Prioritization of habitat construction materials on Mars based on multi-criteria decision-making

Soha Iranfar, Mohammad Mehdi karbala, Mohammad Hossein Shahsavari, Veerle Vandeginste

PII: S2352-7102(23)00043-8

DOI: https://doi.org/10.1016/j.jobe.2023.105864

Reference: JOBE 105864

To appear in: *Journal of Building Engineering*

Received Date: 9 November 2022

Revised Date: 29 December 2022

Accepted Date: 7 January 2023

Prioritization of habitat construction materials on Mars based on multi-criteria decision-making

Soha Iranfar[a,b], Mohammad Mehdi karbala[c], Mohammad Hossein Shahsavari[d] , Veerle Vandeginste[e*]

[a]Department of Petroleum Engineering, Abadan Faculty of Petroleum, Petroleum University of Technology (PUT), Abadan, Iran. S.iranfar@ait.put.ac.ir

[b]Department of Mining and Metallurgical Engineering, Yazd University, Yazd, Iran.

[c]Rock Mechanics Division, School of Engineering, Tarbiat Modares University, Tehran, Iran. m.karbalayi@modares.ac.ir

[d]Amirkabir University of Technology (Tehran Polytechnic), Hafez Avenue, Tehran, Iran. m.h.shahsavari@aut.ac.ir

[e]KU Leuven Campus Bruges, Department of Materials Engineering, B-8200 Bruges, Belgium. veerle.vandeginste@kuleuven.be

*Corresponding author

Abstract

Mars is the most accessible planet in the solar system for habitation and could serve as a base for exploring more distant planets. Space agencies and scientists worldwide continue exploring Mars to gain more geologic and atmospheric information in preparation for constructing space habitats. The harsh planetary conditions of Mars require the development of new or modified methods for building infrastructure and formulating binders. Each type of concrete has advantages and disadvantages, and we need to find the best binder for use in construction on Mars.

In this study, eight construction materials, including Ordinary Portland cement (OPC), sulfur concrete, geopolymer, sintered material, polymer-bound regolith, products of geo-thermite reactions, regolith-based magnesium oxychloride, and microbial-induced calcite precipitation, are reviewed according to 14 criteria. The criteria are availability, shipping, water requirement, technical working conditions, curing time, temperature, total required energy, strength, durability, cosmic radiation shield (density and hydrogen content), additives needed, sustainability, safety, and recyclability. We applied the Fuzzy Analytic Hierarchy Process (AHP) approach to assign a weighting to each criterion. Finally, we used three multi-criteria decision-making (MCDM) methods to determine the most suitable mortar for construction under the harsh conditions on Mars.

The results show that if the general conditions of Mars are considered uniform such as different temperatures and geologies dependent on location, geopolymer concrete is the best material for construction based on Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR), and Weighted Aggregates Sum Product Assessment (WASPAS) methods, and sintered material concrete and sulfur concrete

are equally ranked second. Correspondingly, five concretes of Portland cement, products of geo-thermite reactions, regolith-based magnesium oxychloride, polymer-bound regolith, and microbial-induced calcite precipitation are the most efficient construction materials, respectively. In addition, using the Fuzzy AHP method, the criteria of shipping and sustainability have the highest and lowest weighting, respectively, in the decision-making process. The use of MCDM methods and inductive analysis provides a scientific approach that enables the comparison of the potential of several space concrete materials for better decision making in future research and construction within the next 10 to 20 years.

Keywords: building materials, space habitat construction, Martian concrete, MCDM.

1. Introduction

Space colonization has always been a subject of human interest, and about half a century after man's journey into space, we are now thinking of a short-term and long-term stay there. Scientists and investors believe that the Moon and then Mars would be an applicable base for humans' (semi-)permanent presence. However, these activities require natural resources for construction, and due to technical and economic limitations, it is impossible to send large quantities of materials from Earth. In situ resource utilization (ISRU) becomes one of the requirements for long-term missions on other planetary surfaces. The resources will be used to build shelters, launch and landing pads, routes, and factories. In addition, conditions on the Moon and Mars are not comparable to those on Earth. Therefore, researchers should use new methods and materials or modify traditional construction approaches to adapt to harsh conditions.

The Martian gravity is 3.721 m/s^2, and the average atmospheric pressure is 655 Pa. Moreover, its surface is exposed to harmful radiation because its atmosphere is not dense, but the atmosphere still provides a reasonable protection against incoming meteorites, in contrast to the Moon [1, 2]. The temperature on Mars varies considerably depending on surface location, season, and time of day. The temperature range of Mars is -153 to 20 [3-5].

The difference in daily and seasonal cycles between Earth and Mars is a factor that should be considered in space habitat construction. Earth takes 24 hours to complete one spin and revolves around the Sun in about 365 days. In contrast, Mars' rotation takes 24 hours, 39 minutes, and 35 seconds, and its orbit around the Sun takes 687 Earth days - or one Martian year [6, 7].

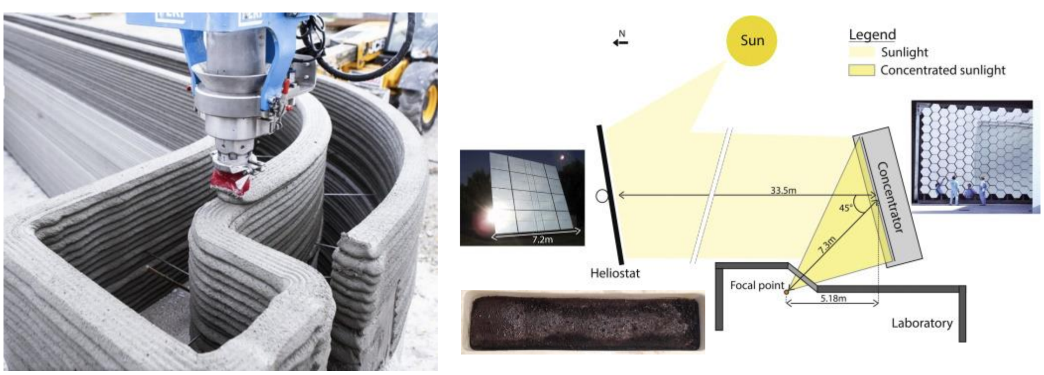
The harsh conditions in space need to be accounted for to reduce predictable and unpredictable risks during and after habitat construction [8]. These extreme planetary conditions challenge engineers to redefine the materials, additives, mixing processes, casting, compacting, and curing conditions [9]. Accordingly, the space materials should meet specific conditions, including [10]:

- The material should have a low working temperature range due to the wide range of low temperatures on Mars.
- The materials must have a good performance and be resistant to the major temperature swings linked to exposure to solar radiation and distance from the Sun.
- The materials should be erosion and corrosion-resistant because of the mechanical erosive (dust-blown wind) and chemical corrosive (CO_2 and UV radiation) environment of Mars [11]
- The material used should not be ferromagnetic because of the presence of magnetic dust on Mars.
- Materials need to act as radiation shields.

The construction materials are usually tested under simulation conditions in a laboratory to determine their shortcomings. One of the factors that significantly affects the results of the experiments is the soil of Mars because its metal oxides usually participate in reactions during processing concrete mortar. However, Martian regolith has not yet been brought from Mars to Earth.

Therefore, Martian regolith simulants are commonly used for space construction experimental tests [12]. The main characteristics of these regoliths are mineralogical composition, morphology, and particle size distribution (PSD).

Moreover, the construction technology is one of the effective parameters that influences the selection of an appropriate concrete. The two main methods proposed for space construction include 3D printing and using sulfur and sintered bricks [13, 14], as shown in Fig.1. Isachenkov, Chugunov, Akhatov and Shishkovsky [15] presented a review comparing recent developments in chemical and technological features of 3D printing using lunar regolith simulant. They formulated the essential requirements and methods to adapt additive manufacturing methods for space conditions. Generally, simple bricks can be easily built by casting in a mold, and additive manufacturing (AM) methods can be customized with complex geometries [16, 17]. In addition to 3D printing and the use of bricks, some areas of space construction remain unexplored, for example, underground and underwater (ice) construction [16, 18, 19].



a b

Fig. 1. (a) 3D printing and (b) solar sintering brick (b) [13, 14]

1.1 Binders for space habitat construction

In the construction industry, several types of concrete are made using different materials and methods. These concretes need primary and secondary conditions to effectively maintain their mechanical properties in the harsh environment of Mars. Primary conditions refer to the construction method, the required temperature, pressure conditions during construction, and the early curing stages. Secondary conditions should consider keeping the temperature and pressure constant until complete curing. The general binders reported in the literature are Ordinary Portland cement (OPC), alkali-activated cement (AAC), geopolymer cement (GC), elemental sulfur (ES), Mg- and Si-based binder (MSBB), and water (by freezing).

Furthermore, many new materials are proposed for use in space construction, including sintered material, polymer-bound regolith, products of geo-thermite reactions, microbial-induced calcite precipitation, and regolith-based magnesium oxychloride. The synthesis of these binders needs considerations regarding energy consumption and raw material availability [1, 8, 20-23]. This study will not attempt to survey all possible material concepts but will scrutinize those that are currently at an advanced stage of development.

1.2 Trade study

Applying state-of-the-art methods and tools for planning, management, information, cost, design trade-off analysis, and simulation substantially enhances the effectiveness of the system design process [24]. Trade studies are decision-making actions used to determine the most reasonable and acceptable technical solution among a set of proposed options. All decisions are inherently subjective and involve risks. Trade studies develop an effective means to address the subjectivity and risks by documenting the decision-making process to provide traceability and repeatability

[25, 26]. Hence, a trade study is an objective comparison taking into account the cost, performance, risk, schedule, and all other criteria of all realistic alternative requirements [27].

The simplest form of trade study comprises the following steps: (i) Defining the alternatives and criteria; (ii) Assessing the performance of each alternative for each criterion; (iii) Comparing the results and choosing the best option; and (iv) Documenting the trade study process and its outcomes. The comparison is generally made by considering two definitions, namely a measure of effectiveness (MOE) - A measure of how well mission goals are achieved ('how well' not 'how') and a measure of performance (MOP) - A quantitative measure that, when met by the design solution, will help ensure that a MOE for a product or system will be satisfied [28].

In the studies by Metzger and Autry [29], Dias, Matijevic, Venkataraman, Smith, Lindemann and Levin [30], a trade study of construction methods of landing pads using cost metrics was introduced. They considered several parameters, including the cost of the transportation of materials from Earth to the lunar surface, the energy expenditure cost, the lifecycle cost of energy systems, and the time required by a construction method (program delay cost). They examined different landing pad construction approaches by focusing on economic analysis, and the physics-based modeling of the construction techniques was not directly involved. In another study, Anderson [31] investigated different technologies of the integrated water recovery system used on the International Space Station (ISS) using a trade study. In addition, Cruz, Cianciolo, Powell, Simonsen and Tolson [32] conducted a trade study that compared various entry, descent, and landing technologies to place payloads on the surface of Mars.

Such trade studies often use a weighted averaging method of several criteria involving both quantitative and qualitative criteria in an aerospace technical subject. However, there are more advanced methods available that provide more accurate results with more comprehensive comparisons, such as multiple-criteria decision-making (MCDM). In addition, using these mathematical methods, comparisons with many options and criteria can be made.

1.2.1 MCDM (Multiple-Criteria Decision-Making)

MCDM is a part of operations research that explicitly considers multiple inconsistent decision-making criteria. Some fields, such as medicine, government, and business, have inconsistent criteria that lead to the complexity of decision-making. This complexity originates from the different nature of the criteria; some are quantitative, whereas others are qualitative [33]. Different inconsistent criteria take part in the decision-making to find the best materials and concrete to build lunar and Martian habitats, and these methods can help space engineers. The criteria, such as technical and economic, are named inconsistent criteria, which are quantitative or qualitative. Qualitative criteria include limitations, shipping, sustainability, and safety in space habitat construction topics. Quantitative criteria include temperature, curing time, strength, and density. Solving an optimization problem by addressing inconsistent criteria is more reliable and precise than a decision considering only one factor.

There are many different MCDM methods with different complexities and assumptions. These differences originate from various chosen score scales and weightings. As a consequence, there is a knowledge gap regarding the reliability of their results. The complexity of the MCDM approaches depends on the statistical features and the mathematical procedure. In these methods, the assumptions are criteria weighting, intensity, and explanation for comparing i rows with j columns in a matrix of pairwise comparisons [34-37].

MCDM methods consist of a wide range of approaches and are classified into three groups [38-40]:

- Value evaluation approaches: A numerical rate is formed for each alternative. Furthermore, a weight (w) is determined for each criterion to demonstrate the influence of the criterion (e.g., AHP).
- Reference level and goal models: These approaches estimate how suitable alternatives affect the achievement of specific targets (e.g., TOPSIS).
- Dominating methods: These models compare the alternatives pairwise for each criterion and determine the superiority of preferring one over the other (e.g., PROMETHEE, ELECTRE).

The ability of MCDM methods has been proven in various sciences such as the military, petroleum, and civil engineering, medical, and space exploration [41-44]. From an aerospace engineering perspective, Tavana [45] used the MCDM to define the risks and advantages associated with three optional mission architecture plans for Mars exploration. Gunaydin, Duvan and Ozceylan [46] defined the best habitable planet using the MCDM method. Nine habitable planets as well as the Moon were studied in their research. The criteria included gravity, mass, escape velocity, diameter density, rotation time, distance from the Sun, length of the day, perihelion, aphelion, orbital period, orbital inclination, orbital velocity, orbital eccentricity, mean temperature, obliquity to orbit, and the number of satellites. Furthermore, the Analytic Hierarchy Process (AHP) approach was applied to determine the optimal properties of a lunar construction habitat [47]. In addition, Higgins and Benaroya [47] used the AHP to define optimal lunar habitat construction. In addition, Sánchez-Lozano, Moya and Rodríguez-Mozos [48] ranked and prioritized the exoplanets intending to seek biomarkers using MCDM methods. In another study, Eren and Katanalp [49] investigated the selection problem of Bike-Sharing Systems (BSSs) station sites based on transportation and recreational land uses. Saraswat, Digalwar and Yadav [50] evaluated different energy sources for sustainable development in India by applying the fuzzy AHP and WASPAS methods.

