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Space-native Construction Materials for Earth-independent and Sustainable Infrastructure

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ABSTRACT

A successful space exploration requires establishing permanent and earth-independent infrastructure that are not only resilient to the extreme environment of space but also preferably made of sustainable and indigenous “space-native” construction materials. This review covers feasibility of exploiting in-situ lunar and Martian resources as well as harvesting of elements and compounds, from near Earth objects (NEOs), to produce extraterrestrial materials suitable for construction of space-based infrastructure. This review also details material features and characteristics required to withstand the unique, and harsh, effects of space environment. In essence, this paper reviews past and recent advancements in construction-based materials that could be used in the design and development of space human bases and highlights design consideration for sustainable human settlements. Towards the end of this review, practical and technological challenges associated with development of lunar and Martian indigenous construction materials are identified and examined.

Keywords: Sustainable infrastructure; Construction materials; Space exploration; Lunar and Martian settlements.

INTRODUCTION

Serious attention was first focused towards space exploration in the beginning of the twentieth century as well as during the Second World War, especially after the successful takeoff

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of *Vergeltungswaffe-2*, the first guided missile to reach the outer space. Few years later, the National Aeronautics and Space Administration (NASA) was commissioned with the main goal of expanding space exploration efforts. Yuri Gagarin orbited the Earth in 1961 and became the first human to do so. He was followed by Neil Armstrong who became the first man to land on the Moon eight years later. In parallel with twelve manned Apollo Missions, six of which landed on the Moon, we also continued to remotely explore nearby space bodies and near galaxies in pursuit of a destination suitable for establishing outposts and human migration.

Due to their proximity of the Moon and Mars to Earth, past and recent studies continue to elude to the possibility of human colonization to these bodies [1]. While it is clear that transportation to (and from) the Moon require lesser energy, time, cost, and technology, an inertia towards pursuing exploration (and colonization merit) of Mars has been rising for the past few decades. This inertia capitalizes on number of challenges associated with the harsh lunar environment as listed in Table 1. For example, the gravity on Mars is about twice as much of that on the Moon, and Mars is fortunate to have a unique atmosphere that can offer superior shielding from various radiation sources [2]. Further, one lunar day is equivalent to 27 days on Earth, while one *Sol* on Mars is slightly longer than that on Earth (i.e. about 24 hours and 37 minutes [3]). This large variation in lunar day/night time can cause detrimental health and psychological issues on human crews [4].

Table 1 Selected differences between Earth, Moon, and Mars [2].

Parameter	Earth	Moon	Mars
Total mass compared to Earth (%)	1.0	1.2	10.7
Approximate distance from Earth (km)	0.0	3.84×10^5	2.25×10^8
Day duration (hrs)	23.9	655.7	24.7
Revolution period (days)	365.3	29.5	686.9
Average surface temperature (ºC)	13	-30	-57
Atmospheric pressure (kPa)	101.3	negligible	0.7

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Whether the Moon or Mars is selected for manned exploration missions and to pave the way for large-scale human colonization, this migration is highly dependent upon development of resilient, economical, and sustainable infrastructure that can house and safely guard human subjects and crews. Unfortunately, development of such infrastructure continues to be a major challenge that hinders our ability to realize Earth-independent space exploration programs. Since transportation of infrastructure (or raw/construction materials) can cost between $5,000 to $20,000 to deliver 1 kg from Earth to the Moon; a cost with the potential to scale up if transportation is to reach Mars [5], another alternative would be to build and fabricate such infrastructure on the Moon and Mars using their own (i.e. indigenous) resources.

Remarkably, analysis on collected soils from lunar and Martian landing sites has verified that both the Moon and Mars hold a wealth of materials that can be processed to yield terrestrial-like construction materials such as concrete and metals [6]. It is due to the availability of such substances that number of studies have examined the feasibility of in-situ resources as a mean to establish economical space exploration programs [7]. While it is true that utilizing in-situ raw materials promotes natural development of Earth-independent and sustainable interplanetary infrastructure, our understanding of characterization, and processing of lunar and Martian in-situ resources continues to be lacking especially considering the extreme nature of space environment, including vacuum conditions and severe radiation effects [8].

In order to bridge this knowledge gap, a number of studies were carried out during the last few decades to investigate various aspects and features of space-native resources [9, 10]. The outcome of such studies have predominantly engineered specifically tailored materials spanning

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from traditional construction materials, i.e. ceramics, and metals/alloys, to those of biological origin (nature-inspired), and/or possess special characteristics including self-healing and energy harvesting abilities [11, 12]. The outcome of these studies has led to the realization that efficacious utilizing in-situ materials for space construction could reduce the overall cost of a human settlement from $100 to an average of $40 billion (which is about 2-3 times the cost of typical aircraft carrier [13]).

Researchers such as Lin [14] and Toutanji [15], as well as others [16, 17], point out that among all available construction materials, ceramics and/or composites (such as concrete) continue to be regarded as most suitable for use in space-based civil infrastructure. This is due to the fact that the behavior of concrete under severe working environments, i.e., radiation, high temperature, etc., is well-documented (e.g.: nuclear power plants) [18, 19]. Still, the behavior and performance of concrete materials under combination of aforementioned conditions along with vacuum and absence/low gravity has not been fully investigated yet [12, 18].

The recent announcements made by the European Space Agency (ESA) and National Aeronautics and Space Administration (NASA) of a target deadline to start sending manned missions to the Moon on 2021 and to Mars by 2030 call on engineering and material science community to develop construction materials and technologies that enable development of sustainable and Earth-independent space infrastructure. In support of these announcements, this review aims to present a survey of past and most recent research findings on extraterrestrial materials suitable for construction applications in space environment. The present review explores feasibility of utilizing space-native constituents in terms of in-situ lunar and Martian resources as well as elements harvested from Near-Earth Objects (NEOs) to permit development of astro-construction materials. This survey addresses adverse effects of the harsh space environments on such materials and highlights associated venues in-need of immediate research and development.

