Design and Implementation of a Lunar-Sourced Sustainable Habitat Material for Further Manned Space Exploration

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ABSTRACT

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With the success of many spacecraft reaching Mars, the future possibility of a manned Mars landing is nearer than the general public thinks. However, the steps to achieve that objective starts from the Moon and its environment. A lunar base of operations is needed as a foundation for any long-term manned space expeditions. In comparison to Earth, the Moon is much more dangerous when it comes to human health and sustenance. The environment contains radiation and lunar dust that are proven to be deadly to the average human being. Furthermore, the soil on the Moon does not provide the necessary nutrients for seeds and crops to thrive in. With the reasons mentioned, it is important for engineers to provide a structure that will house and sustain the lives of astronauts. Several lunar materials have been researched and developed on as possible lunar construction options, such cast regolith and lunar concrete. However, further research needs to be performed to fully protect astronauts from all the possible dangers in space. Therefore, the next step in research and development is improving the already known construction options through additive manufacturing and fiber implementation. Basalt is an Earth-based simulant that has similar material properties as lunar regolith making it a viable resource for lunar construction research. The program used to research improvements for lunar regolith is the static structural feature of ANSYS. Specifically, applying tensile, compression, and 3-point bending tests will give stress and strain results that can be compared to its baseline data of solely cast regolith. By creating basalt fibers and implementing them into a cast regolith matrix, it can be seen that the composite created becomes more ductile than before while stress values are decreasing slightly for a constant applied force. Therefore, it is possible to improve what is already known about processed regolith. Furthermore, future technologies and research will further improve the aspects that cast regolith contains.

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TABLE OF CONTENTS

ABSTRACT ………………………………………………………………………………………….. i

ACKNOWLEDGEMENTS ……………………………………………………………………….. i

LIST OF TABLES ……………………………………………………………………………….. vii

LIST OF FIGURES ……………………………………………………………………………… viii

NOMENCLATURE …..……..……………………………………………………………….….... xi

1. CHAPTER 1: INTRODUCTION ……………………………………………………….... 1

1.1 Motivation ……………………………………………………………………………….... 1

1.2 Literature Review ………………………………………………………………………..... 3

1.2.1 Importance of Moon Exploration ………………………..………………………….. 3

1.2.2 Lunar Materials ………………………………………………………………………. 4

1.2.3 Human Health Factors ……………………………..…………………………….... 4

1.2.4 Lunar Habitat Concept ……………………………………….……………………..... 5

1.2.5 Technological Possibilities for Construction …………………….………………….… 8

1.3 Problem Objective ………………………………………………………………………… 9

1.4 Methodology ………………………………………………………………………………9

2. CHAPTER 2: MISSION REQUIREMENTS ………………………………………………….. 11

2.1 Lunar Habitat Structure Mission Definition ……………………………………………… 11

2.2 Structural Design Function ………………………………………..…………………... 11

2.2.1 Technical Requirements for Structural System ……………………..……………… 11

2.2.2 Structural Requirements Rationales ……………………………………..…………. 12

2.3 Life Support Design Function ………………………………………………….……... 14

2.3.1 Technical Requirements for Life Support System …………………………….… 14

2.3.2 Life Support Requirements Rationales ……………………………………….……… 14

3. CHAPTER 3: LUNAR REGOLITH PROPERTIES ……………………………………….... 17

3.1 Lunar Regolith ………………………………………………………………………….. 17

3.1.1 Properties of Lunar Regolith ……………………………..……………………… 18

3.1.2 Similar Materials ……………………………………………..…………………. 19

3.2 Processed Lunar Regolith Improvements ………………………………..………………. 20

3.2.1 Advantages and Disadvantages of Lunar Regolith ……………………..…………... 20

3.2.2 Possible Additive Materials for Lunar Regolith Improvement ……………..……… 21

3.3 Numerical Modelling for Lunar Regolith Processing ………………………………..…….... 23

3.3.1 Tensile Failure Test ………………………………………………………………. 23

3.3.2 Compression Failure Test ………………………………..……………………………… 24

3.3.3 Three Point Bending Test …………………………………….……………………… 25

4. CHAPTER 4: MODELLING NUMERICAL TESTS ……………..………………………. 26

4.1 Modelling Through the ANSYS Program ……………………….……………………. 26

4.2 Numerical Testing Process ………………………………………….………………… 26

4.2.1 Material Input and Mesh Appropriateness ……………………………………………… 26

4.2.2 Setup for Tensile Test ……………………………………………..……..…… 27

4.2.3 Setup for Compression Test ……………………………………………..…………. 29

4.2.4 Setup for Three Point Bending Test …………………………..……………..……… 32

4.3 Results Obtained from Numerical Testing………………………………………………..… 34

5. CHAPTER 5: DISCUSSION OF RESULTS …………………………………………………… 36

5.1 Incorporating Additives within ANSYS Engineering Data ……………………………………… 36

5.2 Additive Tensile Test Results Compared to Baseline Results ……………….………………….. 38

5.3 Additive Compression Test Results Compared to Baseline Results …………….......................... 40

5.4 Additive 3pt-Bending Test Results Compared to Baseline Results …………………………….. 42

5.5 Discussion Based on the Results ……………………………………………………………… 43

6. CHAPTER 6: CONCLUSION AND FINAL REMARKS ……………………………………….. 44

6.1 Conclusion 44

6.2 Environmental, Economic, and Social Impacts ……………………………………………….. 44

6.3 Future Technology ……………………………………………………………………..… 45

6.4 Suggested Testing Improvements and Future Work ……………………………………………... 47

REFERENCES ……………………………………………………………………………………. 48

APPENDIX A – Hand Calculations for 15% and 25% Basalt Regolith Composite ……………… 50

LIST OF TABLES

Table 1.1: Elemental compositions within unprocessed and highland unprocessed regolith [7] ... 5

Table 2.1: Estimated surface temperatures on the Moon [10] ……………………………..……. 12

Table 3.1: Cast regolith material properties [14] …………………………………………… 18

Table 3.2: Lunar concrete material properties [14] ………………………………………… 18

Table 3.3: Cast basalt material properties [25] [26] ………………………………………… 19

Table 3.4: Basalt fiber properties [27] ………………………………………………………... 22

Table 3.5: Projected computational testing materials ………………………………………… 23

Table 4.1: ASTM dimensions for the flat A370 specimen [30] ………………………………… 28

Table 4.2: ASTM dimensions for the round A370 specimen [30] ……………………………… 28

Table 4.3: ASTM dimensions for the D695 specimen [31] …………………………………… 30

Table 4.4: ASTM dimensions for the D695 rectangular prism specimen [31] ………………… 31

Table 4.5: ASTM dimensions for the D790 specimen [32] …………………………………….. 36

Table 5.1: Maximum deformations of the aforementioned testing materials …………………… 39

LIST OF FIGURES

Figure 1.1: Artist depiction of an inflatable habitat that contains the needs of astronauts [2] …... 1

Figure 1.2: Planned mission path for manned Mars missions [4] ……………………………….. 2

Figure 1.3: Sketch of Path from Earth to Mars with the Moon and orbiting asteroids …………... 3

Figure 1.4: Business analysis of base power as estimated by Mankins Space Technology [5] … 4

Figure 1.5: Pictures of lunar regolith obtained from previous manned Moon missions [3] …… 5

Figure 1.6: Photos of the Mare Orientale lunar crater showing prominent concentric rings [8] … 6

Figure 1.7: Inflatable habitat with a multilayer wall design [15] ………………………………… 7

Figure 1.8: Rigid/in-situ resourced geodesic dome concept [15] ………………………………... 8

Figure 2.1: Lunar surface temperature based on the time after Noon, in different latitudes [3] ... 12

Figure 2.2: Spherical lunar habitat concept with floor height dimensions [14] ……..……... 13

Figure 2.3: Argon concentration with respect to the subsolar longitude on the Moon [3] ……… 14

Figure 2.4: Helium concentration with respect to the subsolar longitude on the Moon [3] …… 15

Figure 2.5: Lunar habitat concept with surrounding radiation protection [14] ………………… 15

Figure 3.1: Comparative petrology taken by different manned flights to the Moon [10] ……… 17

Figure 3.2: Macro- and microscopic views of basalt fiber [28] ………………………………… 20

Figure 3.3: Regolith implementation for structure protection conceptual sketch [9] …………… 21

Figure 3.4: Process of basalt fiber production [27] …………………………………………… 22

Figure 3.5: Forces on material for tensile test (a), brittleness result (b), and ductility result (c) .. 23

Figure 3.6: Stress-strain graph depicting the results of different materials ……………………. 24

Figure 3.7: Compression testing before (a) and after (b) forces are applied …………………… 24

Figure 3.8: Three point bending test before (a) and after (b) forces are applied ……………….. 25

Figure 4.1: Cast regolith properties implemented in ANSYS engineering data module ……..…. 26

Figure 4.2: ASTM standard longitudinal tensile test specimens, known as A370 [30] ………... 27

Figure 4.3: Rectangular tension test specimen [30] …………………………………………... 27

Figure 4.4: Round tension test specimen [30] ………………………………………………... 28

Figure 4.5: Model, BCs, and load (a) and mesh sizing (b) for ANSYS tensile test ……………. 29

Figure 4.6: Sketched ASTM D695 specimen, in a cylinder and in a rectangular prism ………... 30

Figure 4.7: Sketched ASTM D695 specimen in a rectangular prism …………………………… 31

Figure 4.8: Model, BCs, and load (a) and mesh sizing (b) for ANSYS compression test ……… 32

Figure 4.9: Sketched ASTM D790 specimen …………………………………………………… 32

Figure 4.10: Model, BCs, and load (a) and mesh sizing (b) for ANSYS 3pt bending test ……... 33

Figure 4.11: Test results of the tension test for a fully cast regolith specimen …………………. 34

Figure 4.12: Test results of the compression test for a fully cast regolith specimen ……………. 35

Figure 4.13: Test results of the 3pt-bending test for a fully cast regolith specimen ……………. 35

Figure 5.1: ANSYS simulated SFC (a) and random UDC (b) ………………………………….. 36

Figure 5.2: Solving for Young’s modulus for 5% basalt fiber within a cast regolith matrix …… 37

Figure 5.3: New composite materials inserted into the engineering data module of ANSYS ….. 38

Figure 5.4: ANSYS simulated tensile test with deformation-based gradient …………………… 38

Figure 5.5: Simulated tensile results of SFC-implemented cast regolith ……………………….. 39

Figure 5.6: Simulated tensile results of UDC-implemented cast regolith ………………………. 40

Figure 5.7: ANSYS simulated compression test with deformation-based gradient …………….. 40

Figure 5.8: Simulated compression results of SFC-implemented cast regolith …………………. 41

Figure 5.9: Simulated compression results of UDC-implemented cast regolith ………………... 41

Figure 5.10: ANSYS simulated 3pt-bending test with deformation-based gradient ……………. 42

Figure 5.11: Simulated 3pt-bending results of SFC-implemented cast regolith ………………... 42

Figure 5.12: Simulated 3pt-bending results of UDC-implemented cast regolith ……………….. 43

Figure 6.1: 3D-printed regolith simulant, (A) hollow cone and (B) hollow dome structure [20] . 45

Figure 6.2: NASA technology readiness levels [33] ……………………………………………. 46

Figure 6.3: Lattice structures assembled by a robot [18] ……………………………………….. 47

NOMENCLATURE

Symbol	**Definition**	**Units (SI)**
P	Applied Load	N
A	Original Cross Sectional Area	m^2
L	Original Length	m^2
CS	Compressive Strength	Pa
F	Loading Force	N
E	Modulus of Elasticity	Pa
Greek Symbols		
σ	Stress	Pa
ε	Strain	-----------
δ	Change in Length of the Material	m
Acronyms		
BC	Boundary Conditions	-----------
SFC	Short Fiber Composite	-----------
UDC	Unidirectional Composite	-----------

1. Introduction

1.1 Motivation

Since the most recent manned landing on the Moon in 1972, lunar design missions have been suspended for a period of time. The major factor that led to the suspension had been due to the fact that the cost of the missions was increasing while the federal budget of NASA was decreasing overtime [1]. However, recent significant milestones apropos to the robotic exploration of Mars renewed interest to where scientists and engineers believe that planetary colonization is attainable. Therefore, the usage of a lunar habitat system has become essential for new space exploration programs and the Moon is the most practical and logical first milestone for habitation [2].

The function of the lunar habitat structure is to establish a sustainable base for manned exploration on the Moon. The basic needs for a human to live within any environment are the following:

- Oxygen
- Food
- Water
- Shelter

If there is not an easily-available source for each need, then humans are unable to survive long periods without them. Therefore, lunar habitats are designed to accommodate the needs for astronauts by implementing vegetation, water management, and atmosphere revitalization systems within the structure. Including the structural system, these four systems will provide sustainable living conditions for the explorers of the Moon. Shown in figure 1.1, a conceptual habitat with multiple floors is designed [2].

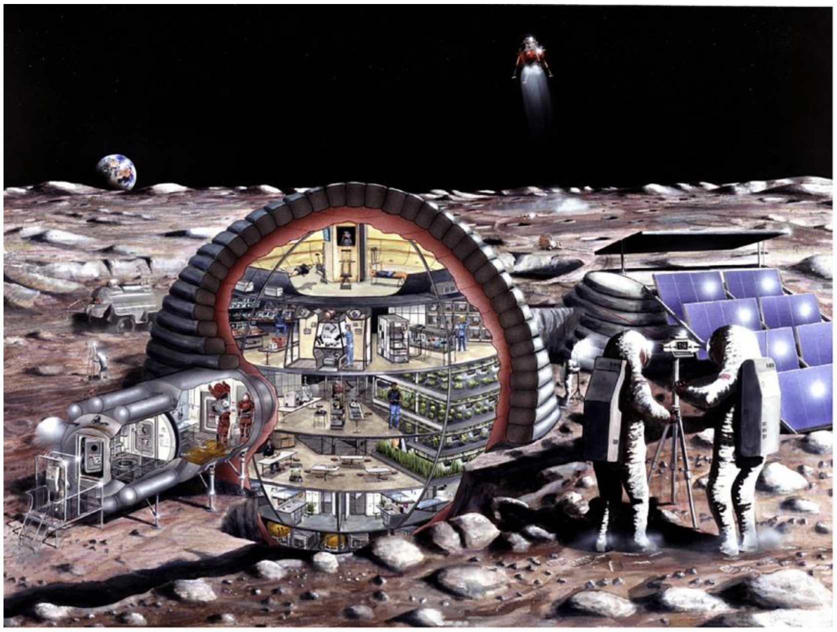


Figure 1.1: Artist depiction of an inflatable habitat that contains the needs of astronauts [2].

However, before constructing a base of operations that will provide the needs for future space pioneers, it is important to take into account the environment in space and on the Moon. The Moon is a challenging environment for a long-term human, due to meteor impacts, high thermal gradients, and the effects of space radiation and plasma [3]. Also, the Moon has a different atmosphere and a different acceleration of gravity compared to the Earth. Meteor impacts threaten the livelihoods of those on the Moon as well as the integrity of structures. High thermal gradients and plasma can cause stress through expansion or contraction that will lead to a failure in construction materials. Radiation affects both construction material and human physiology. These factors are important for the design considerations of a lunar habitat.

One other major factor for the design of a lunar habitat is feasibility, which is whether the mission can be conveniently done. The most ideal case for lunar habitat construction is to use the material that is on the Moon and improve its material properties, such as strength and hardness, by implementing additives. A material that has been obtained from the Moon in previous missions is regolith. Therefore, to optimize and to improve feasibility of the lunar habitat design, regolith containing additives will be researched on and be ideally used as the foundation for the structure.

With current aerospace missions trending towards the manned exploration of Mars, it is significant to consider the Moon as a base of operations for research as well as a proving ground for manned space travel and planetary exploration as shown in figure 1.2 [4]. Therefore, lunar habitation is the next major milestone that will allow scientists and engineers to research sustainable living conditions within planets and astronomical bodies dissimilar to Earth. In return, this will provide a foundation for engineers to conduct missions based on manned spatial exploration.

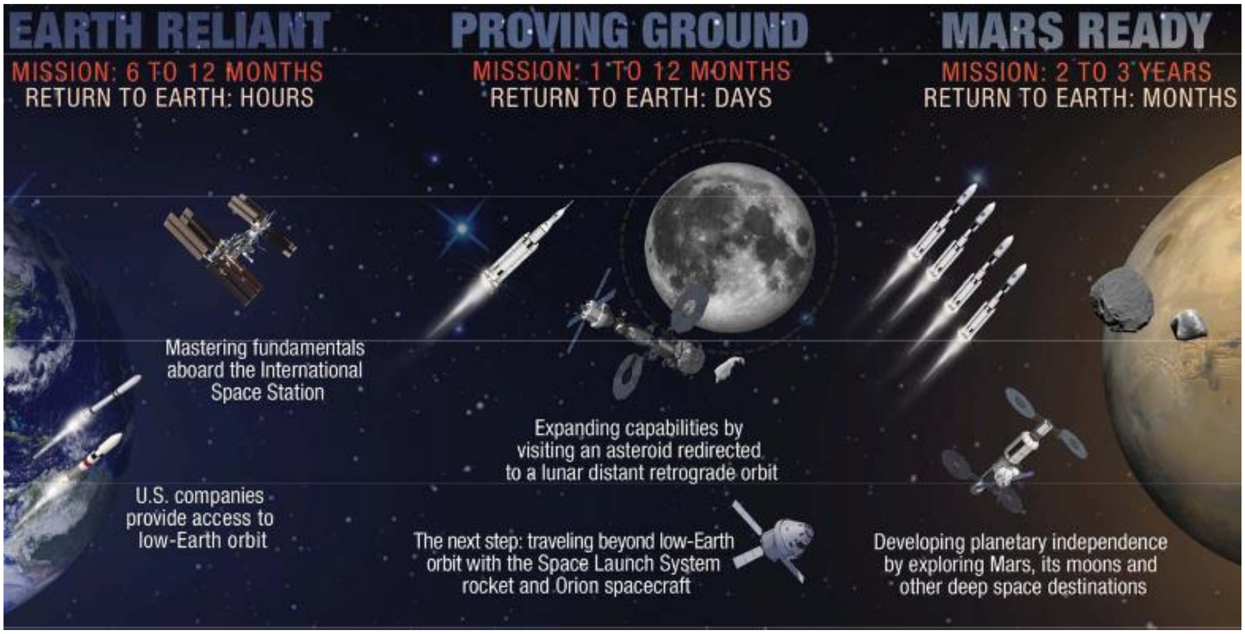


Figure 1.2: Planned mission path for manned Mars missions [4].

1.2 Literature Review

1.2.1 Importance of Moon Exploration

As previously mentioned, establishing human presence on the surface of the Moon will aid the development of manned Mars mission designs [4]. Researching orbits of other astronomical bodies between the Moon and Mars can help engineers determine a path leading to Mars. However, settling on the Moon will provide a foundation for sustainable living conditions that can be used for asteroids that are in the path to Mars. Therefore, research based on the orbit of asteroids and transportation for technology as well as humans are preliminary goals for lunar exploration that must be met to advance towards manned Mars exploration [2]. Figure 1.3 depicts the destinations that a manned spacecraft is expected to take on its way to Mars.