To the authors' knowledge, there is no review yet of proposed space binder materials. Hence, this paper gathers and compares different concretes considering technical, availability, and operation parameters. The two main goals of this research are (i) to present a summary of space mortar concretes and compare them, and (ii) to determine the best material considering inconsistent criteria for the time frame of near-term construction within the next 10 to 20 years. Therefore, eight construction materials are reviewed along with 14 criteria. In this study, the Fuzzy AHP is applied to assign weightings and define the most determining criteria, and Multiple-Criteria Decision-Making (MCDM) methods are used to find the best concretes for Martian habitat construction. In total, three methods of MCDM are used in this study: the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), the VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR), and the Weighted Aggregates Sum Product Assessment (WASPAS). These models are based on estimations rather than direct measurements of mature construction systems because each of these technologies is still under development.

2. Methodology

In order to find the best concrete mortar for the construction of space habitats, the promising primary materials were first discussed, and their advantages and disadvantages were briefly presented. In addition, various effective criteria related to concrete mortars are explained, and finally, Fuzzy AHP, three MCDM methods of TOPSIS, VIKOR, and WASPAS are described. Fig. 2 shows the procedure of applying MCDM methods to select the best space concrete mortar.

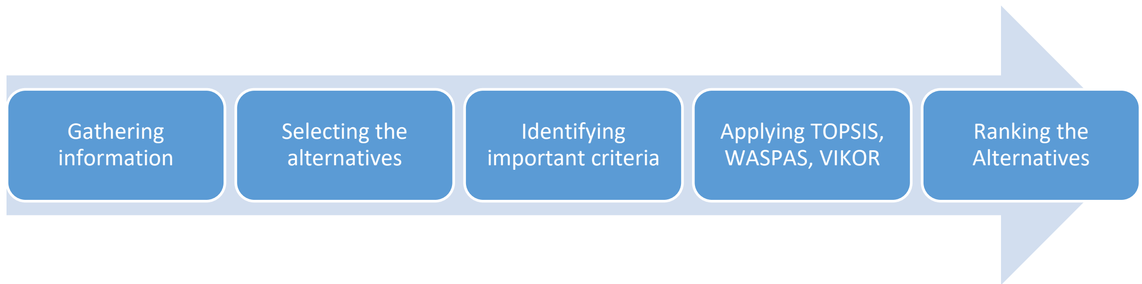


Fig. 2. The procedure of applying MCDM tools to select the best planetary concrete mortar.

2.1 Construction materials

The most important materials proposed for space habitat construction, including ordinary Portland cement, sulfur, geopolymer, sintered material, polymer-bound regolith, products of geo-thermite reactions, microbial-induced calcite precipitation, and regolith-based magnesium oxychloride, are reviewed. Their different main properties, advantages, and disadvantages are also presented. There are three other types of concrete plaster of Paris-based gypsum, water-based ice concretes [51], and cold sintering [52] but there is not enough data available on those that enables comparison with other concretes in this research.

- **Ordinary Portland cement (OPC)**

Ordinary Portland cement (OPC) is a hydraulic cement produced by mixing limestone ($CaCO_3$) with Si-rich clay or shale and heating it at temperatures of approximately 1450 °C [53, 54]. Most research on space construction has been conducted on OPC terrestrial binders because of their high durability, strength, and simplicity [1, 55-59]. One of the disadvantages of the potential use of Portland cement mortar on Mars is the shortage of $CaCO_3$ on Mars, which would not be sufficient for OPC production [8]. Another disadvantage of this cement is that it needs water for the production process, hydration, and curing [60]. Water is an essential requirement for the production of concrete. Liquid water is not thermodynamically stable on the surface of Mars, but it can be found on the sub-surface or could be produced by melting ice [61]. Some ice-water inferred reserves, particularly near the poles, are more localized and less plentiful near the equator [62-64]. Water condensation from atmospheric humidity can be an option to acquire liquid water [8].

The curing time of this cement is 28 Earth days (the pressure and temperature condition of Earth). Certain conditions should be prepared to prevent freezing and evaporation of water during hydration at low temperatures and vacuum pressure conditions [65, 66]. From the perspective of shielding against galactic cosmic rays (GCR) and occasional solar particle events (SPE), Portland cement can be a good option for shielding [67, 68].

- **Sulfur concrete**

Sulfur binder has been studied as a potential cement for space concrete [57, 69-71]. It would be processed from sulfate minerals that are abundant on the Martian surface, such as ferric sulfate ($Fe_2(SO_4)_3$) [72-74].

Barkatt and Okutsu [75] surveyed different thermochemical and electrochemical methods that might be used to produce elemental sulfur from its compounds in Martian regolith. Two critical stages of producing this binder include synthesis by the ferric sulfate pyrolysis at ~900 °C and catalytic reduction of the evolved sulfur dioxide (SO_2) gas [76-81]. A total of 22.5 g of hydrogen and 105 g of Carbon monoxide (CO) are required for one kilogram of ore synthesis, which can be synthesized on Mars from water and Carbon dioxide (CO_2), respectively. The valuable products of this reaction would be 240 g of elemental sulfur, 203 g of water, and 120 g of Oxygen (O_2). The waste products, including 400 g Iron oxide (Fe_2O_3), 165 g CO_2 (gas), water, and carbon dioxide, could be reused to regenerate the hydrogen and CO components.

In order to use elemental sulfur as cement, the mixture of molten sulfur (>120 °C) and grains can be used in casting and printing; when the temperature decreases to 112.8 °C, the mortar sets and hardens rapidly into a solid body. This binder is an interesting cement for space construction because it uses accessible resources and does not need water for mixing and casting. In addition, this cement can be easily reused by heating and recasting. Moreover, this concrete is recyclable and can be easily remolded in new applications [82].

A potential drawback of sulfur concrete is that the structures constructed by sulfur concrete can reach temperatures that exceed that of molten sulfur (>120 °C), for instance, the high temperature of rocket motor plume, which would cause a sulfur concrete structure to fail if the structure is exposed to these conditions [83, 84]. This concrete has desirable mechanical and chemical properties for space applications, but its synthesis is the main challenge in using sulfur [8, 85, 86]. However, Wan, Wendner and Cusatis [70] have suggested the probability that elemental sulfur may be present on the Martian surface. In addition, it is assumed that sulfur sublimation under vacuum conditions could be one of the biggest challenges in the production of sulfur concrete in space [87]. However, Shahsavari, Karbala, Iranfar and Vandeginste [88] predicted that the sublimation rate under vacuum conditions at very low temperatures, -60°C, can be decreased approximately 8000 times compared to 20°C.

- **Geopolymer**

Generally, geopolymers are made from by-products such as fly ash and slag. They are green cement with high uniaxial and flexural strength, suitable durability, and low carbon emission [89-92]. Geopolymers are composed of silico-aluminates in an amorphous to semi-crystalline 3D structure. This binder shows good efficiency, such as fast, controllable setting and hardening time, high compressive strength, freeze-thaw resistance, excellent durability in sulfate and acidic environments, fire resistance with low thermal conductivity, low shrinkage, and adequate radiation shielding [93-98].

One of the disadvantages of this concrete is the need for water. However, a study by Wang, Tang, Cui, He and Liu [99] proposed a method to produce geopolymer concrete in which water is recovered after curing using tektite powder. The low operating temperature (70-90 °C) and one-day curing time of the geopolymer are suitable for space construction. In contrast, Portland cement concrete needs a curing time of 28 Earth days, and sulfur cement and sintered material require a high temperature [100, 101].

- **Products of thermal methods**

Thermally produced construction materials are divided into two common classes: sintered and melting-manufactured construction materials. The most common sintering methods are laser, radiant furnace sintering, and microwave sintering [102, 103].

Sintering is a thermal treatment method that attaches grains into an integrated solid because of mass transport at the atomic scale without completely melting the material [104]. It thermodynamically reduces the overall surface area of two or more grains by coalescing them together and leading to new interfaces between the particles [105]. During this process, regolith is transformed into sintered metal oxide material and a solid by heating under the temperature of the melting point, and it causes the surfaces of the particles to diffuse into each other [16, 106, 107]. Compared to the melting method, sintering needs less energy to produce a solid block and does not require additives or other processes [108]. Examples of sintered products are ancient ceramic clay pots and modern composites. In addition, solar sintering is the most promising space technology in this field, which has been proposed to construct lunar concrete [29, 109].

In contrast to sintering, regolith is liquefied above the melting temperature in the melting and casting processes. These methods can build dense materials with high strength and wear resistance. Materials generated by melting and casting are categorized as glass, glass-ceramic, or cast, depending on the degree of crystallization of the end product [110]. The most critical drawback of these methods is the high temperature and high energy consumption, whereas the main advantage is that no additives are needed [111]. In addition, products of thermal methods production often requires a slow cool-down to prevent cracking from rapid cool-down due to thermal stresses induced from phase transformations during sintering [112].

- **Polymer-bound regolith concrete**

Hintze, Curran and Back [105] used polymers for the first time to bind lunar regolith simulants and prepared a polymer/regolith composite with less than five mass percent polymer. The in situ required polymers may be extracted from volatiles ubiquitous on planetary objects or acquired on asteroids or moons with kerogen-like organic material [105, 113, 114]. Some researchers, such as Chen [115], studied polymer concrete and made a polymer with a high strength/weight ratio with high radiation resistance as a binder to cement together lunar regolith grains firmly. Johnson-Freese [116] provided an overview of the role of polymers as a promising material. It can be used as a shield of radiation, chain scission, and crosslinking. The disadvantage of this concrete is its low strength.

- **Products of geo-thermite reactions**

The geo-thermite reaction is an oxidation-reduction reaction, including a mixture of minerals, glass, and aluminum. This phenomenon is a self-propagating and high-temperature synthesis (SHS) reaction. Chemical reactions between intact aggregates and a reducing agent, which show thermite-type reaction behavior, are known as reactions of geothermite. The geothermite reaction is a method with high potential for ISRU applications in space construction. The heat generated during thermite reaction can melt at least one reactant and bind them together [117-119].

In a study by Delgado, Cordova and Shafirovich [120], the possibility of using Martian regolith has been explored to understand the effect of iron oxide and magnesium contents on reaction mechanisms. However, more research needs to be conducted on this cement. Furthermore, the two most significant barriers to using this method for space habitat construction are the energy-intensive extraction and the large amount of metal needed for the powder [22].

- **Regolith-based magnesium oxychloride**

Magnesium oxide (MgO) has been used on Earth for more than a century as Sorrel cement (magnesium oxychloride) [121]. The magnesium oxychlorides (MOCs), introduced in 1867 by Stanislas Sorel, are non-hydraulic binders. Chemically, they can be defined as various ingredients of the $MgO–MgCl_2–H_2O$ synthesis [122]. Jiangxiong, Yimin and Yongxin [123] and Jin and Al-Tabbaa [124] have illustrated that MgO can be combined with amorphous silica to form magnesium-silica-hydrate (MSH). This mixture is similar to calcium silicate hydrate (CSH) made by conventional Portland cement. Tran and Scott [125] investigated the potential of this cement for high-strength structural applications by building a MgO-silica fume mortar with 87 MPa compressive strength [126]. In another study, magnesium oxide, amorphous silica, and water were mixed with four Martian regolith simulants to produce mortar cube samples [127-129].

MOC cement has a fast setting time, high initial strength, and good rheological and workability properties. In addition, it does not require water for curing [126].

Magnesium is a ubiquitous element on the Martian surface, and there are no restrictions on in situ material utilization and availability. Furthermore, magnesium chloride ($MgCl_2$) or monopotassium phosphate (KH_2PO_4) must be involved in the reaction to complete the cementation process. On the Martian surface, chloride can be processed into brines and phases such as apatite and amphibole [57, 130, 131]. In addition, potassium is present in jarosite, some clays, and micas; these phases have been identified in Meridiani Planum and near Nili Fossae [132, 133].

- **Microbially induced calcite precipitation**

Biocementation, known as microbially induced carbonate precipitation (MICP), involves the use of microorganisms to precipitate calcium carbonate ($CaCO_3$) as a cementing agent [134-137]. This binder is generally used to repair damaged concrete structures, stabilize soil, and replace conventional Portland cement [138, 139].

Many researchers have focused on understanding how in situ construction using MICP can be an interesting option for building Martian habitats. In this method, a urease-producing bacteria favors the precipitation of calcium carbonate between loose aggregates. In addition to the grains and bacteria, a calcium source and urea must be present. The urea reacts with water to produce ammonia and carbonate. In this process, the calcium carbonate formed by the carbonate and calcium ions precipitates because of supersaturation and binds the grains together [140]. Calcium can be extracted by chemical analysis from minerals such as limestone, and the required urea can be obtained from the urine of humans and animals in the space environment. The only substance that needs to be sent to space is the bacteria, the growth media, the setups, and water if there is no access to it in place. Due to the temperature dependence of bacteria, it is also important to provide the proper temperature conditions [141-143].

- **New materials**

Roberts, Whittall, Breitling, Takano, Blaker, Hay and Scrutton [144] studied male and female serum albumin (HSA), a general protein acquired from blood plasma, as cement for Lunar and Martian regolith simulants to create regolith biocomposites. Their samples had a compressive strength of over 25.0 MPa. They also investigated urea, which could be obtained from astronauts' sweat, tears, or urine, and observed that compressive strength increased by more than 300% in some instances. In addition, some new additives were also introduced, such as urine as an accessible superplasticizer on the Moon for lunar geopolymer mixtures. Although new materials and additives are sometimes very attractive in this research area, it is unclear whether they will be practical and valuable in the long term.

2.2 Criteria of construction materials

Fourteen criteria, including availability, shipping, water requirements, technical working conditions, curing time, temperature, total required energy, strength, durability, cosmic radiation shield (density and hydrogen content), additives needed, sustainability, safety, and recyclability, are selected to determine the best concrete mortar for space habitat construction. There are many other parameters, but this study deals with construction materials from a mechanical point of view.

The cost criterion is very important in every decision-making, and it has several parts, namely, shipping, non-recurring engineering (aka development cost), recurring engineering (producing replacement parts), and operations [145]. However, this criterion was not considered here since the different construction methods for Martian conditions have not been finalized for space construction, and their needs have not been studied [146]. In addition, the distribution of mineral resources on Mars is not uniform. For instance, the map of the sulfur concentrations in the upper few tens of centimeters of the Martian surface is shown in Fig. 3 [147]. In this study, it is assumed that the necessary raw materials are uniformly distributed on the surface of Mars, and a discussion based on non-uniform distribution is beyond the scope of this study.