SPACE ENVIRONMENT, AND RESOURCES

Space Environment

Space comprises of a multitude of environments (and actions) that are largely different their Earth counterparts [20]. These actions not only affect fundamental aspects of material formation but also the behavior of materials as well as, their performance, and characteristics. The three main differences between the environments in Earth, Moon (Luna), and Mars are often band together under radiation, vacuum, and low gravitational forces. Radiation is defined as the transit of energy in the form of high-speed particles and electromagnetic waves [21]. Radiation occurs due to electromagnetism such as gamma rays and galactic cosmic radiation which comprise of transmitting heavy ions with a speed approaching the speed of light. Radiation arises from solar and galactic flares resulting from supernova explosions [21].

Another dissimilarity between Earth, Moon, and Mars is the weak atmosphere in the last two space bodies. The atmosphere of Earth primarily comprises of Oxygen and Nitrogen, the Moon on the other hand, does not technically have an atmosphere (mainly due to its low gravity). The atmosphere surrounding Mars consists of Carbon Dioxide, Nitrogen, and Argon and is one percent of that on Earth [31]. The presence of weak atmosphere cause large thermal fluctuations to occur on the surface of the Moon and Mars. The thermal fluctuation on the Moon and Mars varies between -173 to 127°C and between -60 to 125°C, respectively. A fragile atmosphere amplifies effects of vacuum by further causing materials to dry-out and outgas. The hard vacuum has a small magnitude of 3×10^{-13} kPa to 0.7 kPa on the Moon and Mars, respectively, as compared

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to Earth (~101.3 kPa). In one study, Kanamori et al. [23] examined the long-term exposure to vacuum conditions and concluded that vacuum conditions led water to loss and can accelerate material deterioration of mortar specimens.

The lack of atmosphere on the Moon and presence of a very thin atmosphere on Mars shapes a fragile shield against space debris including meteorites and/or micrometeorites. The impact effect of such debris particles was examined by Lindsay [24] as well as Toutanji et al. [25]. These researchers have shown that space particles as small as one thousand of a gram may reach a speed of 20 to 70 km/s. Toutanji et al. [25] also reported outcome of tests carried out by firing projectiles of a mass of 1.4×10^{-4} g into concrete samples at a speed of ~6 km/s. In these tests, the impact of projectiles caused craters damage as large as 1.3 cm diameters in some concrete specimens. The findings of these experiments reveal the disturbing effects of space debris impact, and emphasize the integration of highly resilient construction materials with high shielding properties.

Space Resources

Two main concepts have been proposed over the past few years to arrive at sustainable and Earth-independent space infrastructure. These concepts involve:

1) Direct (or immediate) use of in-situ raw materials available on the Moon and Mars,
2) Mining and harvesting Near-Earth Objects (NEOs) for minerals and compounds,

Realizing the above two concepts is tied with developing effective handling and treatment techniques for extracting elements from collected raws (i.e. ore) to produce construction materials. This section details aspects and principles for exploiting available lunar and Martian surface (and underneath) resources, as well as harvesting of elements and compounds from NEOs.

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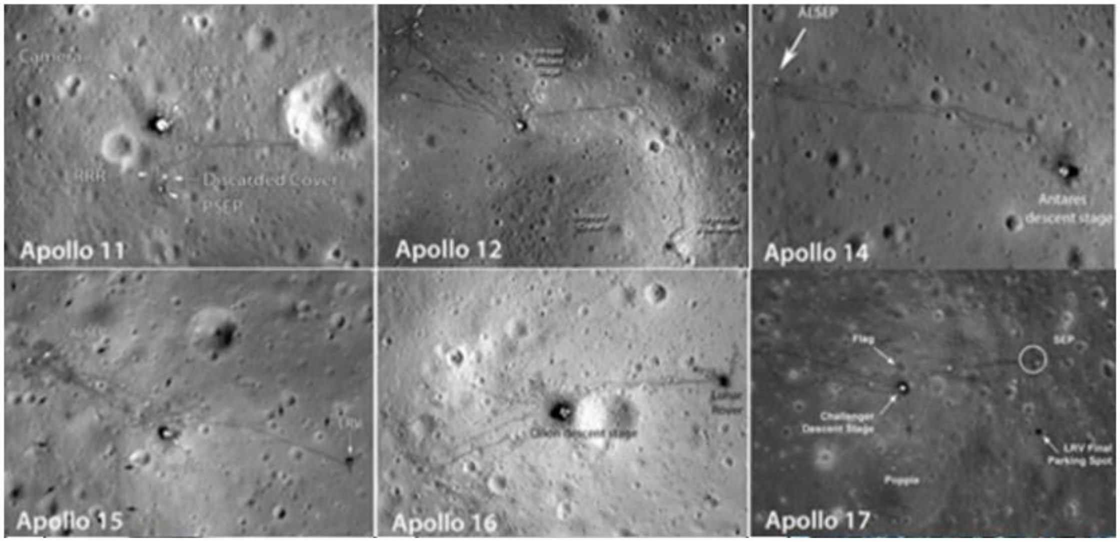
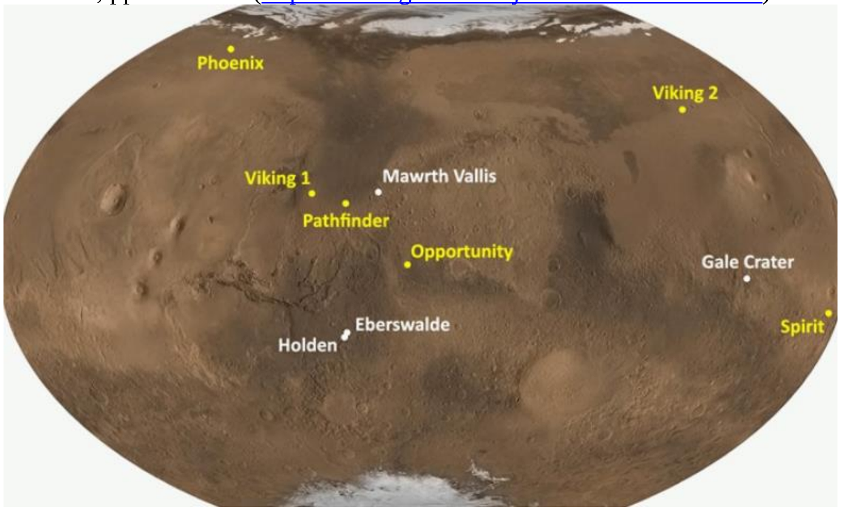
In-Situ Resource Utilization (ISRU)

While the surface of both Moon and Mars continue to be extensively studied through remote sensing technologies, only six manned Apollo missions landed on the Moon (between 1969 and 1972). These Apollo missions managed to collect 381.7 kilo-grams of lunar soil and rocks from six different exploration sites (See Fig. 1). While manned exploration missions have not reached Mars yet, few probes and rovers are able to roam the surface of Mars and explore its environment. The success of these exploration missions permitted appropriate valuation of resources on the Moon and Mars and commenced fundamentals to realizing in-situ resource utilization (ISRU). In-situ resource utilization is defined as harnessing (or utilizing) raw resources found in-situ (whether on surface or subsurface) to produce products that allow efficient and sustainable robotic and human exploration [26].