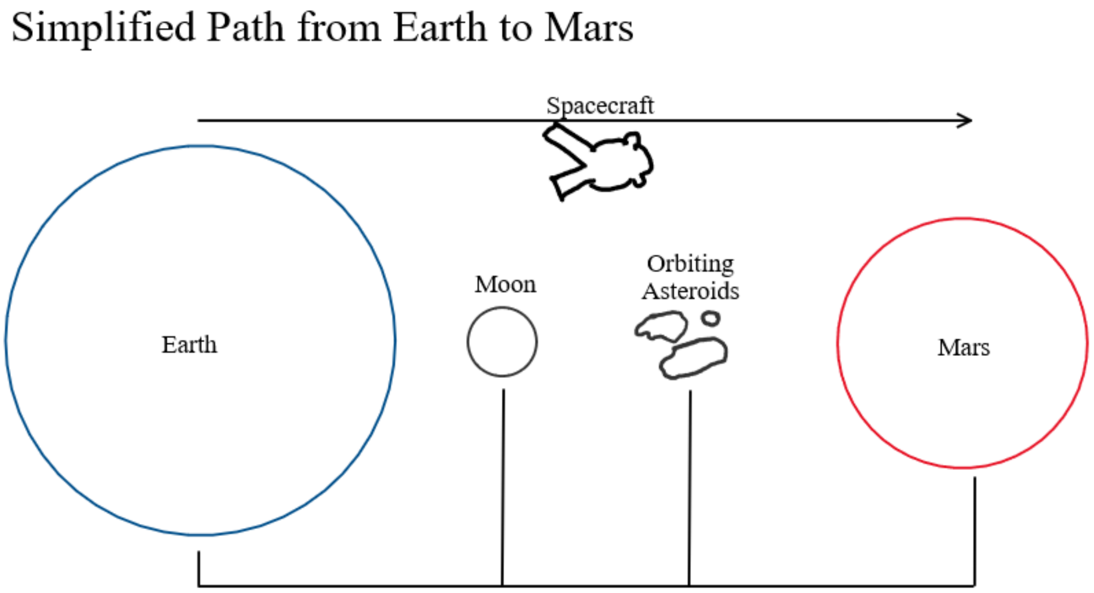


Figure 1.3: Sketch of Path from Earth to Mars with the Moon and orbiting asteroids.

There are several reasons to explore the Moon before proceeding to explore other planets and astronomical bodies. At the very foundation of manned lunar exploration, the financial perspective is a major factor that allows researchers the opportunity to continue space mission designs. Zuniga et al. [1] discuss the incentive for human presence on the Moon by establishing cost-effective industrialization services. In addition to federal aid and support, public and private businesses have given financial subsidies for the hope that communication systems and space products will be a profitable result for the parties involved. As shown in figure 1.4, a partnership between aerospace organizations and industrial companies can reduce the cost and risk of operations. Within the discussed figure, it shows that estimates for solar power development on the Moon makes a simple profit within a business partnership. In this case, both NASA and Mankins Space Technology are able to benefit [5]. Therefore, initial lunar missions are designed to create reusability as well as reduce cost for future spatial exploration missions.

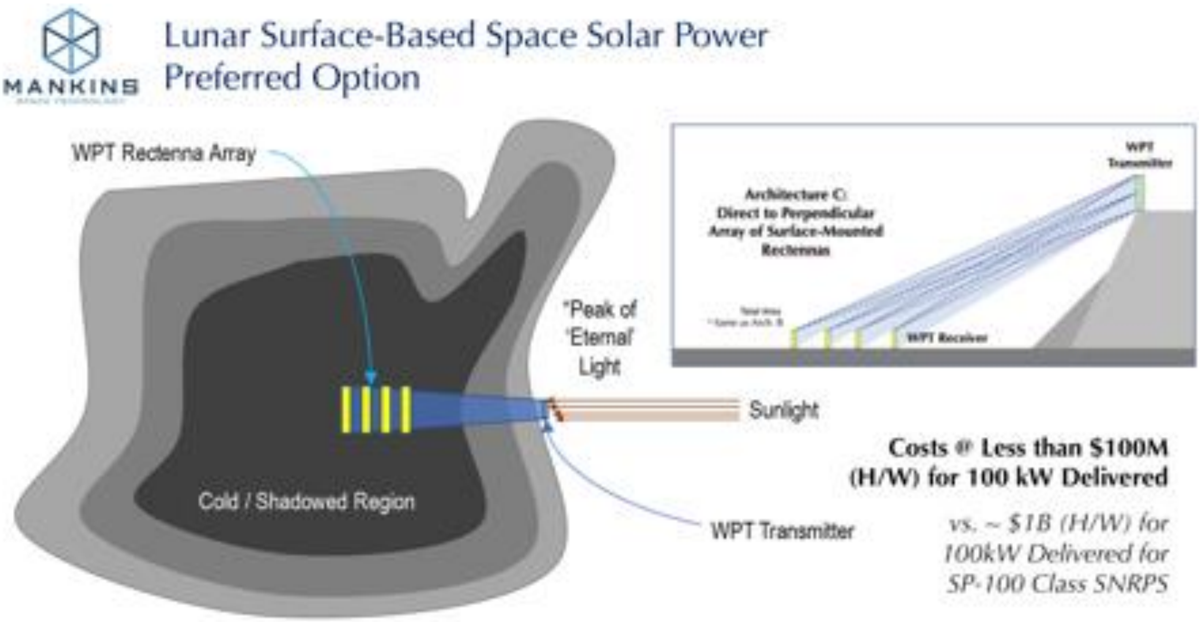


Figure 1.4: Business analysis of base power as estimated by Mankins Space Technology [5].

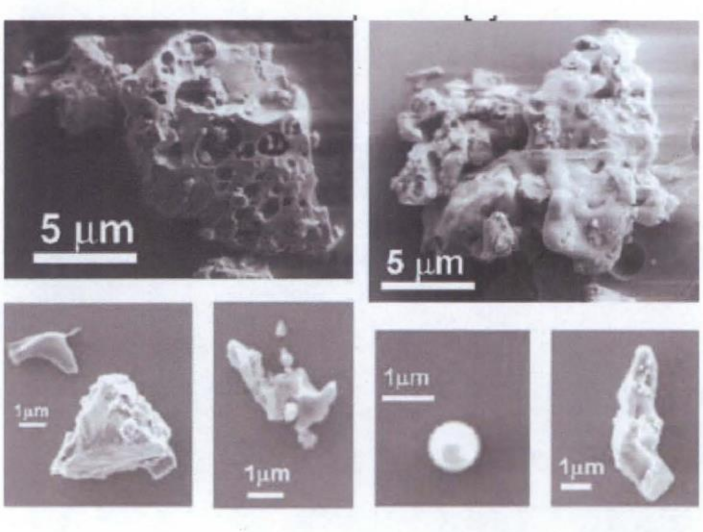
Scientists plan to analyze the material samples that come from the Moon for several purposes, such as date impact events, capture solar winds, and characterize the difference between materials inside and outside permanent shadows [6]. Dating lunar impact events allows scientists to understand the astronomical events that occurred within the solar system, specifically how the Earth has been impacted in relation to the Moon. Since solar winds are a flux of charged particles, capturing it can be utilized as an energy source for lunar habitation. Consequently, engineers will be able to use this energy as a reusable source for further space exploration vehicles. Lastly, engineers will be able to utilize the materials in and out of permanent shadows for construction purposes or for the development of new technologies that will guide future trends of space exploration.

1.2.2 Lunar Materials

There are two different types of readily available lunar materials, which are unprocessed and minimally processed forms of regolith [7]. Unprocessed lunar soil consists of fine rock flour, containing clay-sized to boulder-sized fragments of meteorites. Within its chemistry, this type of regolith is rich with oxygen, silicon, iron, magnesium, and titanium in different concentrations. Soils obtained from highland rocks have a similar elemental composition to the previous type as shown in table 1.1. Furthermore, the undefined values marked by tildes (~) are included into the elements that are not in abundance. Figure 1.5 shows lunar regolith samples varying in size and shape [3].

Table 1.1: Elemental compositions within unprocessed and highland unprocessed regolith [7].

Element	**% of Element in Unprocessed Regolith**	**% of Element in Highland Unprocessed Regolith**
Oxygen (O)	41%	41%
Silicon (Si)	19%	19%
Iron (Fe)	13%	~
Magnesium (Mg)	6%	~
Titanium (Ti)	6%	6%
Aluminum (Al)	~	14%
Calcium (Ca)	~	11%
Other elements not in abundance	15%	9%



[Park et al., 2006]

Figure 1.5: Pictures of lunar regolith obtained from previous manned Moon missions [3].

The Moon and similar astronomical bodies are challenging environments to implement infrastructure due to the exposure of extreme temperatures sourced by space plasma and radiation. Minow et al. [3] have discussed the major environmental problems relating to the Moon which includes the following:

- Lunar atmosphere and dust
- Illumination and thermal environment
- Vibrations and meteor impacts
- Radiation and plasma

Compared to the Earth, the atmosphere of the Moon is tenuous due to its low gravity. Lightweight particles escape the atmosphere of the Moon into space with the aid of the energy that is received from solar heating. The formation of regolith is a result of past meteor impacts and the lack of erosion processes within the Moon. Lunar dust containing regolith is a health and engineering issue within the lunar environment because of its sharp and abrasive characteristics. Chadderton et al. [8] determine that annular and radial structures exist in lunar craters due to meteor impacts and eruptions as shown in figure 1.6. Moreover, an extremely large range of temperatures, varying from 100K to 380K is a consequence of its lack of gravity and low atmosphere [9]. Generally speaking, the energetic particles from the Sun are a minor issue on the Moon. However, large solar particle events pose as a radiation threat to humans and equipment on the surface of the Moon [10].

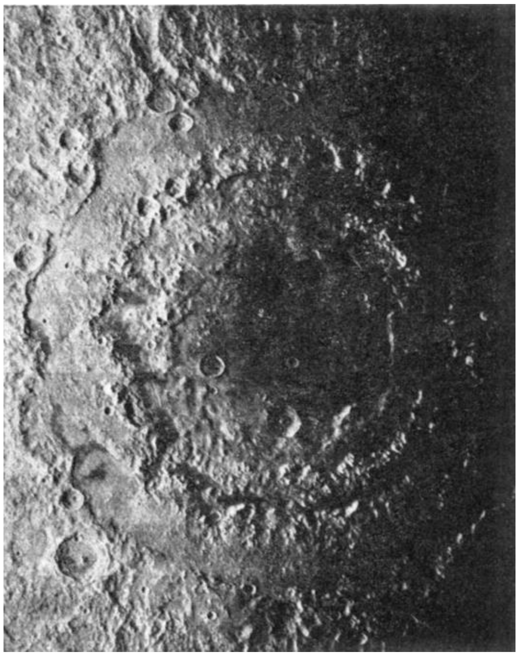


Figure 1.6: Photos of the Mare Orientale lunar crater showing prominent concentric rings [8].

1.2.3 Human Health Factors

As mentioned before, humans have several needs to survive any environment, which are oxygen, food and water, and shelter. Moore et al. [11] describe the effects of spatial environment on the human physiology and how it is important to incorporate design aspects that allow humans to survive within space. For example, the Orion vehicle contains facilities in which the crew can live sustainably, taking into account hygiene, sleep, meal, and exercise within the vehicle.

The human body experiences many physiological effects in flight and in orbit. Over half of all astronauts that have traveled to space have experienced space adaptation syndrome (SAS) which is believed to be caused by conflicting sensory inputs between the inner ear and the eyes. The effects of SAS include the following:

- Space motion sickness
- Headache and back pain
- Insomnia
- Nasal congestion and nosebleed
- Constipation
- Urinary retention and incontinence

However, this syndrome can last at most for two days and can be treated with medicine. The long-term physiological effects that would need physical therapy after a crewed mission in space are listed below [12]:

- Balance disorders
- Cardiovascular deconditioning
- Decreased immune function
- Muscle atrophy
- Bone loss

Human health factors need to be included early in the design process as they are a fundamental requirement for humans to live in space for a prolonged period of time. This can be said for any type of vehicle or shelter system whether it is on land, in air, or in space. Fogarty [12] explains that countermeasures must be put into place for the crew to prevent long-term physiological effects. Suggestions for these countermeasures are resistive exercise, treadmills, and cycle ergometry, where each exercise supports the health of the astronauts onboard. Therefore, comprehending the needs of the astronauts will drive the lunar habitation design and protect capabilities for the following planetary exploration missions.

1.2.4 Lunar Habitat Concept

Lunar construction research has been a topic of interest dating back to 1964, where the amount of facilities within the lunar habitat will drive the cost of the design [13]. Ruess et al. [14] discuss the structural requirements and materials that can be used to optimally construct a lunar habitat. The lunar habitat structure is to be designed to sustain living and inanimate loads, such as vegetation and machinery, with a degree of safety. It must be able to withstand the lunar environment as well as utilize the local materials. Ruess further discusses that processed regolith and composites can be used as the materials for structure, due to the abundance of regolith on the Moon and the effective and lightweight properties in composites.

Human safety is always an important factor when designing an aerospace apparatus. However, research relating to the construction of the Moon must be done to accurately calculate the failure probabilities. Therefore, global safety factors are advised when designing lunar exploration systems.

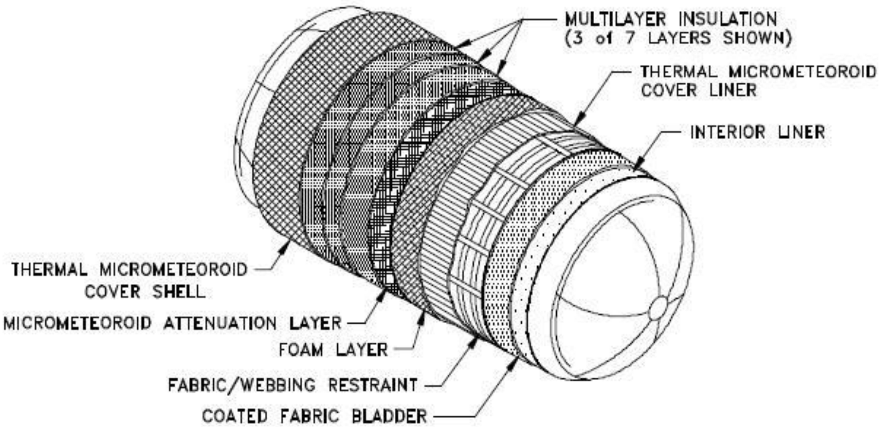


Figure 1.7: Inflatable habitat with a multilayer wall design [15].

Benaroya et al. [2] have explored a few design options for lunar habitat, such as rigid, inflatable, and in-situ resourced structures. The basis for rigid structures consists of metallic paneling forming a cylindrical shell to protect the crew from environmental challenges. However, the issue with rigid structures is transporting the material and constructing the habitat onsite. Therefore, inflatable and in-situ resourced structures, as shown in figures 1.7 and 1.8, are more likely to be early structural options for habitats on the Moon when compared to rigid due to the decreased payload weight for transportation. As previously mentioned, the lunar environment must be taken into account when designing the habitats. Both rigid and inflatable structures offer resistances to the effects of radiation, making them reliable options for habitation designs. The in-situ resourced structure is being researched to determine if it is a viable option against the lunar environmental challenges [15].

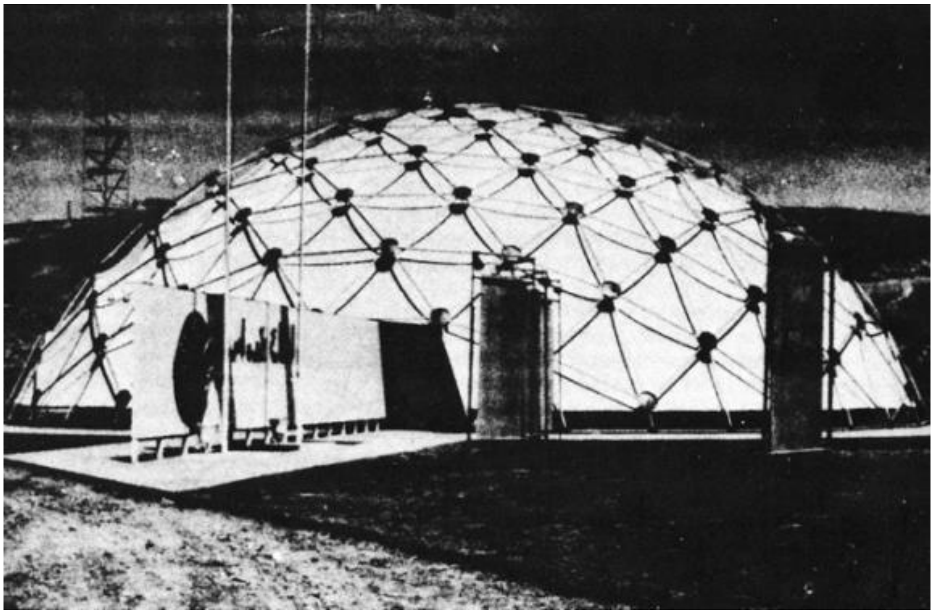


Figure 1.8: Rigid/in-situ resourced geodesic dome concept [15].

A lunar habitat concept designed for the Artemis program integrates non-metallic structural materials to alleviate the radiation health hazard that is emitted from metallic structures. The expected habitat construction to be transported is an inflatable structure due to its packing efficiency and monetary constraints. The proposed structure also includes lunar environment protection as well as human health monitoring [16].

1.2.5 Technological Possibilities for Construction

To explore the Moon, a base of operations must be made to shelter the astronauts from the lunar environment. However, manned construction is not a practical option due to the high risks involved. Robotic habitat construction is a possible alternative that will allow engineers to implement a structure onto the Moon before manned exploration missions are conducted [17]. To progress with robotic structure assembly, guidance, navigation, and control requirements must be met and must be applied within the lunar environment [18].

Through the leverage of industry, academia, and government organizations, in-space manufacturing (ISM) is responsible for the development of manufacturing strategies [19]. Another alternative for lunar construction is 3D-printing with the local materials that are already on the Moon. Additive construction in development will allow engineers to process lunar regolith into a useful source of structural material. Through testing and analysis, it has been shown that 3D additive construction using lunar regolith and basalt fines is a feasible and promising option for lunar habitation design. However, 3D printing has been recently stated to be in the technological readiness level of 3, which means that it is being researched and developed [20]. Further development relating to 3D-printing has come in the form of a NASA Centennial Challenge where the main goal of the challenge is to construct a habitat using natural and recyclable materials fit for the Moon or Mars [21].

1.3 Problem Objective

With the focus of lunar exploration in consideration, habitats and base camps are needed to sustain the lives of the crew. However, many problems will be faced when constructing the habitats, such as the environment and the needs of the astronauts. As space exploration is continuously gaining interest as historical milestones are being met, the process in which these milestones have gone through has been thoroughly investigated to increase reliability, feasibility, and optimize cost effectiveness. Creating sustainable living conditions on the surface of the Moon allows for the progression of space exploration technology. Therefore, the main objective that will be achieved by the end of this report is to determine the material properties of lunar regolith with and without additives and compare the materials to obtain ideal specifications that allow for the construction of a lunar habitat structure on the Moon.

1.4 Methodology

This project will explore the effects of the lunar environment on habitat construction and materials with the following steps:

- *Definitions of requirements and conditions:* Determining the requirements and conditions for the lunar habitat structure will provide engineers with constraints and goals. The constraints will validate whether the habitat is within the expected material characteristics range. Meeting the goals will verify that the habitat can be supported on the Moon.
- *Investigation of local lunar material:* To reduce the cost and weight of material transportation from the Earth to the Moon, processed lunar regolith can be utilized to create the structure of the habitat. However, further research testing based on the material properties, such as tensile strength and hardness, must be analyzed and performed. Moreover, the combination of the regolith and additives have a chance to increase the performance of the lunar material.
- *Comparison between the Earth and the Moon:* The two astronomical bodies differ in many major ways. For one, the Earth contains an atmosphere that protects its inhabitants from radiation emitted from the Sun, while the Moon is practically a vacuum without protection from solar radiation. Secondly, the difference in the acceleration of gravity is significant. Therefore, the construction of the preliminary habitat designs must take into account the lack of solar radiation and the lack of gravity.