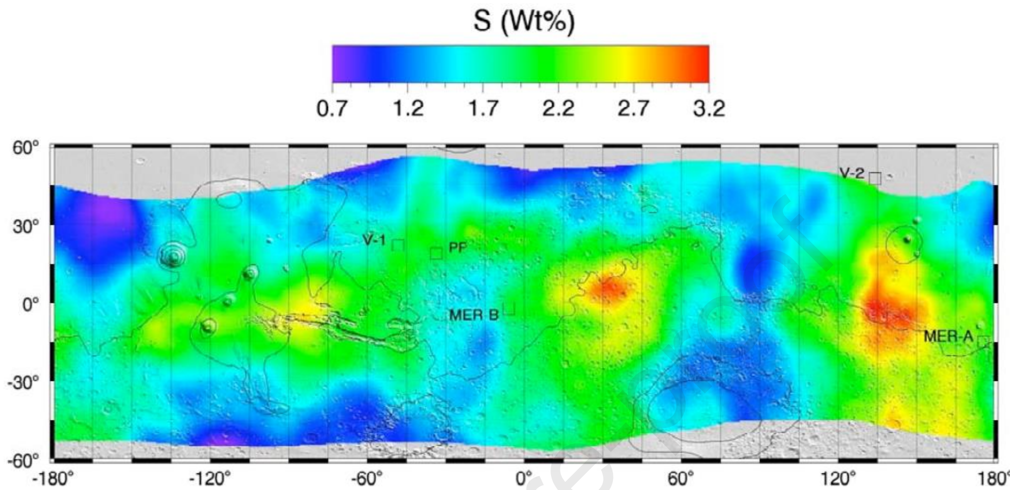


Fig. 3. Map of the sulfur concentrations in the upper few tens of centimeters of the Martian surface [147]

- **Availability**

The construction of permanent planetary habitats is limited by the efficiency of building materials and the availability of in-situ resources [148]. Building with locally available materials reduces transportation costs, equipment costs, etc. The issue of resource availability is a question that engineers and economists have addressed over the past decades [149]. Martian soil, for instance, is abundant, but substances such as water are not ubiquitous. Organic materials such as polymers have also not yet been discovered on Mars. Some materials, such as silicon oxide, iron oxide, and aluminum oxide, are abundant on Mars [150]. On the other hand, some minerals, such as carbonates, are scarce [151]. This parameter strongly affects the construction and type of mortar, and researchers are trying to use in situ materials [152].

Finally, construction methods using resources that are available on the surface of Mars and that do not need extraction or much processing are superior such as the sintering method to other methods.

- **Shipping**

The shipping parameter is an essential factor because the cost of shipping to Mars is very high, about US$10 k to US$200 k per kilogram [29, 153]. Some proposed habitat construction materials require the shipping of specialized reagents such as polymers or bacteria [116, 143, 154]. Due to the high cost of shipping resources from the Earth to Mars, the construction of civil infrastructure from in-situ materials is favored, and the types of concrete that do not require the transfer of resources from Earth are more attractive to researchers, such as concrete produced by the sintering method [145, 155]. One of the major challenges of early ISRU is that feedstocks preferably should require minimum processing and direct application without energy intensive homogenization or transformation steps [112]. However, in the near future, the shipping costs will decrease by new developments such as Starship and propellant production/refueling, which will help the application of new materials with unique properties on Mars [156, 157]. In this manuscript, only the materials that require shipping to Mars are considered and mechanically compared. Any production method may also require specific equipment, but this is beyond the scope of this study.

- **Water requirement**

Water is one of the most significant components that play a decisive role in selecting materials for space habitat construction [51]. Some materials, such as Portland cement, require much water to hydrate, while materials, such as sulfur concrete, do not require water [158]. Although water has been discovered on Mars, it is found as ice beneath rock layers and must be extracted and melted, and hydrated minerals are a likely source of water for future explorers [153, 159]. In general, selected materials that do not require water have an advantage over others.

The criterion of water requirement represents in this work only the water needed in the mixture itself (i.e., for hydraulic binders). However, it is possible that >99% of the water used in concrete is not used in the mixture itself; for instance, the amount of water needed to operate machinery, wash facilities, in the quarry, cement kiln, concrete batch plant, etc. [160].

- **Technical working conditions**

Each construction mortar needs some pre-determined conditions to be used effectively. Technical working conditions include processing raw materials, storage, and transportation to the desired location, and conditions during and after construction. These conditions include printing and curing conditions. For instance, the condition of Portland cement mortar should be controlled during printing to prevent the water in the mortar from freezing at low temperatures and from evaporating at the very low atmospheric pressure. In addition, this type of cement has a curing time of 28 Earth days, and these conditions must be maintained until the full strength of the cement.

Furthermore, this cement needs lengthy processing to turn raw materials into cement [161]. On the other hand, sulfur concrete requires the condition to remain above 120 °C for the material to be melted, but it freezes quickly after printing, and no curing condition is required [158]. Some materials that do not have complex printing and curing conditions, such as the sintered material and most straightforward approaches without specific facilities during printing, are more acceptable to engineers [14].

- **Curing time**

Curing time is one of the critical limiting factors in selecting construction mortar [162]. The curing time is important because once the 3D printer pours the mortar, it needs to cure quickly to prepare the next layer and support the structure [163]. This time should not be too short to allow the grout to cure in the pipes before it leaves the nozzle. The optimization of this time is related to the rheology of the mortar and, for some mortars, can be modified by using retarders and accelerators. For instance, Portland cement mortar needs 28 Earth days to reach its final strength, but sulfur cement and sintered materials reach their maximum strength immediately after decreasing the temperature [8, 164-166]. Generally, materials with a shorter curing time after printing require less and simpler equipment.

- **Temperature**

The temperature issue can be subdivided into the temperature required to process the material, e.g., 1400 °C to produce Portland cement or 900 °C to extract sulfur from Martian regolith [8, 166], and the working temperature during printing [9].

Portland cement mortar must be maintained at a temperature higher than the freezing point of water, and sulfur cement also has a working temperature of 120 °C to keep it molten [71]. On the other hand, some concretes, such as sintered materials, do not require raw material processing, and only a temperature of 1400 °C is used to melt the regolith [102, 112].

Methods with high temperatures require special devices such as nuclear energy or newer technologies, while solar cells are adequate for low temperatures [167]. This study considers the maximum temperature to compare the materials in the decision matrix.

- **Total required energy**

The final amount of energy per unit volume is critical in building a structure [168]. Some mortars must be processed before printing and maintained under the required conditions during curing. Portland cement mortar requires high energy during processing (1400 °C) and 28 Earth days of maintenance at a temperature higher than the freezing point of water for complete hydration [8, 58, 166].

- **Strength**

It can be said that concrete strength is one of the most determining issues in constructing space habitats. The strength of these concretes should support the structure's weight. In addition, resistance to Martian storms is a matter of debate. Gravity on Mars is lower than on Earth; this helps engineers construct taller buildings. These materials' impact and flexural strength are vital because they must also be resistant to most meteorites [78, 112, 162, 169].

- **Durability**

This parameter is essential in the long term, as some materials may degrade under vacuum pressure or severe temperature fluctuations. For example, sulfur concrete is sublimed at temperatures above zero degrees Celsius. This parameter is also related to flexibility and changes in internal and external pressure, temperature changes [87, 170, 171].

- **Cosmic radiation shield (Density and Hydrogen content)**

Shielding humans and equipment against primary radiation, including steady galactic cosmic rays (GCR) and occasional solar particle events (SPE), is an essential concern in space exploration. This radiation is very harmful to the human body, animals, and plants, causing the malfunction of electronic devices and destruction [172, 173]. The dominant radiation in the space environment consists of protons and other ions. The GCR comprises ions with a broad energy range, and SPE generally consists of high-energy protons with gamma and X-rays [174].

In addition, secondary radiation is created when a high-energy particle impacts a material, such as the concrete and the content of Martian and lunar habitats. Nuclear interactions can generate secondary radiation in the form of charged particles, neutrons, and gamma rays. Based on the type of incoming radiation and the shielding materials, secondary radiation can produce a lower or higher dose equivalent to primary radiation [175]. The SEP usually contains particles with lower energy than the GCR and can be easily shielded by the Martian atmosphere [176].

The most crucial factor in shielding is the amount of hydrogen and the density of the material (g/cm^3) [177, 178]. Studies have shown that the composition of lunar regolith does not affect shielding; the most important factors are material compaction and hydrogen content [166, 175, 179-183]. Concretes that contain water and generally have a high hydrogen content, such as polymers, are suitable materials for shielding [116, 184-186].

- **Additives needed**

Cement mortar additives are materials added to cement to optimize its properties. These materials include accelerators, retarders, dispersants, extenders, weighting agents, and foaming agents. Some concrete materials, such as Portland cement, have been developed with dozens of additives to modify the rheological properties of the mortar and increase its final strength. On the other hand, there are no specific additives for some mortars, such as sulfur concrete, or they have not been studied enough.

- **Environmental sustainability**

Sustainability is the ability to remain relatively steady in various aspects of life [187]. In recent decades, this has meant the capability of Earth's biosphere and human habitat to coexist [188, 189]. In the space community, sustainability is used for several meanings - from running space programs with a fixed annual budget to be able to sustain humans in space indefinitely, equitable use of and access to space, maintenance of the space environment, and environmental sustainability. It is also a way to use only renewable and natural resources to allow people to continue their existence in the long term [15, 190, 191].

According to these definitions, some of these concretes are more environmentally friendly, produce fewer pollutants during processing and printing, and have less waste. In addition, from an economic point of view, some concretes require continuous repairs and maintenance at the time of construction (near-term space construction) [79, 192]. However, from a social point of view, these concretes have not yet been studied.

- **Safety**

The safety of concrete includes its effects at different phases of production and utilization [193-195]. Safety is one of the few criteria that has been less studied, but generally, conventional materials that have been used for a long time, such as Portland cement, have a high level of safety. However, the effects of the new materials in the long term are not yet known [196]. Some materials, such as sulfur concrete, have known hazards. The temperature of molten sulfur above 154 °C leads to hydrogen sulfide and sulfur dioxide [79]. In addition, using a highly alkaline Sodium hydroxide ($NaOH$) concentration in geopolymer concrete is unhealthy, and the preparation needs safety precautions [197]. Furthermore, some concretes, such as sintered materials and products of geo-thermite reactions, experience outgassing during their preparation and should be evaluated for safety.

It is worth mentioning that the structures are likely to be built by robots. Even when humans are present, they will be wearing space suits. However, in some instances, humans may come into direct contact with the finished structure or be exposed to the source materials out of a space suit.

- **Recyclability**

Recyclability is an influential factor in selecting these construction concretes for Mars since many energy and raw materials must be expended to produce each gram of these binders. This parameter should be considered in future research. Literally, concrete recycling consists of crushing and removing it from an old location and then creating a new construction [198, 199]. In general, Portland cement is hardly recyclable because the hydration process of the cement is irreversible. On the other hand, sulfur concrete and sintered materials are recyclable because new concrete can be produced again by melting the previous cement [81, 200, 201].

2.3 MCDM (multiple-criteria-decision-making)

Fuzzy AHP, TOPSIS, VIKOR, and WASPAS methods were selected based on expert experience and literature studies because they are applicable in space and civil engineering. Besides, the following factors were considered for each method: The number of alternatives and criteria, computational complexity, agility during the decision process, and uncertainty modeling [202]. The objective of this problem is to rank the alternatives. Therefore, an MCDM method is needed to produce a complete ranking of alternatives. In addition, the method must be able to take into account both advantages and disadvantages and those of a quantitative and qualitative nature [203]. In a fuzzy AHP approach, all pairwise matrices are incorporated using a predefined weight aggregation, and then a single weight vector is calculated [204]. The TOPSIS evaluates how good options reach the defined goals. The VIKOR method is applied to solve decision optimization, considering that compromise is allowed for conflict resolution. It ranks the alternatives, assesses the solution called a compromise and is closest to the ideal [205]. The WASPAS method is highly pragmatic and is heavily based on the concept of ranking accuracy. This method takes advantage of the weighted sum model (WSM) and the weighted product model (WPM). The combination of different aspects of the MCDM methods enhances the ranking accuracy [206-208].

Using the MCDM methods to select the best concrete mortar requires the decision matrix to be developed from different criteria and alternatives. Table 1 displays the decision matrix and A_1, A_2……. A_n are the possible options that the decision-makers select. C_1, C_2, …C_n are the criteria for selecting options, and X_{ij} is the ratio of Ai to C_j. W_j is the weight of C_j. The weight value can be calculated either via a direct way or from a pairwise comparison.

Table 1 Decision matrix

	C_1	C_2	…	C_n
A_1	X_{11}	X_{12}	…	X_{11}
A_2	X_{21}	X_{22}	…	X_{2n}
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
A_m	X_{m1}	X_{m2}	…	X_{mn}
W	W_1	W_1	…	W_1

2.3.1 Fuzzy Analytical Hierarchy Process (Fuzzy AHP)

2.3.1.1 Linguistic variables

Variables that can be expressed linguistically are called linguistic variables. This variable is very useful in ambiguous situations. In this study, the linguistic variables used in the fuzzy AHP process are described in Table 2.

Table 2 The numerical value of the linguistic variables

linguistic variable	Fuzzy numbers for AHP
Indifference	(1,1,1)
Very low Importance	(1,1,3)
Low Importance	(1,3,5)
High Importance	(3,5,7)
Very high Importance	(5,7,9)

2.3.1.2 Analytical Hierarchy Process (AHP)

The AHP was proposed by Saaty [209] to help decision-makers in a multi-criteria decision environment to deal with absolute or unambiguous answers. The fuzzy AHP approach helps solve the ambiguity of decision problems [210, 211]. Applying the fuzzy theory of AHP leads to more efficient and effective results than AHP [212]. The fuzzy AHP is widely used in various fields, including supply chain management, reverse logistics, and project selection [211].