(a) Moon sites



(b) Martian sites

Figure 1. Lunar and Martian exploration sites (Courtesy of NASA)

Analysis on samples collected from the Moon and Mars showed that soil and rocks consist of fine particles (regolith). Regolith is commonly defined as a surficial layer covering the entire lunar, as well as Martian, surface. This regolith is formed by meteorite impact and corresponding physical desegregation of large rock fragments into smaller ones over time. The regolith layer varies in thickness from few meters to tens of meters across various locations. Gradation data for a lunar soil were reported by Cesaretti et al. [27] who also and noted that approximately half of analyzed lunar sample consists of well-graded grains with small-sized diameters (<75 µm). Similarly, Heiken [28] also analyzed actual lunar samples and reported that grains in lunar regolith has an average size between 40 to 270 µm. Although samples from Martian soil have not been brought back, Viking landers and Mariner-9 orbiters as well as on-site analysis has confirmed that soil on Mars has an average grain size that varies between 70-800 µm [29].

The aforementioned studies, along with others [30, 31], also reported that lunar and Martian soil and rocks have unique characteristics such as lack of water, common presence of metallic iron, as well as traces of few chemical elements. Nonetheless, the most of these minerals that make up lunar and Martian soil and rocks are (with a few exceptions) also found on Earth. For example, lunar and Martian soils contain large amounts of silicon dioxide (SiO_2), alumina (Al_2O_3), sulfur (S), and iron (FeO). A Comparison of chemical contents between lunar and Martian samples as well as terrestrial cement is shown in Table 2. As can be seen, lunar and Martian samples have high concentration of SiO_2 ranging from 20.13 to 45.03%, respectively, of the total sample weight. The availability of such substances eludes to the feasibility of producing cementitious terrestrial-like materials [32]. For example, and as will be shown in the following section, SiO_2 can lead to formation of calcium silicate hydrates (in Portland cement binders) as well as alkali-aluminosilicate hydrates in geopolymer concretes/binders. It can then be inferred that identification of in-situ resources, and development of processing methods that allow direct and full utilization of in-situ resources, can minimize dependence on Earth, and also establish economically sustainable space exploration.

Table 2 Chemical compositions (wt.%) of Martian and lunar soil samples.

Constituent	Lunar sample[1]	Lunar sample[2]	Martian sample[3]	Cement[4]
SiO_2	45.03	37.79	44.7	20.13
Al_2O_3	21.09	19.66	-	-
FeO	16.45	8.44	8.3	1.19
Fe_2O_3	8.01	10.74	5.6	64.01
MgO	7.27	8.85	5.7	5.98
CaO	2.54	12.97	0.9	0.37
K_2O	0.06	0.05	<0.3	0.77
TiO_2	-	-	18.2	2.35
SO_3	-	-	7.7	-
Cl	-	-	0.7	-

[1]Apollo 12 and [2]Apollo 17 (Greeley and Spudis [33]); [3]Chryse Planitia (Toulmin et al. [34]); [4]from Khitab et al. [35].

Another material that is widely available on the Moon and Mars is basalt. Basalt is a mafic extrusive comprising of more than 90% of volcanic rocks and Fig. 2 shows a sample obtained from NASA's inventory. This material is mainly made of SiO_2 and has a density of 2,600 kg/m^3. Further, basalt also has a compressive strength in the range of 140-290 MPa which is about 4-6 times stronger than commercially normal strength concrete. A number of recent studies have eluded to the merit of sintering regolith with basalt-heavy content in order to fabricate building blocks or to use basalt rocks/aggregate to develop extraterrestrial concrete-like material [36, 37]. The same studies also point out that due to the weak atmosphere on the Moon and Mars, solar energy can be collected and concentrated to achieve high level of continuous and practically abundant energy required to efficiently sinter regolith.

(a) Basalt rock (collected from Apollo 17, sample no. 70135)

(b) Cast regolith (collected from Apollo 16, sample no. 65035)

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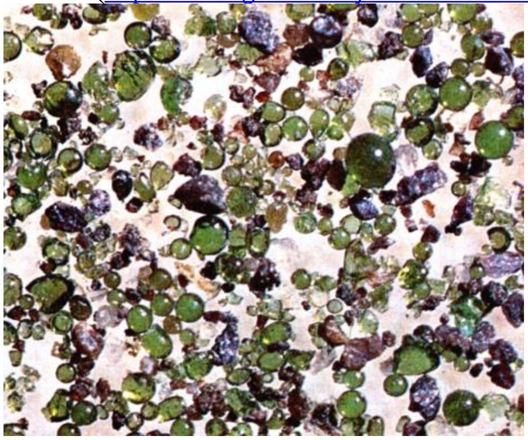

(c) Green glass pyroclastics (collected from the Apollo 15 landing site)
Fig. 2 Sample of lunar materials (courtesy of NASA)

Happel [30] reported mechanical properties of some of Moon-based in-situ materials, specifically regolith and glass, made through natural erosion and space weathering processes (see Fig. 2). Upon impact, regolith melts and slowly crystallizes. The resulting material is referred to as cast regolith. Happel showed that such materials retain high strength. More specifically, lunar material can achieved a compressive and tensile strength of 538 and 34.5 MPa, respectively. These materials, if utilized properly, could be beneficial for various space constructions (see Table 3).