- *Establishment of manufacturing strategies for the lunar habitat:* There are various design concepts for the lunar habitat structure and many researchers are finding cost-effective and feasible technologies that will aid its construction. In its most basic constructional form, a crew of astronauts have the ability to build on the Moon with the resources that are transported alongside. Other types of construction methods that will be delved into are the use of robots to build the lunar habitat and the possibility of 3D printing. Both these technological options rely less on the crew constructing the habitat and more on the technology constructing it.

2. Mission Requirements

2.1 Lunar Habitat Structure Mission Definition

The lunar habitat structure must withstand the extreme conditions on the Moon and in space. Moreover, it is imperative that the structure must be able to shelter and to provide sustenance to the crew that will be establishing a base of operations on the Moon. Therefore, the mission is to design and integrate a structure on the Moon that will provide safety and sustainability to a crew of astronauts.

Design considerations and technical mission requirements will ideally be implemented and achieved to fulfill the lunar habitat mission. The design considerations, as mentioned in the previous chapter, relate to the lunar environment and how it can negatively impact the well-being of both the structural integrity and the health of an astronaut on a lunar exploration mission. The technical mission requirements verify and validate the design of the lunar habitat structure that will factor in the environmental and health considerations.

2.2 Structural Design Function

The overall structure of the lunar habitat will be designed to withstand the lunar environment. Several factors will drive the design of the lunar habitat structure, such as lunar atmosphere and dust, thermal environments, meteor impacts, radiation, and plasma [3]. Each of these factors can negatively impact the integrity of the structure in different ways. Therefore, the materials used for the structural design must negate the effects of the lunar environment to uphold the security of the habitat structure.

2.2.1 Technical Requirements for Structural System

Technical requirements are based on lunar structure research that has been recently conducted. With the assumption that there is not any seismic activity on the Moon, the structural system design will adhere to the following technical requirements to achieve practicality, reliability, feasibility, and, lastly, sustainability.

1. The lunar habitat structure shall overcome the gravity of the Moon of 1/6 g.

2. The structure shall withstand the extreme temperatures of the Moon, ranging from 40K to 380K with an error range of ±140K.

3. The structure shall stand firm against meteor impacts at speeds of 20km/s to the extremes of 70km/s, addressing the impact ejecta environment.

4. The structure shall accommodate lunar materials in a higher ratio than materials that will be brought onto the Moon.

5. Radiation shielding shall have similar material properties as a regolith cover to prevent the material expansion of the lunar habitat structure.

6. The lunar habitat structure shall provide a minimum habitable volume of 120m^3 per crew member stationed on the Moon.

2.2.2 Structural Requirements Rationales

Compared to the 9.81 m/s acceleration of gravity on Earth, the Moon has a 1.62 m/s acceleration of gravity, which poses a problem for construction purposes. This means that any structure on the Moon will have about six times of the weight bearing capacity when compared on Earth. The weigh, or load, bearing capacity ultimately determines the maximum weight a material can carry without any displacement. Gravity is important for construction as it holds the structure of a building together and allows for construction machines to secure itself onto the surface. When accounting for gravity, mass-based criteria are utilized rather than weight-based criteria to maximize the use of lunar structural concepts [14]. It is much simpler to conduct measurements based on mass rather than converting the measurements of weight between the differing accelerations of gravity of Earth and of the Moon. Table 2.1 shows the surface temperatures at different locations of the Moon [10]. Recent studies show that thermal conditions on the Moon range from 40K to about 380K shown in figure 2.1.

Table 2.1: Estimated surface temperatures on the Moon [10].

	Shadowed Polar Craters	Other Polar Areas	Front Equatorial	Back Equatorial	Limb Equatorial	Typical Mid-Latitudes
Average Temperature	~40K	220K	254K	256K	255K	220 < T < 255 K
Monthly Range	None	± 10K	± 140K	± 140K	± 140K	± 110K

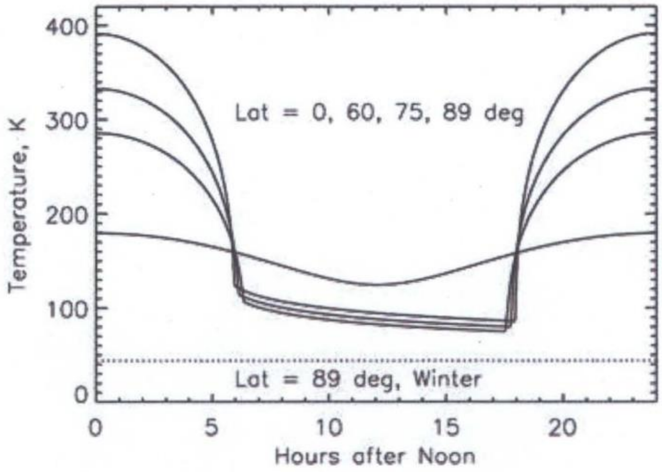


Figure 2.1: Lunar surface temperature based on the time after Noon, graphed in different latitudes [3].

Compared to many astronomical body in the solar system, the Moon has a wide temperature variation except when it is compared to Mercury. The reason for implementing a technical requirement in regards to the high thermal gradients on the Moon is to determine the ideal material for construction. Therefore, the material that will be determined for construction will contain a low thermal expansion coefficient to prevent sections of the lunar habitat structure from experiencing stress due to expansion. The temperature requirement can be verified through heat test measurements and through computational simulations based on the properties of local lunar materials. Materials are usually temperature dependent in many of their material properties, unless there is little variation from the ambient temperature. For many materials, yield strength and compressive strength decrease as the temperature increases. However, the temperature on the Moon can drastically change between freezing temperatures to melting temperatures based on the latitude.

The possibility of meteors striking the Moon is an issue that must be addressed before manned lunar exploration can be conducted. Meteors can vary in shape and composition and have the ability to create a crater with a depth similar to or less than the diameter. Although the likelihood of a meteor striking an astronaut is slim, the more significant hazard is to the vital structures that will be implemented for long durations onto the Moon [9]. Risk analysis can be performed for the lunar habitat structure. However, meteor hazards cannot be fully constrained until a base layout is designed. To satisfy the impact requirement, using compacted regolith, or other materials that are similar, as a layer of shielding will protect the structure from micrometeoroid impacts since dense regolith, specifically, can absorb kinetic energy of the impact [14]. Meteor protection systems that are used by other spacecraft are viable options for shielding. However, the utilization of local lunar materials is more feasible and will provide a basis for other planetary habitation missions. Testing for this requirement can be done through stress simulations to determine the material characteristics that are needed. Therefore, the impact requirement adds another property that must be researched to find the most ideal material.

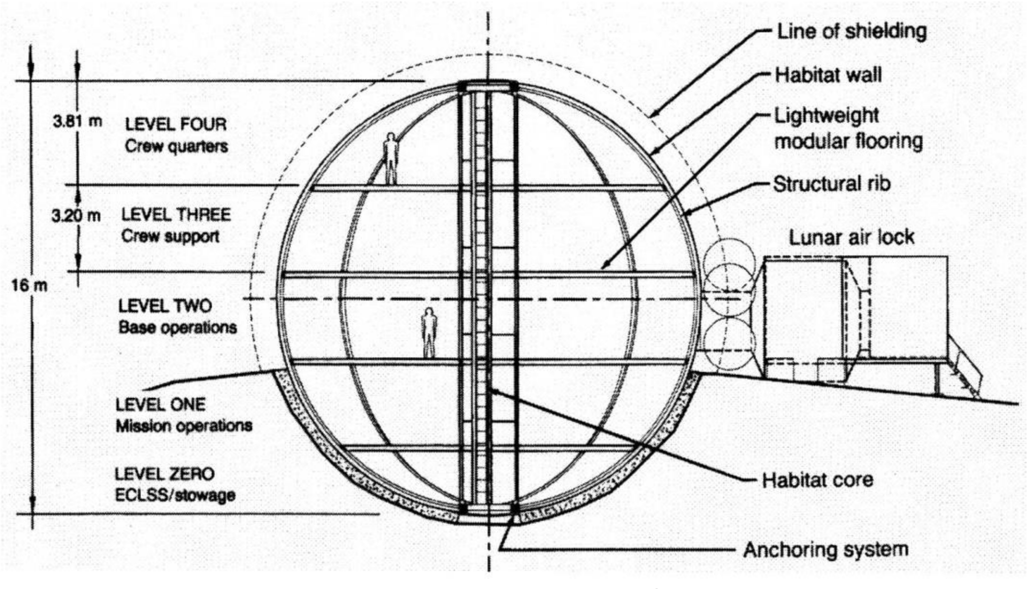


Figure 2.2: Spherical lunar habitat concept with floor height dimensions [14].

The lunar habitat structure will be designed to protect the health of the crew stationed on the Moon. Furthermore, it will have reasonable dimensions that will allow the crew to move freely about the structure. Figure 2.2 depicts a conceptual lunar habitat design that incorporates floor height dimensions.

2.3 Life Support Design Function

The overall function of the life support system will be designed to shelter the lunar exploration crew from the extreme environments on the Moon and provide sustenance to maintain the health of the crew. The factors that will drive the life support system design will be based on the lunar environment as well as the needs of humans. The conditions on the Moon that can negatively affect the crew are the lunar atmosphere and dust, and radiation. The needs of the humans are shelter, which is already established in the structural system, oxygen, and sustenance.

2.3.1 Technical Requirements for Life Support System

The technical requirements for life support design will solve the problems of sustainability and reliability.

1. The lunar habitat structure shall provide a shelter from the lunar atmosphere and dust that will filter oxygen to allow the astronauts to breathe.

2. The radiation shielding shall be at least 2.5 m thick to adhere to the allowable and workable radiation level of 5 rem.

3. Modules within the base of operations will provide 1 kg, ±0.1 kg, worth of food per meal each day and 11 liters, ±0.5 liters, of water per day, per crew member.

2.3.2 Life Support Requirements Rationales

The atmosphere is significantly different on the Moon than that on Earth since it has a high concentration of argon and helium (Ar and He, respectively). Similar to Earth, the subsolar longitude of the Moon determines the atmospheric conditions as graphed in figures 2.3 and 2.4.

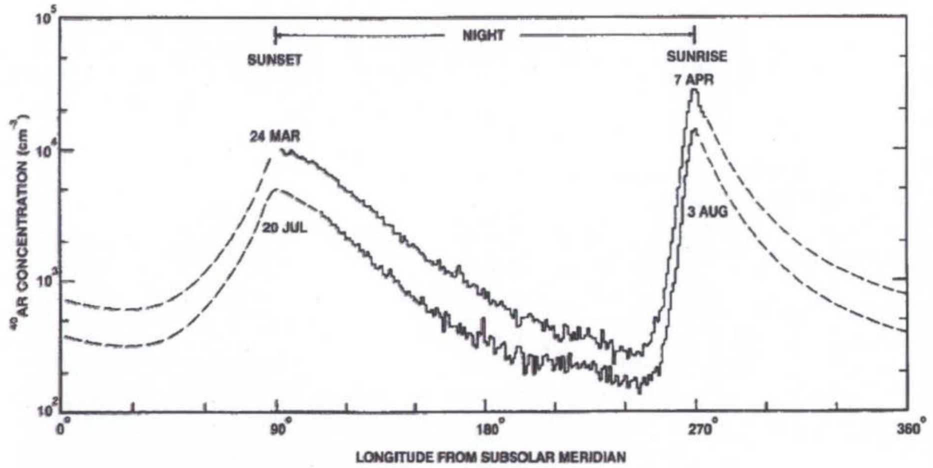


Figure 2.3: Argon concentration with respect to the subsolar longitude on the Moon [3].

In detail, figure 2.3 shows the concentration levels of argon in cubic centimeters. The correlation between the Earth and the Moon is depicted on the graph as dates based on the longitude of the subsolar meridian. The levels of argon peak at the 90° and the 270° marks and are at its minimum at 30° and at 240°.

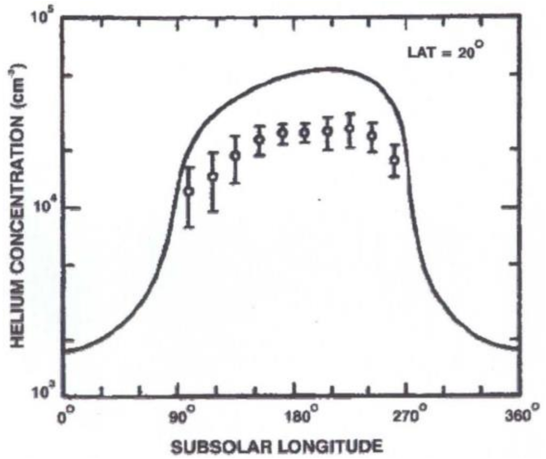


Figure 2.4: Helium concentration with respect to the subsolar longitude on the Moon [3].

The same concept can be seen in figure 2.4 where the helium concentration differs based on the subsolar longitude. However, the differences between argon and helium are the maximums and minimums of the concentration levels. For helium, the maximum is at the 180° point and the minimum is at the 0° or the 360° point. The difference in the atmospheric conditions between the Earth and the Moon make it impossible for humans to live on the Moon without oxygen support. Therefore, it is vital for the lunar habitat structure to incorporate an air revitalization system to utilize CO_2 and generate O_2. Furthermore, the shelter will protect astronauts from lunar dust as well [22].

A challenge for structures within space is the crew being protected from radiation events. In general, energetic particles from the Sun are not a major issue for humans. However, large solar particle events may happen about every ten years and this would lead to major radiation hazards for both the crew and the equipment if exposed on the surface of the Moon [10]. For long-term colonization on the Moon, solar particle events will accelerate the degradation of the equipment on the lunar surface. Radiation shielding will be needed to prevent these types of occurrences.

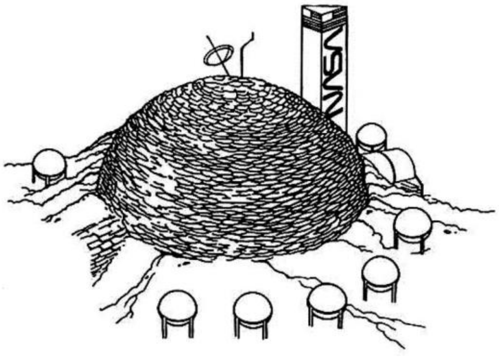


Figure 2.5: Lunar habitat concept with surrounding radiation protection [14].

Other types of shielding concepts include bulk shielding with a different material, electromagnetic and electrostatic shielding, and chemical radioprotection. Each have their own benefits. However, the most feasible option that will be further discussed is bulk shielding using compact regolith. As shown in figure 2.5, the lunar habitat is surrounded by 3 m of regolith to act as a radiation protection. Although this concept will work against radiation and is favored due to simplicity and safety, it is also labor intensive for the crew that will be exploring the Moon. Radiation shielding through regolith covers has been extensively researched and simulated. Using a layer of compacted regolith will absorb the kinetic energy of radiation to allowable radiations levels of 5 rem and will reduce extreme temperature cycle effects on the Moon [14].

The final technical requirement that will be discussed is related to the health of the crew. As mentioned in the previous chapter, humans need several things to survive, which are oxygen, food, water, and shelter. Oxygen and shelter have already been discussed in a previous section of the chapter. However, food and water must be provided in order for the lunar exploration crew to survive the length of the mission. Therefore, it is vital for the modules within the lunar habitat structure to produce enough food and water for the astronauts that will be conducting research for multiple days on the Moon [23].

3. Lunar Regolith Properties

3.1 Lunar Regolith

Regolith is a term based on the general consistency of materials that covers the surface of the land. Earth-based regolith is processed by the presence of oxygen, wind, and water, as well as by the activities of life. However, lunar regolith is processed by the meteor impacts and the charged atomic particle impacts from the Sun. Due to the shock overpressures and heat produced by impacts, the material that has been pulverized is then melted and welded together to create breccias and impact melt rocks. These types of regolith forms make up a significant portion of the surface of the Moon [10].

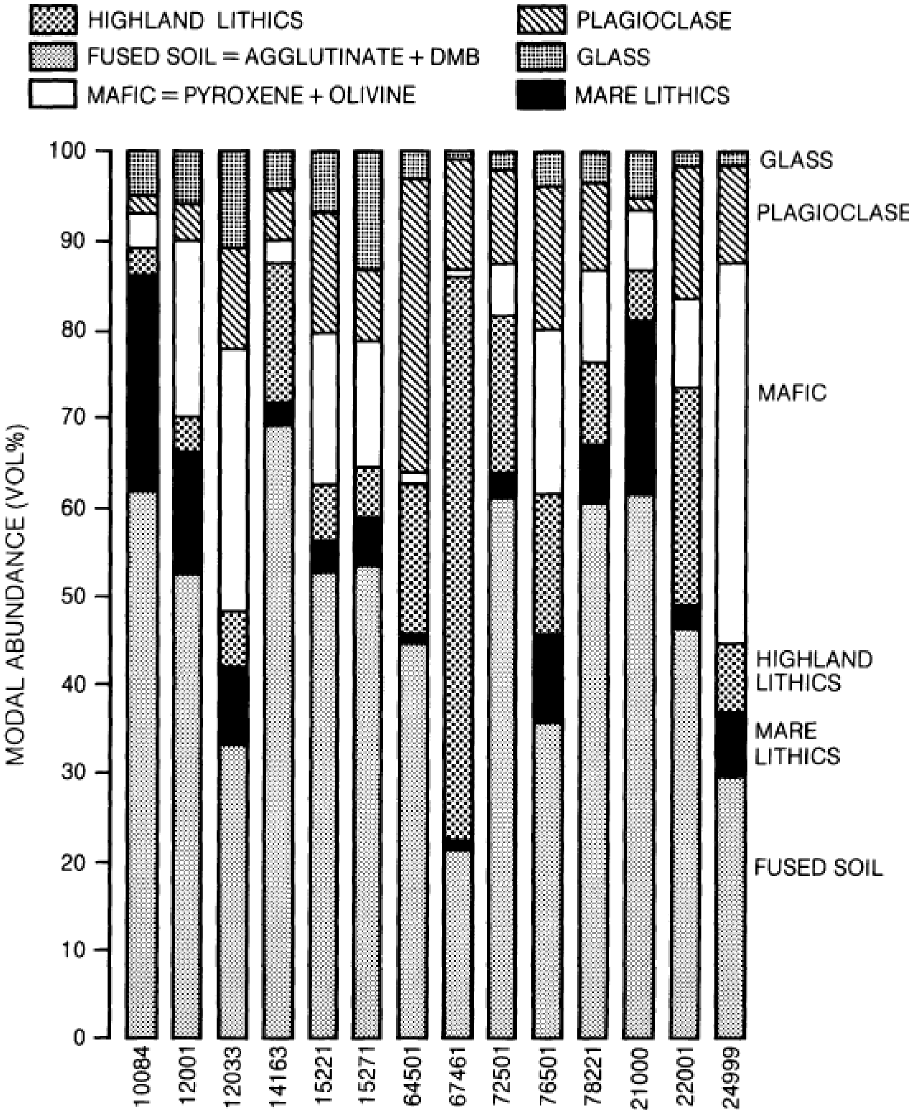


Figure 3.1: Comparative petrology taken by different manned flights to the Moon [10].