The fuzzy AHP steps are as follows:

Step 1: The matrix of triangular fuzzy pairwise comparisons is expressed as follows:

$$\tilde{Z} = \left(Z_{ij}\right)n * n \begin{bmatrix} (1,1,1) & (p_{12}, q_{12}, r_{12}) & (p_{1n}, q_{1n}, r_{1n}) \\ (p_{21}, q_{21}, r_{21}) & (1,1,1) & (p_{2n}, q_{2n}, r_{2n}) \\ (p_{n1}, q_{n1}, r_{n1}) & (p_{n2}, q_{n2}, r_{n2}) & (1,1,1) \end{bmatrix} \quad (1)$$

Where $z_{ij} = \left(p_{ij}, q_{ij}, r_{ij}\right)$

If $X = \{x_1, x_2, x_3, \dots, x_n\}$ is considered as a data set and $T = \{t_1, t_2, t_3, \dots, t_n\}$ as a target set, each data is taken, and then the value analysis is performed. Therefore, the values of the analysis for each data are obtained according to the following signs.

$M_{g_i}^1, M_{g_i}^2, \dots, M_{g_i}^m, i = 1,2, \dots, n$

Where $M_{g_i}^j (j = 1,2, \dots, m)$ is triangular fuzzy numbers.

Step 2: The value of the fuzzy combination value relative to the ith object is determined as follows:

$$S_i = \sum_{j=1}^{m} M_{ti}^j * \left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{ti}^j\right]^{-1} \tag{2}$$

Where $\sum_{j=1}^{m} M_{ti}^j$ is obtained as follows:

$$\sum_{j=1}^{m} M_{ti}^j = \left(\sum_{j=1}^{m} p_j, \sum_{j=1}^{m} q_j, \sum_{j=1}^{m} r_j\right) \tag{3}$$

And also, $\sum_{i=1}^{n} \sum_{j-1}^{m} M_{ti}^j = \left(\sum_{i=1}^{n} p_j, \sum_{i=1}^{n} q_j, \sum_{i=1}^{n} r_j\right)$ which inverse vector is calculated as follows:

$$\left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{ti}^j\right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n} r_j}, \frac{1}{\sum_{i=1}^{n} q_j}, \frac{1}{\sum_{i=1}^{n} p_j}\right) \tag{4}$$

Step 3: The degree of probability of $M_2(p_2, q_2, r_2) \geq M_1(p_1, q_1, r_1)$ is defined as follows:

$$V(M_2 \geq M_1) = sup\left[min\left(\mu_{M_1}(x), \mu_{M_1}(y)\right]\right. \tag{5}$$

Which can be defined as follows:

$$V(M_2 \geq M_1) = \mathrm{hgt}(M_1 \cap M_2) = \mu_{M_2}(d) = \begin{cases} 1 & \text{if } q_2 \geq q_1 \\ 0 & \text{if } p_2 \geq r_2 \\ \frac{p_1 - r_2}{(q_2 - r_2) - (q_1 - p_1)} & \text{otherwise} \end{cases} \tag{6}$$

Where d is the length of the highest common denominator between μ_{M_1} and μ_{M_2}. For comparison between $M_1$and M_2 both $V(M_1 \geq M_2)$ and $V(M_2 \geq M_1)$ values are required.

Step 4: The possibility degree for a convex fuzzy number higher than k convex fuzzy $M_i(i = 1,2, \dots, k)$ numbers are determined by the following equations.

$V(M \geq M_1, M_2, \dots, M_k) = V[(M \geq M_1), (M \geq M_2), (M \geq M_3), \dots,$ and $(M \geq M_1)]$

$$= minV(M \geq M_i), i = 1,2,3, \dots, k \quad (7)$$

If we assume: for $k \neq i$ and, $k = 1,2, \dots, n, d(A_i) =$ m $V(S_i \geq S_k)$ the weight vector is then obtained as follows:

$$W = \left(d'(A_1), d'(A_1), \dots, d'(A_1)\right)^T \quad (8)$$

So that $A_i(i = 1,2, \dots, n)$ and n is the number of members.

Step 5: By normalizing (scaling), the normalized weight vector is defined as follows:

$$W = \left(d(A_1), d(A_1), \dots, d(A_1)\right)^T \quad (9)$$

2.3.2 TOPSIS

The TOPSIS method is a kind of multi-criteria decision-making method introduced by Hwang and Yoon [213]. TOPSIS can be easily used to solve a problem with various criteria. Compared to other approaches, TOPSIS represents a more realistic form of modeling that includes or excludes other solutions [214, 215].

The reasoning behind the TOPSIS method is that the selected option should gain the longest geometric distance from the negative ideal solution (NIS) and the shortest geometric distance from the positive ideal solution (PIS) [216]. TOPSIS considers that the criteria are consistently increasing or decreasing. Since the parameters or criteria in this method are in opposite dimensions, normalization is generally required [213, 217].

The TOPSIS method consists of the following steps:

1) Determine the alternatives and criteria in the decision matrix.
2) Define qualitative and quantitative criteria.
3) Change the qualitative criteria to quantitative ones by bipolar reference space.
4) Normalize the decision matrix by the norm method, as shown in equation 10.

$$N = \left[n_{ij}\right], n_{ij} = \frac{a_{ij}}{\left[\sum_{i=1}^{m} a_{ij}^{2}\right]^{\frac{1}{2}}} \tag{10}$$

5) Assess individual criterion weight using Shannon maximum entropy

For this purpose, these steps should be applied:

1. Suppose the decision matrix as in Table 1.
2. Define P_{ij} by using the following equation:

$$P^{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \quad = \quad \forall_{i,j} \tag{11}$$

3. The entropy of the *j*th criteria is calculated as follows:

$$E_j = -k \sum_{i=1}^{m} \left[P_{ij} \ln P_{ij}\right] \quad ; \quad \forall_j \tag{12}$$

Next, calculate the degree of deviation d_j and unreliability of j criteria to indicate how much the criteria related to j offers essential information to the decision-maker.

$$d_j = 1 - E_j \quad ; \quad \forall_j \tag{13}$$

4. Compute weight w_j using the following equation:

$$w_j = \frac{d_j}{\sum_{i=1}^{n} d_j} \quad ; \quad \forall_j \tag{14}$$

6) Calculate the balanced normalized matrix. For this purpose, multiply the normalized matrix by a square matrix (Wn*n) whose main diagonal elements are the criterion weights and whose other elements are zero.

$$V = N \times W_{n\times n} \tag{15}$$

7) Determine the negative ideal solution (NIS) and the positive ideal solution (PIS) and calculate the geometric distances from the positive ideal and the geometric distance from the negative ideal.

Therefore, determine the following indices:

Positive ideal solution (V_j^+) = [vector of the best value of each criterion]

Negative ideal solution (V_j^-) = [vector of the worst value of each criterion]

And next, calculate;

$$d_i^+ = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^+)^2} \ , \quad i = 1,2,\dots,m \tag{16}$$

$$d_i^- = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^-)^2} \ , \quad i = 1,2,\dots,m \tag{17}$$

d_i^+ and d_i^- are geometric distance from the positive ideal and negative ideal, respectively.

8) Calculate relative proximity (CL) with the following equation:

$$CL_i^* = \frac{d_i^-}{d_i^- + d_i^+} \tag{18}$$

The highest amount of CL shows the best method.

2.3.3 VIKOR

The VIKOR method is another multi-criteria decision-making technique introduced by Opricovic and Tzeng [205] and used to solve decision problems with conflicting criteria. This method includes the following steps [205, 218]:

Step 1: Creation of a decision matrix with m options and n criteria (m×n matrix)

Step 2: Normalization of the matrix using the vector norm.

Normalization or scaling is done with the help of vector normalization. The following equation is used for this type of normalization.

$$n_{ij} = \frac{a_{ij}}{\sqrt{\sum_i a_{ij}^2}} \tag{19}$$

Step 3: Calculate the weight of the criteria

Step 4: Calculate the normal weight matrix

Using the following equation, the scaleless weighted matrix (V) is calculated:

$$V = N \times W_{n\times n} \tag{20}$$

Where N is a scaleless matrix by vector norming, and W is a weights matrix of indexes.

Step 5: Define the positive ideal point and the negative ideal point

The best $(V_j^+)$and worst (V_j^-) of all options are determined for each criterion. If i_{th} criterion is a positive one, we will have:

$$V_j^+ = maxV_{ij} \tag{21}$$

$$V_j^- = minV_{ij} \tag{22}$$

For the negative criterion, the inverse of the above expression occurs.

Step 6: Calculate the utility (S_i) and regret (R_i) values using the following equation:

$$S_i = L_{1,i} = \sum_{i=1}^{n} \frac{w_j\left(V_j^* - V_{ij}\right)}{\left(V_j^* - V_j^-\right)} \tag{23}$$

$$R_i = L_{\infty,i} = \mathrm{m} \ \left[\sum_{i=1}^{n} W_j\left(V_j^* - V_{ij}\right)/\left(V_j^* - V_j^-\right)\right] \tag{24}$$

Which for positive criteria, $V_j^* = maxV_{ij}, V_j^- = \mathrm{max}V_{ij}$, and $W_j$is the criterion weight of j.

Step 7: Calculate the VIKOR index for each option

VIKOR index for each option (Q_i) is calculated through the following equation:

$$Q_i = V \times \frac{(S_i - S^-)}{(S^* - S^-)} + (1 - V) \times \frac{(R_i - R^-)}{(R^* - R^-)} \tag{25}$$

Where $S^- = minS_i\,; S^* = maxS_i$ and $R^- = minR_i\,; R^* = maxR_i$

Step 8: Ranking of options

The final ranking of each option is done in the VIKOR method according to the values S, R, and Q. The best option has the lowest value for these three parameters.

Step 9: The best option for the parameter Q has the following two conditions:

First condition: establish the following relationship:

$$Q(A_2) - Q(A_1) \geq \frac{1}{N-1} \tag{26}$$

Where A_1 and A_2 are the first and second best options among all alternatives and N is the number of criteria.

Second condition: The option that ranks first according to parameter Q must also rank first for at least one of parameters S and R. If the second condition is not met, the ranking will be as follows

$A_1, A_2, \ldots, A_m$Which A_m is determined by the following relation:

$$(A_m) - Q(A_1) < \frac{1}{N-1} \quad (27)$$

If the first condition is not met, A_1 and A_2 are selected as the best option.

2.3.4 WASPAS

The WASPAS method was first introduced by Zavadskas, Turskis, Antucheviciene and Zakarevicius [219]. This technique was obtained by combining two weighted sum models (WSM) and a weighted product model (WPM). Studies performed using this method show the high accuracy of this method. This method has a unique ability in simple and multiple optimization problems. Its simple mathematics is fully applicable in the real world and can be successfully used in decision problems [197].

The steps of this method are:

Step 1: Form the status quo matrix based on the designed indicators.

Step 2: Standardize the status quo matrix. In this research, the status quo matrices have positive and negative directions, and the functions (28) and (29) were used to standardize.

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \rightarrow \forall \mathrm{j} = 1,2,\ldots,\mathrm{n} \quad (28)$$

$$r_{ij} = \frac{\frac{1}{x_{ij}}}{\sqrt{\sum_{i=1}^{m} \frac{1}{x_{ij}^2}}} \rightarrow \forall \mathrm{j} = 1,\ldots,\mathrm{n} \quad (29)$$

Step 3: Calculate the weight of each index

Step 4: Estimation of variance of the standardized values according to the following relation

$$\sigma^2(\overline{x_{ij}}) = \left(0.05\overline{x_{ij}}\right)^2 \tag{30}$$

Step 5: Calculation of variance of $\sigma^2\left(\sigma_i^{(1)}\right)$ and $\sigma^2\left(\sigma_i^{(2)}\right)$ by the following functions

$$\sigma^2\left(\sigma_i^{(1)}\right) = \sum_{j=1}^{n} \overline{x_{ij}} w_j^2 \cdot \sigma^2(\overline{x_{ij}}) \tag{31}$$

$$\sigma^2\left(\sigma_i^{(2)}\right) = \sum_{j=1}^{n} \left[\frac{\prod_{j=1}^{n} (\overline{x_{ij}})^{wj} \times w_{ij}}{(x_{ij})^{wj} (\overline{x_{ij}})^{1-wj}}\right] \cdot \sigma^2(x_{ij}) \tag{32}$$

Step 6: Calculate the values of (λ) and Q_i to rank the options using the following functions:

$$\lambda = \frac{\sigma^2\left(\sigma_i^{(2)}\right)}{\sigma^2\left(\sigma_i^{(1)}\right) + \sigma^2\left(\sigma_i^{(2)}\right)} \tag{33}$$

$$Q_i = \lambda \sum_{j=1}^{n} \overline{x_{ij}}\, w_j + (1-\lambda) \prod_{j=1}^{n} \left(\overline{x_{ij}}\right)^{wj}, \lambda = 0, \ldots, 1 \tag{34}$$

Any alternative with more Q_i will be a better option.

3. Results and discussion

Figure 4 displays the criteria and alternatives considered for this study to select the best space concrete mortar using MCDM methods.

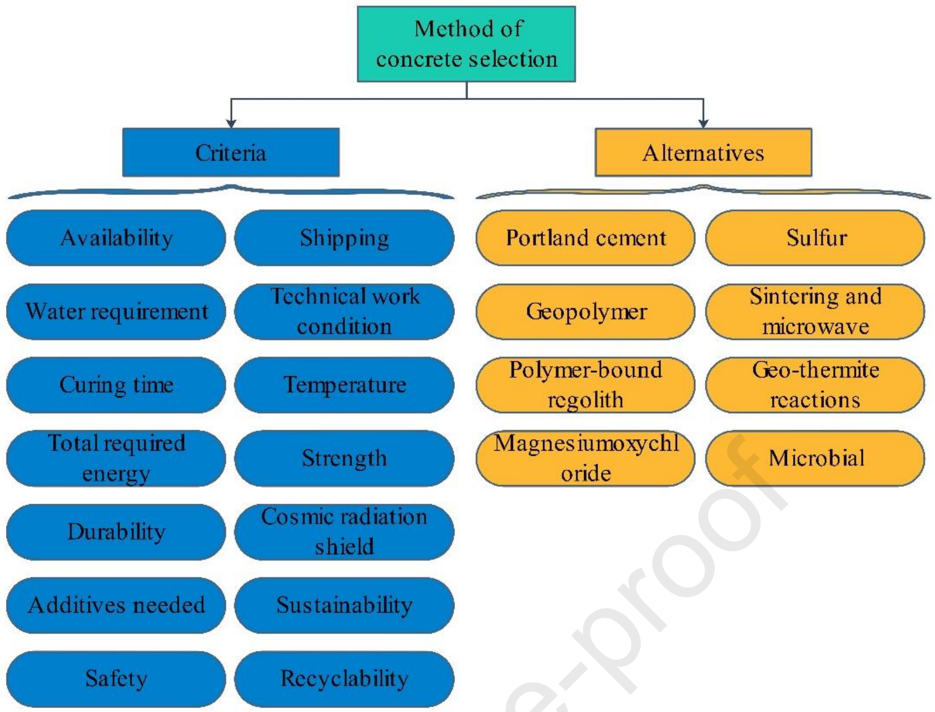


Fig. 4. Considered criteria and options for selecting the best planetary concrete mortar using MCDM methods.