Table 3 Properties of lunar in-situ materials [30].

Property	**Basalt rock**	**Cast regolith**	**Lunar glass**
Compressive strength (MPa)	140-290	538	-
Tensile strength (MPa)	-	34.5	-
Density (kg/m^3)	2600	3000	-
Modulus of elasticity (GPa)	-	100	450
Coefficient of thermal expansion (1/°C).	-	8×10^{-6}	-
Bending strength (MPa)	-	-	100-125

Harvesting Materials from NEOs

In lieu of ISRU, harvesting of materials (element/compounds) from Near-Earth Objects (NEOs) such as asteroids and/or moons could potentially lead to sustainable space exploration programs and perhaps much more economic development of earth-independent infrastructure. This could be attributed to the fact that NEOs are energetically more accessible than Luna and Mars as NEOs have a fraction of the size of the Moon and Mars and as a result they hold small gravitational attraction that require a small amount of propulsive energy to approach (or leave) those in the same orbit as the Earth. Other advantages to harvesting NEOs is that they may require a round-trip measured in days (as opposed to years in the case of Mars) and may offer substances that are rare or even absent on the Moon and Mars. Lewis [38] reported that some meteorites can contain free metals with high concentration of about 100 times that in lunar regolith. Thus, if an NEO is to be found to be easily accessible and minable as well, such an NEO would be attractive to harvest and could justify costs associated with transporting harvested materials.

In this concept, ore can be mined from an NEO using spacecraft and robots. Once ore is mined, this ore can be treated in-situ, or contingent upon distance from Earth/Moon/Mars, can be shipped for further processing on Earth or Moon/Mars. This notion of exploiting material resources present on smaller space bodies (predominantly asteroids) has gained attraction due to the work of Tsiolkovsky [39] in early twentieth century and then re-surfaced as a consequence to recent scientific advancements that identify possible material-rich NEOs, capture, and transport NEOs for material harvesting purposes [40, 41].

To pursue this concept, manned or unmanned spacecraft can plan routes at which to track, capture, and mine comets and asteroids to harvest their ore during travel to final destination. Once an NEO is captured, minerals and free materials can be scraped using mechanical limps. Minerals and ore can also be mined using onsite shafts. NEOs with loose metal contents could be collected via large magnets or drag conduits. A number of geological or physio-chemical methods can also

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be utilized to extract or separate minerals, compounds, and elements from parent NEOs and to prepare collected ore for final processing [42]. Collected minerals can then be treated or processed while being transported to their final destination or transported to a “working” orbit or a larger space “mining” workstation [43, 44].

It is worth noting that in a recent study, Brophy et al. [45] anticipated that an NEO of a diameter of 7 m and estimated mass between 250 to 1,000 metric-tons can be mined of minerals and elements which could be worth $10-12 billion. Some of the identified asteroids currently being considered for mining include *162173 Ryugu*, *101955 Bennu*, and *65803 Didymos*. These asteroids have been shown to contain high levels of minerals such as nickel, iron, and cobalt as well as water. Unfortunately, only few studies were able to test physical properties of NEOs (meteorites) [38, 41]. These studies have shown that there is large variation in strength and porosity in NEO-collected samples. In fact, stoney specimens achieved a compressive strength ranging from 6-260 MPa while iron-based sample have a compressive strength of 100-360 MPa.

PROPERTIES OF SPACE-NATIVE CONSTRUCTION MATERIALS

A notable sum of research associated with ISRU as well as development of extraterrestrial (astro) construction materials to promote sustainable infrastructure has been duly noted in the past forty years [9, 25, 30, 46-48]. This section highlights properties of space-native construction materials such as concrete-derivatives, metals, and alloys.

Concrete-like hybrids

The inherent resiliency and durable characteristics of concrete have established its potential as the first material of choice for lunar and Martian constructions [14]. The suitability of *concrete*, and concrete derivatives, for human settlement and infrastructure was examined under similar

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environments to space throughout the past three decades [49-51]. In one study, Cullingford and Keller [49] tested number of 300×150 mm concrete cylinders under semi-vacuum conditions of magnitude of 3.99×10^{-4} Pa. These researchers reported that properly designed traditional concrete could achieve adequate performance under extreme temperature and vacuum conditions. This finding was based on the observation that the compressive strength of concrete cured under vacuum conditions did not drop despite the fact that vacuum effects have led to faster release of free water from concrete cylinders at a rate of 0.04% per day. Cullingford and Keller also observed that concrete has a stable outgassing rate of 10^{-6} $\text{torr}\cdot\text{l/cm}^2\cdot\text{sec}$ after 73 hours of exposure to vacuum which was predominantly related to the aforementioned water vapor loss.

In another work, Swint and Schmidt [50] suggested expressions to improve mix design of lunar concrete through analysis of five different variables, namely cement type, low pressure exposure (26 kPa as oppose to 101 kPa on Earth), plasticizer type, wetting agent, and additive reinforcements. Then, using 80 different mixture combinations, these researchers examined the performance of casted concrete cylinders in terms of maximum compressive strength, maximum flexural strength, Poisson's ratio, and stiffness. Based on the finding of Swint and Schmidt, an optimum concrete mix would be that comprising of calcium aluminate cement, 2% of wetting agent and plasticizer and cured at low pressure conditions for four days was proposed.

Lin et al. [9] investigated the performance of actual lunar soil, awarded by NASA, in terms of physical properties, and feasibility as aggregates for fabrication of lunar concrete. In this study, Lin et al. casted concrete specimens (i.e. cubes/slabs) primarily made of lunar soil, water and aluminum cement. These specimens were cured and then tested under compression loading. Outcome of these tests infer that it is possible to fabricate concrete with moderate-to-high

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compressive strength and modulus reaching about 76 MPa and 21 GPa, respectively. In a follow up study, Lin et al. [51] examined the effect of diurnal lunar thermal cycling on concrete material and panels and established that developed thermal stresses due to diurnal temperatures is minor (of about 0.21 MPa) and much lower than the typical tensile strength of concrete.