Within the specifics of lunar regolith is the petrography, which is the classification of rocks within a microscopic study. As shown in figure 3.1, the soil samples obtained from various manned exploration missions on the Moon, depicted as five digit numbers at the bottom of the figure, consists of different materials and their abundances defined as a percentage of the sample volume. Knowing the petrography of the lunar soil samples allows researchers to determine the type of materials and the chemical composition of lunar regolith. Fused soil consists of agglutinates and dark matrix breccia (DMB), both of which are formed by meteor impacts. Mare and highland lithics are different types of rock fragments. Lastly, the other materials measured are single mineral and glass fragments.

3.1.1 Properties of Lunar Regolith

Two types of lunar material have been processed and researched to determine their material properties. As a result, table 3.1 refers to the properties of cast regolith and table 3.2 refers to the properties of lunar concrete. Cast regolith can be used for structural purposes that are under a high compression environment. If prestressed lunar materials are used within cast regolith, then its application will offer different shapes and structures. Similar to cast regolith applications, lunar concrete is used for construction purposes.

Table 3.1: Cast regolith material properties [14].

Property (units)	Value
Tensional Strength (N/mm^2)	34.5
Compressive Strength (N/mm^2)	538
Young’s Modulus (kN/mm^2)	100
Density (g/cm^3)	3
Thermal Expansion Coefficient (10^{-6}/K)	7.5 - 8.5
Estimated Energy Consumption (kWh/MT)	360
Poisson’s Ratio	0.28

Table 3.2: Lunar concrete material properties [14].

Property (units)	Value
Compressive Strength (N/mm^2)	39 – 75.7
Young’s Modulus (kN/mm^2)	21.4
Ultimate Strain (%)	~
Density (g/cm^3)	2.6
Thermal Expansion Coefficient (10^{-6}/K)	5.4
Estimated Energy Consumption (kWh/MT)	2,200

Cast regolith can be processed by melting raw lunar regolith and cooling it to form crystals rather than glass. This process can be done in a vacuum, which will enhance the quality of the cast regolith. However, recent construction projects have not been performed using the material. Due to its high hardness, cast regolith can be used for high abrasion resistance, but shaping the material is difficult. Furthermore, producing the material is energy intensive. Cast regolith is very similar to that of terrestrial cast basalt. Lunar concrete does not have the same characteristics as cast regolith, but can be shaped into many different ways. Radiation shielding of cast regolith will prevent the structure of the lunar habitat from experiencing high stress due to radiative expansion [14].

3.1.2 Similar Materials

Materials that are similar to lunar regolith can be used for mechanical properties testing and simulations without having to obtain lunar soil samples. It will allow engineers to research manufacturing processes that can be feasibly used for lunar habitat construction, specifically by improving lunar regolith through the use of additives. With the problematic availability of lunar regolith samples on Earth, it is imperative to determine a simulant that can be recreated with the following properties:

- Chemistry
- Mineralogy
- Textural features

Two very similar materials, as discussed by Sibille et al., are mare basaltic simulants, consisting of low titanium basalt, and anorthositic highland simulants, consisting of high calcium anorthosite [24]. Cast basalt is the terrestrial material that has similar mechanical properties as well as similar mineral and chemical compositions as cast regolith. Similar to that of cast regolith, cast basalt has an extremely high abrasion resistance that surpasses steel alloy. However, its mechanical strength and impact strength are inferior when compared to metal materials.

Table 3.3: Cast basalt material properties [25] [26].

Property (units)	Value
Compressive Strength (N/mm^2)	450
Young’s Modulus (kN/mm^2)	110
Density (g/cm^3)	2.9
Temperature Coefficient (10^{-6}/K)	6 - 8

Table 3.3 shows the values for the mechanical properties of cast basalt that can be found in literature. When compared between table 3.1 and table 3.3, the values pertaining to cast basalt are close in range with those to cast regolith. Therefore, cast basalt is a viable substitute for lunar apparatus modelling and testing. Lunar concrete has the same characteristics as terrestrial concrete. However, the process in manufacturing lunar concrete requires water and the Moon does not have a reliable water source.

3.2 Processed Lunar Regolith Improvements

There are several options to improve the mechanical properties of processed lunar regolith, such as including different materials in the chemical composition of lunar regolith. By including materials that have different characteristics as lunar regolith, it is possible to improve its disadvantages, such as brittleness and non-machinability. Figure 3.2 is a possible material additive that will reinforce and increase fracture toughness in the matrix of a composite [27]. Additive manufacturing can also be performed to improve the mechanical properties of lunar regolith. This process is done by forming an object through bonding added material under the control of a computer with the hope of producing zero waste. Furthermore, this process is also within the domain of three-dimensional (3D) printing [20].

Figure 3.2: Macro- and microscopic views of basalt fiber [28].

3.2.1 Advantages and Disadvantages of Lunar Regolith

There are many advantages that have been previously discussed for lunar regolith, which include the following:

- High abundance of lunar regolith
- High compressive strength
- High abrasion resistance
- Feasible when fully researched

First and foremost, there is a high abundance of lunar regolith on the Moon that can be used and processed for specific purposes, such as construction and shielding. Utilizing lunar regolith as the main source for lunar construction will allow engineers to develop a strategy for establishing human presence on any other planetary body within space. Furthermore, building with local lunar material will reduce the weight and cost for rocket travel and will provide space for other necessities to build a sustainable base of operations on the Moon. Another benefit of cast regolith is the high compressive strength that can be used to build structures that are able to withstand high stresses and loads. This is particularly useful for dome-shaped bases that contain multiple floors as machinery and appliances will be implemented to sustain the lives of the lunar base crew. Furthermore, any radiative or thermal expansion on conjoining bars will also withstand compressive stress. One major advantage for cast regolith is the high abrasion resistance that it offers, which makes it an ideal building option for debris shields, as seen in figure 3.3. When meteors or lunar dust come in contact with a cast regolith lunar structure, building with high abrasion resistance materials will reduce the deterioration of the building material. The high abundance would make cast regolith structures a feasible option for construction.

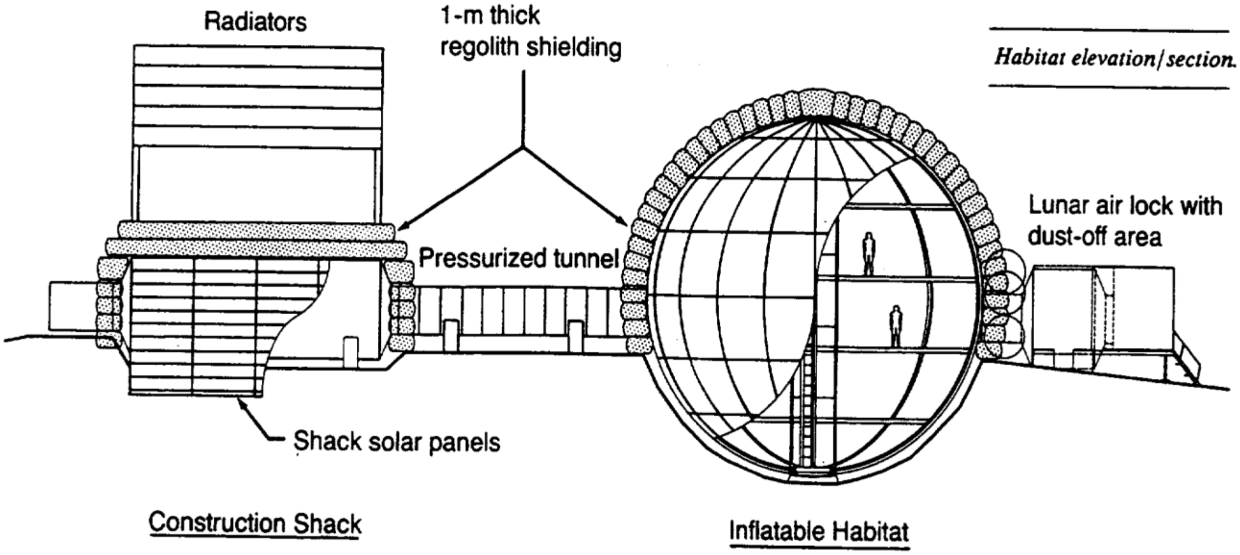


Figure 3.3: Regolith implementation for structure protection conceptual sketch [9].

As there are advantages, there also exists disadvantages for the mechanical properties of lunar regolith, such as the following:

- Energy intensive and long process
- Brittleness
- Difficulty in machinability

These downsides can affect the length of time for a lunar construction mission due to the process of manufacturing and the resources that are needed to make an improved cast regolith. Due to its energy intensive nature, producing cast regolith requires high temperatures to reach its melting point. Reaching high temperatures will require time and high temperature resistant machinery. A hard material that is brittle makes it difficult to cut and machine in different shapes and sizes. At its current state, the use of local lunar material is not a feasible option until further research is conducted for fracture and fatigue measurements. Therefore, improving lunar regolith through the use of additives will allow structures to be reliable and feasible.

3.2.2 Possible Additive Materials for Lunar Regolith Improvement

Processed lunar regolith follows the same characteristics as that of a ceramic in terms of material science concepts. This means that the lunar regolith has high compressive strength and high rigidity, but does not perform well in terms of impact strength and is usually brittle in nature, as mentioned previously. Therefore, implementing additives to lunar regolith may result in improved characteristics that will reduce the brittleness of ceramics and may possibly increase its ductility.

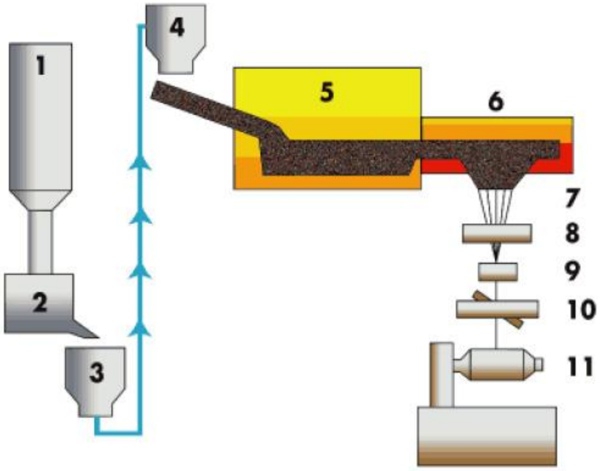


Figure 3.4: Process of basalt fiber production [27].

Basalt fiber is an example of a reinforcement for composite and processed materials due to its high characteristics. This fiber is also significantly cheaper than other materials that are made from carbon fiber. Due to the similarities between basalt and lunar regolith, it may be possible to create a regolith-type of fiber by doing the same process as basalt fiber as shown below. The process listed below is currently not a feasible option as it requires to move several pieces of heavy machinery to the Moon. To make this process feasible, lightweight machinery must be made. Figure 3.4 is a diagram of basalt fiber production that will be described into 3 major steps [27]:

1. Raw basalt is crushed within a stone silo to create a fine powder that will be loaded and transported to the batch charging station (1 to 4, in figure 3.4, respectively).
2. The fine powder is then melted and it keeps its melted form in a controlled heat zone (5 to 6, in figure 3.4, respectively).
3. Lastly, the melted basalt is formed into filaments to then be sized for strand formation. Once the strands are made, they are then stretched as the strands are winding into a roll for application (7 to 11, in figure 3.4, respectively).

Table 3.4: Basalt fiber properties [27].

Property (units)	Basalt Fiber Values
Compressive Strength (N/mm^2)	3,000 – 4,840
Young’s Modulus (kN/mm^2)	79.3 – 93.1
Fiber Diameter (µm)	6 - 21
Temperature Withstand (°C)	(-260) – (+700)

Without considering feasibility on the Moon, the testing material that will be researched on will include cast lunar regolith, basalt fiber. A computational simulation of only cast regolith will be conducted as a basis future material computations. Table 3.6 shows the different composition of materials that will be used for comparison of the base data. Discussion and results will determine if basalt fiber is a viable option to improve the mechanical properties of cast regolith.

Table 3.5: Projected computational testing materials.

Material Test Number	Cast Regolith Percentage	Basalt Fiber Percentage (SFC)	Basalt Fiber Percentage (Random UDC)
1	100%	0%	0%
2	95%	5%	5%
3	85%	15%	15%
4	75%	25%	25%

3.3 Numerical Modelling for Lunar Regolith Processing

To understand cast regolith in a computational sense, numerical modelling will be done through the structural analysis application of the ANSYS software. Several computational tests will be conducted that will confirm and determine the values of the elastic modulus and the shear modulus for processed lunar regolith with and without the additive, specifically basalt fiber, that will be implemented. Therefore, the three main tests that will be conducted will be the following:

- Tensile failure testing
- Compression failure testing
- 3 point bending testing

These three tests will be conducted with and without additives to show either the improvement or the setback that the additives have contributed.

3.3.1 Tensile Failure Test

The first numerical test that shall be done is the tensile failure test. This test will essentially pull a material on two opposite sides until the material fractures into two pieces. If the material splits in two without any deformation, then the material has a brittle nature. If the opposite where the material splits and there is a load deformation, then the material has a ductile nature. Figure 3.5 shows a clear example of the concept for a tensile test as well as the possible results for each case.

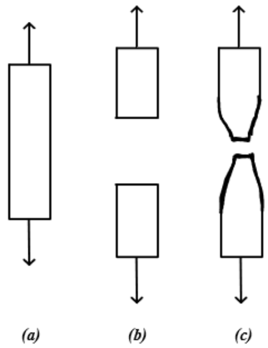


Figure 3.5: Forces on material for a tensile test (a), brittleness result (b), and ductility result (c).

To relate the results of the tensile test to a stress-strain graph, the following equations will be used:

$$\sigma = \frac{P}{A} \tag{1}$$

$$\varepsilon = \frac{\delta}{L} \tag{2}$$

The equations shown above determine the stress (σ) and strain (ε) of a material. For the stress, the value can be found by determining the applied load (P) over the original cross sectional area (A). The strain can be determined by calculating the change in the length of the material (δ) over the original length (L). Ideally, the values will be obtained through a program that will calculate the stress and strain as the applied force is increasing. Then, the results of the stress and strain values will be put into a graph relating to one another as shown in figure 3.6. By looking at the results of the test, the tensile test can determine if lunar regolith containing additives is a viable material that can pass the strength and elongation requirements for lunar base construction.

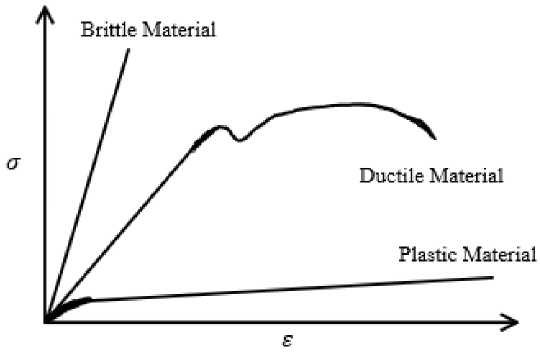


Figure 3.6: Stress-strain graph depicting the results of different materials.

3.3.2 Compression Failure Test

The next test that will be numerically performed is the compression failure test. Instead of applied forces pulling on opposite sides of a material like the tensile test, the forces for a compression test are pushed towards each other as shown in figure 3.7.

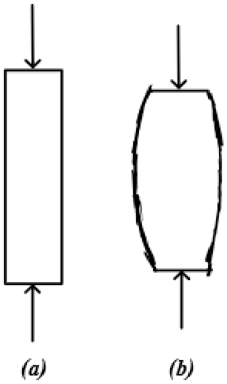


Figure 3.7: Compression testing before (a) and after (b) forces are applied.

The compression test results measure the fracture properties of elasticity and compression of brittle materials, and can also determine other vital information, such as the elastic modulus and compressive strength. Knowing these properties will aid in determining the proper materials that are needed to improve the performance of the processed lunar regolith.

3.3.3 Three Point Bending Test

Lastly, the three point bending test is designed to determine the Young’s modulus using a rectangular beam-shaped material. Similar to that of the tensile test, the bending test applies tensile stresses that contribute to yielding or fracture. Furthermore, it can also evaluate the strength of materials. However, the main difference between the two tests is due to the concentration of stresses. For the tensile test, the stress is occurring throughout the entirety of the volume. Whereas, the stress in a bending test occurs in small regions within the volume of the beam. As shown in figure 3.8, a single force is applied at the top towards the other two forces that are applied at the bottom of the beam. By numerically modelling the mechanical properties of processed lunar regolith, it can then be compared to lunar regolith with additives to determine whether or not the additives improve the performance of the local lunar material.

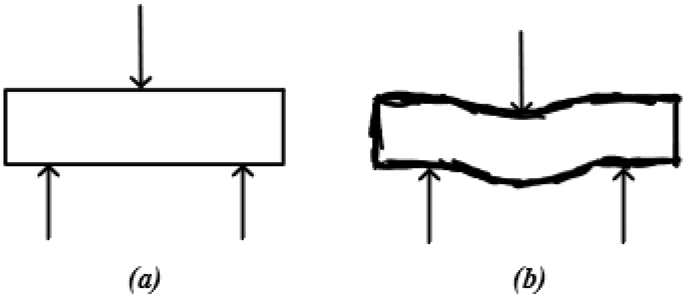


Figure 3.8: Three point bending test before (a) and after (b) forces are applied.

4. Modelling Numerical Tests

4.1 Modelling Through the ANSYS Program

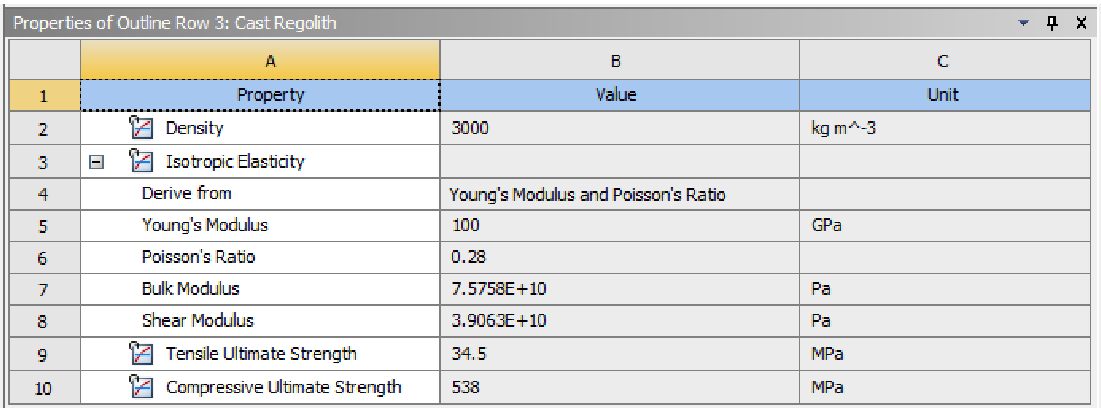
To simulate the numerical tests, ANSYS will be used to visualize the mechanical properties of processed lunar regolith. Stress tests, such as tensile and compression tests, will be simulated to compare the difference between lunar regolith with and without additives implemented. As mentioned previously, meteor impacts and moonquakes are sources of stress that may occur on the Moon. Therefore, it is imperative to determine a viable material through simulations and testing that will protect lunar habitat structures from deteriorating due to high impacts and high stresses.