Table 3 shows the alternatives and criteria data for space habitat construction based on the literature review. The negative and positive criteria are shown in red and green, respectively. The positive criteria mean the system gains and improves, whereas the negative criteria decrease efficiency [220].

Table 3 Decision matrix for selecting the best concrete for space habitat construction

Concrete	Shipping (-)	Water requirement (-)	Technical working conditions (-)	Curing time (-)	Temperature (°C) (-)	Total required energy (-)	Availability (+)	Strength (MPa) (+)	Durability (+)	Cosmic radiation shield (+)		Additives needed (+)	Sustainability (+)	Safety (+)	Recyclability (+)
										Density (gr/cm^3) (+)	Hydrogen content (+)				
Portland cement	none	high	high	high	1450	high	low	15-35	high	2.40	low	very high	moderate	very high	low
Sulfur	none	none	moderate	very low	900-120	high	None (As elemental sulfur)	20-65	moderate	2.24	none	very low	high	moderate	high
Geopolymer	none	moderate	moderate	low	20-90	moderate	high	16-36	high	2.46	low	high	moderate	high	moderate
Sintered materials	none	none	moderate	very low	900-1400	very high	very high	2-60	moderate	2.1	none	low	very high	high	high
Polymer-bound regolith	moderate	none	moderate	moderate	-100 to 400	moderate	none	20-100	moderate	1.40	high	high	low	moderate	low
Products of geo-thermite reactions	low	none	moderate	low	900-1900	high	moderate	10-18	low	1.7	none	moderate	very high	high	moderate
Regolith-based magnesium oxychloride	low	very low	very high	high	20-800	high	moderate	20-80	high	2.5	low	moderate	high	high	low
Microbial induced calcite precipitation	moderate	low	very high	moderate	-20 to +50	low	none	1-5	low	1.56	low	low	low	moderate	moderate

3.1 AHP for planetary concrete selection

Sustainability has the lowest weight, and shipping has the highest weight (Fig. 5), as shown by the numerical values of the linguistic variables and the fuzzy AHP. These weights indicate the importance of each criterion. They were determined based on the judgments between the criteria and the number of studies conducted on a criterion.

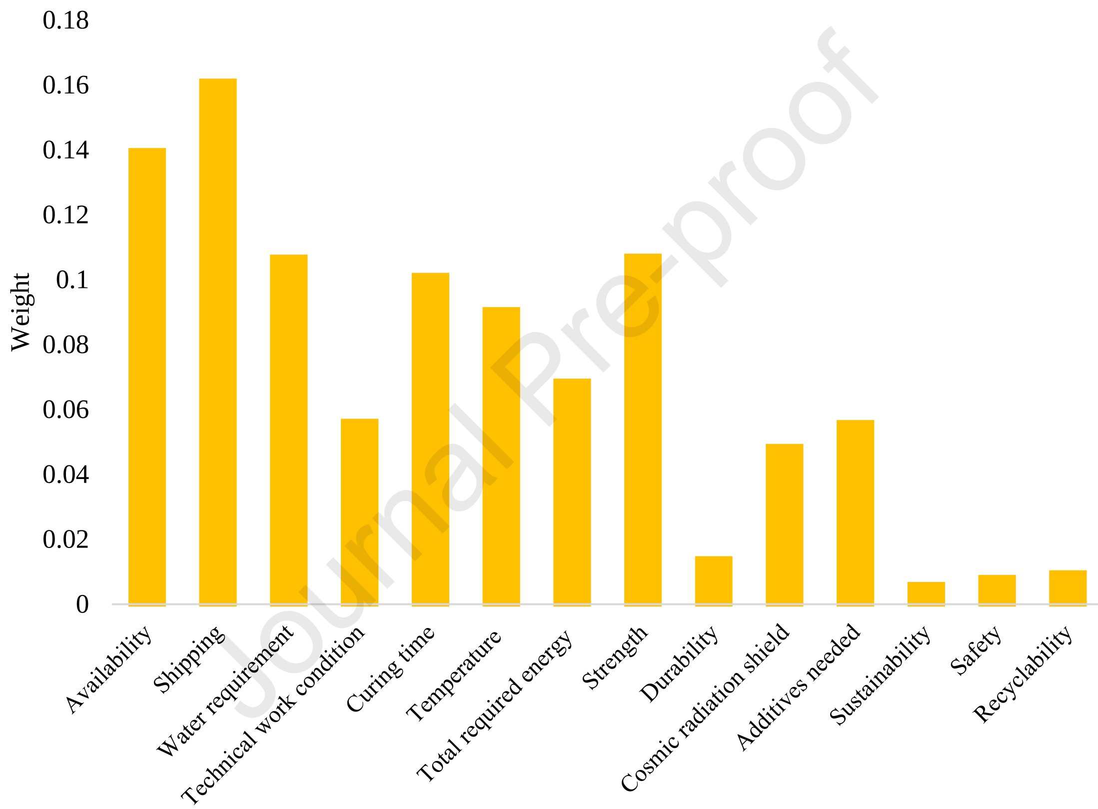


Fig.5. Weights obtained from the Fuzzy AHP method for different criteria

3.2 TOPSIS for planetary concrete selection

The result of TOPSIS according to relative proximity (CL) is shown in Table 4. The results show that sintered materials, sulfur, geopolymer, regolith-based magnesium oxychloride, products of geo-thermite reactions, Portland cement, polymer-bound regolith, and microbial induced calcite precipitation are the best alternatives for space construction concrete, respectively.

Table 4 The results of the ranking of the TOPSIS method

Concretes	TOPSIS
Portland cement	6
Sulfur	2
Geopolymer	3
Sintered materials	1
Polymer-bound regolith	7
Products of geo-thermite reactions	5
Regolith-based magnesium oxychloride	4
Microbial-induced calcite precipitation	8

3.3 VIKOR for planetary concrete selection

In the VIKOR method, the final ranking of each option is gained according to the values of S, R, and Q. Since the first condition is not met, according to the VIKOR instructions and conditions, both the sulfur and geopolymer concretes are the best options (Table 5).

Table 5 The results of the ranking of the VIKOR method.

Concretes	VIKOR
Portland cement	4
Sulfur	1
Geopolymer	1
Sintered materials	3
Polymer-bound regolith	7
Products of geo-thermite reactions	6
Regolith-based magnesium oxychloride	5
Microbial-induced calcite precipitation	8

3.4 WASPAS for planetary concrete selection

In WASPAS logic, any alternative with a higher Qi value is a better option. The best and worst mortars for space habitat construction are geopolymer and regolith-based magnesium oxychloride, respectively (Table 6).

Table 6 The results of the ranking of the WASPAS method.

Concretes	WASPAS
Portland cement	4
Sulfur	3
Geopolymer	1
Sintered materials	2
Polymer-bound regolith	5
Products of geo-thermite reactions	6
Regolith-based magnesium oxychloride	8
Microbial-induced calcite precipitation	7

3.5 Average rating method

The three MCDM approaches of TOPSIS, VIKOR, and WASPAS show slightly different results. The discrepancies are due to different score scales, weightings, and distributions of scores. This study used the average rating method to select the best concrete mortar for Mars based on the average scores.

The results of the three different MCDM approaches and the average score of the different concretes are shown in Table 7. Based on this method, geopolymer is the best concrete for the harsh conditions of Mars. The sulfur and sintered materials are ranked equally second, and it can be seen that the microbial induced calcite precipitation method is the last option for habitat construction.

Table 7 The results of the three different MCDM approaches and the average score of the different concretes

Concretes	VIKOR	WASPAS	TOPSIS	Final Rank
Portland cement	4	4	6	3
Sulfur	1	3	2	2
Geopolymer	1	1	3	1
Sintered materials	3	2	1	2
Polymer-bound regolith	7	5	7	5
Products of geo-thermite reactions	6	6	5	4
Regolith-based magnesium oxychloride	5	8	4	4
Microbial-induced calcite precipitation	8	7	8	6

Considering almost all effective parameters in construction by concrete on Mars' harsh conditions, the geopolymer, sulfur, and sintered concretes were selected as the best types for space habitat construction. Many papers have addressed space concrete but have only compared different materials [8, 166] or focused on two or three effective parameters of concrete construction. Each concrete may have an outstanding feature with a specific application, but an optimal choice can be used in different situations. In addition, due to high costs and investment risks in space researches, all parameters must be considered in decision-making [221]. Nevertheless, laboratory tests in versatile simulation conditions are more acceptable to determine the best concrete. When the empirical analysis is feasible and makes economic sense, it should be preferred [222].

According to the previous literature, it is expected that Portland cement should be a lower rank due to material unavailability. Nevertheless, other parameters of this concrete, such as strength, are suitable for construction and can be considered as a method to be used in the distant future. Furthermore, by considering the regolith properties, sulfur concretes can be applied for places on the surface of Mars with higher sulfur content. On the other hand, the sintered material could be used anywhere on the surface of Mars regardless of the distribution of a particular substance since they do not require any binder and are produced by the fusion of mineral particles.

Considering the requirements to produce geopolymer concrete, it is known that glassy particles with a high aluminum content are needed to prepare this concrete [223]. The glass content in the regolith of Mars is not high enough and Martian regolith is 70 to 80% crystalline and unsuitable for geopolymers. Alexiadis, Alberini and Meyer [224] experimentally investigated the geopolymers made from Lunar and Martian regolith simulants. They showed that the concrete made from the Martian regolith lacked sufficient strength.

The results of this study may change in the future depending on further research on the aforementioned concretes and can be revised by re-tuning weights and subjective probabilities. In addition, applying uncertainty, probability, and neural networks in MCDM studies can improve decision-making accuracy [225]. Furthermore, other effective criteria can also be added to the decision matrix, such as costs. However, more economic studies are needed in this area [226]. The results of this research can be used as input for feasibility studies such as research done by Metzger and Autry [29].

4. Conclusion

The objective of the current study was to determine the best concrete mortar for the construction of Martian habitats based on 14 technical criteria. The cost criterion was not considered in this study due to a lack of data for the different materials. For this purpose, three types of MCDM methods were used: TOPSIS, VIKOR, and WASPAS. These MCDM methods had similar ranking results. The geopolymer was selected as the best construction material by using the average rating method. In addition, the sintered concrete and sulfur concrete ranked equally second. The highest priority of other concretes is Portland cement, products of geo-thermite reactions, regolith-based magnesium oxychloride, polymer-bound regolith, and microbial-induced calcite precipitation, respectively. In addition, the Fuzzy AHP method was used to determine that the shipping and sustainability criteria had the highest and lowest weightings in the decision-making process. This study presented a scientific method for the comparison of concretes in order to increase the accuracy of decisions about space concrete selection. The decision-making methods presented in this paper can also be used to make decisions regarding other complex space technologies.

Acknowledgements

The last author acknowledges support from KU Leuven Internal Funds Bijzonder Onderzoeksfonds 2020, grant number STG/20/013.

References

[1] D.S. McKay, C.C. Allen, Concrete—A practical construction material for mars, Engineering, Construction, and Operations in Space V1996, pp. 566-570.
[2] G. Flynn, D. McKay, Meteorites on Mars, Mars Sample Return Science, 1988.
[3] N. Spanovich, M. Smith, P. Smith, M. Wolff, P. Christensen, S. Squyres, Surface and near-surface atmospheric temperatures for the Mars Exploration Rover landing sites, Icarus 180(2) (2006) 314-320.
[4] C. Sagan, G. Mullen, Earth and Mars: Evolution of atmospheres and surface temperatures, Science 177(4043) (1972) 52-56.
[5] M.A. Gurwell, E.A. Bergin, G.J. Melnick, V. Tolls, Mars surface and atmospheric temperature during the 2001 global dust storm, Icarus 175(1) (2005) 23-31.
[6] S. Piqueux, S. Byrne, H.H. Kieffer, T.N. Titus, C.J. Hansen, Enumeration of Mars years and seasons since the beginning of telescopic exploration, Icarus 251 (2015) 332-338.
[7] M. Allison, Accurate analytic representations of solar time and seasons on Mars with applications to the Pathfinder/Surveyor missions, Geophysical Research Letters 24(16) (1997) 1967-1970.
[8] Y. Reches, Concrete on Mars: Options, challenges, and solutions for binder-based construction on the Red Planet, Cement and Concrete Composites 104 (2019) 103349.
[9] S.L. Anderson, E.K. Sansom, P.M. Shober, B.A. Hartig, H.A. Devillepoix, M.C. Towner, The proposed Silicate-Sulfuric Acid Process: Mineral processing for In Situ Resource Utilization (ISRU), Acta Astronautica 188 (2021) 57-63.
[10] G. Sharma, J. Gautam, S. Gurusideswar, Material selection and its characterization for Mars environment and a study on full field strain analysis, AIP Conference Proceedings, AIP Publishing LLC, 2021, p. 020045.
[11] L.M. Calle, W. Li, M.R. Johansen, J.W. Buhrow, C.I. Calle, Corrosion on Mars: An Investigation of Corrosion Mechanisms Under Relevant Simulated Martian Environments, 2017.
[12] G.H. Peters, W. Abbey, G.H. Bearman, G.S. Mungas, J.A. Smith, R.C. Anderson, S. Douglas, L.W. Beegle, Mojave Mars simulant—Characterization of a new geologic Mars analog, Icarus 197(2) (2008) 470-479.