However, in most above-mentioned works, a vital challenge that continues to hinder the use of concrete in development of space infrastructure and human habitats is the need for water, to mix, hydrate, and cure concrete. When water is mixed with concrete, a chemical agent referred to as cement paste forms which binds raw materials (i.e. aggregate, sand, fines etc.) used in concrete and fills voids between fines and coarse aggregates. It can then be inferred that accessibility of water is necessary to produce concrete on the Moon (or Mars). While recent exploration missions have inferred to the availability of water in the vicinity of the poles on the Moon and Mars [52, 53], a number of researchers raised concerns regarding ease of access and quality of water. If such water is not of high quality or easily accessible, then conventional concrete may not be easily produced on the Moon and/or Mars. This would impose a major limitation to space exploration efforts and development of sustainable space infrastructure.

In order to overcome such limitation, developing non-hydraulic (i.e. waterfree) concrete through the use of polymers, matrices epoxies, and/or possible lunar and Martian in-situ elements was explored in recent years [54-57]. This concrete is often referred to as *polymer concrete* and comprises of inorganic aggregates and polymeric resin binders. Kumar [55], Reis and Ferreira [58], and Lee et al. [59] reported outcome of successful integration of epoxy-based polymers as replacements for cement in concrete. These studies have shown that depending on the quantity and

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form of epoxy resin, epoxy concrete can have an average compressive strength that significantly vary from 17 to 60 MPa; which is comparable to that used in traditional construction applications.

Another variant of polymer concrete, is *epoxy concrete* which was investigated by Reis and Ferreira [58]. This concrete comprised of 80% of foundry sand and 20% of commercially available epoxy resin (EPOSIL 551). This type of concrete was also reinforced with synthetic fibers (i.e. carbon and glass) to assess the influence of fiber type on fracture properties of polymer concrete. In this study, Reis and Ferreira measured the fracture properties of synthetically reinforced polymer concretes and found out that its fracture toughness of the newly developed polymer concrete reinforced with carbon fibers improved by 29%, while concrete reinforced with glass fiber achieved minor improvements in fracture energy, estimated at 13%.

Lee et al. [59] developed a polymer-based concrete mixture consisting of 90% lunar simulant soil and 10% polymer. This concrete did not contain any water and the polymer matrix was thermally bonded to the lunar soil through exposing the concrete mixture a temperature of 230ºC. Within five hours of curing, the achieved strength of polymer concrete was 12.75 MPa. Lee et al. [59] also reported outcome of curing of polymer concrete made of lunar simulant bounded with thermoplastic polymer. They reported that this concrete has a compressive strength of about 35 MPa. The porosity of newly developed concrete was also examined and found to be equivalent to that of Portland cement concrete. Lee et al. [59] inferred that this concrete can be utilized to construct launching and landing pads (among other structural systems) on the Moon and/or Mars

Montes et al. [76] have shown that geopolymers could be produced by melting (or sintering) surface regolith. Thus, an alternative type of concrete-like cementitious material is one developed from geopolymers. Geopolymers are construction materials formed by interaction between an aluminosilicate and an alkaline solution and highly sensitive to the ratio of silicon to aluminum present in the concrete mixture [61]. These geopolymers can have an average compressive strength between 16.6 to 33.1 MPa, and as such could be used in constructing space human settlements infrastructures. Not only that but Montes et al. [60] also noted that similar *geopolymers* and *geopolymer concretes* can have radiation protection properties which would be beneficial in lunar and Martian environments. On the contrary, Davis et al. [62] described results of tests on concrete specimens made of a regolith based geopolymer cement in a simulated lunar environment. While the results of aforementioned tests did not seem to fulfill the US Marine Corp specified compressive strength (of 25-30 MPa), the availability of readily present regolith makes geopolymer concrete very attractive material for construction or sustainable structures.

Another alternative to the traditional, polymer-based, and geopolymer concrete, is sulfur (waterfree) concrete. Sulfur concrete has gained major attraction in the last few years, especially after detecting high amounts of troilite (FeS) on the Moon and Mars. This presents a unique opportunity to extract sulfur and use it as a binding agent to arrive at non-hydraulic concrete [54]. *Sulfur concrete* is made by heating sulfur at high temperature reaching 120-150°C so that it liquefies. The melted sulfur is then injected into lunar and/or Martian soil after which is left to cool off. Upon cooling down, the sulfur hardens, and the compound is referred to as sulfur concrete. Typically, sulfur-based concrete is made of 80-90% aggregate, 10-20% sulfur, and could be supplemented with plasticizers (of 5% wt.) to control cracking of cooled sulfur [63]. Loov et al. [64] showed that one of the key advantages of sulfur concrete is its rapid curing time as compared to traditional concrete (see Fig. 3).

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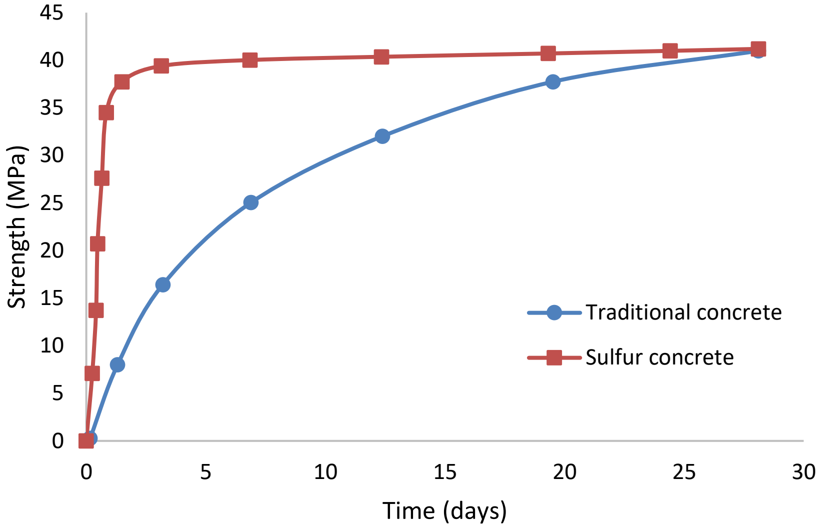

Fig. 3 Comparison of strength gain of sulfur concrete and traditional concrete [64]

A few studies explored the practicality of sulfur concrete as a construction material in space construction [48, 65]. For instance, Wan et al. [48] reported various physical properties of a sulfur-based lunar and Martian concretes (see Table 4). As shown in Table 4, the mechanical strength of samples made of lunar and sulfur concrete ranges from 39 to 75.7 MPa and from 20 to 63 MPa, respectively. The tensile strength and stiffness of Martian concrete was found to be 20-40% lower than that on lunar concrete. Toutanji and Grugel carried out number of tests to investigate the performance of sulfur and glass fiber-reinforced sulfur concrete [65]. In a notable study, the aforementioned researchers showed that sulfur concrete can achieve a compressive strength of 5.5-17 MPa and this strength could be significantly improved (by up to 45%) through reinforcing the concrete structure with glass fibers.