4.2 Numerical Testing Process

Various shapes and sizes for testing specimens have been conducted to determine the values for specific mechanical properties for steel and other materials, such as rectangular prisms and cylinders. These shapes are used in lateral and in longitudinal testing to determine the effects of applied loads in each direction of the testing specimens. To keep consistency with many pieces of literature for testing material properties, the testing specimen that will be simulated in ANSYS will follow ASTM standard specimen dimensions for tension, compression, and 3-point bending tests. The ASTM designs for each test will be discussed in the following sections. Following data from literature review for the mechanical property values of cast lunar regolith will provide baseline simulation and results that will be compared once additives are included and simulated. Within ANSYS, the static structural module will be utilized for the numerical tests. In general, this module is used to determine stresses and strains on a testing specimen that are caused by applied loads.

4.2.1 Material Input and Mesh Appropriateness

The engineering data application within the ANSYS program allows users to input mechanical property values to create materials. The aforementioned values for cast regolith are inserted into the engineering data, as shown in figure 4.1, which will then be utilized for the following tests that will be set up.



Properties of Outline Row 3: Cast Regolith

	A	B	C
1	Property	Value	Unit
2	Density	3000	kg m^-3
3	⊟ Isotropic Elasticity		
4	Derive from	Young's Modulus and Poisson's Ratio	
5	Young's Modulus	100	GPa
6	Poisson's Ratio	0.28	
7	Bulk Modulus	7.5758E+10	Pa
8	Shear Modulus	3.9063E+10	Pa
9	Tensile Ultimate Strength	34.5	MPa
10	Compressive Ultimate Strength	538	MPa

Figure 4.1: Cast regolith properties implemented in ANSYS engineering data module.

Determining whether the tests will contain high stress gradients is vital for mesh sizing. Fine mesh sizes are used for the region with the highest stress gradients, whereas, coarse meshes are used elsewhere. In doing so, simulations are quicker to perform and the effects of applied loads within the high stress gradient regions are clearer to see under fine mesh sizes than coarse mesh sizes. For brittle materials, high stress gradients can be seen throughout the testing model. Therefore, the use of a fine mesh in all three tests will be significant for the clarity of the effects from the applied forces.

4.2.2 Setup for Tensile Test

The tension test determines the measured load under which a testing specimen will rupture. By using a CAD design of the common ASTM standard tensile testing specimen, known values for cast regolith will be implemented within the engineering data of the ANSYS program. Two different types of testing specimens, as shown in figure 4.2, have been commonly used to measure the yield strength and many other tensile properties of various alloys. Longitudinal testing examines the stress applied to a test specimen in the direction parallel to the greatest extension. Both the flat and the round specimens can be used for longitudinal testing. However, transverse testing is usually measure with the flat test specimen due to loading complexity for the round test specimen. For the longitudinal flat tension test specimen, table 4.1 shows its standard dimensions in inches and in millimeters. Each variable in table 4.1 correlates with figure 4.3.

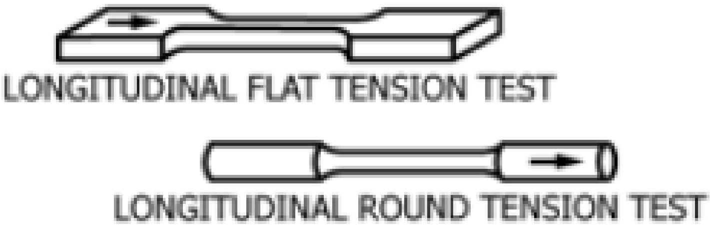


Figure 4.2: ASTM standard longitudinal tensile test specimens, known as A370 [30].

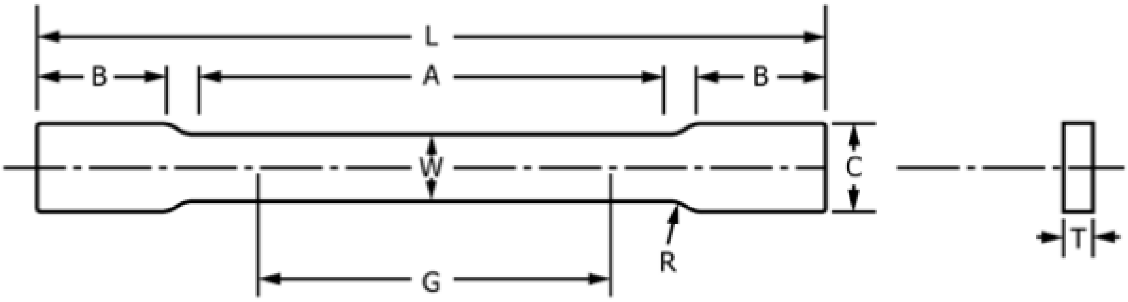


Figure 4.3: Rectangular tension test specimen [30].

Table 4.1: ASTM dimensions for the flat A370 specimen [30].

Dimensions				
	Standard Specimens (Plate Types)			
	8 in (200 mm) Gauge Length		2 in (50 mm) Gauge Length	
	inches	millimeters	inches	millimeters
G: Gauge Length	8.00	200	2.000	50.0
W: Width	1 ½	40	1 ½	40
T: Thickness	$^{3}/_{16}$	5	$^{3}/_{16}$	5
R: Radius of Fillet	½	13	½	13
L: Overall Length	18	450	8	200
A: Length of Reduced Section	9	225	2 ¼	60
B: Length of Grip Section	3	75	2	50
C: Width of Grip Section	2	50	2	50

As for longitudinal round tension test specimen, the dimension variables for table 4.2 correlate with the variables on figure 4.4.

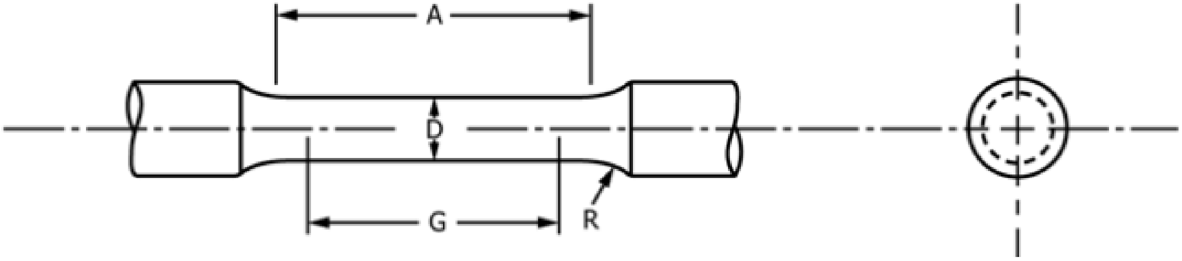


Figure 4.4: Round tension test specimen [30].

Table 4.2: ASTM dimensions for the round A370 specimen [30].

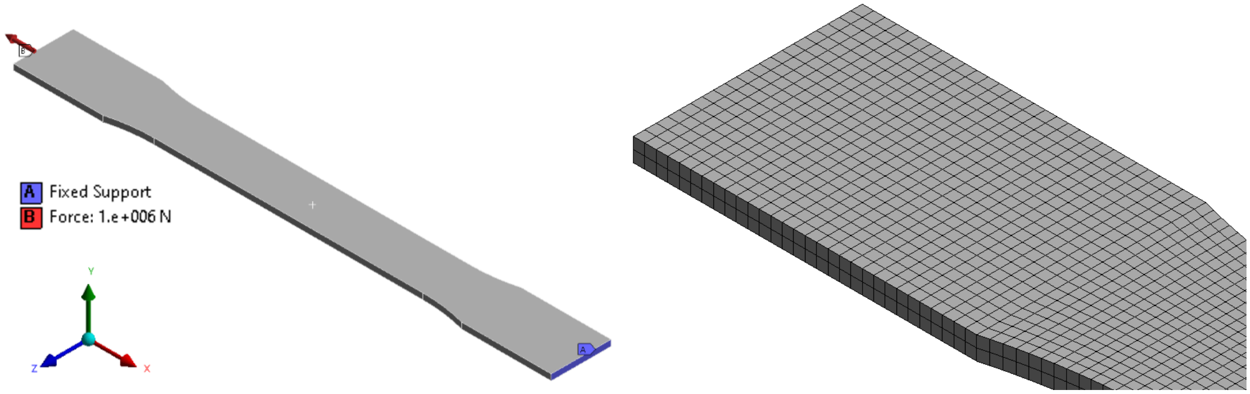
Dimensions		
Nominal Diameter	Standard Specimen	
	inches	millimeters
	0.500	12.5
G: Gauge Length	2.00	50.0
D: Diameter	0.500	12.5
R: Radius of Fillet	$^{3}/_{8}$	10
A: Length of Reduced Section	2 ¼	60

The tensile properties that can be found, if not already known, through the physical measurements and ANSYS simulations are the following:

- Yield point
- Yield strength
- Ultimate tensile strength
- Elongation

Within the ANSYS program, there are several steps to take that will ultimately simulate and help visualize tensile stress on the test specimens that will be subject to loads pulling from either side. To begin the simulation, engineering data about cast lunar regolith must be applied in order for the program to accurately depict the change of the cast regolith under load. The steps that will be taken to simulate a tensile test are the following:

1. Apply engineering data for cast regolith and for the additive that will be used. In this case, the additive that will be used is basalt fiber because it contains high tensile strength and high modulus of elasticity.
2. Determine the geometry of the testing specimen. As mentioned previously, the geometry for tensile test specimens will follow the ASTM standard dimensions of the A370 specimen. To incorporate both longitudinal and transverse testing, the flat plate will be implemented.
3. Change the material from the default to the testing material and create a fine mesh to accurately show the effects of the load that will be applied. Add the boundary conditions that will ultimately pull the specimen from its fixed side.
4. Determine the specific values that will be found from the analysis and solve.



(a) **(b)**

Figure 4.5: Model, BCs, and load* (a) *and mesh sizing* (b) *for ANSYS tensile test.

4.2.3 Setup for Compression Test

Similar to that of the tensile test, the compression test is designed to measure the compressive strength and modulus of a material. The compressive strength can be found by determining the maximum compressive load that it can handle and the minimum cross-sectional area at the point of fracture. The compressive modulus of the material can be determined by measuring the change in stress and the change in strain. These values can be found by using the following equations, respectively:

$$CS = \frac{F}{A} \tag{4.1}$$

$$E = \frac{\Delta\sigma}{\Delta\varepsilon} \tag{4.2}$$

The equations above are used to determine the compressive strength (*CS*) and the Young's modulus (*E*). The loading force (*F*) divides into the minimum cross-sectional area (*A*) to obtain the compressive strength, and the modulus of elasticity is obtained by using the change in stress ($\Delta\sigma$) and the change in strain ($\Delta\varepsilon$).

The geometric model that will be used for the compressive test analysis in ANSYS will be an ASTM standard rectangular prism (D695) as shown in figure 4.7. For the D695 model, the standard dimensions are shown in table 4.4 [31].

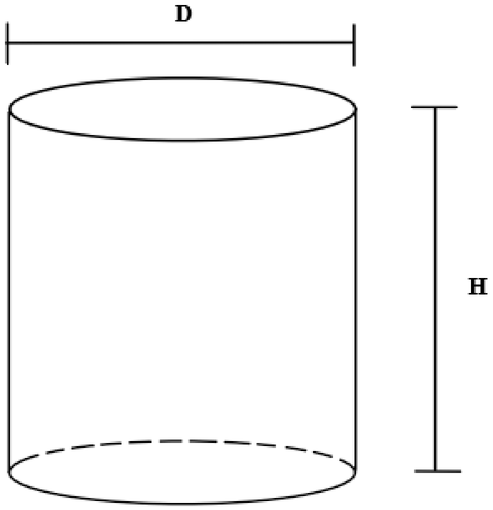


Figure 4.6: Sketched ASTM D695 specimen, in a cylinder and in a rectangular prism.

Table 4.3: ASTM dimensions for the D695 cylindrical specimen [31].

Dimensions		
	Standard Specimen	
	inches	millimeters
D: Diameter	½	12.7
H: Height	1	25.4

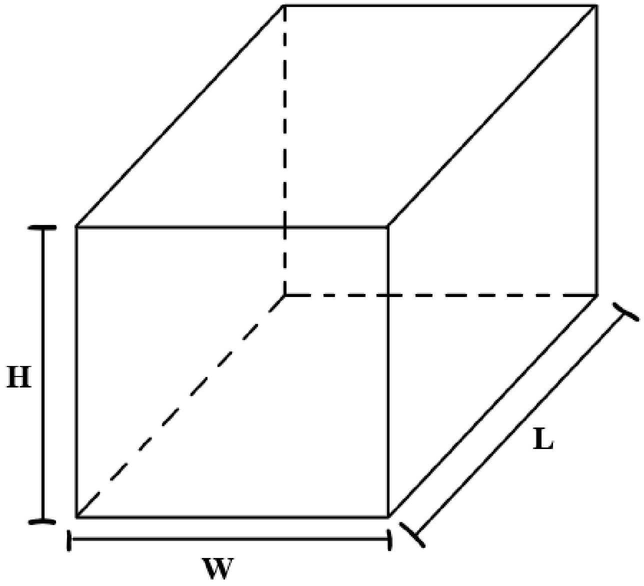


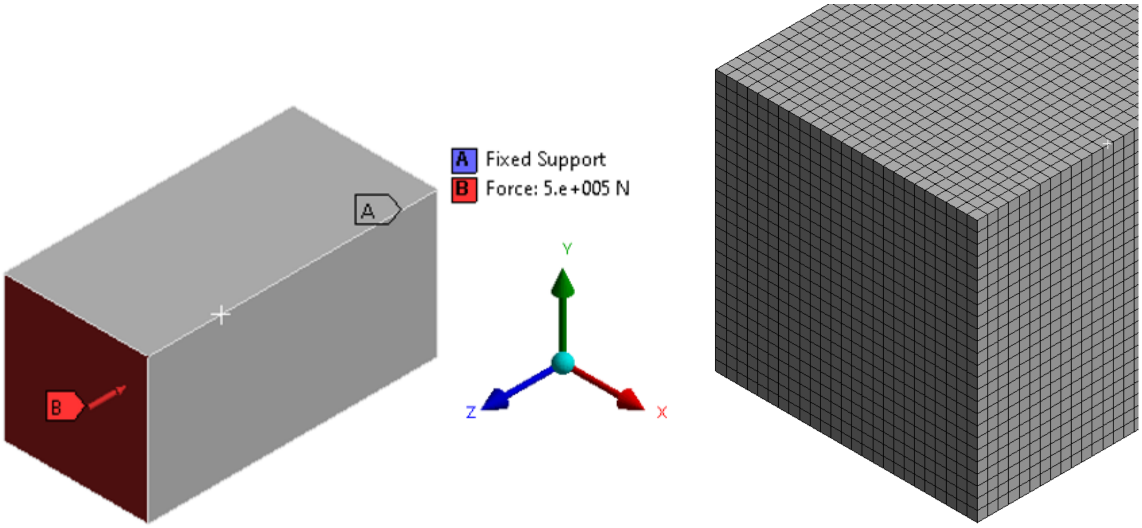
Figure 4.7: Sketched ASTM D695 specimen in a rectangular prism.

Table 4.4: ASTM dimensions for the D695 rectangular prism specimen [31].

Dimensions		
	Standard Specimen	
	inches	millimeters
H: Height	½	12.7
W: Width	½	12.7
L: Length	1	25.4

The ANSYS process for the compression test has similar steps as the aforementioned tensile test. However, the major difference is that the loading force is pushing into the material rather than pulling out of the material. Furthermore, in step 2, the testing specimen is the ASTM standard rectangular prism.

1. Apply engineering data for cast regolith and for the additive that will be used. In this case, the additive that will be used is basalt fiber because it contains high tensile strength and high modulus of elasticity.
2. Determine the geometry of the testing specimen. As mentioned previously, the geometry for tensile test specimens will follow the ASTM standard dimensions of the D695 specimen.
3. Change the material from the default to the testing material and create a fine mesh to accurately show the effects of the load that will be applied. Add the boundary conditions that will ultimately push the specimen towards its fixed side.
4. Determine the specific values that will be found from the analysis and solve.



(a) (b)

Figure 4.8: Model, BCs, and load* (a) *and mesh sizing* (b) *for ANSYS compression test.

4.2.4 Setup for 3-point Bending Test

The three point bending test, also known as the flexural test, measures the force that is needed to bend a beam under three point loading conditions. This piece of information is often used for determining a material that will support loads without bending and its modulus is used to measure the stiffness of a material when bent. One major consideration is temperature as physical properties of a material can depend on the temperature that it is being subject to. Furthermore, the data that can be found in the three point bending test are the following:

- Flexural stress and strain at yield
- Flexural stress and strain at break
- Flexural stress at 5.0% (ASTM) deflection
- Flexural modulus

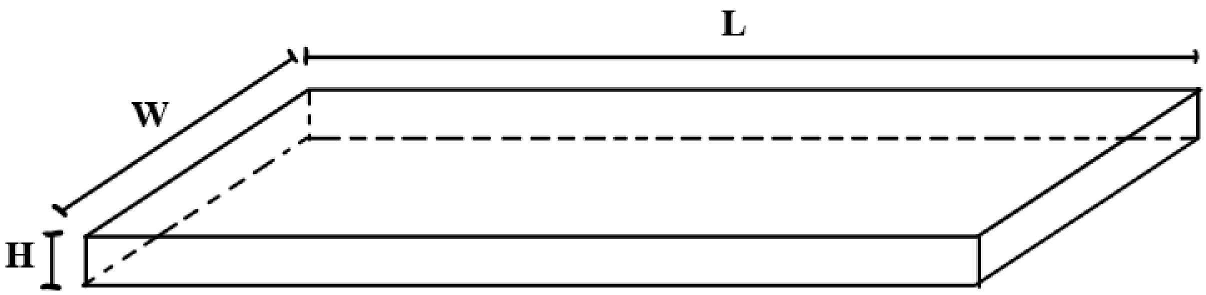


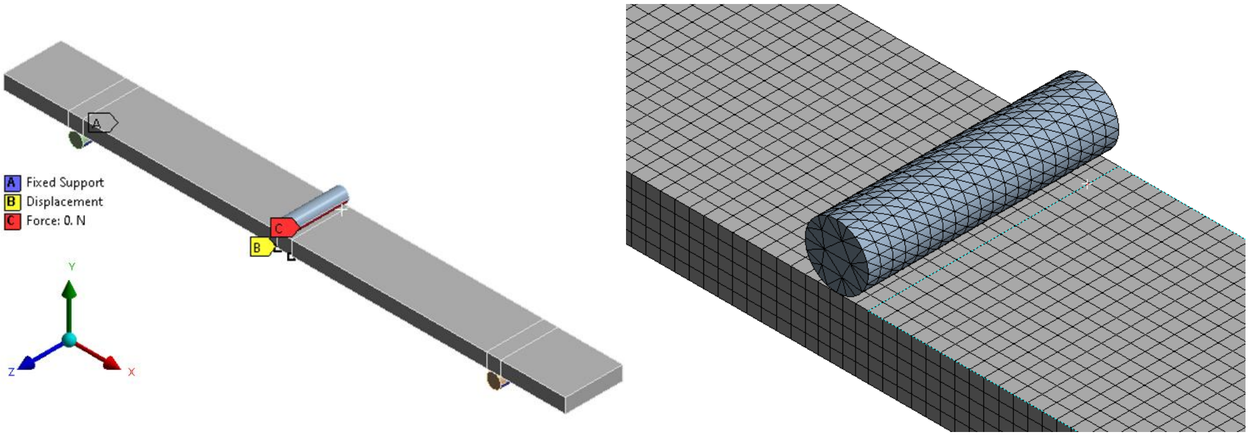
Figure 4.9: Sketched ASTM D790 specimen.