[13] C. Menna, J. Mata-Falcón, F.P. Bos, G. Vantyghem, L. Ferrara, D. Asprone, T. Salet, W. Kaufmann, Opportunities and challenges for structural engineering of digitally fabricated concrete, Cement and Concrete Research 133 (2020) 106079.
[14] A. Meurisse, A. Makaya, C. Willsch, M. Sperl, Solar 3D printing of lunar regolith, Acta Astronautica 152 (2018) 800-810.
[15] M. Isachenkov, S. Chugunov, I. Akhatov, I. Shishkovsky, Regolith-based additive manufacturing for sustainable development of lunar infrastructure–An overview, Acta Astronautica (2021).
[16] S. Lim, V.L. Prabhu, M. Anand, L.A. Taylor, Extra-terrestrial construction processes–Advancements, opportunities and challenges, Advances in Space Research 60(7) (2017) 1413-1429.
[17] L.V. Miranda, J.R. Valdes, D.D. Cortes, Solar bricks for lunar construction, Construction and Building Materials 139 (2017) 241-246.
[18] R.G. Clinton, J.E. Edmunson, M. Fiske, M.R. Effinger, E. Jensen, J. Ballard, Overview of NASA's Moon-to-Mars Planetary Autonomous Construction Technology (MMPACT), ASCEND 20212021, p. 4072.
[19] T. Wait, Development of Material for 3D Printed Habitats with Extraplanetary Applications, South Dakota State University2018.
[20] M. Naser, Space-native construction materials for earth-independent and sustainable infrastructure, Acta Astronautica 155 (2019) 264-273.
[21] M. Naser, Q. Chen, Extraterrestrial Construction in Lunar and Martian Environments, Earth and Space 20212021, pp. 1200-1207.
[22] S. Wilhelm, M. Curbach, Review of possible mineral materials and production techniques for a building material on the moon, Structural Concrete 15(3) (2014) 419-428.
[23] J. Liu, H. Li, L. Sun, Z. Guo, J. Harvey, Q. Tang, H. Lu, M. Jia, In-situ resources for infrastructure construction on Mars: A review, International Journal of Transportation Science and Technology (2021).
[24] Y.S. Sherif, W.J. Kolarik, Life cycle costing: concept and practice, Omega 9(3) (1981) 287-296.
[25] G. Bleakley, A Systems Engineering Trade Study to Support Green Initiatives with Model-Driven Development, IBM Software Group, Somers, NY (2009).
[26] P.J. Baker, J.T. Whalen, Survey of trade study methods for practical decision-making, Proc. Annu. NASA IV&V Workshop, 2012, p. 1.
[27] H.M. Eide, C. Haskins, Trade study of alternative controls and power distribution architecture in subsea processing, INCOSE International Symposium, Wiley Online Library, 2016, pp. 2148-2163.
[28] M.G. Alexander, Requirement assurance: A verification process, 2011.
[29] P.T. Metzger, G.W. Autry, The Cost of Lunar Landing Pads with a Trade Study of Construction Methods, arXiv preprint arXiv:2205.00378 (2022).
[30] W.S. Dias, J.R. Matijevic, S.T. Venkataraman, J.H. Smith, R.A. Lindemann, R.R. Levin, Directions for lunar construction-A derivation of requirements from a construction scenario analysis, Engineering, Construction, and Operations in space-III: Space'92 1 (1992) 357-367.
[31] M. Anderson, Summary of Water Processing Trade Studies and Analysis of JSC Integrated Water Recovery System (IWRS), CTSD-ADV-543, JSC 62185. Anderson2004. pdf, 2004.
[32] J.R. Cruz, A.D. Cianciolo, R.W. Powell, L.C. Simonsen, R.H. Tolson, Entry, descent, and landing technology concept trade study for increasing payload mass to the surface of Mars, 4th International Symposium on Atmospheric Reentry Vehicles and Systems, 2005.
[33] M. Hashemi, H.R. Pourzamani, S. Fadaei, F. Heidari, G. Safa, I. Parseh, H. Mohammadi, S. Parastar, Locating industrial landfill using analytical hierarchy process (AHP)(Case study: Natanz-Isfahan industrial suburbs), Journal of Advances in Environmental Health Research 4(4) (2016) 182-189.
[34] F. Tscheikner-Gratl, P. Egger, W. Rauch, M. Kleidorfer, Comparison of multi-criteria decision support methods for integrated rehabilitation prioritization, Water 9(2) (2017) 68.

[35] C. Macharis, J. Springael, K. De Brucker, A. Verbeke, PROMETHEE and AHP: The design of operational synergies in multicriteria analysis.: Strengthening PROMETHEE with ideas of AHP, European journal of operational research 153(2) (2004) 307-317.

[36] G. Kabir, R. Sadiq, S. Tesfamariam, A review of multi-criteria decision-making methods for infrastructure management, Structure and infrastructure engineering 10(9) (2014) 1176-1210.

[37] N. Lazar, K. Chithra, A comprehensive literature review on development of Building Sustainability Assessment Systems, Journal of Building Engineering 32 (2020) 101450.

[38] E.K. Zavadskas, Z. Turskis, S. Kildienė, State of art surveys of overviews on MCDM/MADM methods, Technological and economic development of economy 20(1) (2014) 165-179.

[39] V. Belton, S. Theodor, Multiple criteria decision analysis: an integrated approach: Springer Science & Business Media, (2002).

[40] C. Bai, A. Satir, J. Sarkis, Investing in lean manufacturing practices: an environmental and operational perspective, International Journal of Production Research 57(4) (2019) 1037-1051.

[41] M.H. Shahsavari, E. Khamehchi, Optimum selection of sand control method using a combination of MCDM and DOE techniques, Journal of Petroleum Science and Engineering 171 (2018) 229-241.

[42] Z. Dugger, G. Halverson, B. McCrory, D. Claudio, Principal component analysis in mcdm: an exercise in pilot selection, Expert Systems with Applications (2021) 115984.

[43] D.U. Ozsahin, L. Hamidat, F.D. Alimi, B. Uzun, I. Ozsahin, Evaluation of migraine drugs using MCDM methods, Applications of Multi-Criteria Decision-Making Theories in Healthcare and Biomedical Engineering, Elsevier2021, pp. 261-275.

[44] R.R. Nadkarni, B. Puthuvayi, A comprehensive literature review of Multi-Criteria Decision Making methods in heritage buildings, Journal of Building Engineering 32 (2020) 101814.

[45] M. Tavana, A subjective assessment of alternative mission architectures for the human exploration of Mars at NASA using multicriteria decision making, Computers & Operations Research 31(7) (2004) 1147-1164.

[46] G. Gunaydin, G. Duvan, E. Ozceylan, Determining the Most Habitable Planet Using Multi-Criteria Decision Making Techniques, (2021).

[47] M. Higgins, H. Benaroya, Utilizing the Analytical Hierarchy Process to determine the optimal lunar habitat configuration, Acta Astronautica 173 (2020) 145-154.

[48] J.M. Sánchez-Lozano, A. Moya, J.M. Rodríguez-Mozos, A fuzzy Multi-Criteria Decision Making approach for Exo-Planetary Habitability, Astronomy and Computing 36 (2021) 100471.

[49] E. Eren, B.Y. Katanalp, Fuzzy-based GIS approach with new MCDM method for bike-sharing station site selection according to land-use types, Sustainable Cities and Society 76 (2022) 103434.

[50] S. Saraswat, A.K. Digalwar, S.S. Yadav, Sustainability Assessment of Renewable and Conventional Energy Sources in India Using Fuzzy Integrated AHP-WASPAS Approach, Journal of Multiple-Valued Logic & Soft Computing 37 (2021).

[51] M. Morris, C. Ciardullo, K. Lents, J. Montes, O. Rudakevych, M. Sono, Y. Sono, M. Yashar, Mars Ice House: Using the physics of phase change in 3D printing a habitat with H2O, AIAA SPACE 20162016, p. 5528.

[52] L. Karacasulu, D. Karl, A. Gurlo, C. Vakifahmetoglu, Cold sintering as a promising ISRU technique: A case study of Mars regolith simulant, Icarus 389 (2023) 115270.

[53] J. Karni, E.Y. Karni, Gypsum in construction: origin and properties, Materials and Structures 28(2) (1995) 92-100.

[54] G. James, G.E. Chamitoff, D. Barker, Resource utilization and site selection for a self-sufficient martian outpost, National Aeronautics and Space Administration, Lyndon B. Johnson Space Center1998.

[55] T. Lin, S. Bhattacharja, Lunar and Martian resources utilization: cement, Space 981998, pp. 592-600.

[56] G. Scheerbaum, In-Situ manufacture of martian construction materials, Space 20002000, pp. 934-940.

[57] M.J. Werkheiser, M. Fiske, J. Edmunson, B. Khoshnevis, On the development of additive construction technologies for application to development of lunar/martian surface structures using in-situ materials, AIAA SPACE 2015 conference and exposition, 2015, p. 4451.
[58] J.J. Sokołowska, P. Woyciechowski, M. Kalinowski, Rheological Properties of Lunar Mortars, Applied Sciences 11(15) (2021) 6961.
[59] G. Vialle, H.S.H.-S. Habitats, Martian In Situ Habitat Assembly.
[60] M. Troemner, E. Ramyar, R. Marrero, K. Mendu, G. Cusatis, Marscrete: A Martian Concrete for Additive Construction Applications Utilizing In Situ Resources, Earth and Space 20212020, pp. 801-807.
[61] D. Barker, G. Chamitoff, G. James, Resource utilization and site selection for a self-sufficient martian outpost, 1998.
[62] S.W. Squyres, S. Clifford, R. Kuzmin, J.R. Zimbelman, F. Costard, Ice in the martian megaregolith, Mars (1992).
[63] V.R. Baker, V.C. Gulick, J.S. Kargel, Water resources and hydrogeology of Mars, Resources of near-earth space (1993) 765-797.
[64] A. Abbud-Madrid, D. Beaty, D. Boucher, B. Bussey, R. Davis, L. Gertsch, L. Hays, J. Kleinhenz, M. Meyer, M. Moats, Mars water in-situ resource utilization (ISRU) planning (M-WIP) study, Report of the Mars Water In-Situ Resource Utilization (ISRU) Planning (M-WIP) Study 90 (2016).
[65] J.M. Neves, S. Ramanathan, P. Suraneni, R. Grugel, A. Radlińska, Characterization, mechanical properties, and microstructural development of lunar regolith simulant-portland cement blended mixtures, Construction and Building Materials 258 (2020) 120315.
[66] M. Shangguan, Y. Xie, S. Xu, C. Gao, G. Long, F. Wang, M. Liu, Mechanical properties characteristics of high strength concrete exposed to low vacuum environment, Journal of Building Engineering (2022) 105438.
[67] M. Glinicki, A. Antolik, M. Gawlicki, Evaluation of compatibility of neutron-shielding boron aggregates with Portland cement in mortar, Construction and Building Materials 164 (2018) 731-738.
[68] R. Gallaher, A.S. Kitzes, Summary report on Portland cement concretes for shielding, Oak Ridge National Lab., 1953.
[69] R. BOYD, P. THOMPSON, B. CLARK, Duricrete and composites construction on Mars, The case for Mars III: Strategies for exploration- General interest and overview(A 90-16651 05-12). San Diego, CA, Univelt, Inc., 1989 (1989).
[70] L. Wan, R. Wendner, G. Cusatis, A novel material for in situ construction on Mars: experiments and numerical simulations, Construction and Building Materials 120 (2016) 222-231.
[71] B. Khoshnevis, X. Yuan, B. Zahiri, J. Zhang, B. Xia, Construction by Contour Crafting using sulfur concrete with planetary applications, Rapid Prototyping Journal (2016).
[72] N. Demidov, A. Bazilevskii, R. Kuz'Min, Martian soils: Varieties, structure, composition, physical properties, drillability, and risks for landers, Solar System Research 49(4) (2015) 209-225.
[73] P.L. King, S.M. McLennan, Sulfur on mars, Elements 6(2) (2010) 107-112.
[74] Y. Jin, Q. Yu, S. Chang, Catalytic reduction of sulfur dioxide to elemental sulfur, American Chemical Society, Washington, DC (United States), 1994.
[75] A. Barkatt, M. Okutsu, Obtaining elemental sulfur for Martian sulfur concrete, Journal of Chemical Research 46(2) (2022) 17475198221080729.
[76] V. Petkova, Y. Pelovski, Comparative DSC study on thermal decomposition of iron sulphates, Journal of thermal analysis and calorimetry 93(3) (2008) 847-852.
[77] T. Rosenqvist, Principles of extractive metallurgy, Tapir academic press2004.
[78] R. Fediuk, Y. Mugahed Amran, M.A. Mosaberpanah, A. Danish, M. El-Zeadani, S.V. Klyuev, N. Vatin, A critical review on the properties and applications of sulfur-based concrete, Materials 13(21) (2020) 4712.

[79] A.-M.O. Mohamed, M. El-Gamal, Sulfur concrete for the construction industry: a sustainable development approach, J. Ross Publishing2010.

[80] M. Troemner, G. Cusatis, Martian material sourcing challenges propel earth construction opportunities, Matter 1(3) (2019) 547-549.

[81] B. Khoshnevis, A. Carlson, N. Leach, M. Thangavelu, Contour crafting simulation plan for lunar settlement infrastructure buildup, Earth and Space 2012: Engineering, Science, Construction, and Operations in Challenging Environments2012, pp. 1458-1467.

[82] M.A. Gulzar, A. Rahim, B. Ali, A.H. Khan, An investigation on recycling potential of sulfur concrete, Journal of Building Engineering 38 (2021) 102175.

[83] R. Savino, S. Mungiguerra, G. Di Martino, Testing ultra-high-temperature ceramics for thermal protection and rocket applications, Advances in Applied Ceramics 117(sup1) (2018) s9-s18.

[84] B. Khoshnevis, M. Thangavelu, X. Yuan, J. Zhang, Advances in contour crafting technology for extraterrestrial settlement infrastructure buildup, AIAA SPACE 2013 Conference And Exposition, 2013, p. 5438.

[85] R. Anyszka, D.M. Bieliński, M. Siciński, M. Imiela, P. Szajerski, J. Pawlica, R. Walendziak, Sulfur Concrete–Promising Material for Space-Structures Building, Proceedings of the European Conference on Spacecraft Structures Materials and Environmental Testing, Toulouse, France, 2016, pp. 27-30.

[86] H.A. Omar, M. Issa, Production of lunar concrete using molten sulfur, Proceedings: 4th Conf. on Space, 1994, pp. 952-959.

[87] R.N. Grugel, H. Toutanji, Sulfur "concrete" for lunar applications–Sublimation concerns, Advances in Space Research 41(1) (2008) 103-112.