Table 4 Properties of lunar and Martian concrete [54].

Property	Lunar concrete	Martian concrete
Compressive strength (MPa)	39-75.7	20-63
Tensile Strength (MPa)	8.3	2.7-3.6
Density (kg/m^3)	2,600	-

Young’s modulus (GPa)	21.4	6.5-10
Coefficient of thermal expansion (1/°C).	5.4×10^{-6}	-
Bending strength (MPa)	-	1.65

Grugel [66] investigated the performance of sulfur concrete under analog temperatures to that on the Moon. Upon further examination into microstructure of sulfur concrete, sulfur concrete cubes exhibited de-bonding between cooled sulfur and aggregates as a result of sulfur shrinkage. This shrinkage seem to develop large voids within cured concrete, which severely weaken the internal structure of sulfur concrete. Grugel and Toutanji [63] also observed behavior of two sulfur concretes primed in vacuum conditions for 60 days. Observations from this work shows how vacuum conditions caused mass loss due to sulfur sublimation. The porousness of sulfur concrete was evaluated by Osio-Norgaard and Ferraro [67] who noted that this concrete can be more permeable than Portland cement concrete. This higher permeability arises from the tendency to regolith to quickly absorption of melted sulfur.

Heating a powder-like material up to below its melting point (while being under a certain pressure) is referred to as *sintering* [68, 69]. Sintering can be applied to directly transform regolith into a concrete-like structural components with load bearing capabilities (i.e. bricks). Sintering can be carried out by focusing energy rays such as sunlight, laser, or microwaves through lens or solar furnaces towards a granular material to heat it. This enables the powder material to bond together and form a low porosity solid material [60].

Different sintering techniques for processing of extraterrestrial construction materials, such as solar and microwave sintering, were investigate recently. Meurisse et al. [70], for instance, investigated the prospect of fabricating bricks of 20×10×3 cm within five hours at 1000°C. Meek

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et al. [71] showed that microwave energy (with ultra-high frequency (UHF)) can be utilized to fabricate bricks of basalt and ilmenite-rich rocks. In a another study, Meek et al. [71] also used microwave sintering to sinter three lunar simulants with similar constituents to that of lunar soils obtained by Apollo 11, 15 and 16 missions [71]. The measured compressive strength and hardness of sintered materials varied between 0.84-20.9 MPa and 96 to 705 kg/m^3, respectively. Allen et al. [7] was able to fabricate building bricks measuring 7.9×5.5×3.6 cm by sintering two lunar simulants at temperatures between 1000-1250°C for 30-180 minutes.

Metals and Alloys

Though metals are not readily available on Luna or Mars, elements that exist in lunar and Martian in-situ resources could be first extracted and then used to produce metals (or even alloys). This has been made clear by findings of recent studies which analyzed lunar regolith, as well as remote sensing and on-site analysis of Martian soil (i.e. using rovers) [72, 73]. These studies indicated that there is an abundance of aluminum (Al), magnesium (Mg), iron (Fe), and titanium (Ti) as well as traces of other elements such as vanadium (V), zirconium (Zr), and chromium (Cr). It is worth noting that aluminum is found in the form of aluminum oxide (Al_2O_3) in large amounts in lunar Highlands (making approximately 15% of soil weight) [74]. Similarly, McCallum et al. [75] reported that magnesium has been found in the form of olivine (Mg, Fe_2SiO_4) containing 32% of magnesium oxide (MgO). The availability of such elements in lunar and Martian in-situ resources, if utilized and processed properly, can lead to sustainable production of metals and alloys. A summary of mechanical properties of these elements, together with their fraction of existence (by weight), is listed in Table 5.

Table 5 Properties of lunar and Martian elements

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Element	**Tensile strength (MPa)[76]**	**Specific gravity[76]**	**Young's modulus (GPa) [76]**	**Melting point (°C)[77]**	**Elongation[77]**	**wt. (%)[72]**
Al	170	2.7	70	660	45	7.5
Mg	200	1.7	45	650	5	6.5
Fe	280	7.9	196	1,535	45	4.5
Ti	2,300	4.6	119	3,287	18	1.5

Due to their relatively low density and appropriate physical properties, *aluminum* and *magnesium* are equally considered suitable elements for interplanetary constructions. These elements have low melting points, as compared to other elements and hence can be easily processed, formed, and molded into structural shapes (i.e. load bearing members). While aluminum and magnesium can be used to form as stand-alone structural members (i.e. aluminum beams etc.), it is worth noting that aluminum can also be melted to bind into lunar (or Martian) soil and form waterless aluminum-based concrete [15]. On the other hand, magnesium also has unique physical characteristics such as electromagnetic shielding which makes it suitable for extraterrestrial construction. Besides its usefulness in radiation sheltering [78], magnesium also has 30 times damping effect to that of aluminum, and hence magnesium could be better suited in external shields of space habitats against meteorite impacts [79].

Number of researchers have explored the use of aluminum and magnesium for development of space infrastructure [80, 81]. For example, Apollo space program utilized aluminum to develop rigid units that could be deployed as space modules (habitats). The use of magnesium-based igloo-shaped space structure (habitat) was investigated by Mottaghi and Benaroya [81]. The behavior of this habitat under lunar thermal and seismic loading was examined through highly nonlinear finite element simulations. These researchers reported the adequate performance of a magnesium-based igloo-shaped space settlement concept and proposed its employment in lunar environment.