Table 4.5: ASTM dimensions for the D790 specimen [32].

Dimensions		
	Standard Specimen	
	inches	millimeters
L: Length	5.0	125
W: Width	½	12.7
H: Height	¼	3.2

Within ANSYS,

1. Apply engineering data for cast regolith and for the additive that will be used. In this case, the additive that will be used is basalt fiber because it contains high tensile strength and high modulus of elasticity.
2. Determine the geometry of the testing specimen. As mentioned previously, the geometry for tensile test specimens will follow the ASTM standard dimensions of the D790 specimen. To incorporate both longitudinal and transverse testing, the flat plate will be implemented.
3. Include 3 extruded semicircle to mimic the 3 loading force points. Two of the force point will be at each end of the specimen on one side, and the third point will be on the opposite side and at the middle of the specimen.
4. Change the material from the default to the testing material and create a fine mesh to accurately show the effects of the load that will be applied. Apply the desired force directions for each point.
5. Determine the specific values that will be found from the analysis and solve.



(a) **(b)**

Figure 4.10: Model, BCs, and load* (a) *and mesh sizing* (b) *for ANSYS 3pt bending test.

4.3 Results Obtained from Numerical Testing

The ANSYS program will be able to calculate and determine the maximum stress and strain values for a brittle material, such as cast regolith. By determining values for the additive fiber that will be implemented along with the cast regolith, simulated data will conclude whether the fiber enhances the mechanical properties of cast regolith. By conducting simulations for cast regolith without any fibrous materials implemented, those simulations results can be compared to the simulations that do contain fibers within cast regolith. The overall goal of this project is to determine whether implementing a fiber material within a brittle matrix material is a viable option to improve the mechanical properties of cast regolith for lunar structure application.

The following three figures (4.11 - 4.13) depict the stress-strain curves for tension, compression, and 3 point bending tests. As can be seen in the figures, the stress-strain graph follows the trend as that of a brittle material. These results are expected for a brittle material as it does not show a permanent deformation but rather a failure due to high stresses. Physical testing of the materials are conducted to obtain all the material properties before they are used for computer simulations. The results do not follow the same property values as it was inputted in the material card. This may be due to lack of public failure and fracture data for lunar regolith materials.

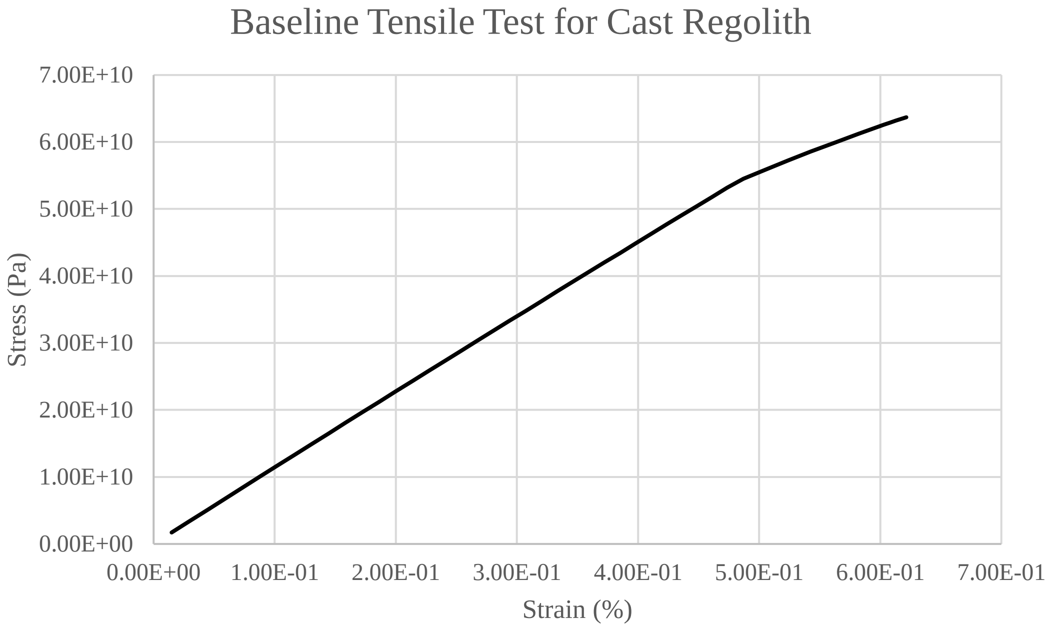


Figure 4.11: Test results of the tension test for a fully cast regolith specimen.

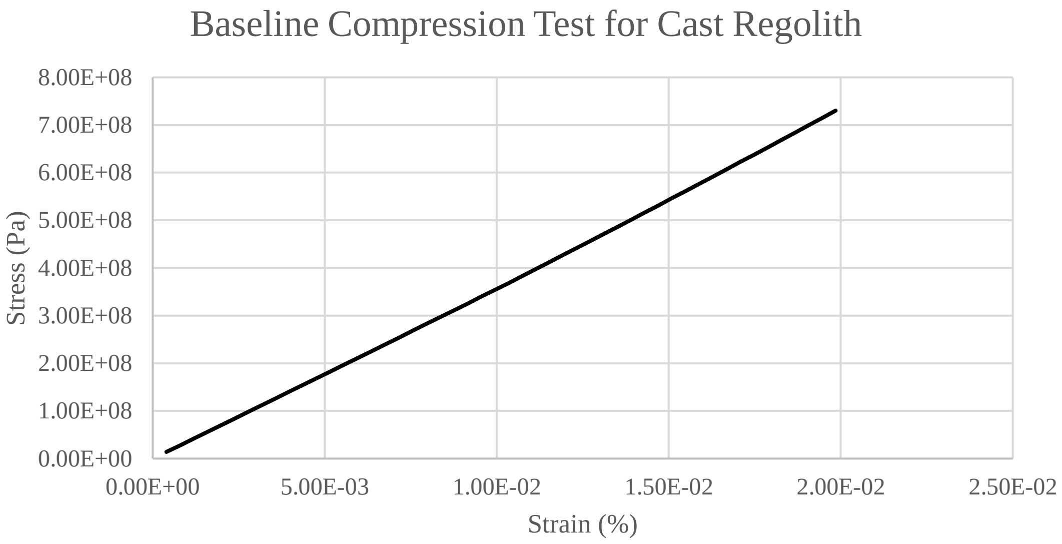


Figure 4.12: Test results of the compression test for a fully cast regolith specimen.

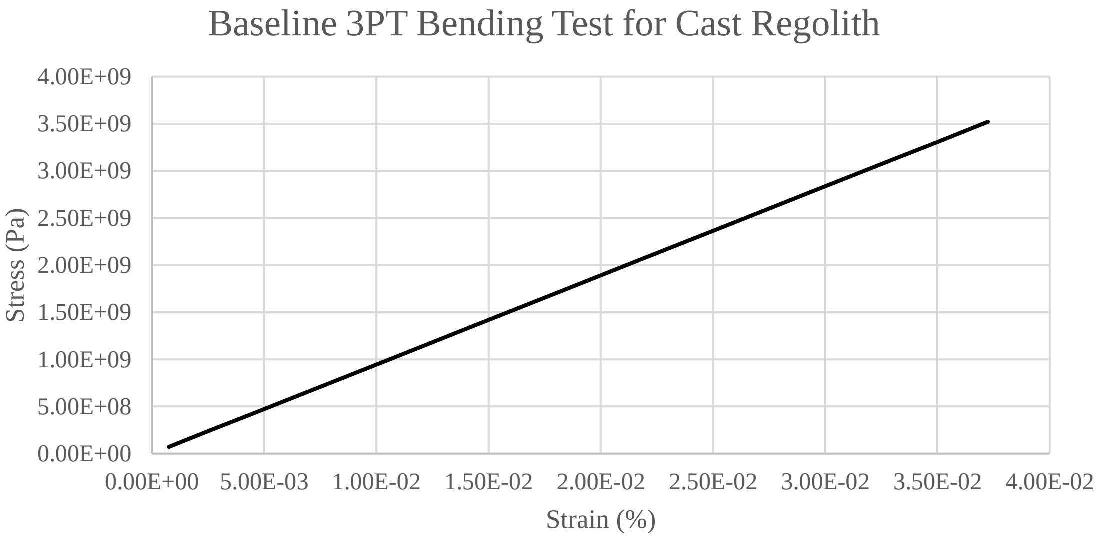


Figure 4.13: Test results of the 3pt-bending test for a fully cast regolith specimen.

5. Discussion of Results

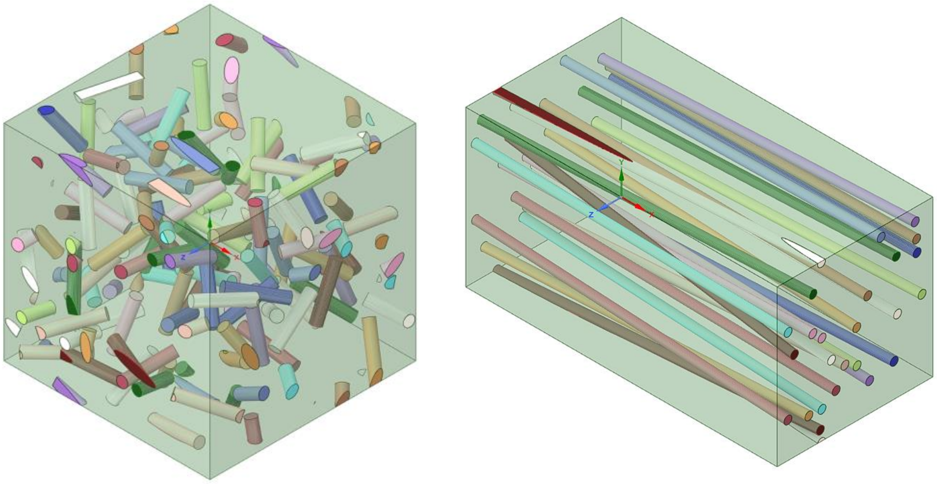
Using ANSYS software, the basalt fiber is implemented in two cases. The two cases are short fiber composites and random unidirectional composites, represented as SFC and random UDC respectively. These two different design of experiment parameters are to determine whether or not basalt fiber is a feasible option for enhancing the material properties of lunar material. Basalt is a common material that has the same properties as lunar regolith, meaning that physical testing and simulations to enhance the properties can be done without the need to obtain actual regolith from the Moon.

5.1 Incorporating Additives within ANSYS Engineering Data

Knowing the Poisson's ratio and the Young's modulus, basalt fiber can be created as a new material in the engineering data of ANSYS that can be used to possibly improve the material properties of processed lunar regolith. The material designer module of ANSYS can be used to incorporate and specify the ratio between basalt fiber and cast regolith matrix. The fibers can be oriented within the matrix in several different ways, such as the following:

- Lattice
- UD composite (UDC)
- Random UD composite
- Short fiber composite (SFC)
- And woven composite

However, the main orientations that will be tested on are SFC and random UDC. For SFC, basalt fiber in the microscopic view have a similar shape that can be inserted as lunar regolith is processed into cast regolith. The orientation of SFC can be seen in figure 5.1a, showing that the fibers are randomly oriented throughout a matrix cube. However, the orientation that closely resembles the process of additive manufacturing, or 3D-printing, is a random UDC as shown in figure 5.1b.



(a) **(b)**

***Figure 5.1: ANSYS simulated SFC* (a) *and random UDC* (b).**

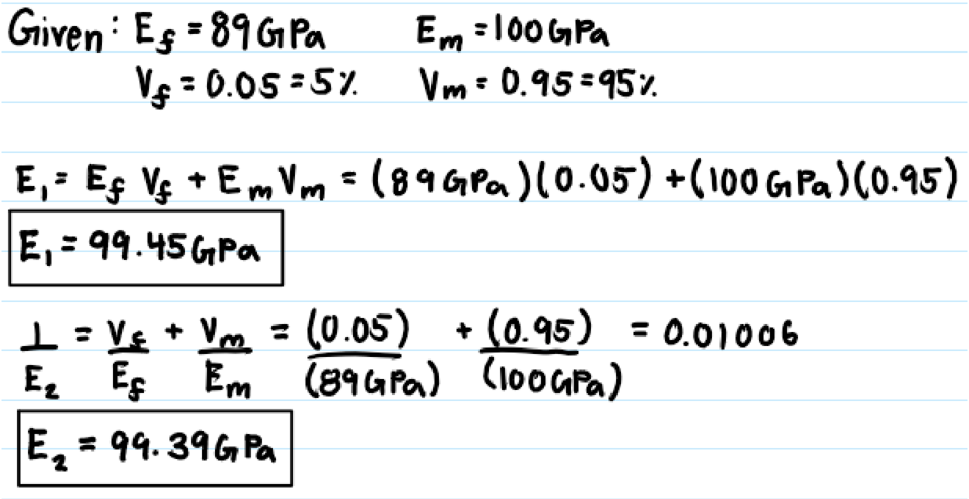
Once the geometry and the fiber orientation are decided, the next process is to calculate the following for the new composite material that is made:

- Young’s modulus, or modulus of elasticity, of the three orthogonal directions
- Shear modulus of the three orthogonal directions
- And Poisson’s ratio of the three pairs of orthogonal directions

These values can be calculated by hand and then implemented into the engineering data of ANSYS or they can be calculated through the material designer module of ANSYS. An example of how the longitudinal and transverse Young’s moduli can be solved by hand is by referring to equations 5.1 and 5.2, respectively, as well as figure 5.2. Once the values have been calculated in the material designer module, the created composite can then be inserted into the engineering data as its own new material as shown in figure 5.3.

$$E_1 = E_f V_f + E_m V_m \tag{5.1}$$

$$\frac{1}{E_2} = \frac{V_f}{E_f} + \frac{V_m}{E_m} \tag{5.2}$$



Given: $E_f = 89\,GPa$ $\quad E_m = 100\,GPa$

$V_f = 0.05 = 5\%$ $\quad V_m = 0.95 = 95\%$

$$E_1 = E_f V_f + E_m V_m = (89\,GPa)(0.05) + (100\,GPa)(0.95)$$

$$\boxed{E_1 = 99.45\,GPa}$$

$$\frac{1}{E_2} = \frac{V_f}{E_f} + \frac{V_m}{E_m} = \frac{(0.05)}{(89\,GPa)} + \frac{(0.95)}{(100\,GPa)} = 0.01006$$

$$\boxed{E_2 = 99.39\,GPa}$$

Figure 5.2: Solving for Young’s modulus for 5% basalt fiber within a cast regolith matrix.

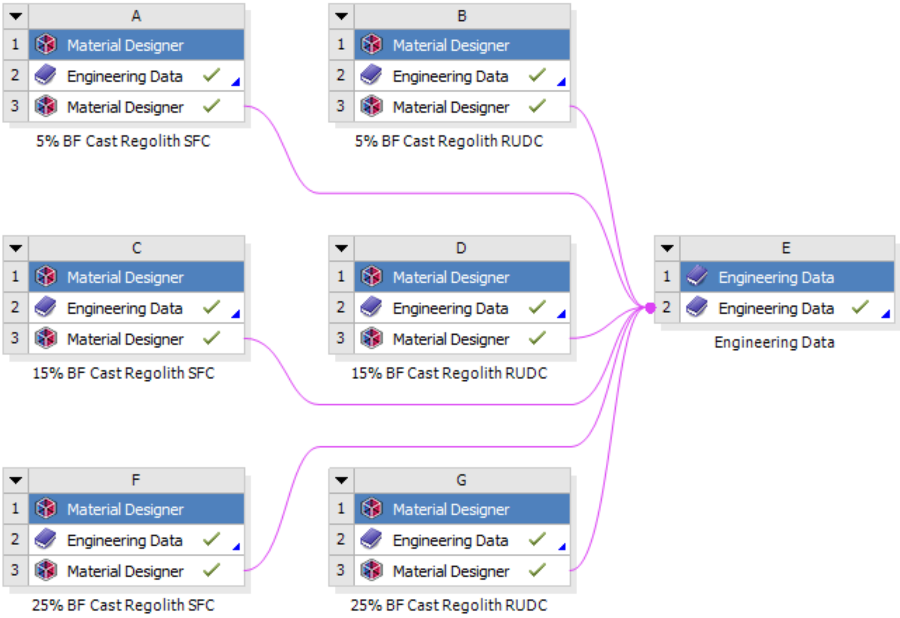


Figure 5.3: New composite materials inserted into the engineering data module of ANSYS.

5.2 Additive Tensile Test Results Compared to Baseline Results

As mentioned previously, the tensile test is set up to have on fixed face and the opposite face will be experiencing a pulling force. Shown in figure 5.4, the gradient determines the distance at which the element has traveled from its original position. At an applied force of 10 mega-newtons, the farthest that the specimen has reached differs between the designs of experiment before its failure, and can be shown in table 5.1.

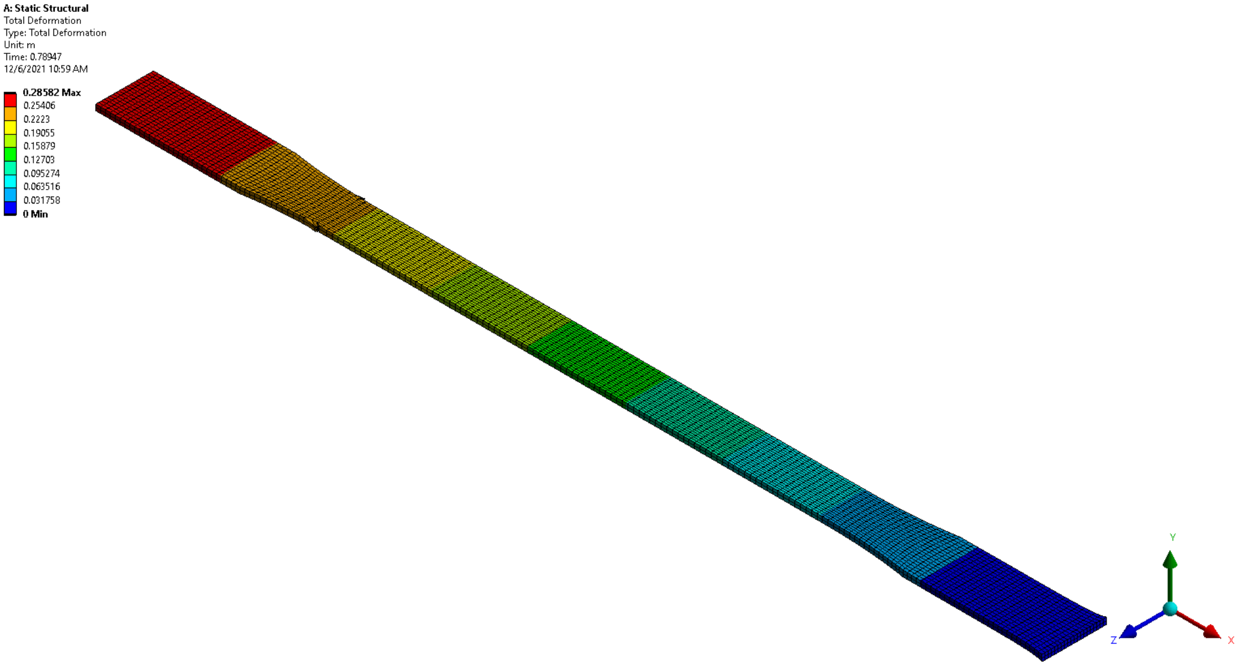


Figure 5.4: ANSYS simulated tensile test with deformation-based gradient.

