preparing the material with an additional amount of minerals that can have a positive impact on the production process, binding and final properties of the component. By increasing the amount of ferric-sulfate or albite by 5%, the thermal treatment resulted in a material with twice higher mechanical values compared to the original composition, because these minerals have the lowest melting temperature in the regolith. Whereas, the addition of amorphous phase minerals improved the results of the compression process twice.

To optimise the efficiency of the production process another addition to the material was considered – powder sulfur. The molten sulfur acts as a binder in the material. Although it's related to the extra payload in the rocket (because the sulfur in required form doesn't occur on Mars), the composition with 30% of sulfur powder increased Young's Modulus four times. The drawback of this option is the dependence on Earth because, for each habitat, the sulfur powder needs to be transported.

What are the available in situ production processes in terms of efficiency and sustainability?

Before choosing the potential production processes for regolith, the requirements were determined based on the literature review of the Martian mission's conditions regarding efficiency and sustainability. Due to the payload limitations, the approach for designing energy efficient processes and minimizing the number of resources brought from Earth was essential. The mass and volume of the equipment were also taken into consideration. To minimize the amount of energy generating equipment and resource, the production process was designed to be simple, with a small number of processing steps. In terms of energy source, in order to make the project economic and sustainable, solar energy was chosen as the main source. It decreased the payload significantly and made the building process less dependent on Earth. The secondary source is nuclear energy, with an emphasis on the fact that it needs to be limited, and if possible, supplemented with a developed ISRU energy generation like a fuel cell. This option is still not tested on Mars, therefore the first missions wouldn't use it as the reliable source.

The resources brought from Earth were minimized by choosing a production process which doesn't require additives for the material composition. To improve the properties of the final product, only the in-situ material should be considered. To bind the loose, dusty material together only thermal treatment was used to melt some minerals as other processes were more complex or required water. Water usage was avoided because it would result in extra payload, more complex equipment. Moreover, the role of water during the missions is too important in terms of life support systems to 'waste' it on the building.

Due to the requirement for multiple missions and the possibility of building in different locations, the process had to be adjustable to slightly different compositions of regolith. The equipment should be compact and easy to transport, maintain or prepare.

In terms of sustainability, it was important to propose a method that produces a small amount of waste. If there is any waste produced, it should be possible to recycle it back to the process. The production process which won't change the material significantly would allow to just landfill the waste as it would keep natural form.

Different production processes were chosen based on the literature study on ongoing researches regarding building on Mars. The mentioned requirements were essential in the selection process. Finally, the compression was chosen as the main process, due to its low-tech characteristic, energy efficiency and promising mechanical properties of the product. To reach better results, the thermal treatment (in 600˚C, 800˚C and 1000˚C) was tested as the additional process, however, the results of just compressed samples could reach same properties of the material when the optimized composition was used. With this production regolith, adobe can be made. Properties of the final product will be updated after the next experiments are finished

What are the requirements for the structure, and construction and which technologies and building forms meet these requirements?

As the building component is a regolith block, the structure had to be designed and optimised in order to create a compression-only form. The brittle properties of the material, high compressive strength and low tensile strength require from the structure to minimize the inner shear and tensile stresses. The proposed form is based on the adobe structures designed and built on Earth.

Due to the fact, that the material is not resistant to high tensile force, the regolith structure acts as a second layer which protects the habitable and pressurized module from wind load, micrometeorite impacts and radiation. This allows for smaller and lighter habitat module, which needs to be brought from Earth, due to complex installations and requirement for tested and reliable human shelter. The loads, that the regolith structure needs to withstand are 6,25 Pa of wind load, and14000N impact force from micrometeorites. In the future, resistance to marsquakes might be added as the other condition, however, they are very low, therefore there is no numeric data on it yet.

In terms of functional requirements, the structure needs to allow for modular habitat, as well as its possible expansion or rearrangement. It is important to include flexibility for connecting modules so it can adapt to different missions. Although the shortest mission on the surface of Mars can last only two-three weeks, the structure can be used longer considering multiple planned mission scenarios. Therefore, the structure has to last longer than one mission (which in the future might take even 3 years).

The construction phase is designed to be fully automated and autonomous, however, the structure should be possible to construct within one mission so it can be tested and developed during the first manned mission. The energy demand, similarly to the production process should be minimized, and the required building and preparation steps limited. Therefore, the interlocking system implemented in the regolith blocks was designed. It allows for dry-stacking construction method, which might lead to simple compression-only structures.

What is the sustainable construction method for designed building material and structure?

The interlocking system is based on the research and design developed on Earth. The sustainable aspect of this system is the dry-stacking of the blocks instead of using adhesive. It means, that the blocks can be recycled or downcycled because there is no permanent binding implemented. The shape of brick allows erecting curved shapes, which improves the resistance to the loads.

MAIN QUESTION

How to sustainably construct on Mars with regolith and energy efficient in-situ fabrication process?

The main requirements for sustainable building on Mars are related to efficiency and environment protection. The efficiency is related to different aspects of transportation issues like mass and volume of payload, costs and time. The construction, in order to be sustainable, must be independent of Earth. Ideally, the building material should be 100% in-situ, the production and building process should be energy efficient and not environmentally harmful. Therefore, the energy source must be clean and renewable.

The design proposed in this research uses regolith as the building material, however, the composition and grain size distribution is optimized in order to achieve better mechanical properties of the product. This optimization doesn't require much energy as it can be achieved with sieving and limited milling process. The main production process is compression, which creates an adobe-like component with interlocking system included in the shape of the block. This form allows constructing without any binding between blocks, which would require additional payload from Earth and another production process.

The structure is optimised in order to increase the resistance against wind load and micrometeorites impacts. The shape of the structure allows for flexible and adjustable rearrangement of the habitable modules which are located beneath the regolith shell.

GENERAL CONCLUSIONS

- **Discussion about sustainability in space is needed. Can be tested and analysed during first missions.**
- **Dust and fine grain regolith allows for efficient extraction and production process.**
- **Composition of the regolith can optimise the production process and improve final properties.**
- **First structures on Mars can be made with simple technology using in-situ resources.**

6.2. FUTURE RESEARCH

- Sustainability on Mars
- Composition adjustment options study
- Interlocking mould
- Conditions Simulation – impact on material and process

One of the topics, that could be further developed is the aspect of sustainability on Mars. The research done for the purpose of this thesis starts a new discussion which needs to be tackled by researchers from different fields of studies as the topic is very broad and complex. The most important is to determine the environmental impacts on the Red Planet. The conditions are significantly different from the Earth ones and the approaches we developed on our planet can't be implemented directly on Mars. Moreover, the mission conditions and their goals need to be considered while determining Martian sustainability.

The introduced optimization method, using regolith composition adjustment, is a promising way of improving the efficiency of the production process and increasing the mechanical properties of the building material. This composition could be further developed by finding the best ratio between minerals and best grain size distribution. In this report the compositions had only one variant (which was adding an extra 5% of chosen mineral), however, there might be a better percentage. Moreover, the combinations between these optimisations can be researched.

The production process, that wasn't researched in this project – geopolymerization could be another potential topic to develop. There are few research papers related to this production method, but there could be the compositional optimization introduced to the process, as well as the water recycling system development. It would result in a sustainable alternative to the production proposed in this paper.

To develop further the concept of building with regolith, the Martian conditions like pressure, temperature and atmosphere need to be included in the tests. The impact of these factors on the production process and construction wasn't analysed in the research. Additionally, the behaviour of the structure and material regarding long-term exposure to these conditions should be tested, as there is no information on this in any research papers.