Iron is another suitable element for civil development on the Moon and Mars environments as a result of its favorable properties and extensive usage in common Earthly construction [82-84]. Another reason why iron is a favorable material is because it can be used to produce steel. Zhuk et. al. [85] reported that production of aluminum requires 6 to 10 times more energy than producing steel estimated at 211 GJ/tonne for aluminum, as compared to 22.7 GJ/tonne for steel). *Titanium*, while has much improved mechanical properties that iron, magnesium, and aluminum, still it is only available in small quantities in ilmenite ($FeTiO_3$) [86]. A key constraint of using titanium in infrastructure applications is it high reactivity with oxygen which may limit its integration in interior load bearing systems.

In lieu of the above listed minerals in Table 5, number of investigations were carried out on mixture of metals and alloys that could be produced from in-situ materials and produced on the Moon or Mars [87-89]. For instance, Gionet [87] tested another type of aluminum alloy, i.e. 2014-T6 Aluminum, under impact and thermal lunar loading. In the same study, Gionet implied that such an infrastructure can successfully endure the harsh environment of the Moon. Yin [88] examined aluminum lithium (8090-T8771) and magnesium (ZCM711) alloys as possible alloys for designing a cylindrical-shaped horizontal human habitat. Yin [88] proposed integrating aluminum lithium alloy in internal framing as well as cables and limiting magnesium alloy for compression-like load bearing members due to its embrittlement at low temperature.

In the event that aluminum and/or magnesium alloys do not meet specific requirements (i.e. strength, thermal fatigue), titanium alloys are often employed. Ti6Al4V, is one such titanium alloy that due to its higher strength, Young's modulus, and practically low coefficient of thermal expansion can replace aluminum alloys [90]. Szilard [91] suggested the use of other alloys, specifically *beryllium* alloy in the design of sphere-like lunar infrastructure. This alloy has very low density and offers the highest stiffness of any naturally occurring material. The main limitation on use of beryllium is toxicity to the human respiratory tract, if not properly fabricated. Table 6 lists various properties of the aforementioned aluminum, magnesium, titanium, and beryllium alloys.

Table 6 Properties of various metal alloys.

Property	**2014-T6**[87]	**8090-T8771**[88]	**ZCM711**[88]	**Ti6Al4V**[92]	**Beryllium Alloy**[93, 94]
Ultimate strength (MPa)	-	441.3	275	925	307
Yield strength (MPa)	410	344.8	185	860	222
Elongation (%)	-	1.25	12	5-18	2-3
Young's modulus (GPa)	72.5	80. 7	45	108.5	303
Density (kg/m^3)	2,800	2,519	1,795	4,420	-
Coefficient of thermal expansion (1/°C).	-	23×10^{-6}	27×10^{-6}	9.2×10^{-6}	-

DESIGN CONSIDERATIONS FOR SUSTAINABLE SPACE INFRASTRUCTURES

Despite the fact that space structures are to be fabricated on the Moon and Mars, which is entirely different than that on Earth, these infrastructures are still required to provide a safe and workable environment for human settlers and researchers. In addition to that, space infrastructure need to be designed to be resilient, preferably made of space materials, and also to achieve much higher standards with regard to sustainability and durability simply due to the extreme nature of space environments and associated high risk involved with human safety and continuation of space exploration missions.

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One of the major differences between the Earth, Moon and Mars, from material and structural points of view, is the type of loadings construction materials (and by extension space infrastructure) need to withstand. While the primordial loadings on Earth comprise of gravitational and environmental live loads (i.e. wind etc.), such loads can be of much lesser importance on the Moon and Mars [95]. For example, due to the lack of atmosphere on the Moon and Mars, wind formation is not common. Similarly, the weak gravity effects on the Moon and Mars produce insignificant Moon- and Martian-quakes; estimated at magnitude of 2-4 on Richter scale [95].

As gravity on the Moon and Mars is about 17% and 38% that of Earth, both Clarke [96] and Benaroya et al. [97] suggested that design loads (i.e. dead loads, live loads etc.) can be scaled to the equivalent gravity of Luna or Mars. As a result, space infrastructure can be able to carry 3 to 6 times the mass on Earth. Hence, space infrastructure can theoretically have much larger spans and also fabricated of thinner (or slender) load bearing members. This also implies that these structural members need not to be fabricated of construction materials with high strength and stiffness properties as the excess of strength/stiffness is not necessary. This would technically result in significant savings in amount and physical characteristics of construction materials, erection time, and overall resource utilization. In order to demonstrate this hypothesis, Clarke [96] estimated that the mass of the 182 m diameter radio telescopes (of 36,000 tons) that was envisioned for construction in West Virginia, US, could be reduced to about 4,000 tons if built on the Moon surface as a result of low gravity and absence of dynamic loads.

Benaroya et al. [97] and Chua et al. [98] also studied fundamental characteristics of geotechnical design and pointed out that the extreme diurnal temperature on lunar (and Martian) surface can cause fatigue-related expansion and contraction of regolith and thus foundations need

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to be positioned underneath the depth of thermal cycling to control settlement. In one study, Gromov [32] showed that lunar and Martian soils have an average cohesion, and bearing capacity of 2.35 kPa, and 31 kPa, as well as 0.75 kPa, and 55 kPa respectively. It is worth noting that in low gravity, a foundation (or footing) can hypothetically support higher levels of load if the soil surrounding that foundation is assumed to have elastic behavior. Thus, failure in space footing could occur as a result to settlement rather than soil failure.

It can be inferred from the above discussion that the main loading types on lunar and Martian infrastructure would be radiation, temperature variation, and meteorites impact. In order to overcome some of the other types of loadings, space infrastructure are proposed to be shielded or buried into the surface of the Moon or Mars. One approach of habitat shielding is to cover the structure with a layer of regolith varying in depth between 1-6 m [98]. While this approach is attractive and easy to apply, covering the infrastructure with regolith can also complicate maintenance, and inspection procedures, as well as ingress (or egress/evacuate) the facility.

It has been envisioned that structural systems in space infrastructure would have similar characteristics to that used on Earth, with some adjustments to permit for autonomous and quicker assembly and inspection. Such modifications may include, avoidance of extensive detailing to allow for easy erection, and also speed up the construction process, as well as minimize the need for regular upkeep and inspection. In order to avoid the need for retrofitting and upgrade in case of deterioration or upon micrometeorite impact, space infrastructure may employ self-healing and self-sensing construction materials. Considering the extreme environment of space, space outposts (and infrastructure) are to be integrated with high level of intelligence, redundancy, autonomy and resiliency [99, 100].

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CURRENT CHALLENGES AND FUTURE RESEARCH DIRECTIONS

This review highlights main differences between Earth as well as lunar and Martian environments such as weak gravity, lack of atmosphere (vacuum), extreme radiation, high probability of meteorite (or micrometeorite) impact etc. The discussion on aforementioned environmental factors has been a focal point of research in the past few years [87, 91]. While these studies managed not only to detail aspects of space environment on humans, but also proposed solutions to overcome some of these effects through proposing novel design concepts for lunar and Martian.

Unfortunately, most of such concepts are built on two assumptions, 1) availability of in-situ construction-ready materials, 2) the behavior of such materials is well-known and has favorable performance under the extreme environment of space. While the first item has been examined to some degree, the second item warrants detailed investigation continues to hinder our ability to realize sustainable space exploration missions. These challenges if not appropriately addressed, could result in momentous risk, and delay of future manned exploration missions. This section points out, from a construction materials point of view, some of the knowledge gaps and research directions needed to overcome such limitations.

Characterization of Modern Construction Materials under Space Environments

As a result of recent advancement in material science, a number of new and/or improved materials are being inducted into the construction industry. Some of these materials include ultra-high-performance fiber-reinforced concrete (UHPFRC), high strength metals/alloys (HSM/A), as well as binders, advanced materials and composites [101-103]. Overall, there is good documentation on the behavior of such materials at ambient working (Earth-like) conditions and rightfully so as these materials have been primarily designed to satisfy requirements of traditional construction as in high-rise buildings and bridges [104, 105].

While it would be costly, and perhaps impractical, to transport concrete-like materials to the Moon and Mars, composites on the other hand, are known to have high strength-to-weight ratio, among other favorable properties, and may could be transported and utilized in specialized applications (i.e. connections). Thus, understanding the behavior of similar materials under simulated environments can establish benchmarking studies that may lead to the development of improved terrestrial, or even extraterrestrial, derivatives of modern construction materials. The current lack of knowledge on this front can be attributed to the limited availability of research facilities (such as Skylab, International Space Station etc.) able of simulating space environment conditions (i.e. micro-gravity). Other limitations may also include lack of testing equipment and instrumentation (e.g.: sensors), expertise, and trained personnel etc. required to design and carry out refined material characterization tests.

Terrestrial Simulants and Property Characterization of Space-native Construction Materials

Much of the lunar samples collected by Apollo and Luna missions are still available to this day. However, these samples were only collected from mare sites deemed safe for unmannaed and manned landings. While these samples have provided the scientific community with most of our current understanding on the Moon's geologic composition, together with its physical, and chemical aspects etc., these collected samples only present a limited glimpse into the lunar in-situ resources. As a result, there seem to be a deficient understanding of the behavior of space-native

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construction materials as well as on deriving fitting constitutive material models for integrating such materials into structural engineering of such infrastructure.

In order to avoid using NASA's lunar sample inventory in destructive testing, number of researchers developed lunar/Martian soil simulants (such as MLS-1, JSC-1 etc.). These simulants, although made of Earth-based materials, still possess similar composition and features to that of the collected samples [106]. Unfortunately, such terrestrial simulants are not formed under similar environmental exposures or loading conditions as that expected on the Moon and Mars. Thus, it can be inferred that it is necessary to carry out systematic research efforts that allow better understanding of properties as well as performance of space-native in-situ resources. In lieu of physical and chemical characterization, these efforts also need to prioritize properties associated with space-based structural engineering (i.e. load bearing application). The outcome of such research efforts may include material constitutive laws which could be vital to developing validated numerical models that can accurately capture behavior of space-native resources. This may evade the need to testing or obtaining physical samples and may reduce associated time and cost of designing and conducting expensive experimental tests.

Development Efforts for Sustainable Space Infrastructure

The design, development, and fabrication of Earth-independent and resilient lunar and Martian infrastructure is a challenging, but yet interesting, task. This challenge does not only arise from current technical limitations with regard to development of suitable (sustainable) construction materials, but also with aspects associated with key logistics such as building fabrication units to process lunar and Martian in-situ resources, mixing construction materials and casting structural members. Perhaps processing modules would be sent from Earth and assembled on the Moon or

Mars in early exploration stages. It is envisioned that such units will be highly autonomous and as such would consume large amount of energy to satisfy processing and production needs [107-110]. It is also expected that processing units would employ novel production techniques such as those activated by combustion, radiation and/or vacuum in order to allow feasible production of space-native construction materials to be feasible [12].

Development of space infrastructure also necessitates parallel efforts in neighboring arenas other than engineering and material science such as physics, medicine, economy, and politics. Most of all, realizing space infrastructure might require modern reconceptualization of the principles associated with sustainability with focal emphasis directed towards efficiently and economically utilizing in-situ resources as well as mitigating various space-based risk factors. A key aspect of sustainability, relating to the societal component, might be of a smaller scale than that required on Earth, but still need to be considered in developing space settlements. Details on such development efforts are not covered herein for brevity but can be found elsewhere [111, 112].

SUMMARY AND CONCLUSIONS

This review shows that in order to achieve and maintain successful space exploration programs, sustainable and resilient Earth-independent infrastructure are to be fabricated of indigenous "space-native" materials. Specific outcomes of this review can also be summarized as follows:

- The extreme environment of space presents a unique challenge to development of extraterrestrial constructions.

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- The abundance of high amounts of SiO_2 in in-situ resources eludes to the possibility of producing cementitious terrestrial-like materials attractive and possible.
- Utilizing lunar and Martian resources would eventually lead to sustainable infrastructure that can be fabricated with minimum, if not completely free-off, Earth-based raw construction materials.
- Serious efforts are to be made to overcome challenges hindering space exploration, especially those associated with developing and processing construction materials, and structural design etc.

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VITAE

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