Table 5.1: Maximum deformations of the aforementioned testing materials.

Material Test Number	SFC Maximum Deformation	Random UDC Maximum Deformation
1	0.28661 m	
2	0.2905 m	0.28516 m
3	0.30688 m	0.28983 m
4	0.32712 m	0.30279 m

As shown in table 5.1, randomly oriented short fiber composites allow for the cast regolith to be more flexible. Without the additives implemented, the maximum deformation that cast regolith experiences is 0.28661 meters. However, in SFC orientation with a 5% basalt fiber additive, the composite experiences a 1.35% increase in its maximum deformation, concluding that adding fibers to cast regolith improves the ductility of the material. This can also be shown for random UDC orientation as the maximum deformation increases above the maximum deformation for cast regolith without any additives.

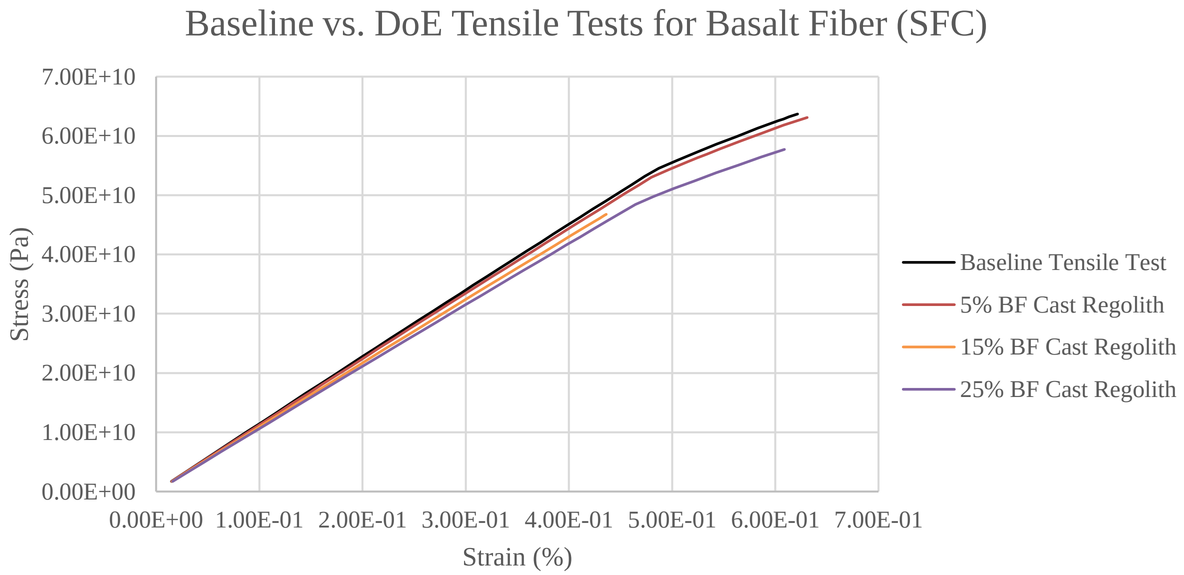


Figure 5.5: Simulated tensile results of SFC-implemented cast regolith.

The maximum deformation before failure increases as the amount of fiber increases as well. Based on the simulations done in ANSYS using the static structural feature, it can be seen that implementing basalt fiber in short random orientations deteriorates the material properties of cast regolith.

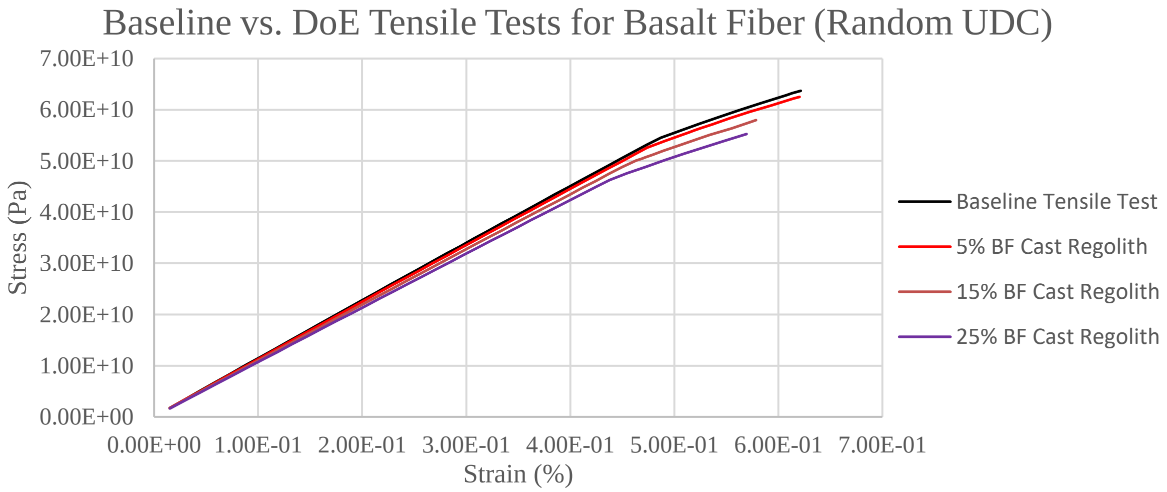


Figure 5.6: Simulated tensile results of UDC-implemented cast regolith.

Referring to table 5.1, random unidirectional composites follow the same trend as that of the short fiber composites. However, it is less ductile than short fiber composites. At the cost of stress, implementing basalt fibers to cast regolith increases the ductility property.

5.3 Additive Compression Test Results Compared to Baseline Results

As mentioned previously, fiber implementation increases the ductility of cast regolith and can be demonstrated not only from the tensile test, but the compression test results as well. Figure 5.7 shows the deformation of the compression test specimen in which the applied force is pushing towards the fixed face.

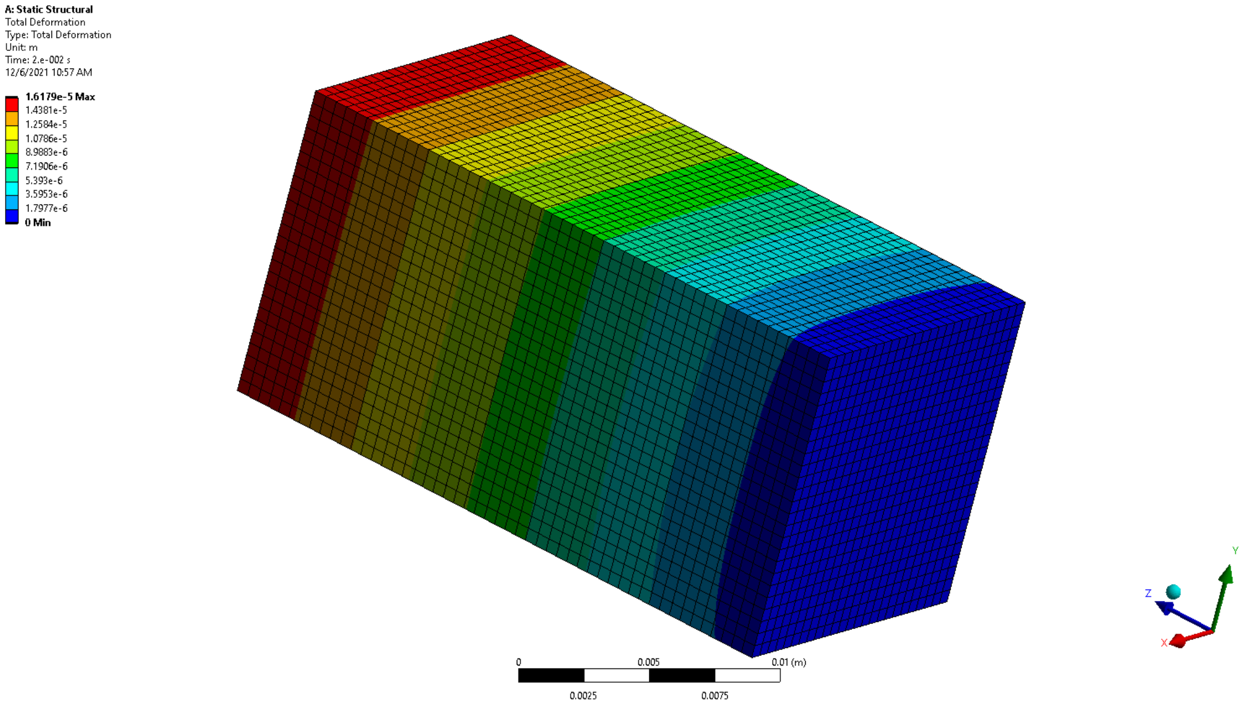


Figure 5.7: ANSYS simulated compression test with deformation-based gradient.

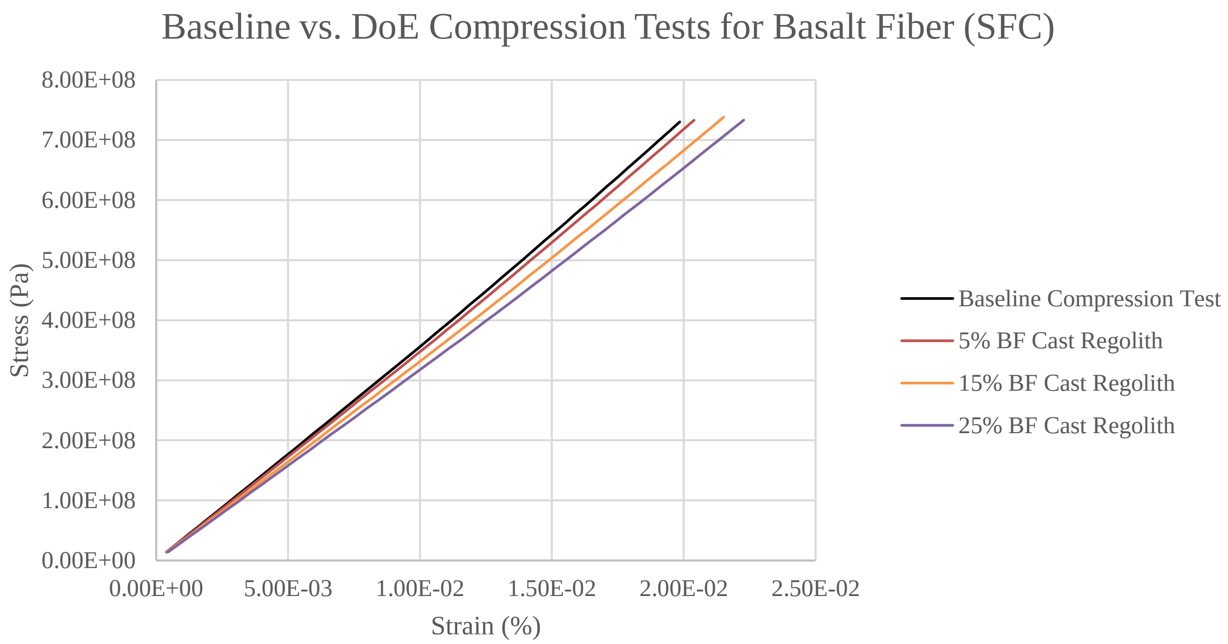


Figure 5.8: Simulated compression results of SFC-implemented cast regolith.

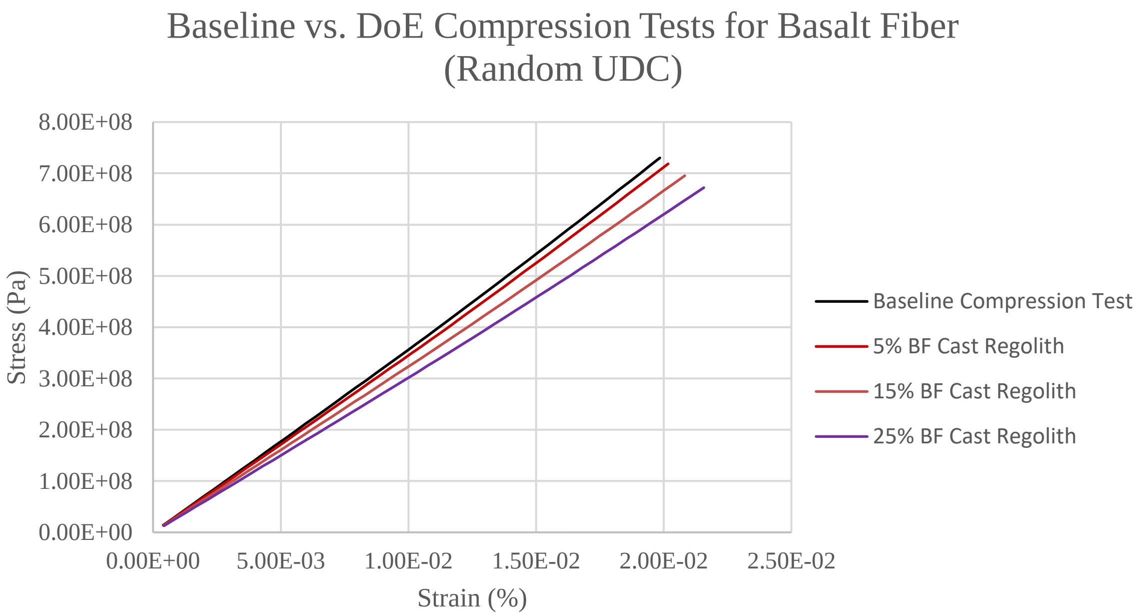


Figure 5.9: Simulated compression results of UDC-implemented cast regolith.

As seen from figure 5.8, short fiber composites retain its original matrix maximum stress based on the applied load, but the inclusion of the fibers increases the ductility as higher strain can be seen in the figure. Figure 5.9 shows the same trend as the previous compression test results as the fibers increase ductility. However, the stress decreases as the amount of fiber is increasing, showing an indirect relationship between the two properties.

5.4 Additive 3pt-Bending Test Results Compared to Baseline Results

The 3 point bending test is used to determine the flexural strength of a material. Ideally, brittle materials will not bend, but fracture when the applied force is high enough. However, any force below the fracturing force will provide an elastic response, meaning that the material will resist permanent distortional effects. Figure 5.10 is a result and an example of a force being applied in the middle of a cast regolith beam and the maximum displacement that is shown is about a 5 millimeter change. This shows the brittleness as well as the rigidity of cast regolith when a force is applied.

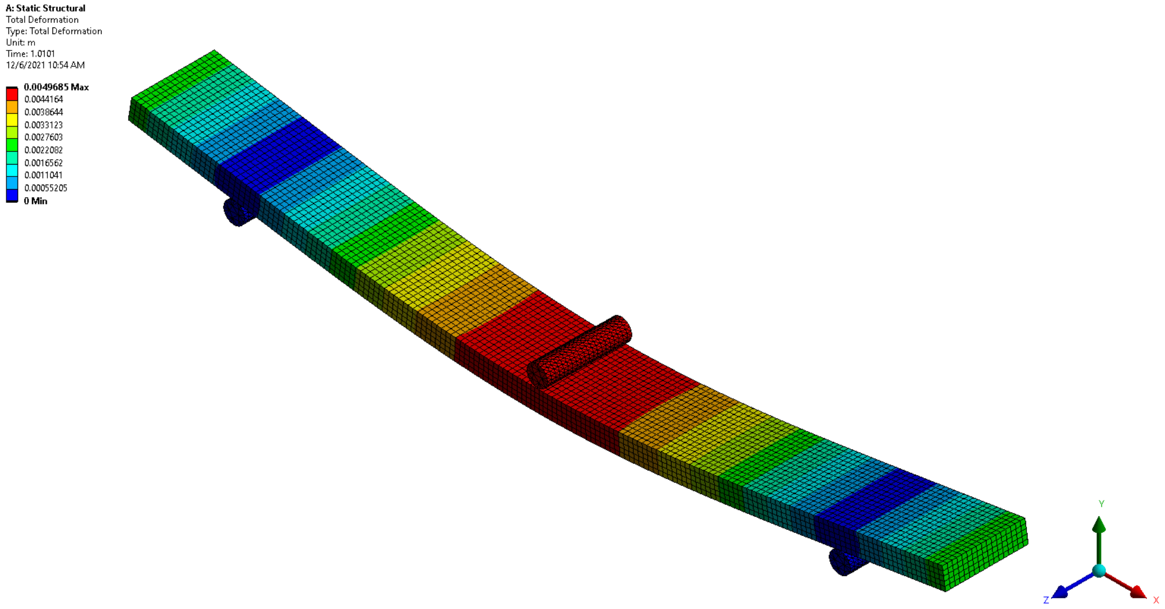


Figure 5.10: ANSYS simulated 3pt-bending test with deformation-based gradient.

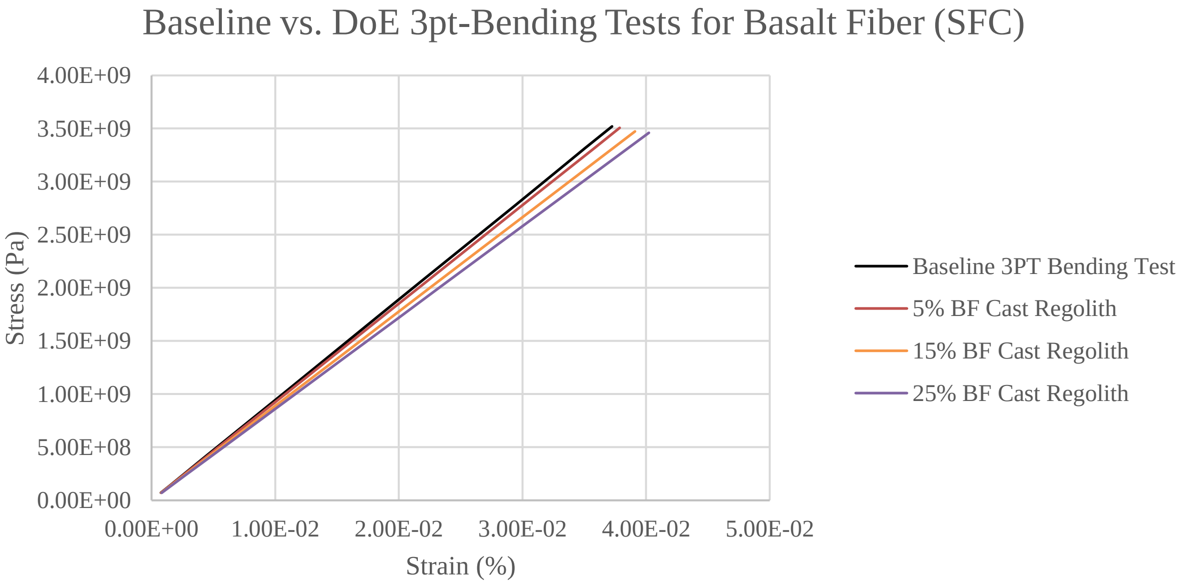


Figure 5.11: Simulated 3pt-bending results of SFC-implemented cast regolith.

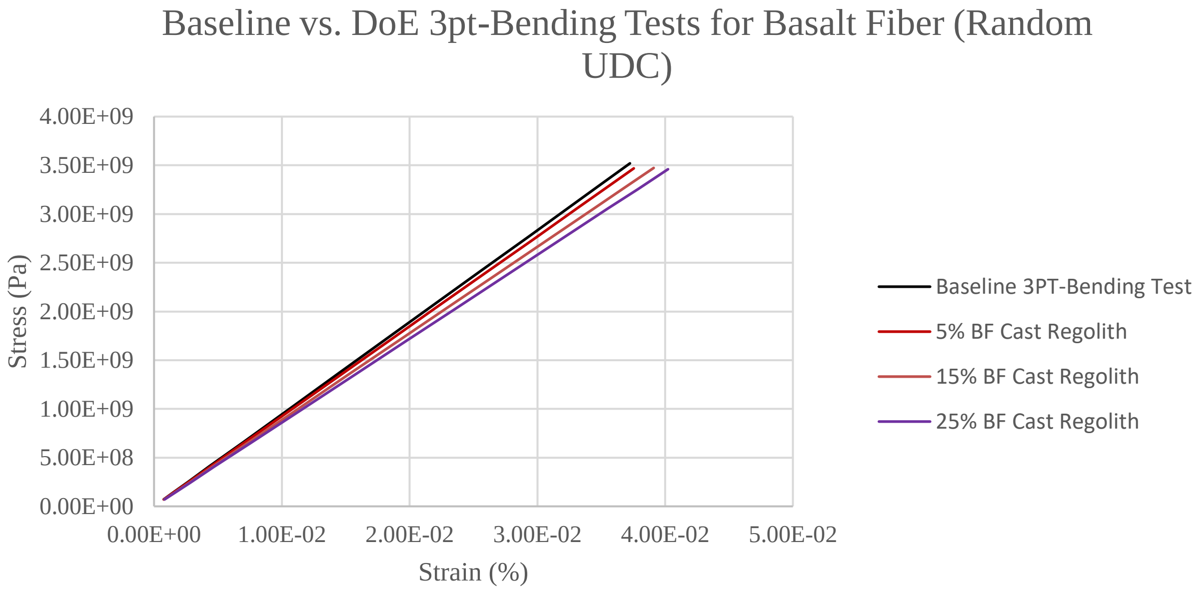


Figure 5.12: Simulated 3pt-bending results of UDC-implemented cast regolith.

It can be seen in figure 5.11 and 5.12 that the stress values remain relatively the same as the same force is being applied whether it is for the short fiber composites or the random unidirectional composites. There is a slight difference for the strains as the short fiber composites still show improvement for cast regolith when compared to unidirectional composites. Overall, this test is to determine the flexural strength of a composite material.

5.5 Discussion Based on the Results

Throughout the simulations and graphs of the stress tests, it can be seen that additives deteriorate the mechanical properties of cast regolith. Specifically, the tensile test shows that the basalt fiber and cast regolith composite, in both SFC and random UDC orientations, reduces the ultimate tensile strength of the material. This can be justified by the fact that basalt fiber has a lower Young’s modulus than cast regolith, which makes fracturing and failure easier than if basalt fiber was not implemented. For SFC fiber orientation, the compression test depicts that the stress remains the same when the same force applied, but the strain/elongation is increased. This ultimately shows that the composite is more ductile than without the additives. This relationship can also be seen in the 3-point bending test results as well. For the random UDC orientation, the maximum stress due to the applied load decreases as the maximum strain increases. Therefore, the implementation of basalt fiber to a cast regolith matrix deteriorates the material property values, but increases the ductility of the material. A material that can possibly improve the maximum stress values of cast regolith is carbon fibers as its Young’s modulus is approximately 180 GPa which is about 125% more than that of basalt fiber and about 80% more than cast regolith.

6. Conclusion and Final Remarks

6.1 Conclusion

As interplanetary habitation is trending, the main goal for aerospace engineers is to determine feasible materials that will allow expeditions further in space to be at low cost. Ideally, engineers will use in-situ resources to construct bases of operations for space pioneers. Not only do engineers have to consider the wellbeing of the astronauts, but they do have to consider the environment in which to place habitat structures. For the Moon, specifically, the radiation and lunar soil are proven dangerous for astronauts. The use of in-situ lunar material can prove vital for future space explorations depending on how it is used and improved.

Within this report, the main technology to consider is additive manufacturing with the main focus being a combination of cast regolith and basalt fiber. The reason for choosing cast regolith is due to the high tensile and compressive strengths that the material has compared to lunar concrete. Furthermore, the reason for basalt fiber is due to the bountiful amount that the Earth possesses in volcanic regions as well as the similarities in mechanical properties that basalt has with lunar soil. By simulating tensile, compressive, and 3-point bending tests on the static structural feature of ANSYS, results and data shows that implementing basalt fiber slightly increases and improves the performance of cast regolith, allowing the composite to be more ductile than before the fiber implementation. The maximum deformation within the SFC model showed a 1.35% increase when compared to cast regolith without any additives implemented. This holds true for random UDC models as well once enough basalt fiber is included. However, the maximum stress that the composite experiences is decreased due to the lower Young's modulus that basalt fiber has compared to cast regolith. Therefore, the need for a higher Young's modulus within a fiber will provide cast regolith with a higher ultimate tensile strength than a basalt fiber and cast regolith composite. A possible fiber option that is used throughout aerospace application is carbon fiber due to its high Young's modulus and fatigue resistance.

6.2 Environmental, Economic, and Social Impacts

Many benefits can be achieved from utilizing in-situ materials in a majority of planetary structures that will significantly impact the future of space travel. Many benefits from the impacts coincide with one another. This will shape how space exploration can be further achieved as it will allow engineers with an opportunity to implement structures for base of operations on any astronomical body.

In its raw form, lunar regolith possesses various troublesome aspects that can endanger the lives of expecting lunar inhabitants. Therefore, construction on the Moon is imperative as it will provide a source of protection from the environmental dangers. The aspiration for utilizing the material on the Moon for lunar construction also has advantages that can benefit the Earth as well. By obtaining samples of lunar materials, the mechanical properties can be found for regolith and then compared to similar terrestrial materials. This will allow engineers to use the terrestrial material similar to the regolith to determine the best method for processing lunar regolith into a viable construction material. The advantage of doing so will provide Earth with a construction material as well. Therefore, the environmental impact not only affects the Moon but it also affects Earth by providing a basis for affordable and sustainable housing [21].

The main economic goal for constructing with lunar material is to decrease the cost for materials to travel into space. By improving the mechanical properties of lunar regolith through the use of additive materials, engineers will be able to transport the necessary technology needed to process lunar regolith into a viable constructing material. Once transported, further transport missions will provide the additive material for construction as well as other pieces of equipment that will allow the inhabiting space pioneers to obtain the necessary life support requirements. Decreased space travel missions ultimately result in decreased cost for both aerospace organizations and industrial companies that desire to profit from space. As mentioned previously, lunar regolith simulants can also impact the economy on Earth by providing affordable housing solutions. Overall, the initial cost of travel will be greatly higher than the cost for any future transportation missions and research on lunar regolith improvements allows Earth to benefit as well.

(A) ***(B)***

Figure 6.1: 3D-printed regolith simulant, (A) hollow cone and (B) hollow dome structure [20].

Through the lens of aerospace, the social impact of in-situ construction materials will greatly increase the interest of space exploration to other planets. Companies will be invested in utilizing space as a commercial product, which will allow for the increase in funding for aerospace missions. With the technology to 3D-print construction materials, several structures can be made to benefit the infrastructure within Earth, such as the following [20]:

- Blast protection structures
- Affordable housing and shelters
- Paved roads
- Radiation and ablative heat shielding

6.3 Future Technology

Including additive manufacturing, software and technology are improving to reduce cost and material as well as perform the necessary tasks needed efficiently. This can be demonstrated by referring to the NASA technology readiness levels (TRL) as shown in figure 6.2.

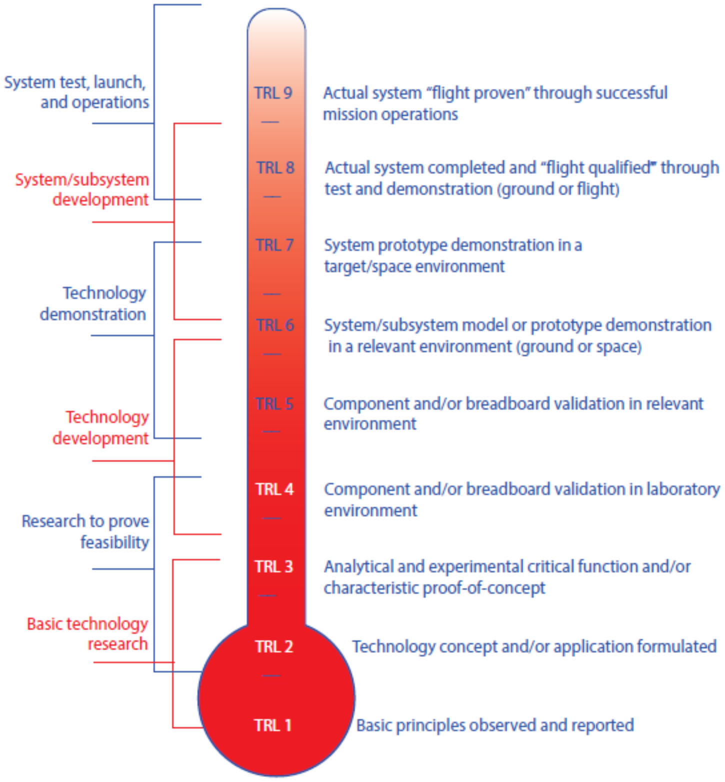


Figure 6.2: NASA technology readiness levels [33].

As seen in figure 6.2, there are 9 levels that describe the status of a piece of technology in development. The first three levels is the basic research that defines and establishes concepts and functions for the developing technology. Therefore, the proof-of-concept for basalt additive manufacturing was still in development. The higher levels of the TRL chart depicts technological development and demonstration as well as system development and operations. Technology development and demonstration validates the components within its specified environment. The system development and operation ultimately determines whether the technology is ready to be used in its specific mission after conducting tests to prove its reliability [33].

Referring to figure 6.1 as an example, the technology readiness level of additive manufacturing for basalt regolith simulants had a low technology readiness level of 3 in 2015. This means that the basic principles of additive manufacturing has been observed and reported, and its concepts and application can be formulated. Mueller et al. has shown that additive manufacturing through the use of basalt fines is a feasible manufacturing method due to the high abundance of basalt in volcanic territories, such as Hawaii and Arizona. This manufacturing method can also be done on the Moon and Mars due to its high abundance of basalt-like material that are commonly found on the surface of the spatial body [20]. The next steps are to validate the systems by testing its components in the desired environments of operation, such as the Moon or Mars.

Another technological development that is being researched on is robotic and how to utilize them to assemble in-space structures. The two-legged robot, as seen in figure 6.3, is designed to assemble large flexible structures while taking into account disturbance inputs caused by structure assembly [18]. With the complexity of coding the functions for assembling lattices as well as feedback controllers, the robot is in the same TRL as additive manufacturing as the concepts have been observed but further validation of its components and coding still need to be tested in its specified environments.

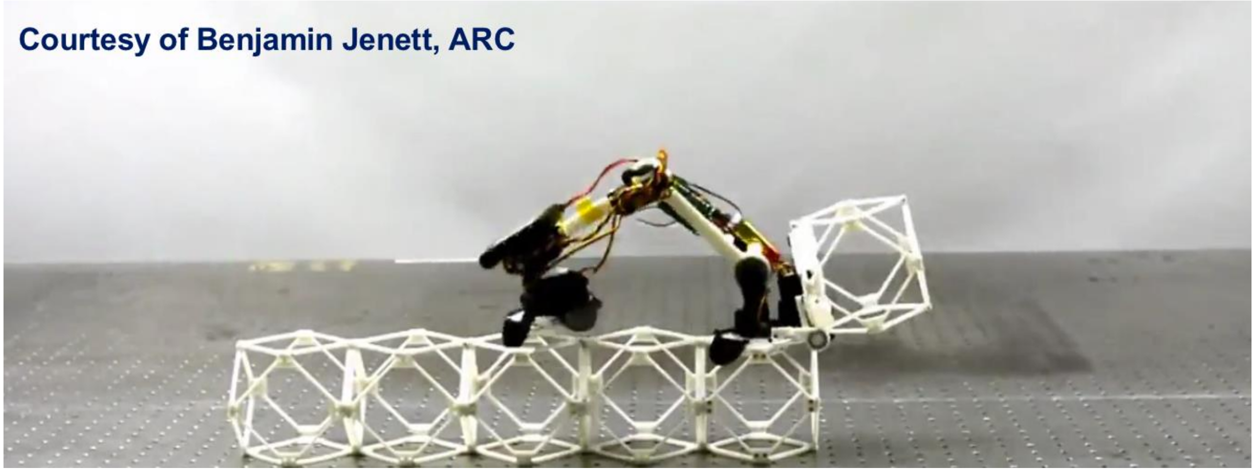


Figure 6.3: Lattice structures assembled by a robot [18].

6.4 Suggested Testing Improvements and Future Work

One major key to consider is physical testing. Currently, there is not enough failure and fracture data available for lunar materials. Therefore, physical testing is not only necessary but also feasible as it will allow for accurate measurements and less time for researching specific data that may or may not be available to the public.

For future work, a design of experiment to consider is changing the applied forces accordingly to depict the difference in material properties, specifically the stress values. Due to the constant force values, the stress did not change drastically but the strain did. Stress simulation tests within the transverse direction can also be applied to determine whether cast regolith has improved transversally rather than longitudinally as it has been tested within this report. Furthermore, different types of fibers can be implemented to determine the ideal fiber that will allow lunar regolith to perform efficiently all while being feasible.

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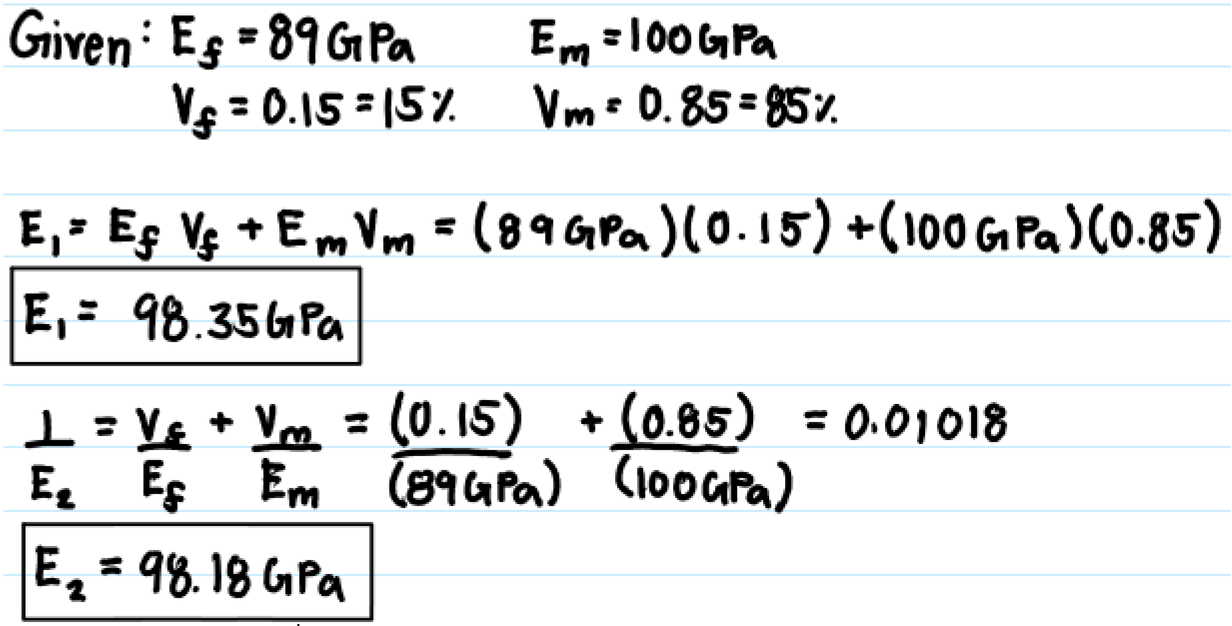
APPENDIX A – Hand Calculations for 15% and 25% Basalt Regolith Composite



Given: $E_f = 89\,GPa$ $\quad E_m = 100\,GPa$

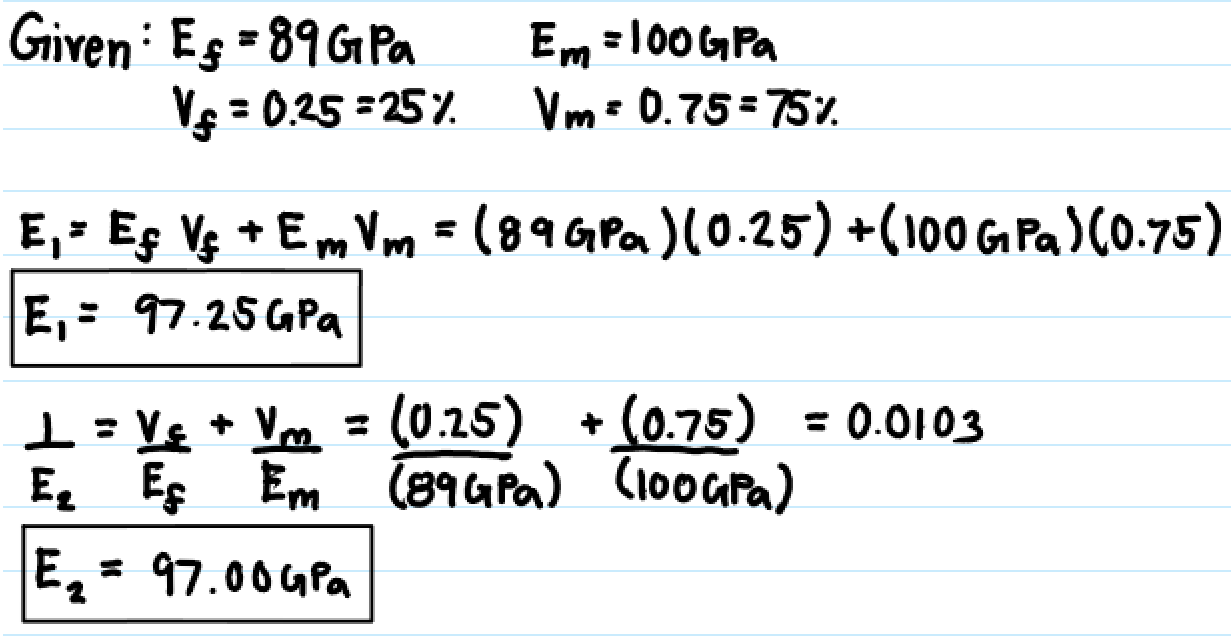
$V_f = 0.15 = 15\%$ $\quad V_m = 0.85 = 85\%$

$$E_1 = E_f V_f + E_m V_m = (89\,GPa)(0.15) + (100\,GPa)(0.85)$$

$$\boxed{E_1 = 98.35\,GPa}$$

$$\frac{1}{E_2} = \frac{V_f}{E_f} + \frac{V_m}{E_m} = \frac{(0.15)}{(89\,GPa)} + \frac{(0.85)}{(100\,GPa)} = 0.01018$$

$$\boxed{E_2 = 98.18\,GPa}$$



Given: $E_f = 89\,GPa$ $\quad E_m = 100\,GPa$

$V_f = 0.25 = 25\%$ $\quad V_m = 0.75 = 75\%$

$$E_1 = E_f V_f + E_m V_m = (89\,GPa)(0.25) + (100\,GPa)(0.75)$$

$$\boxed{E_1 = 97.25\,GPa}$$

$$\frac{1}{E_2} = \frac{V_f}{E_f} + \frac{V_m}{E_m} = \frac{(0.25)}{(89\,GPa)} + \frac{(0.75)}{(100\,GPa)} = 0.0103$$

$$\boxed{E_2 = 97.00\,GPa}$$