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APPENDIX

Appendix 1

Table 52: Research timeline

Products			Research by design and testing			Experimental research on production process and fabrication			Experimental research on material			Research on Sustainability			Background Research			Phase	
Reflection	report	presentation	Conclusions	scale mockup + testing	Design of a structure and construction method	Conclusions	Testing (physical and computational simulation)	Production Process Optimization	Pilot Tests	Material Production	Determine simulant's composition	Programme of Requirements with sustainability	Circularity in Space	Sustainability in Space Law	Determination of Program of Requirements	Analysis & Conclusions	Literature Study	Activity	
																	■	Oct 29th -Nov.-2nd	
																	■	Nov. 5th - 9th	P1
																	■	Nov. 12th - 16th	
																	■	Nov. 19th - 23rd	
																■	■	Nov. 26th - 30th	
																■	■	Dec. 3rd - 7th	
■	■	■													■	■	■	Dec. 10th - 14th	
■	■	■													■	■	■	Dec. 17th - 21st	
																		Dec-Jan 24th-4th	
	■														■	■	■	Jan 7th - 11th	P2
	■										■			■	■	■	■	Jan 14th - 18th	
	■										■			■	■	■	■	Jan 21st - 25th	
	■										■			■	■	■	■	Jan-Feb 28th-1st	
																		Feb.4th-8th	
	■										■	■	■	■	■	■	■	Feb 11th-15th	
	■										■	■	■	■				Feb 18th-22nd	
	■										■	■						Feb-Mar.25th-1st	
	■										■	■						Mar 4th-8th	
■	■	■								■	■	■						Mar 11th- 15th	
■	■	■								■		■						Mar 18th-22nd	
	■								■	■								Mar 25th-29th	P3
																		Apr 1st-5th	
	■								■	■								Apr 8th-12th	
	■								■	■								Apr 15th-19th	
	■							■	■	■								Apr 22nd-26th	
																		Apr-May 29th-3rd	
	■					■	■	■										May 6th-10th	
■	■	■			■	■	■	■										May 13th-17th	
■	■	■	■		■	■	■	■										May 20th-24th	
	■		■		■	■	■	■										May 27th-31st	P4
	■		■		■	■	■	■										June 3rd-7th	
	■		■		■	■	■	■										June 10th-14th	
	■	■	■	■	■	■	■	■										June 17th-21st	
	■	■	■	■	■													June 24th-28th	
■	■	■		■														July 1st-5th	
■	■	■		■														July 8th-12th	P5