[88] M.H. Shahsavari, M.M. Karbala, S. Iranfar, V. Vandeginste, Martian and lunar sulfur concrete mechanical and chemical properties considering regolith ingredients and sublimation, Construction and Building Materials 350 (2022) 128914.

[89] B. Nematollahi, M. Xia, J. Sanjayan, Current progress of 3D concrete printing technologies, ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction, IAARC Publications, 2017.

[90] B. Panda, M.J. Tan, Experimental study on mix proportion and fresh properties of fly ash based geopolymer for 3D concrete printing, Ceramics International 44(9) (2018) 10258-10265.

[91] J. Davidovits, Geopolymers based on natural and synthetic metakaolin—a critical review, Proceedings of the 41st International Conference on Advanced Ceramics and Composites, Wiley Online Library, 2017, pp. 201-214.

[92] J.H. Lim, B. Panda, Q.-C. Pham, Improving flexural characteristics of 3D printed geopolymer composites with in-process steel cable reinforcement, Construction and Building Materials 178 (2018) 32-41.

[93] D. Hardjito, C.C. Cheak, C.H.L. Ing, Strength and setting times of low calcium fly ash-based geopolymer mortar, Modern applied science 2(4) (2008) 3-11.

[94] A. Allahverdi, S. Pilehvar, M. Mahinroosta, Influence of curing conditions on the mechanical and physical properties of chemically-activated phosphorous slag cement, Powder technology 288 (2016) 132-139.

[95] A.M. Fernandez-Jimenez, A. Palomo, C. Lopez-Hombrados, Engineering properties of alkali-activated fly ash concrete, ACI Materials Journal 103(2) (2006) 106.

[96] S. Pilehvar, M. Arnhof, R. Pamies, L. Valentini, A.-L. Kjøniksen, Utilization of urea as an accessible superplasticizer on the moon for lunar geopolymer mixtures, Journal of Cleaner Production 247 (2020) 119177.

[97] B. Rich, H. Läkk, M. Arnhof, I. Cheibas, ADVANCED CONCEPTS FOR ISRU-BASED ADDITIVE MANUFACTURING OF PLANETARY HABITATS.

[98] B. Panda, C. Unluer, M.J. Tan, Investigation of the rheology and strength of geopolymer mixtures for extrusion-based 3D printing, Cement and Concrete Composites 94 (2018) 307-314.
[99] K.-t. Wang, Q. Tang, X.-m. Cui, Y. He, L.-p. Liu, Development of near-zero water consumption cement materials via the geopolymerization of tektites and its implication for lunar construction, Scientific reports 6(1) (2016) 1-8.
[100] A. Mishra, D. Choudhary, N. Jain, M. Kumar, N. Sharda, D. Dutt, Effect of concentration of alkaline liquid and curing time on strength and water absorption of geopolymer concrete, ARPN Journal of engineering and Applied Sciences 3(1) (2008) 14-18.
[101] F.A. Memon, M.F. Nuruddin, S. Demie, N. Shafiq, Effect of curing conditions on strength of fly ash-based self-compacting geopolymer concrete, International Journal of Civil and Environmental Engineering 5(8) (2011) 342-345.
[102] K.W. Farries, P. Visintin, S.T. Smith, P. van Eyk, Sintered or melted regolith for lunar construction: state-of-the-art review and future research directions, Construction and Building Materials 296 (2021) 123627.
[103] J. Wang, J. Binner, B. Vaidhyanathan, N. Joomun, J. Kilner, G. Dimitrakis, T. Cross, Evidence for the microwave effect during hybrid sintering, Journal of the American Ceramic Society 89(6) (2006) 1977-1984.
[104] R. German, Sintering: from empirical observations to scientific principles, Butterworth-Heinemann2014.
[105] P. Hintze, J. Curran, T. Back, Lunar surface stabilization via sintering or the use of heat cured polymers, 47th AIAA Aerospace Sciences Meeting including The New Horizons Forum and Aerospace Exposition, 2009, p. 1015.
[106] A. Meurisse, J. Beltzung, M. Kolbe, A. Cowley, M. Sperl, Influence of mineral composition on sintering lunar regolith, Journal of Aerospace Engineering 30(4) (2017) 04017014.
[107] A. Bonanno, L. Bernold, Exploratory review of sintered lunar soil based on the results of the thermal analysis of a lunar soil simulant, Journal of Aerospace Engineering 28(4) (2015) 04014114.
[108] K. Grossman, Regolith-Based Construction Materials for Lunar and Martian Colonies, (2018).
[109] B. Imhof, D. Urbina, P. Weiss, M. Sperl, W. Hoheneder, R. Waclavicek, H. Madakashira, J. Salini, S. Govindaraj, J. Gancet, Advancing solar sintering for building a base on the Moon, 68th International Astronautical Congress (IAC), Adelaide, Australia, 2017, pp. 25-29.
[110] A.A. Altun, F. Ertl, M. Marechal, A. Makaya, A. Sgambati, M. Schwentenwein, Additive manufacturing of lunar regolith structures, Open Ceramics 5 (2021) 100058.
[111] C. Ray, S. Reis, S. Sen, J. O'Dell, JSC-1A lunar soil simulant: Characterization, glass formation, and selected glass properties, Journal of Non-Crystalline Solids 356(44-49) (2010) 2369-2374.
[112] D. Karl, K.M. Cannon, A. Gurlo, Review of space resources processing for Mars missions: Martian simulants, regolith bonding concepts and additive manufacturing, Open Ceramics (2021) 100216.
[113] M.D. Hogue, R.P. Mueller, P.E. Hintze, L. Sibille, D.J. Rasky, Regolith-derived heat shield for planetary body entry and descent system with in situ fabrication, Earth and Space 2012: Engineering, Science, Construction, and Operations in Challenging Environments2012, pp. 526-536.
[114] P. Hintze, J. Curran, R. Back, The use of Solar Heating and Heat Cured Polymers for Lunar Surface Stabilization, 2008.
[115] T.-H. Chen, Developing Lunar “Cement” Using Lunar Soils, UC San Diego, 2015.
[116] J. Johnson-Freese, Build on the outer space treaty, Nature News 550(7675) (2017) 182.
[117] E.J. Faierson, Influences of reaction parameters on the product of a geothermite reaction: A multi-component oxidation-reduction reaction study, Virginia Tech, 2009.
[118] E.J. Faierson, K.V. Logan, B.K. Stewart, M.P. Hunt, Demonstration of concept for fabrication of lunar physical assets utilizing lunar regolith simulant and a geothermite reaction, Acta Astronautica 67(1-2) (2010) 38-45.

[119] M. Hobosyan, K. Martirosyan, Sintering of regolith by activated thermites: A novel approach for lunar in-situ resource utilization, Lunar and Planetary Science Conference, 2012, p. 1019.
[120] A. Delgado, S. Cordova, E. Shafirovich, Thermite reactions with oxides of iron and silicon during combustion of magnesium with lunar and Martian regolith simulants, Combustion and Flame 162(9) (2015) 3333-3340.
[121] S.A. Walling, J.L. Provis, Magnesia-based cements: a journey of 150 years, and cements for the future?, Chemical reviews 116(7) (2016) 4170-4204.
[122] S. Sorel, On a new magnesium cement, CR Acad. Sci 65 (1867) 102-104.
[123] W. Jiangxiong, C. Yimin, L. Yongxin, The reaction mechanism between MgO and microsilica at room temperature, Journal of Wuhan University of Technology-Mater. Sci. Ed. 21(2) (2006) 88-91.
[124] F. Jin, A. Al-Tabbaa, Strength and hydration products of reactive MgO–silica pastes, Cement and Concrete Composites 52 (2014) 27-33.
[125] H. Tran, A. Scott, Strength and workability of magnesium silicate hydrate binder systems, Construction and Building Materials 131 (2017) 526-535.
[126] A. Misra, R. Mathur, Magnesium oxychloride cement concrete, Bulletin of materials science 30(3) (2007) 239-246.
[127] A. Scott, C. Oze, M.W. Hughes, Magnesium-Based Cements for Martian Construction, Journal of Aerospace Engineering 33(4) (2020) 04020019.
[128] A.-M. Lauermannová, I. Faltysová, M. Lojka, F. Antončík, D. Sedmidubský, Z. Pavlík, M. Pavlíková, M. Záleská, A. Pivák, O. Jankovský, Regolith-based magnesium oxychloride composites doped by graphene: Novel high-performance building materials for lunar constructions, FlatChem 26 (2021) 100234.
[129] J. Osio-Norgaard, A.C. Hayes, G.L. Whiting, Sintering of 3D printable simulated lunar regolith magnesium oxychloride cements, Acta Astronautica 183 (2021) 227-232.
[130] M. Osterloo, V. Hamilton, J. Bandfield, T. Glotch, A. Baldridge, P. Christensen, L. Tornabene, F. Anderson, Chloride-bearing materials in the southern highlands of Mars, Science 319(5870) (2008) 1651-1654.
[131] J. Filiberto, A.H. Treiman, Martian magmas contained abundant chlorine, but little water, Geology 37(12) (2009) 1087-1090.
[132] G. Klingelhöfer, R.V. Morris, B. Bernhardt, C. Schröder, D.S. Rodionov, P. De Souza, A. Yen, R. Gellert, E. Evlanov, B. Zubkov, Jarosite and hematite at Meridiani Planum from Opportunity's Mössbauer spectrometer, Science 306(5702) (2004) 1740-1745.
[133] B.L. Ehlmann, J.F. Mustard, G.A. Swayze, R.N. Clark, J.L. Bishop, F. Poulet, D.J. Des Marais, L.H. Roach, R.E. Milliken, J.J. Wray, Identification of hydrated silicate minerals on Mars using MRO-CRISM: Geologic context near Nili Fossae and implications for aqueous alteration, Journal of Geophysical Research: Planets 114(E2) (2009).
[134] A. Dessy, N. Abyor, H. Hadi, An overview of biocement production from microalgae, International Journal of Science and Engineering 2(2) (2011) 31-33.
[135] D. Ariyanti, N. Handayani, Hadiyanto (2012) Feasibility of using microalgae for biocement production through biocementation, J Bioprocess Biotechniq 2(111) (2012) 2.
[136] D. Mujah, M.A. Shahin, L. Cheng, State-of-the-art review of biocementation by microbially induced calcite precipitation (MICP) for soil stabilization, Geomicrobiology Journal 34(6) (2017) 524-537.
[137] J.-W. Choi, Geomechanics of subsurface sand production and gas storage, Georgia Institute of Technology, 2011.
[138] A.M. Sharaky, N.S. Mohamed, M.E. Elmashad, N.M. Shredah, Application of microbial biocementation to improve the physico-mechanical properties of sandy soil, Construction and Building Materials 190 (2018) 861-869.

[139] S.-G. Choi, S.-S. Park, S. Wu, J. Chu, Methods for calcium carbonate content measurement of biocemented soils, Journal of materials in civil engineering 29(11) (2017) 06017015.

[140] J. Henze, D.G. Randall, Microbial induced calcium carbonate precipitation at elevated pH values (> 11) using Sporosarcina pasteurii, Journal of Environmental Chemical Engineering 6(4) (2018) 5008-5013.

[141] C. Bogdahn, A. Breaum, H. Breum, H. Larsen, M. Løvenskjold, T.-H. Kristiansen, In-situ Habitat Design on Mars, (2019).

[142] J. Gleaton, Z. Lai, R. Xiao, Q. Chen, Y. Zheng, Microalga-induced biocementation of martian regolith simulant: Effects of biogrouting methods and calcium sources, Construction and Building Materials 229 (2019) 116885.

[143] R. Dikshit, A. Dey, N. Gupta, S.C. Varma, I. Venugopal, K. Viswanathan, A. Kumar, Space bricks: From LSS to machinable structures via MICP, Ceramics International 47(10) (2021) 14892-14898.

[144] A. Roberts, D. Whittall, R. Breitling, E. Takano, J.J. Blaker, S. Hay, N.S. Scrutton, Blood, sweat and tears: extraterrestrial regolith biocomposites with in vivo binders, (2021).

[145] D. Kornuta, A. Abbud-Madrid, J. Atkinson, J. Barr, G. Barnhard, D. Bienhoff, B. Blair, V. Clark, J. Cyrus, B. DeWitt, Commercial lunar propellant architecture: A collaborative study of lunar propellant production, Reach 13 (2019) 100026.

[146] R. Allouzi, W. Al-Azhari, R. Allouzi, Conventional Construction and 3D Printing: A Comparison Study on Material Cost in Jordan, Journal of Engineering 2020 (2020).

[147] S. McLennan, W. Boynton, S. Karunatillake, B. Hahn, G. Taylor, G. Mars Odyssey, Distribution of sulfur on the surface of Mars determined by the 2001 Mars Odyssey Gamma Ray Spectrometer, 41st Annual Lunar and Planetary Science Conference, 2010, p. 2174.

[148] I. Casanova, V. Aulesa, Construction materials from in-situ resources on the Moon and Mars, Space 20002000, pp. 638-644.

[149] E. Alonso, J. Gregory, F. Field, R. Kirchain, Material availability and the supply chain: risks, effects, and responses, ACS Publications, 2007.

[150] A.S. Yen, R. Gellert, C. Schröder, R.V. Morris, J.F. Bell, A.T. Knudson, B.C. Clark, D.W. Ming, J.A. Crisp, R.E. Arvidson, An integrated view of the chemistry and mineralogy of Martian soils, Nature 436(7047) (2005) 49-54.

[151] B.L. Ehlmann, J.F. Mustard, S.L. Murchie, F. Poulet, J.L. Bishop, A.J. Brown, W.M. Calvin, R.N. Clark, D.J. Des Marais, R.E. Milliken, Orbital identification of carbonate-bearing rocks on Mars, Science 322(5909) (2008) 1828-1832.

[152] M. Anand, I.A. Crawford, M. Balat-Pichelin, S. Abanades, W. Van Westrenen, G. Péraudeau, R. Jaumann, W. Seboldt, A brief review of chemical and mineralogical resources on the Moon and likely initial in situ resource utilization (ISRU) applications, Planetary and Space Science 74(1) (2012) 42-48.

[153] (!!! INVALID CITATION !!! {}).

[154] F.Z. Michael, Lunar & Mars Habitat Construction the Simple Cost Effective and Inexpensive Way, Available at SSRN 3904874 (2019).