Appendix 2

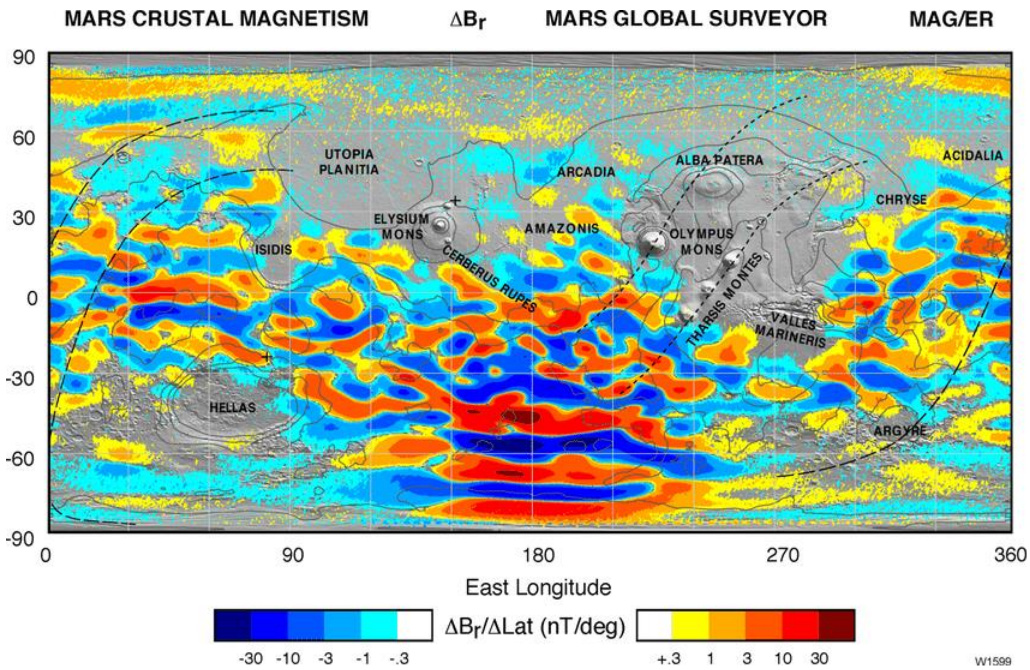

Figure 69: Mars Crustal Magnetic field, MGS Mission, Source: NASA

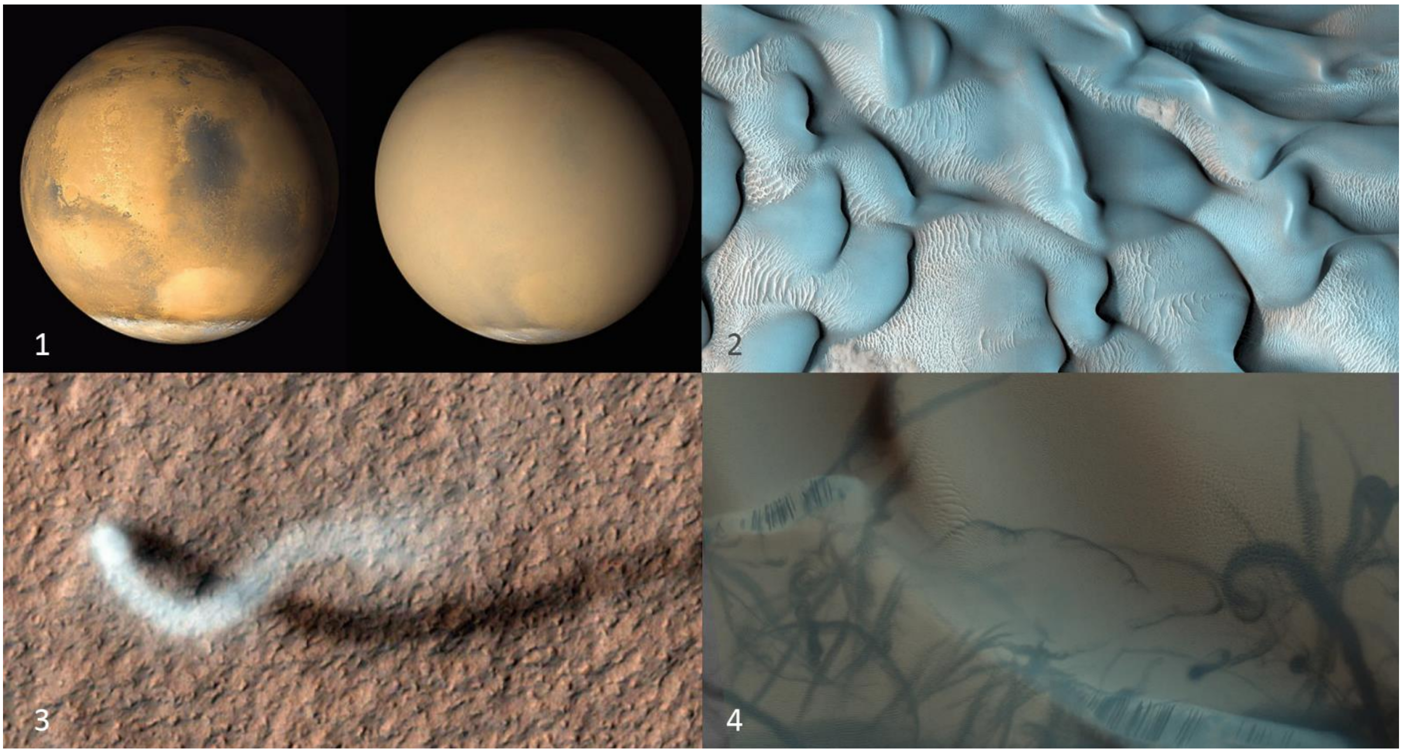

Figure 70: 1 - Comparison of images of the tranquil Mars and Mars covered with dust storm, Source: NASA, 2- sand dunes on Mars, Source: HiRise University of Arizona, 3- example of a dust devil with a base 30m long, Source: HiRise, University of Arizona, 4- Effect of dust devils, dark paths, Source: HiRise, University of Arizona.

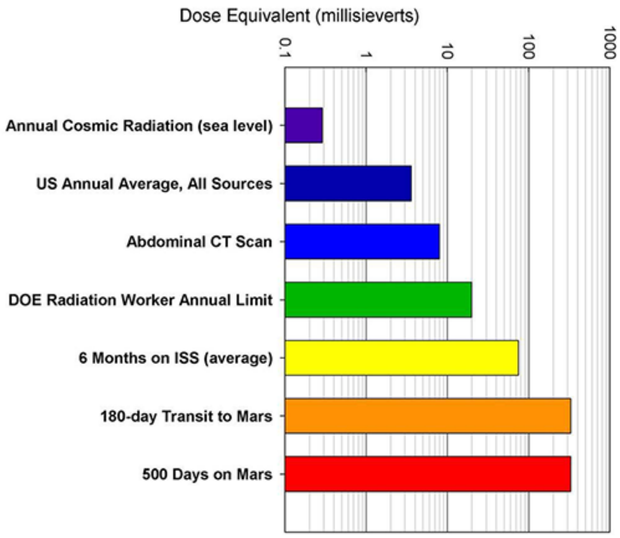

Figure 71: Radiation dose rates. Data for Mars collected by Curiosity mission. Note the scale is drawn in logarithmic increments. Source: M. Bennett, 2015

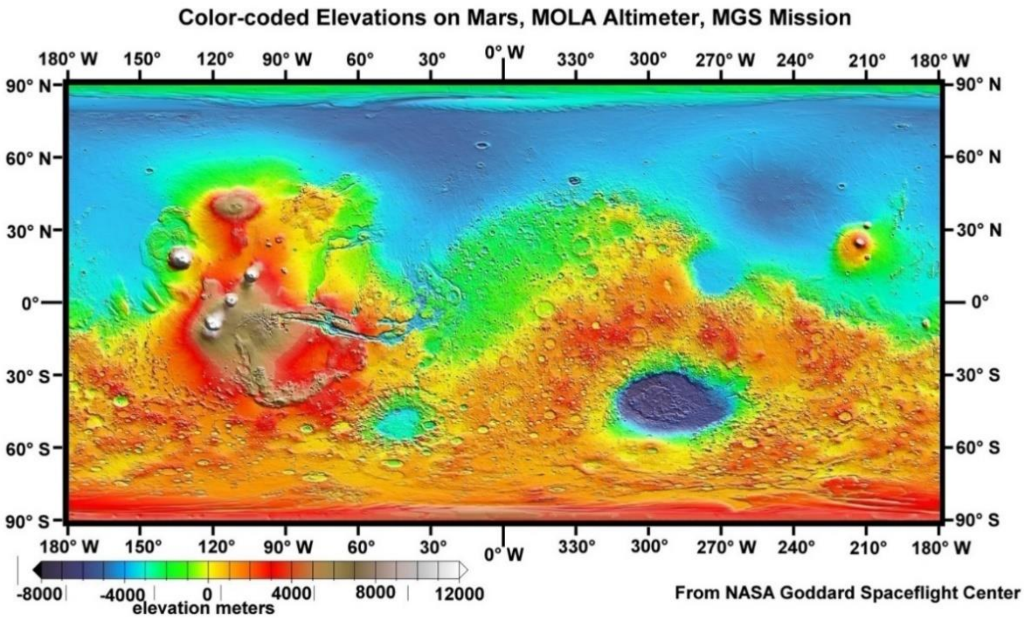

Figure 72: Color-coded elevations on Mars, MOLA Altimeter, MGS mission, Source: NASA Goddard Spaceflight Centre

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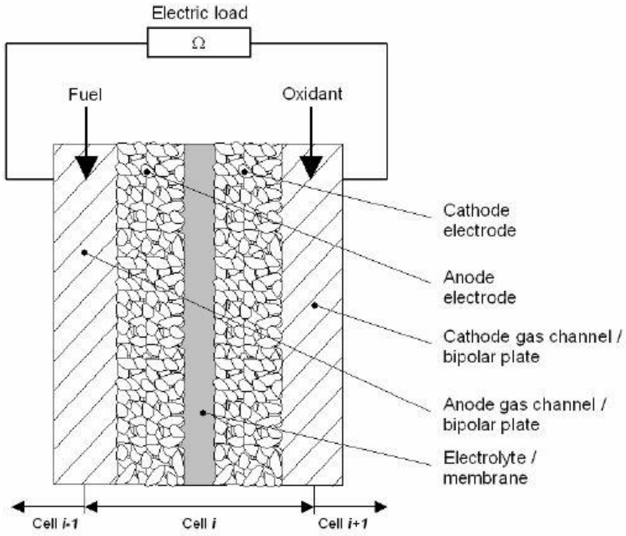

Figure 73: Basic elements of a fuel cell, Source: Soediono, 2009

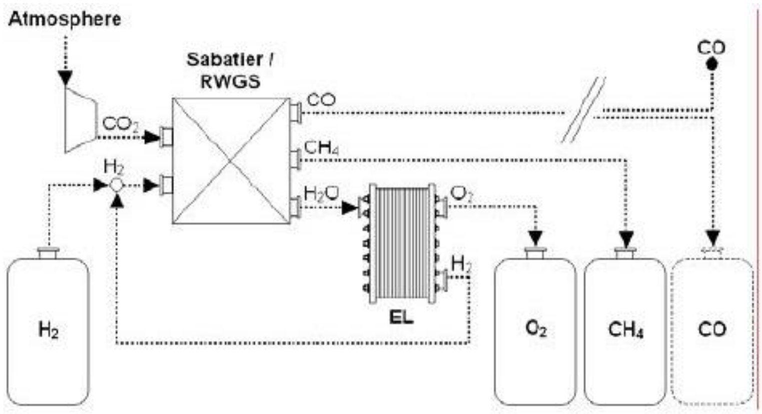

Figure 74: Basic design of the Sabatier reactor, Source: Soediono, 2009

Appendix 3

Table 53: Estimations of the required amount of material for the experiments

length (cm)	width (cm)	height (cm)	density (g/cm^3)	g per sample	amount of samples	g total	kg required
average soil density							
5	5	5	1,33	166,25	50	8312,5	8,3125
5	5	5	1,33	166,25	35	5818,75	5,81875
5	5	5	1,33	166,25	20	3325	3,325
MGS-1 simulant density							
5	5	5	2,72	340	50	17000	17
5	5	5	2,72	340	35	11900	11,9
5	5	5	2,72	340	20	6800	6,8
Pathfinder analysis density							
5	5	5	1,64	205	50	10250	10,25
5	5	5	1,64	205	35	7175	7,175
5	5	5	1,64	205	20	4100	4,1
Viking 1 analysis density							
5	5	5	1,15	143,75	50	7187,5	7,1875
5	5	5	1,15	143,75	35	5031,25	5,03125
5	5	5	1,15	143,75	20	2875	2,875

APPENDIX 4

Table 54: Experiment 1.2 specimens data

No.	BATCH TYPE	MASS 2 (g)	x (mm)	y (mm)	t (mm)	AREA (mm^2)	VOLUME (mm^3)	FORCE (N)	DEFORM. (mm)	STRESS (MPa)	STRAIN	YOUNGS MODULUS (MPa)	COMMENT	GRAPH COMMENT	INTERPRETATION
1a_s	1	4,9	16,5	24,14	7,69	279,32	2148,00	735,51	1,00	2,63	0,13	20,25	a pilot test, determining the required rate and maximum compression value, the sample didn't break and there were no specific cracks on the surface	the curve is concave upward and reaches linear shape at the end	there is a micro-fracture at the beginning of the compression, there is no yield drop in the curve
1b_s	1	4,9	16,5	24,14	6,69	279,32	1868,68	2792,81	0,92	10,00	0,12	83,32	sample broke, the round edges cracked vertically and split off, one crack on the top surface going along the straight edge	the curve starts with the concave upward shape, linear shape until 2/3 of the failure load, reaches rounded peak	the material indicates brittle behaviour
2_s	1	2,9	10,2	25,12	7,5	153,73	1153,01	230,73	0,37	1,50	0,05	30,18	sample broke, the round edges cracked vertically and split off, one crack on the top surface going across the sample	the curve starts with the concave upward shape, linear shape until 3/5 of the failure load, has two compression peaks	the material indicates brittle behaviour, after one stress peak which caused the significant crack the material resisted another increase of load, the strength is almost 5 times lower than the heated specimen with the same composition
3_s	1	5,4	28,2	27,33	4,7	660,00	3102,00	9003,45	1,12	13,64	0,24	57,25	the sample didn't break and no cracks appeared, the testing stopped because the deformation reached the limit	the curve is concave upward and reaches linear shape at the end	the material shows compressive strength higher than 50MPa, however, the deformation of the sample reached almost 1/3 of the height
3_b	1	5,4	28,2	27,33	3,58	660,00	2362,80	32973,9 9	1,21	49,96	0,34	147,75	the sample's edges cracked, the centre of the specimen hardened and became darker than the outer surface	the curve is concave upward, reaches linear shape until the middle, changes into slightly concave downwards curvature. Moreover, the strain reached highly disturbing 0,56 value	although there is no visible yield drop the edges of the sample cracked when the curvature changed into concave downwards. This moment can indicate the compression (60MPa) at which a bigger sample would reach the peak
4.1a_s	1	7	17,9	33,89	8,42	450,80	3795,73	4786,00	1,60	10,62	0,19	55,87	the sample didn't break and no cracks appeared, the testing stopped because the deformation reached the limit	the curve is concave upward and reaches linear shape at the end	there is a micro-fracture at the beginning of the compression, there is no yield drop in the curve
4.1b_s	1	7	17,9	33,89	6,82	450,80	3074,45	4509,26	0,50	10,00	0,07	135,23	the sample didn't break and no cracks appeared, the testing stopped because the load reached the limit	the curve is concave upward, reaches linear shape until the middle, changes into slightly concave downwards curvature.	although there is no visible yield drop the edges of the sample cracked when the curvature changed into concave downwards. This moment can indicate the compression (10MPa) at which a bigger sample would reach the peak
4.1_b	1	7	17,9	33,89	5,94	450,80	2677,75	6289,74	0,65	13,95	0,11	128,01	the sample's edges cracked, the centre of the specimen hardened and became darker than the outer surface	the curve starts with the concave upward shape, linear shape until 4/5 of the failure load, reaches rounded peak	the material indicates brittle behaviour, resisted slightly higher stress than the heated specimen with composition Batch 1
4.2_s	1	7,1	14,6	31,9	6,08	333,74	2029,17	1670,08	0,60	5,00	0,10	50,72	-	the curve starts with the concave upward shape, linear shape until 4/5 of the failure load, reaches rounded peak	the material indicates brittle behaviour, resisted almost 3 times lower stress than the baked sample

No.	BATCH TYPE	MASS 2 (g)	x (mm)	y (mm)	t (mm)	AREA (mm²)	VOLUME (mm³)	FORCE (N)	DEFORM. (mm)	STRESS	STRAIN	YOUNGS MODULUS (MPa)	COMMENT	GRAPH COMMENT	INTERPRETATION
5_b	1	12,74	34,6	34,6	7,58	838,01	6352,13	15042,80	1,10	17,95	0,15	123,46	the sample's edges cracked, the centre of the specimen hardened	the curve is concave upward, reaches linear shape until the middle, changes into slightly concave downwards curvature.	although there is no visible yield drop the edges of the sample cracked when the curvature changed into concave downwards. This moment can indicate the compression (18MPa) at which a bigger sample would reach the peak
6.1_b	2	2,3	15,2	30,74	4,2	360,35	1513,47	3602,13	0,86	10,00	0,20	48,85	the sample's edges cracked, the centre of the specimen hardened	the curve starts with the concave upward shape, linear shape until 1/3 of the failure load, then the yield appears, but at the ε=0,35 the curvature becomes linear again and the stress increases until the limit value	at the yielding section the fracture occurs, which might be the source of the edge cracks. The stress around this point (25MPa) might be the actual peak stress
6.2_s	2	3,3	18,2	32,16	4	518,90	2075,62	9011,20	1,16	17,37	0,29	60,08	the sample didn't break and no cracks appeared, the testing stopped because the deformation and load reached the limit	the curve is concave upward and reaches linear shape at the end	the material shows compressive strength higher, however, the deformation of the sample reached almost 1/3 of the height
6.2_b	2	3,3	18,2	32,16	2,84	518,90	1473,69	15543,42	0,90	29,95	0,32	94,83	the sample's edges cracked, the centre of the specimen hardened and became darker	the graph similar to 6,1_b though with higher values. After the yielding section, the strain exceeded 0,5 which resulted in an increase of the stress, because the specimen became a thin disk	at the yielding section the fracture occurs, which might be the source of the edge cracks.
7.1_b	3	3	18	30,65	4,67	440,13	2055,43	4400,64	0,83	10,00	0,18	56,12	the sample's edges cracked, the centre of the specimen hardened	the curve starts with the concave upward shape, linear shape until almost 1/3 of the failure load, then the yield appears, but at the ε=0,32 the curvature becomes linear again and the stress increases until the limit value	at the yielding section the fracture occurs, which might be the source of the edge cracks. The stress around this point (15MPa) might be the actual peak stress
7.2_s	3	3,4	17,1	27,39	3,88	374,70	1453,82	8994,06	0,96	24,00	0,25	97,18	the sample didn't break and no cracks appeared, the testing stopped because the deformation and load reached the limit	the curve is concave upward and reaches linear shape at the end	the material shows compressive strength higher, however, the deformation of the sample reached almost 1/4 of the height
7.2_b	3	3,4	17,1	27,39	2,92	374,70	1094,11	11225,90	0,77	29,96	0,26	114,23	the sample's edges cracked, the centre of the specimen hardened	the graph similar to 6,2_b. After the yielding section, the strain exceeded 0,5 which resulted in an increase of the stress, because the specimen became a	at the yielding section the fracture occurs, which might be the source of the edge cracks.
8	3	11,9	33,2	31,77	7,82	792,33	6195,99	11846,61	1,36	14,95	0,17	85,94	the sample's edges cracked, the centre of the specimen hardened. Few short cracks appeared in the centre	the curve is concave upward, reaches linear shape until the middle, changes into slightly concave downwards curvature.	although there is no visible yield drop the edges of the sample cracked when the curvature changed into concave downwards. This moment can indicate the compression (15MPa) at which a bigger sample would reach the peak

No.	BATCH TYPE	MASS 2 (g)	x (mm)	y (mm)	t (mm)	AREA (mm²)	VOLUME (mm³)	PEAK FORCE 1 (N)	TOTAL DEFORM. (mm)	PEAK STRESS	PEAK STRAIN	YOUNGS MODULUS (MPa)	COMMENT	GRAPH COMMENT	INTERPRETATION
9.1	4	4,3	18,5	33,06	8,86	428,59	3797,31	4693,56	1,19	10,95	0,13	81,74	the sample's edges cracked, the centre of the specimen hardened. Few short cracks appeared in the centre	the curve starts with the concave upward shape, linear shape until 4/5 of the failure load, reaches rounded peak	the material indicates brittle behaviour
9.2	4	3,4	17,2	33,3	8,59	400,23	3438,00	2399,67	0,65	6,00	0,08	78,88	the sample's edges cracked, multiple short cracks appeared in the centre	the curve starts with the concave upward shape, linear shape until 4/5 of the failure load, reaches rounded peak	the material indicates brittle behaviour
10.1	4	7,5	18	33,62	5,21	423,61	2207,02	8453,72	1,47	19,96	0,28	70,89	the sample's edges slightly cracked, the centre of the specimen hardened	the curve starts with the concave upward shape, linear shape until almost 2/3 of the failure load, then the yield appears, but at the ε=0,35 the curvature becomes linear again and the stress increases until the deformation limit	at the yielding section, the fracture occurs, which might be the source of the edge cracks. The stress around this point (25MPa) might be the actual peak stress
10.2	4	5	15,5	25,14	5,2	273,12	1420,23	2730,09	0,70	10,00	0,14	73,98	the sample's edges cracked, multiple short cracks appeared in the centre	the curve starts with the concave upward shape, linear shape until 4/5 of the failure load, reaches rounded peak	the material indicates brittle behaviour
11	5	5,9	34,3	34,5	3,78	934,35	3531,83	25206,28	2,00	26,98	0,53	50,99	the sample didn't break and only small cracks appeared, the testing stopped because the deformation reached the limit	the curve is concave upward and reaches linear shape at the end	the material shows compressive strength higher than 50MPa, however, the deformation of the sample exceeded 1/2 height
12.1	6	12,9	18,8	33,35	7,8	554,90	4328,23	3604,45	0,96	6,50	0,12	52,81	the sample's edges cracked, few short cracks appeared in the centre	the curve starts with the concave upward shape, linear shape until 2/3 of the failure load, reaches rounded peak	the material indicates brittle behaviour
13	7,1	13,1	26	31,21	7,5	764,64	5734,80	15258,45	1,41	19,96	0,19	106,49	the sample's edges cracked, the centre of the specimen hardened.	the curve is concave upward, reaches linear shape until the middle, changes into slightly concave downwards curvature.	although there is no visible yield drop the edges of the sample cracked when the curvature changed into concave downwards. This moment can indicate the compression (22MPa) at which a bigger sample would reach the peak
14.2	7,2	12,82	17,8	33,94	7,57	498,56	3774,08	6955,34	0,96	13,95	0,13	110,21	the sample's edges cracked, few short cracks appeared in the centre	the curve starts with the concave upward shape, linear shape until 4/5 of the failure load, reaches rounded peak	the material indicates brittle behaviour
15	7,3	14,18	31,2	34,32	8,24	924,62	7618,89	41564,68	1,56	44,95	0,19	237,38	the sample's edges cracked, the centre of the specimen hardened.	the curve is concave upward, reaches linear shape until 4/5, changes into concave downwards curvature.	although there is no visible yield drop the edges of the sample cracked when the curvature changed into concave downwards. This moment can indicate the compression (45MPa) at which a bigger sample would
16	7,4	13,95	35	35	7,59	961,63	7298,73	23997,60	1,24	24,96	0,16	152,44	the sample's edges cracked, multiple circular cracks appeared around the centre. Cracking sound during compression	the curve is concave upward, reaches linear shape until 2/3, changes into concave downwards curvature with some yield drops due to instant cracking.	sound maybe due to the sulfur particles were breaking. The circular crack around the centre due to flattening and expansion of the sample