[155] R.W. Moses, D.M. Bushnell, Frontier in-situ resource utilization for enabling sustained human presence on mars, National Aeronautics and Space Administration, Langley Research Center2016.

[156] E. Musk, Making humans a multi-planetary species, New Space 5(2) (2017) 46-61.

[157] G.F. Sowers, The Business Case for Lunar Ice Mining, New Space 9(2) (2021) 77-94.

[158] M. Roman, M. Yashar, M. Fiske, S. Nazarian, A. Adams, P. Boyd, M. Bentley, J. Ballard, 3D-Printing Lunar and Martian Habitats and the Potential Applications for Additive Construction, 2020 International Conference on Environmental Systems, 2020.

[159] M. Nazari-Sharabian, M. Aghababaei, M. Karakouzian, M. Karami, Water on Mars—a literature review, Galaxies 8(2) (2020) 40.

[160] M. Marceau, M.A. Nisbet, M.G. Van Geem, Life cycle inventory of portland cement manufacture, Portland Cement Association Skokie, IL, USA, 2006.

[161] A. Akhnoukh, H. Al-Khateib, J. Edmunson, M. Fiske, J. Fikes, Developing Concrete Mixes using Micro Sized Lunar and Martian Regolith for Space Applications, EPiC Series in Built Environment 2 (2021) 182-190.
[162] A. Mintus, Building on Mars: Experimental research on efficient and sustainable production process and construction method, (2019).
[163] M. El Gamal, K. El-Sawy, A.-M.O. Mohamed, Integrated mixing machine for sulfur concrete production, Case Studies in Construction Materials 14 (2021) e00495.
[164] B. Panda, N.A. Noor Mohamed, S.C. Paul, G. Bhagath Singh, M.J. Tan, B. Šavija, The effect of material fresh properties and process parameters on buildability and interlayer adhesion of 3D printed concrete, Materials 12(13) (2019) 2149.
[165] S. Chakraborty, Geopolymerization of Simulated Martian Soil, Tennessee Technological University, 2019.
[166] M. Naser, Extraterrestrial construction materials, Progress in materials science 105 (2019) 100577.
[167] V. Badescu, Mars: prospective energy and material resources, Springer Science & Business Media2009.
[168] T. Zhang, Y. Li, Y. Chen, X. Feng, X. Zhu, Z. Chen, J. Yao, Y. Zheng, J. Cai, H. Song, Review on space energy, Applied Energy 292 (2021) 116896.
[169] S.J. Schuldt, J.A. Jagoda, A.J. Hoisington, J.D. Delorit, A systematic review and analysis of the viability of 3D-printed construction in remote environments, Automation in Construction 125 (2021) 103642.
[170] M. Hojati, S. Nazarian, J.P. Duarte, A. Radlinska, N. Ashrafi, F. Craveiro, S. Bilén, 3D printing of concrete: A continuous exploration of mix design and printing process, Proceedings of the 42nd IAHS World Congress on Housing, Naples, Italy, 2018, pp. 10-13.
[171] A. Siddika, M.A.A. Mamun, W. Ferdous, A.K. Saha, R. Alyousef, 3D-printed concrete: Applications, performance, and challenges, Journal of Sustainable Cement-Based Materials 9(3) (2020) 127-164.
[172] M.Y. Marov, Radiation and space flights safety: An insight, Acta Astronautica 176 (2020) 580-590.
[173] V. Castano, I. Schagaev, Impact of radiation on electronics, Resilient computer system design, Springer2015, pp. 79-111.
[174] M. Dobynde, Y. Shprits, A.Y. Drozdov, J. Hoffman, J. Li, Beating 1 sievert: Optimal radiation shielding of astronauts on a mission to Mars, Space Weather 19(9) (2021) e2021SW002749.
[175] A. Meurisse, C. Cazzaniga, C. Frost, A. Barnes, A. Makaya, M. Sperl, Neutron radiation shielding with sintered lunar regolith, Radiation Measurements 132 (2020) 106247.
[176] M. Kim, S. Thibeault, R. Kiefer, J. Wilson, J. Buckley, Processing of structural shielding materials for martian in-situ resource utilization, 40th AIAA Aerospace Sciences Meeting & Exhibit, 2002, p. 466.
[177] H. Binici, O. Aksogan, A.H. Sevinc, A. Kucukonder, Mechanical and radioactivity shielding performances of mortars made with colemanite, barite, ground basaltic pumice and ground blast furnace slag, Construction and Building Materials 50 (2014) 177-183.
[178] J. Wood, Computational methods in reactor shielding, Elsevier2013.
[179] L. Röstel, J. Guo, S. Banjac, R.F. Wimmer-Schweingruber, B. Heber, Subsurface radiation environment of Mars and its implication for shielding protection of future habitats, Journal of Geophysical Research: Planets 125(3) (2020) e2019JE006246.
[180] H.A. Toutanji, R. Grugel, Performance of “waterless concrete”, Concrete Solutions, CRC Press2009, pp. 229-232.
[181] C. Montes, K. Broussard, M. Gongre, N. Simicevic, J. Mejia, J. Tham, E. Allouche, G. Davis, Evaluation of lunar regolith geopolymer binder as a radioactive shielding material for space exploration applications, Advances in Space Research 56(6) (2015) 1212-1221.
[182] H.A. Toutanji, S. Evans, R.N. Grugel, Performance of lunar sulfur concrete in lunar environments, Construction and Building Materials 29 (2012) 444-448.

[183] P. Bartos, Fresh concrete: properties and tests, Elsevier2013.
[184] A. Borggräfe, M. Quatmann, D. Nölke, Radiation protective structures on the base of a case study for a manned Mars mission, Acta Astronautica 65(9-10) (2009) 1292-1305.
[185] H. Baltas, M. Sirin, A. Celik, İ. Ustabas, A. El-Khayatt, Radiation shielding properties of mortars with minerals and ores additives, Cement and Concrete Composites 97 (2019) 268-278.
[186] C.C. Schiavone, Polymeric Radiation Shielding for Applications in Space: Polyimide Synthesis and Modeling of Multi-Layered Polymeric Shields, (2013).
[187] P. James, Urban sustainability in theory and practice: circles of sustainability, Routledge2014.
[188] L. Magee, A. Scerri, P. James, J.A. Thom, L. Padgham, S. Hickmott, H. Deng, F. Cahill, Reframing social sustainability reporting: Towards an engaged approach, Environment, development and sustainability 15(1) (2013) 225-243.
[189] J. Rezende, D. Souza, D. Santos, Habitat Marte Educational Program: Space, Sustainability and Agriculture for People, 2020 International Conference on Environmental Systems, 2020.
[190] W.P. Schonberg, R. Putzar, F. Schaefer, Sustainable Lunar Habitat Protection Against Damage By Meteoroid Impacts, Earth & Space 2008: Engineering, Science, Construction, and Operations in Challenging Environments2008, pp. 1-8.
[191] J.C. Stormont, S.G. Fernandez, M.R. Taha, E.N. Matteo, Gas flow through cement-casing microannuli under varying stress conditions, Geomechanics for Energy and the Environment 13 (2018) 1-13.
[192] M. Dugarte, G. Martinez-Arguelles, J. Torres, Experimental evaluation of modified sulfur concrete for achieving sustainability in industry applications, Sustainability 11(1) (2019) 70.
[193] A. Pathak, Occupational Health & Safety in Cement industries, Int. J. Inst. Saf. Eng. India (IJISEI) 2 (2019) 8-20.
[194] D. Sahai, Cement hazards and controls: health risks and precautions in using Portland cement, Constr Safety Mag 12 (2001).
[195] F. Abbasi Balochkhaneh, F. Golkhani, S. Baesmat, Determining the Most Important Hazards in the Cement Industry with a Cost Reduction and Process Optimization Approach, Health Education and Health Promotion 4(3) (2016) 3-11.
[196] H. Klee, Briefing: The Cement Sustainability Initiative, Proceedings of the Institution of Civil Engineers-Engineering Sustainability, Thomas Telford Ltd, 2004, pp. 9-11.
[197] S. Chakraborty, E.K. Zavadskas, Applications of WASPAS method in manufacturing decision making, Informatica 25(1) (2014) 1-20.
[198] M. De Schepper, P. Van den Heede, I. Van Driessche, N. De Belie, Life cycle assessment of completely recyclable concrete, Materials 7(8) (2014) 6010-6027.
[199] L.H.M. Vefago, J. Avellaneda, Recycling concepts and the index of recyclability for building materials, Resources, conservation and recycling 72 (2013) 127-135.
[200] A. Meurisse, J. Carpenter, Past, present and future rationale for space resource utilisation, Planetary and Space Science 182 (2020) 104853.
[201] M. Fateri, A. Meurisse, M. Sperl, D. Urbina, H.K. Madakashira, S. Govindaraj, J. Gancet, B. Imhof, W. Hoheneder, R. Waclavicek, Solar sintering for lunar additive manufacturing, Journal of Aerospace Engineering 32(6) (2019) 04019101.
[202] F.R.L. Junior, L. Osiro, L.C.R. Carpinetti, A comparison between Fuzzy AHP and Fuzzy TOPSIS methods to supplier selection, Applied soft computing 21 (2014) 194-209.
[203] A. Guitouni, J.-M. Martel, Tentative guidelines to help choosing an appropriate MCDA method, European journal of operational research 109(2) (1998) 501-521.
[204] S. Lee, Application of AHP and fuzzy AHP to decision-making problems in construction, 52nd ASC Annual International Conference Proceedings, 2016.

[205] S. Opricovic, G.-H. Tzeng, Compromise solution by MCDM methods: A comparative analysis of VIKOR and TOPSIS, European journal of operational research 156(2) (2004) 445-455.

[206] A. Baykasoğlu, İ. Gölcük, Revisiting ranking accuracy within WASPAS method, Kybernetes (2019).

[207] E. Mulliner, N. Malys, V. Maliene, Comparative analysis of MCDM methods for the assessment of sustainable housing affordability, Omega 59 (2016) 146-156.

[208] A. Valipour, H. Sarvari, J. Tamošaitiene, Risk assessment in PPP projects by applying different MCDM methods and comparative results analysis, Administrative Sciences 8(4) (2018) 80.

[209] T.L. Saaty, The analytic hierarchy process (AHP), The Journal of the Operational Research Society 41(11) (1980) 1073-1076.

[210] D.-Y. Chang, Applications of the extent analysis method on fuzzy AHP, European journal of operational research 95(3) (1996) 649-655.

[211] O. Taylan, A.O. Bafail, R.M. Abdulaal, M.R. Kabli, Construction projects selection and risk assessment by fuzzy AHP and fuzzy TOPSIS methodologies, Applied Soft Computing 17 (2014) 105-116.

[212] A.H. Lee, W.-C. Chen, C.-J. Chang, A fuzzy AHP and BSC approach for evaluating performance of IT department in the manufacturing industry in Taiwan, Expert systems with applications 34(1) (2008) 96-107.

[213] C.-L. Hwang, K. Yoon, Methods for multiple attribute decision making, Multiple attribute decision making, Springer1981, pp. 58-191.

[214] R. Greene, R. Devillers, J.E. Luther, B.G. Eddy, GIS-based multiple-criteria decision analysis, Geography compass 5(6) (2011) 412-432.

[215] V. Jain, A.K. Sangaiah, S. Sakhuja, N. Thoduka, R. Aggarwal, Supplier selection using fuzzy AHP and TOPSIS: a case study in the Indian automotive industry, Neural computing and applications 29(7) (2018) 555-564.

[216] A. Assari, T. Mahesh, E. Assari, Role of public participation in sustainability of historical city: usage of TOPSIS method, Indian Journal of Science and Technology 5(3) (2012) 2289-2294.

[217] E.K. Zavadskas, A. Zakarevicius, J. Antucheviciene, Evaluation of ranking accuracy in multi-criteria decisions, Informatica 17(4) (2006) 601-618.

[218] A.A. Ameri, H.R. Pourghasemi, A. Cerda, Erodibility prioritization of sub-watersheds using morphometric parameters analysis and its mapping: A comparison among TOPSIS, VIKOR, SAW, and CF multi-criteria decision making models, Science of the Total Environment 613 (2018) 1385-1400.

[219] E.K. Zavadskas, Z. Turskis, J. Antucheviciene, A. Zakarevicius, Optimization of weighted aggregated sum product assessment, Elektronika ir elektrotechnika 122(6) (2012) 3-6.

[220] M. Ramezanzade, H. Karimi, K. Almutairi, H.A. Xuan, J. Saebi, A. Mostafaeipour, K. Techato, Implementing MCDM Techniques for Ranking Renewable Energy Projects under Fuzzy Environment: A Case Study, Sustainability 13(22) (2021) 12858.

[221] A. Farhang Mehr, I.Y. Tumer, Risk-based decision-making for managing resources during the design of complex space exploration systems, (2006).

[222] L.M. Lodish, Experience with decision calculus models and decision support systems, Wharton School, University of Pennsylvania, Marketing Department1979.

[223] S. Parathi, P. Nagarajan, S.A. Pallikkara, Ecofriendly geopolymer concrete: a comprehensive review, Clean Technologies and Environmental Policy (2021) 1-13.

[224] A. Alexiadis, F. Alberini, M.E. Meyer, Geopolymers from lunar and Martian soil simulants, Advances in Space Research 59(1) (2017) 490-495.

[225] H. Haleh, A. Hamidi, A fuzzy MCDM model for allocating orders to suppliers in a supply chain under uncertainty over a multi-period time horizon, Expert Systems with Applications 38(8) (2011) 9076-9083.

[226] J. Kozicka, Low-cost solutions for Martian base, Advances in Space Research 41(1) (2008) 129-137.

Journal Pre-proof

- MCDM is used to review 8 building materials based on 14 criteria
- Geopolymer concrete is the best material for construction on Mars
- Sintered material and sulphur concrete are equally ranked second
- Using Fuzzy AHP, shipping has the highest weighting
- Using Fuzzy AHP, sustainability has the lowest weighting

CRediT author statement

Soha Iranfar: Investigation, Validation, Formal analysis, Visualization

Mohammad Mehdi karbala: Investigation, Data Curation, Resources

Mohammad Hossein Shahsavari: Conceptualization, Methodology, Writing - Original Draft, Project administration

Veerle Vandeginste: Project administration, Supervision, Writing - Review & Editing

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: