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Review article

A comprehensive review of extraterrestrial construction, from space concrete materials to habitat structures

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ABSTRACT

This review explores the development and potential applications of space concrete, a critical material for future extraterrestrial construction. Space concrete, adapted to withstand the harsh conditions of outer space, such as extreme temperatures, vacuum, microgravity, and radiation, offers a sustainable solution for building habitats and infrastructure on celestial bodies like the Moon and Mars. Emphasizing the innovative approaches in formulating space concrete, including the use of lunar and Martian soil as aggregates and the exploration of alternative binders to traditional water-based cement, this review highlights the significance of in-situ resource utilization (ISRU) and 3D printing technologies in advancing extraterrestrial construction. Additionally, the current designs and applications of space concrete structures are discussed. By providing a detailed analysis of the challenges faced in space construction and the latest advancements in material and structural research, the review underlines the pivotal role of space concrete in supporting space exploration and long-term habitat.

1. Introduction

In recent years, enthusiasm for space exploration has significantly increased, leading to advancements in space technology by various countries. The NASA Artemis program marks steps towards establishing long-term habitats on the Moon and Mars [1]. Developing extraterrestrial resources addresses the scarcity of resources on Earth and supports future space colonization and interstellar travel. Increasingly, scholars are beginning to research space technologies and materials to prepare for the establishment of long-term space habitats. Building safe and reliable extraterrestrial infrastructure is a critical challenge. Traditional Earth-based materials may not satisfy space environment requirements, necessitating the development of innovative materials. Recent advancements include thermosetting materials, regolith melting/forming, laser sintering, microwave sintering, and space concrete [2,3].

Thermosetting materials are polymers that form irreversible bonds when heated, offering excellent mechanical properties and heat resistance. Regolith melting and forming involve reshaping lunar or Martian soil at high temperatures, directly utilizing in-situ resources to create strong and durable structures. Laser sintering and microwave sintering technologies employ focused laser beams and microwave radiation, respectively, to fuse regolith particles into dense, robust structures, enabling the construction of complex and resilient infrastructures on the lunar or Martian surface [4,5].

Space concrete offers several distinct advantages as compared to other materials such as thermosetting polymers, regolith melting, and sintering technologies. Unlike thermosetting polymers, which require complex manufacturing processes and robust equipment for curing in microgravity, space concrete does not need high temperatures or immense energy, rendering it more practical for space environments. In contrast with regolith melting, which demands high energy and durable equipment to reshape lunar or Martian soil, space concrete is more energy-efficient and easier to produce, utilizing available resources with minimal additional infrastructure. As compared to laser and microwave sintering technologies, which require precise energy control and complex equipment maintenance, space concrete uses straightforward mixing and setting processes, reducing the technological and operational complexities. Moreover, the high compressive strength and durability of space concrete render it ideal for constructing robust and reliable infrastructure on the Moon or Mars, capable of withstanding the harsh space conditions. These benefits of simplicity, efficiency, and structural integrity make space concrete a highly promising material for extraterrestrial construction [6].

The progress in space concrete technology is crucial to human endeavours in space exploration and extraterrestrial construction, marking a significant turning point in adapting to and utilizing space

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environments. As human activities explore beyond Earth, especially in exploring celestial bodies and establishing habitation modules and scientific research facilities, the development of robust and durable architectural infrastructures becomes increasingly important. Space concrete faces unique challenges and opportunities [7,8]. Unlike Earth-based construction, it must be engineered to resist the harsh conditions of extraterrestrial environments. Addressing these challenges is crucial for the successful deployment of space concrete, paving the way for the sustainable architecture and habitation [9,10]. Fig. 1(a) exhibits size and surface gravity comparison between Earth, Mars, and the Moon. Mars is about half the size of Earth with gravity approximately one-third that of Earth, while the Moon is about one-fourth the size of Earth with gravity roughly one-sixth. Lower gravity on Mars and the Moon is a primary factor influencing the development of space concrete, as it significantly alters the mixing and curing processes and the final physical properties of materials. Fig. 1(b) depicts the orbital paths of Earth and Mars around the Sun. Mars has a more elliptical orbit. Earth completes its orbit in about 365 days, while Mars takes 687 Earth days. The elongated orbit of Mars results in longer seasons and a broader range of temperature fluctuations as compared to Earth.

The scarcity of water and conventional aggregates necessitates the consideration of a new type of concrete for constructing space structures. This material diverges from traditional concrete by relying on local materials such as lunar regolith or Martian soil. Embracing ISRU aims to reduce dependency on Earth resources. This approach helps mitigate the significant costs and complexities of space transportation. It also represents a critical step towards sustainable space exploration and the potential for future colonization [12–14].

The current research has focused on enhancing the mechanical strength, durability, and radiation shielding capabilities of space concrete. This endeavour is dedicated to developing sustainable construction structures that can withstand the harsh environment of outer space, ensuring long-term viability and safety for residents. To achieve these objectives, researchers are engaged in pioneering studies to optimize the curing process of concrete through chemical additives in a zero-gravity environment. Simultaneously, they are working towards formulating mixtures capable of withstanding or repairing damage caused by extreme space conditions [15]. These studies play a pivotal role in constructing resilient space structures while guaranteeing the safety and sustainability of habitats and infrastructures in outer space.

As the interest in space research continues to grow, an increasing number of studies are focusing on space concrete. However, despite the wealth of literature available, there is a lack of a systematic and comprehensive review. This has led to fragmented research, making it difficult for researchers to fully understand the latest advancements and key challenges in this field. To address this gap, this study aims to provide a systematic review that comprehensively analyses the current state of research, technological advancements, and future directions in space concrete, covering all aspects from materials to structures. Specifically, the material properties, manufacturing processes, structural design, and concrete performance under harsh conditions are reviewed. It synthesizes advancements in space concrete technology, addressing environmental challenges, solutions, and implications for extraterrestrial construction, including various types of space concrete. Moreover, this review explores potential engineering structures on the Moon and Mars, highlighting space concrete as a key construction material.

2. Factors to consider in the preparation of space concrete

Research on lunar and Martian habitats addresses the formidable environmental challenges posed by temperature variations, vacuum conditions, radiation, seismic activity, and resource scarcity. These studies primarily focus on adapting construction material - space concrete and utilizing in-situ resources to ensure sustainability. Innovative approaches aimed at overcoming extraterrestrial construction challenges are highlighted, with an emphasis on the importance of tailored materials and techniques for space exploration.

2.1. Extreme temperature variations

According to information from NASA, the Moon undergoes extreme temperature fluctuations, largely due to its tenuous atmosphere and slow rotation. Equatorial regions can experience temperatures ranging from 121 °C during the day to −133 °C at night, with each lasting approximately two weeks due to the lunar day being about 29.5 Earth days [16]. The poles, with less severe fluctuations, have some areas where temperatures are consistently near −233 °C, harbouring potential ice deposits valuable for exploration and lunar base establishment.

Mars, while having less severe temperature extremes than the Moon due to its thin carbon dioxide atmosphere, still experiences significant diurnal shifts from about −125 °C to 20 °C. The seasons on the planet, resulting from a 25-degree axial tilt, lead to a variety of climate zones, each characterized by unique temperature patterns, as illustrated in Fig. 2 by Hargitai [17]. These variations in climate across the eight climate zones of Mars require tailored design approaches for concrete structures on Mars to ensure resilience and functionality under the specific conditions of each zone.

Extreme temperature fluctuations evidently affect the performance of space concrete, inducing thermal stress and potentially causing structural damage, particularly when different parts of the concrete experience varying rates of temperature change [18]. These significant temperature fluctuations affect cement hydration in concrete. High temperatures accelerate hydration, resulting in rapid strength gains but also causing uneven shrinkage and cracking. Conversely, low temperatures decelerate hydration, thereby extending the curing process. Frequent changes induce surface expansion and contraction, increasing fatigue damage and cracks. These fluctuations also cause uneven internal moisture and stress distribution, exacerbating cracks and reducing durability. Rapid temperature changes can significantly deteriorate concrete through three primary mechanisms: freeze-thaw cycling, differential thermal expansion, and alkali-silica reaction (ASR). Freeze-thaw cycles cause internal stresses due to water expansion within

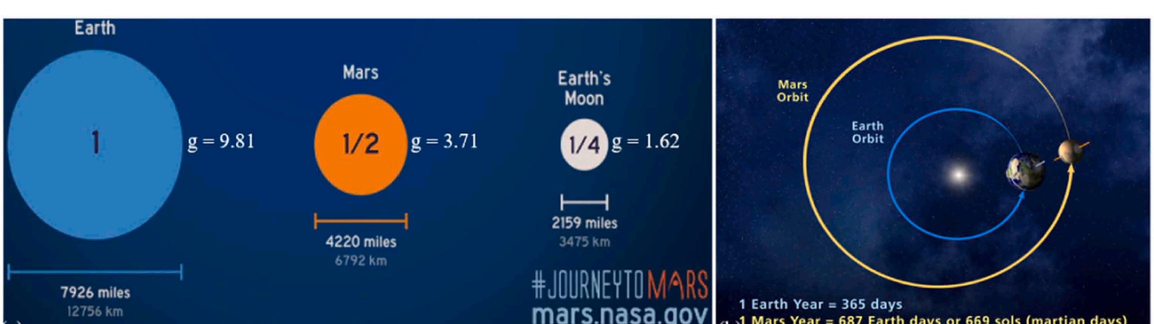

Fig. 1. (a) Comparison of Mars and the Moon with Earth and (b) orbital trajectories of Earth and Mars around the Sun [11].

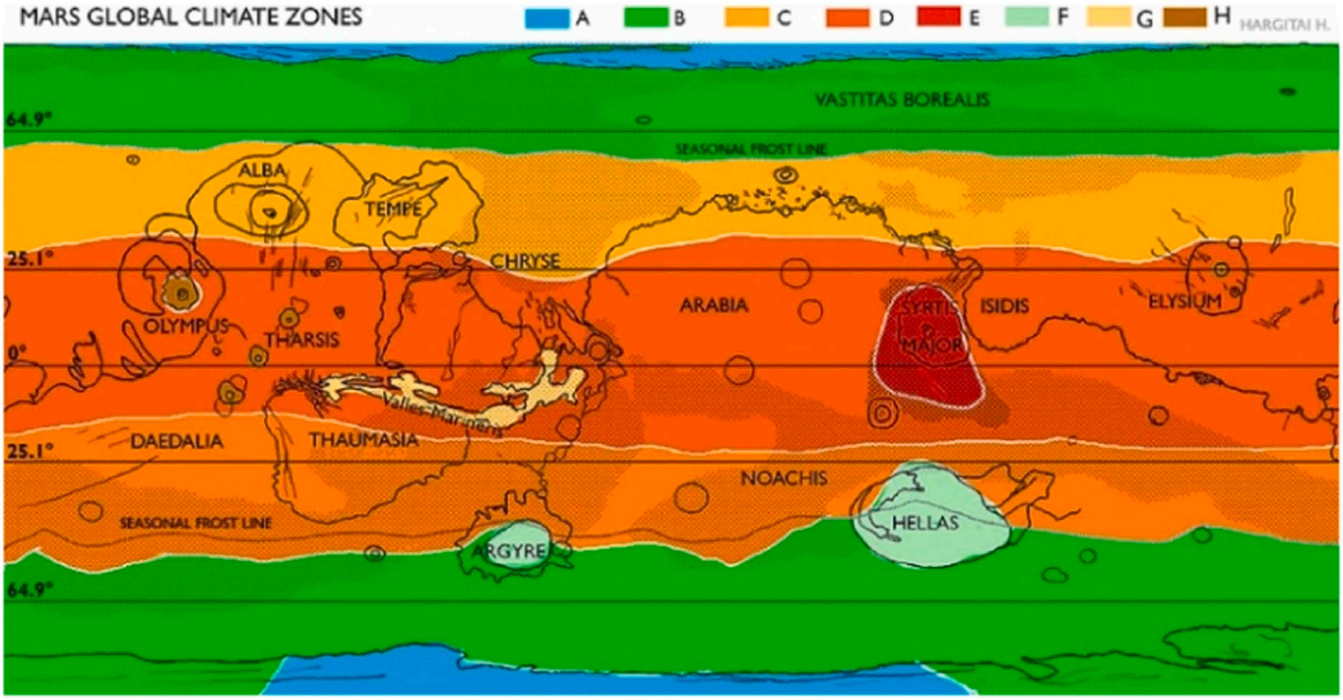

Fig. 2. Mars climate zones distribution. A: Glacial; B: Polar; C: Transitional; D: Tropical; E: Low albedo tropical; F: Subpolar Lowland; G: Tropical Lowland; H: Subtropical Highland [17].

the concrete pores, leading to micro-cracking. Differential thermal expansion occurs because aggregates and cement paste expand and contract at different rates, creating internal stresses and surface cracking. ASR involves reactive silica in aggregates reacting with alkali hydroxides in cement, forming an expansive gel that induces cracking [19]. Fig. 3(a) shows concrete after undergoing one hundred cycles of freeze-thaw temperature changes, with cracks visible at the microscopic level and Fig. 3(b) illustrates a significant reduction in compressive and splitting tensile strengths of concrete under rapid temperature changes and after multiple freeze-thaw cycles. It was evident that after the rapid cooling to −196 °C and undergoing only three freeze-thaw cycles, the compressive and splitting strengths were reduced to merely 30% and 18%, respectively. With gradual cooling and after 12 freeze-thaw cycles, the compressive and splitting strengths retained only 50% and 38% of their original values.

Numerous scholars have explored the impact of extreme temperature variations on the lunar and Martian surfaces from a thermodynamics perspective for space architecture site selection. Song et al. [22] studied the impact of different heat sources on lunar surface temperatures through a heat transfer model and suggested that polar regions were suitable for establishing lunar bases. Tripathi et al. [23] used numerical methods to analyse the temperature variations at different times and depths in the equatorial region of the Moon and provided key insights for the design of thermal shielding systems for lunar habitats. Schreiner et al. [24] developed models for different thermophysical properties of lunar regolith, based on Apollo mission samples and high-temperature molten regolith simulants, to assist in the analysis and design of lunar regolith processing hardware and geological simulations. Luo et al. [25] analysed the surface temperature of Mars in the Tianwen-1 landing zone and its spatio-temporal relationship with environmental factors, providing a theoretical foundation for understanding the Martian surface environment and its implications for Martian architecture.

2.2. Vacuum and microgravity

Under vacuum conditions, the rapid evaporation of water from traditional cement can lead to the formation of micro-cracks and voids, consequently diminishing the compressive strength of concrete. The study by Horiguchi et al. [26] demonstrated that using traditional wet-mix concrete in a vacuum causes quick water evaporation, which reduced strength and caused problems with volume stability. This highlights the necessity for alternative concrete formulations or curing

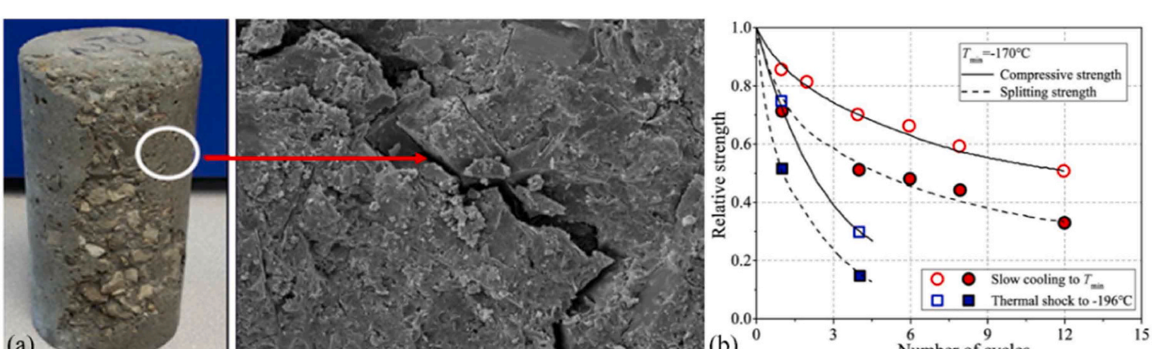

Fig. 3. (a) Concrete after 100 freeze-thaw cycles, with microscopic view showing formed cracks [20] and (b) strength alteration following freeze-thaw cycles [21].

methods. In response to this challenge, Wilhelm et al. [27] introduced the dry-mix/steam-injection (DMSI) method, which reduced water usage while maintaining compressive strength through the application of high temperature and steam pressure. They also noted the importance of controlling the cooling process during manufacturing to mitigate cracking, emphasizing the significance of temperature control [4]. Moreover, the study by Zuo et al. [28] revealed that sulfur concrete exhibits comparable curing strength in both vacuum and standard atmospheric environments. They also noted an increased porosity in sulfur concrete samples cured under vacuum conditions, as depicted in Fig. 4.

The significantly low gravity environments of Mars and the Moon, with gravitational forces only about 38% and 17% of Earth, respectively, play a crucial role in the curing and stability of concrete in space [30,31]. Meier et al. [32] focused on the crystallization of ettringite during the early hydration process of Portland cement and found that microgravity affects ettringite formation, resulting in differences in crystal size and aspect ratio. Lei et al. [33] investigated the crystallization of ettringite under both normal and zero gravity conditions, revealing that crystals formed in microgravity are typically smaller but more numerous due to the absence of convection and limitations on ion diffusion. Collins et al. [34] conducted a thorough study on concrete materials containing lunar regolith simulant JSC-1A and discovered that despite being prepared under different gravitational conditions, gravity did not significantly affect the in-situ mechanical properties of the concrete hydrated phases. However, Collins et al. [35] pointed out that the lower gravity conditions increase the air porosity in the concrete structure, suggesting that concrete structures in low-gravity environments be less compact, as illustrated in Fig. 5.

2.3. Radiation exposure and seismic activity

In space, astronauts face radiation exposure from solar particle radiation, galactic cosmic rays (GCRs), and solar wind, posing health risks [22,36]. Solar particle radiation comes from solar flares and coronal mass ejections. It sends out high-energy charged particles such as protons and electrons. These can go through spacecraft and protective gear, raising the risk of radiation sickness, cancer, and neurological damage. GCRs, high-energy particles from outside the solar system, can cause cellular damage, genetic mutations, and elevated cancer risk due to their penetrating power. The solar wind, a less energetic stream of charged particles from the Sun, also contributes to the cumulative radiation dose, potentially harming astronauts over long periods. These radiation sources are particularly concerning for deep space missions beyond Earth magnetic shielding. Concrete serves as an effective radiation shielding material in space structures, helping to mitigate the impact of these radiation types on astronauts [36,37]. The density and thickness of concrete are beneficial in absorbing the high-energy particles, thereby reducing the radiation dosage received by the astronauts. The effectiveness of concrete shielding holds particular relevance for habitats on lunar or Martian surfaces, where the lack of a protective atmosphere, such as that of Earth, elevates the importance of radiation protection.

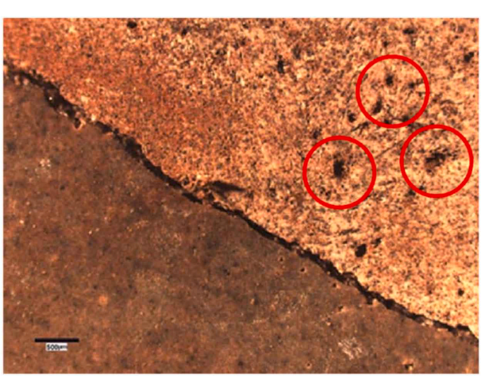

Fig. 4. Comparison of sulfur concrete cured under normal (left) and vacuum conditions (right) [29].

The research by Toda et al. [36] focused on the radiation shielding properties of geopolymer cement derived from simulated lunar rock sand. They synthesized high-strength geopolymer cement using alkali fusion with sodium hydroxide and assessed its gamma-ray shielding efficiency. The study utilized a setup with a Uraninite radiation source, a cement shield, and detectors at 5–20 cm distances to evaluate the shielding properties, as shown in Fig. 6(a). The research indicated that the geopolymer (GP) cement possessed a comparable radiation shielding capacity to Portland cement (PC), as demonstrated in Fig. 6(b), which compared radiation doses at different distances for GP cement, PC, and without shielding.

Montes et al. [38] created "Lunamer," a concrete made from lunar regolith that provides strong structure and radiation defence, possibly fitted for building on the Moon. In parallel, Toutanji et al. [39,40] addressed the efficacy of sulfur concrete in space radiation shielding, noting its need for increased thickness as compared to JSC-1 simulant, while highlighting the advantageous shielding properties conferred by carbon and hydrogen content. Ulubeyli [41] further examined shielding strategies, including the use of lunar soil, and determined that significant layers of such soil, or precise amounts of geopolymer and sulfur concrete, could effectively shield against solar and cosmic radiation. Specifically, effective protection was achieved with 2.5 m of lunar soil, 50 cm of geopolymer concrete, or 7 cm of sulfur concrete.

When designing space structures on the Moon and Mars, it is crucial to consider the unique, relatively weak seismic activities of these celestial bodies. Moonquakes, as observed during the Apollo missions, mainly consist of deep quakes caused by the cooling and contracting of the interior of the Moon [42,43]. Since NASA InSight lander arrived on Mars in 2018, it has recorded Marsquakes primarily of light to moderate intensity, reflecting the geological activity owing to internal stress changes and the fracturing of rock layers, as illustrated in Fig. 7. These seismic events underscore the importance of meticulous engineering in space structures on the Moon and Mars, taking their distinct seismic characteristics into account to ensure durability and safety in the extreme conditions of space. Consequently, engineers must innovate in the materials selection, structural design, and construction techniques to meet the challenges posed by these environments.

Oberst et al. [43] quantified the seismic threat to lunar operations, estimating a shallow Moonquake with a magnitude above 4.5 within 100 km of a lunar base occurred about once every 400 years. Ruiz et al. [45] depicted the magnitude probability distribution of the shallow Moonquakes in Fig. 8(a), using a bar chart with varying *b* values that convey the frequency of different-sized seismic events on the Moon. Patiño et al. [46] highlighted that the lunar habitats made with sulfur concrete might face structural failure from seismic disturbances despite withstanding gravity and pressure loads. The work by Mottaghi et al. [47], shown in Fig. 8(b), presented a lunar habitat with a magnesium frame and sandbag shielding. This design was made to be stable and resist seismic activity on the Moon.

The investigation by Soureshjani et al. [48] into Martian-compatible structures using anhydrous sulfur-based concrete revealed that their designs could withstand the Martian seismic loads, enhancing the cost-effectiveness of Mars colonization by leveraging the local materials. Soureshjani et al. [49,50] further analysed the Marsquake origins, depths, and frequencies, finding that the Martian seismic activity, primarily stemming from the mantle, posed limited threat to Martian structural design due to its lower intensity as compared to Earth seismic activity.

2.4. Limited resource

In the field of space exploration, the limited availability of resources poses a significant challenge for the construction of habitats and structures. Traditional building materials and methods commonly used on

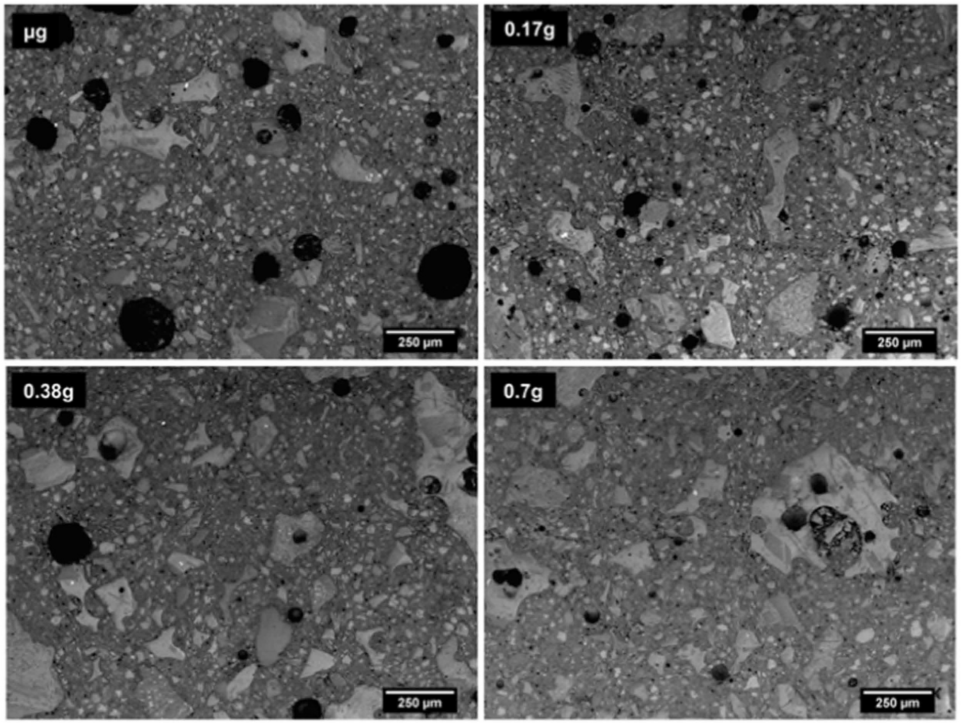

Fig. 5. Microstructure of concrete cured under different gravitational conditions [35].

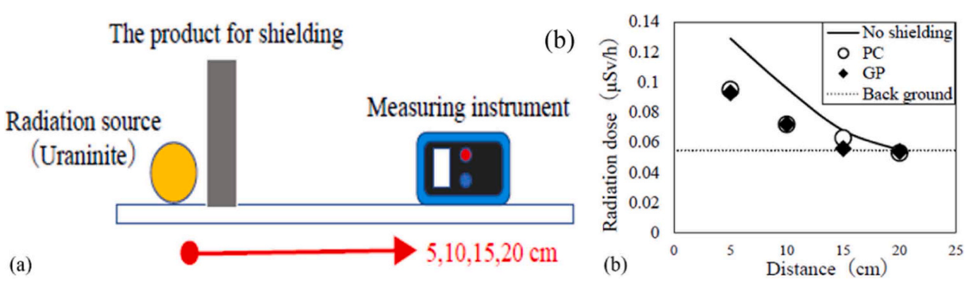

Fig. 6. (a) Radiation shielding measurement method and (b) radiation dose of the GP and PC [36].

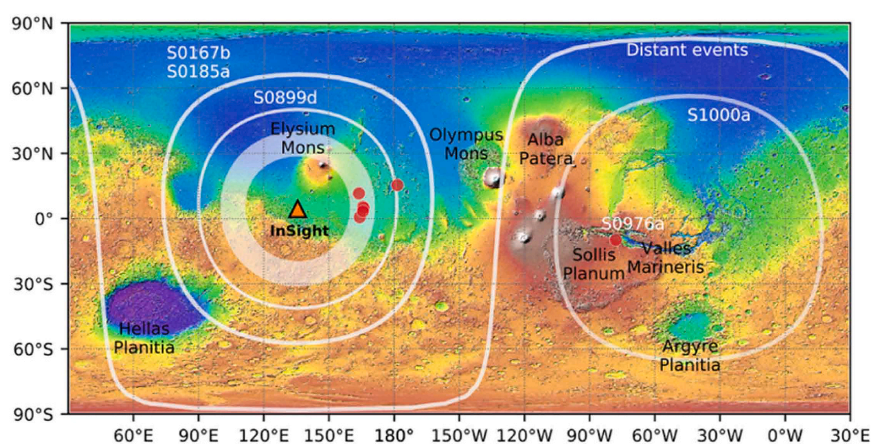

Fig. 7. The seismic regions detected by the InSight lander on Mars [44].

Earth become impractical due to the high cost and logistical complexity of transporting materials to space [51,52]. Therefore, it is crucial to maximize the use of local resources in space environments.

The soil on the Moon and Mars, namely lunar regolith and Martian soil, is one of the most abundant resources in space environments [53–55]. These resources can serve as the foundation for building materials, reducing dependence on Earth-based resources. In the development of space concrete, researchers are attempting to use these soils as

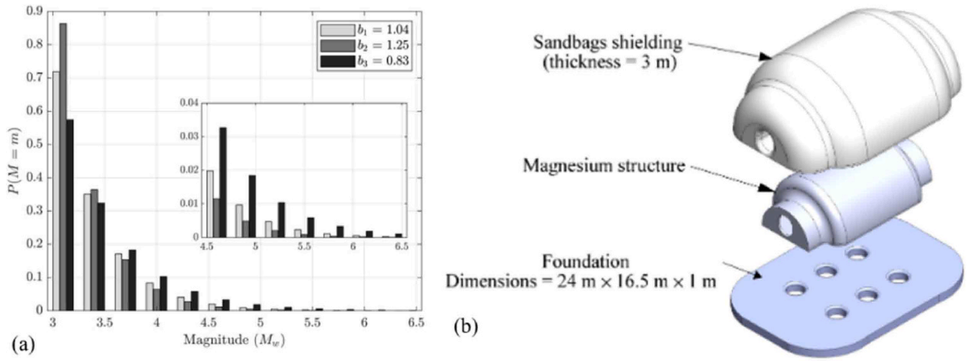

Fig. 8. (a) Statistical occurrence rates of shallow lunar seismic events [45] and (b) design schematic of a seismically resilient lunar habitat [47].

the main component, combined with special binders adapted to space environments, to create building materials suitable for extraterrestrial conditions. Consequently, scientists have created simulants of lunar and Martian soil based on lunar regolith and Martian soil prototypes. Fig. 9 displays four common distinct soil simulants commonly used to replicate extraterrestrial conditions, in which (a) and (b) are lunar regolith simulants and (c) and (d) are Martian soil simulants.

In space construction, the use of lunar and Martian soil via ISRU is crucial for the sustainability of space exploration [53,59]. ISRU diminishes reliance on Earth-based materials, reducing logistical and economic burdens of material transport, and supports the prospect of permanent human settlement. The utilization of in-situ materials offers cost and energy savings, simplifies mission logistics, promotes environmental sustainability, and provides research opportunities by leveraging the distinct properties of space resources [54,60]. Such a strategy is essential for achieving self-sufficiency in space missions and for advancing construction technologies suited to the challenging conditions of space. Sander et al. [61] outlined the comprehensive process of ISRU for space construction, focusing on the steps from the resource extraction to the habitat establishment. It highlighted the crucial areas such as material processing, modular construction technique, site planning, and infrastructure maintenance essential for building in extraterrestrial environments. This framework underscored the integration of local resources and advanced manufacturing in developing sustainable off-world structures, as detailed in Fig. 10.

Space concrete can utilize lunar and Martian soils as aggregate or extract necessary elements directly from these soils. However, like its terrestrial counterpart, the majority of concrete formulations require water - an element markedly scarce in space. Section 3 will offer a detailed introduction to lunar and Martian soil simulants that are crucial for developing concrete in extraterrestrial environments. These simulants replicate the unique properties of actual lunar and Martian soils, which are fundamental for constructing space habitats. On this basis, the discussion will naturally progress to the vital topic of water resources. The role of water in the hydration process is pivotal for the structural integrity of traditional concrete. The scarcity of water on the Moon and Mars presents major challenges, leading to the exploration of alternative hydration methods and the adaptation of concrete mixtures for these dry space environments. Addressing these challenges becomes a crucial part of ongoing exploration efforts [62].

Fig. 9. Lunar regolith and Martian soil simulants: (a) BP-1 lunar simulant [56], (b) JSC-1A lunar simulant [57], (c) MGS-1 Mars global simulant [58], and (d) MGS-1C Mars global simulant enriched with smectite [58].

Fig. 10. ISRU strategies for space construction [61].

The investigations conducted by Carr [63], Nazari-Sharabian et al. [64], and Abbud-Madrid et al. [65] converged on the pivotal role of Martian water resources, outlining the evolution of Mars from an once water-abundant planet to one where water now predominantly existed in the form of ice and within water-rich minerals. Carr [63] provided insights into the historical abundance of Martian water that evolved into current forms of the ice, atmospheric vapor, and brines. Nazari-Sharabian et al. [64] found that the Martian ice was widely distributed and deeply intertwined with the planet geological and mineralogical fabric, highlighting the intricate nature of Martian water resources. These observations were corroborated by the visual data in Fig. 11(a), which indicated the extensive distribution of hydrated minerals on Mars, with the green markers significant coverage across the Martian surface. Moreover, Abbud-Madrid et al. [65] inquired into the utilization aspects, emphasizing the challenges and the significance of these resources in supporting human activities on Mars. They framed the extraction/transformation of Martian water resources as a critical yet formidable task, given the planet harsh conditions. Fig. 11(b) provides an evidence of Mars' historical presence of liquid water. Parallel discussions on lunar water resources by Kleinhenz et al. [66] emphasized the analogous environmental challenges faced in extracting the lunar water, particularly from the permanently shadowed and cold traps at the lunar poles. This research accentuated the feasibility of utilizing lunar ice for critical applications like fuel production, underlining the essentiality of ISRU strategies for the sustainable lunar and Martian exploration.

3. Types of space concrete

The development of space concrete for extraterrestrial constructions marks a key innovation in materials science and space exploration. Designed to endure the space extreme conditions, such as severe temperatures, radiation, and vacuum or reduced gravity, researchers are exploring various formulations. These include using lunar or Martian regolith as aggregate, developing alternative binders to water, and creating concrete that can be processed or cured with space-available

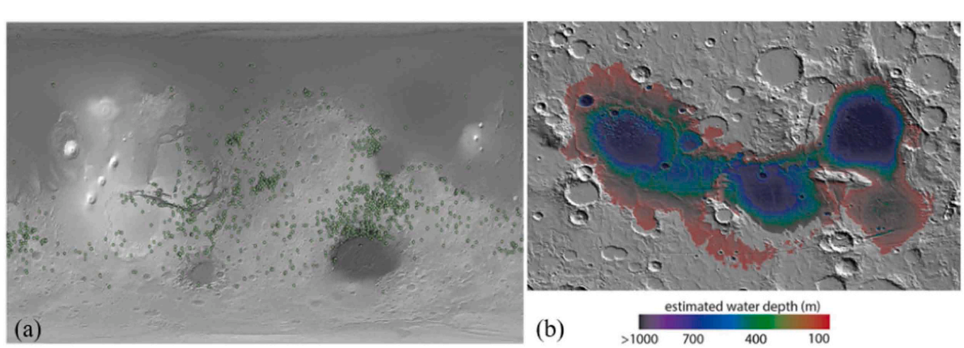

Fig. 11. (a) Hydrated minerals on Mars [67] and (b) evidence of water on Mars (Eridania Sea) [68].

resources [69,70].

3.1. Lunar and Martian regolith simulants

Lunar and Martian regolith simulants are crucial for developing space concrete, as they replicate the soil properties of the Moon and Mars, enabling the testing and optimization of concrete formulations on the Earth for use in outer space [71–73]. These simulants are key for evaluating concrete performance under extreme space conditions and improving its adaptability and durability. They also aid in research ISRU technologies, which leverage local celestial resources to reduce the logistical costs of space exploration. Furthermore, simulants are instrumental in validating construction technologies, such as 3D printing, for building on lunar and Martian bases, ensuring their effectiveness in space environments.

The Moon features maria - iron and titanium-rich basalt plains, and ancient highlands - rich in anorthosite and feldspar [74]. Apollo missions led to the development of lunar soil simulants that mirror the Moon geology, aiding lunar research and construction. These simulants are crucial for lunar exploration and are divided into mare and highlands types [75]. Mare simulants match the chemical and mineral content of the lunar maria, incorporating basalt and olivine, while highlands simulants reflect the mineral composition of the highlands, mainly anorthosite. Tables 1 and 2 respectively display the chemical composition of lunar soil samples, showcasing the varied makeup of Moon soil, and the specifications and nomenclature of common lunar regolith simulants.

Studies conducted by NASA Mars rovers, notably Curiosity and Opportunity, have elucidated that the Martian regolith is primarily comprised of SiO_2, FeO, MgO, CaO, Al_2O_3, along with the presence of sulfides and chlorides. This compositional heterogeneity across different Martian locales signifies the planet intricate geological and environmental evolution. In an effort to accurately simulate these extraterrestrial conditions, Martian soil simulants are synthesized utilizing terrestrial materials that closely replicate the chemical and physical attributes of Martian regolith. Tables 3 and 4 respectively show the chemical composition from a specific Martian region and detail common Martian soil simulants.

3.2. Ordinary Portland concrete (OPC)

Traditional Portland cement concrete, combining cement, aggregates (fine like sand and coarse like gravel), and water, is crucial for the construction on Earth. However, as space exploration advances, the feasibility of using Portland cement for outer space bases is challenged by space harsh conditions, including microgravity, limited resources, high radiation, and extreme temperatures, necessitating alternative building strategies for off-world construction.

Table 2
Common lunar regolith simulants.

Category	Simulant name	Source from	Type	Reference
Lunar mare simulants	MLS−1	Minnesota, USA	High-Ilmenite (TiO_2 and FeO)	Weiblen et al.[77]
	MLS−1 P	Minnesota, USA	High TiO_2	Weiblen et al.[77]
	ALS	Arizona, USA	Low TiO_2	Desai et al. [78]
	JSC−1/1A/1AF/1AC/2A	Johnson Space Centre, USA	Low TiO_2	McKay et al. [79]
	FJS−1 (type 1)/(type 2)	Fuji, Japan	Low TiO_2	Kanamori et al.[80,81]
	FJS−1 (type 3)	Fuji, Japan	High TiO_2	Kanamori et al.[80,81]
	CAS−1	Chinese Academy of Sciences, China	Low TiO_2	Zheng et al. [82]
	CLRS−1	Chinese Academy of Sciences, China	Low TiO_2	Zhao et al. [83]
	CLRS−2	Chinese Academy of Sciences, China	High TiO_2	Zhao et al. [83]
	CUG−1	China University of Geosciences, China	Low TiO_2	He et al.[84]
	TJ−1/2	Tongji University, China	Low TiO_2	Jiang et al. [85]
	GCA−1	Goddard Space Centre, USA	Low TiO_2	Taylor et al. [53]
	Oshima	Japan	High TiO_2	Sueyoshi et al.[86]
	BP−1	USA	Low TiO_2	Rahmatian et al.[87]
Lunar highlands simulants	MLS−2	Minnesota, USA	High SiO_2, Low TiO_2	Tucker et al. [88]
	OB−1	Canada	-	Richard et al. [89]
	NU-LHT−1 M/2 M/3 M/1D/2 C	NASA/USGS, USA	-	Stoeser et al. [90]
	NAO−1	China	-	Li et al.[91]
	LHS−1	USA	-	Cannon et al. [55]

Transporting Portland cement to space for construction is considered impractical because of the high costs of space transport. Even though costs have decreased from $19,000 to $3,000 per kilogram, they are still too high for the large amounts needed for space bases. Investigating the

Table 1
Chemical compositions in lunar soil samples collected by the Apollo missions [76].

Chemical oxides (wt%)	Apollo 11 (Mare)	Apollo 12 (Mare)	Apollo 14 (Highlands)	Apollo 15 (Highlands)	Apollo 16 (Interface Area)	Apollo 17 (Interface Area)
SiO_2	42.15	46.30	48.10	46.95	45.26	40.95
TiO_2	7.80	3.20	1.70	1.60	0.66	7.61
Al_2O_3	13.65	13.35	17.40	12.70	25.48	12.78
Cr_2O_3	0.30	0.38	-	0.47	0.25	0.46
Fe_2O_3	-	-	-	-	-	-
FeO	15.55	16.30	10.40	16.29	6.58	15.76
MnO	0.20	0.22	0.14	0.22	0.34	0.21
MgO	7.85	9.70	9.40	10.75	6.19	9.99
CaO	11.95	10.65	10.70	10.49	15.17	11.03
Na_2O	0.49	0.46	0.70	0.33	0.45	0.32
K_2O	0.13	0.24	0.55	0.09	0.13	0.08
P_2O_5	0.08	-	0.51	0.16	0.11	0.06
S	-	-	-	0.07	0.07	0.12
LOI	0.12	-	-	-	0.07	-

Notes: “LOI” denotes loss of ignition, and “-” denotes absence of the substance detected.

Table 3
Chemical compositions of Martian soil.

Chemical compositions (Weight %)	Global soil	Mars average soil[92]	Rocknest [93]	Gobabeb [94]
SiO_2	45.90	46.52	41.18	47.88
TiO_2	1.24	0.87	1.14	0.88
Al_2O_3	12.88	10.46	8.98	9.78
FeO	11.68	16.38	19.30	17.91
MnO	0.15	0.33	0.39	0.37
MgO	8.28	8.93	8.33	7.57
CaO	8.46	6.27	6.96	7.30
Na_2O	2.34	3.02	2.59	2.75
K_2O	0.64	0.41	0.47	0.49
P_2O_5	0.18	0.83	0.90	0.79
Cl	0.002	0.61	0.44	0.50
SO_3	7.4	4.90	5.24	3.36

Table 4
Common Martian soil simulants.

Simulant name	Source from	Reference
JSC Mars−1/1A	Johnson Space Centre, USA	Allen et al.[95]
MMS/MMS−1/2	USA	Peters et al.[96]
SSC−1/2	Surrey Space Centre, UK	Scott et al.[97]
ES−1/2/3/4	UK	Brunskill et al.[98]
JMSS−1	China	Zeng et al.[99]
UC Mars1	New Zealand	Scott et al.[100]
Neu Mars1	China	Guan et al.[101]
OUCM/EB/HR/SR−1/2	UK	Ramkissoon et al.[102]
JSC-RN	Johnson Space Centre, USA	Clark et al.[103]
MGS−1/1 C/1S	USA	Cannon et al.[58]

availability of Portland cement raw materials on extraterrestrial bodies, research has shown that lunar and Martian soils are rich in silicon, aluminium, and iron, but lack calcium carbonate, essential for Portland cement [104,105]. Lunar soil contains calcium in forms like anorthite, rather than the limestone found on Earth. Moreover, producing Portland cement requires high energy, with temperatures around 1400 °C, posing additional challenges on the Moon due to the lack of traditional energy sources and calcination equipment [106]. This necessitates exploring alternative methods and materials for constructing space infrastructure.

Martian soil and rocks contain silicon, iron, and other minerals beneficial for cement production [107,108]. Carbonate minerals have also been discovered on the Mars, indicating possible sources of calcium carbonates. Like the Moon, Mars may have some essential components for cement production, but their forms, distribution, and availability are different from those on Earth. Neves et al. [109] suggested that although transporting OPC to space is costly, scientists could carry a small amount to construct some bases or equipment, serving as a preliminary step towards utilizing local resources.

However, in space environments like the Moon and Mars, obtaining water poses a significant challenge. The lunar surface lacks liquid water, but there might be water resources in the form of ice [66]. Evidence of water on Mars includes ice and potential liquid water, both primarily in ice form. Extracting large quantities of water in outer space is a daunting task. Additionally, transporting substantial amounts of water to space faces preservation issues. For example, in the Moon low-gravity environment, water swiftly evaporates and is decomposed into hydrogen and oxygen by solar radiation, with extreme temperature variations further influencing its state. The situation on Mars is the same, with liquid water rapidly evaporating due to the low atmospheric pressure, hence the presence of ice near the poles of both celestial bodies [62,64].

Lin et al. [106] and Neves et al. [109] explored the viability of traditional Portland cement in extraterrestrial environments, focusing on natural material availability and the unique casting and curing conditions on the Moon and Mars. Their research highlighted the challenges posed by vacuum or low gravity, with studies on tricalcium silicate (C3S) paste revealing that the microgravity significantly influenced the cement curing and microstructural development. Microgravity was found to cause more uniform phase distribution, increased porosity and pore size, and altered calcium hydroxide (CH) crystal shapes and sizes in C3S paste. Adjusting the cement-to-water ratio and adding superplasticizers can help overcome some of the challenges posed by microgravity. These modifications can enhance strength but also require optimization to avoid issues like air bubble formation and cracks, which Collins et al. [34,35] noted could harm the cement performance and durability. This highlights the need for specialized cement formulations and curing methods for space construction to maintain structural integrity and longevity.

Under the reduced gravity condition, cement paste suffers increased cracking and air bubble accumulation (Fig. 12), negatively impacting its performance and durability. Collins et al. [34] highlighted that such conditions lead to changes in pore structure and consolidation, adversely affecting the cement mechanical performance and durability owing to the decreased compactness. Experiments conducted by Shangguan et al. [110,111] further revealed that while compressive strength of concrete may increase under low vacuum conditions, flexural and shear strength tend to decrease. This discrepancy was attributed to a more pronounced drying effect in low vacuum environments, causing shrinkage and more microcracks, particularly in the concrete interfacial transition zone.

3.3. Calcium aluminate concrete

Calcium aluminate concrete, made from cement calcined from limestone and bauxite at high temperatures (1700 °C), requires less water for preparation as compared to traditional Portland cement concrete due to its higher aluminate content. This type of concrete hardens rapidly at lower water levels, aiding in faster construction and denser concrete. However, careful water management is crucial to obtain desired mechanical properties, highlighting the importance of adjusting water levels based on the unique hydration needs of calcium aluminate cement.

Calcium aluminate concrete, known for its swift hardening, elevated initial strength, chemical resilience, and durability, is deemed especially apt for space settings due to its capacity to endure severe temperature variations. Khaliq et al. [112] conducted a study on the material properties of calcium aluminate concrete at various high temperatures, ranging from 23 °C to 800 °C. They found that calcium aluminate concrete exhibited improved mechanical behaviour at high temperatures, including enhanced compressive strength and crack resistance, in contrast with traditional OPC concrete. Heikal et al. [113] pointed out that calcium aluminate cement also possessed good corrosion resistance. In corrosive media of 5% sodium chloride, 5% magnesium sulfate, and 5% ammonium sulfate, the compressive strength of calcium aluminate cement increased after 90 days of curing while slightly decreased after 120 days.

Calcium aluminate concrete, prepared on Earth through wet-mixing methods suitable for on-site pouring but water-intensive, faces challenges in space due to water scarcity. Wet-mixing involves combining all components, including a substantial water volume, to form a pourable mix. Lin [114] introduced the dry-mix/steam-injection (DMSI) method as a more feasible alternative for space applications, minimizing water usage. This method involved dry-mixing cement and aggregates, followed by hydration under high temperature and pressure using steam, to promote rapid cement hardening. The DMSI method significantly reduced the demand for water and cement, halved the cement requirement, and doubled the compressive strength as compared to traditional methods. By using pressurized steam, this method accelerated the hydration process, decreased porosity, and increased strength. Research by Lin et al. [115] confirmed the effectiveness of DMSI across various cementitious formulations, demonstrating its ability to produce high-strength concrete while minimizing material consumption. Fig. 13 shows the efficacy of the DMSI method from a microscopic perspective

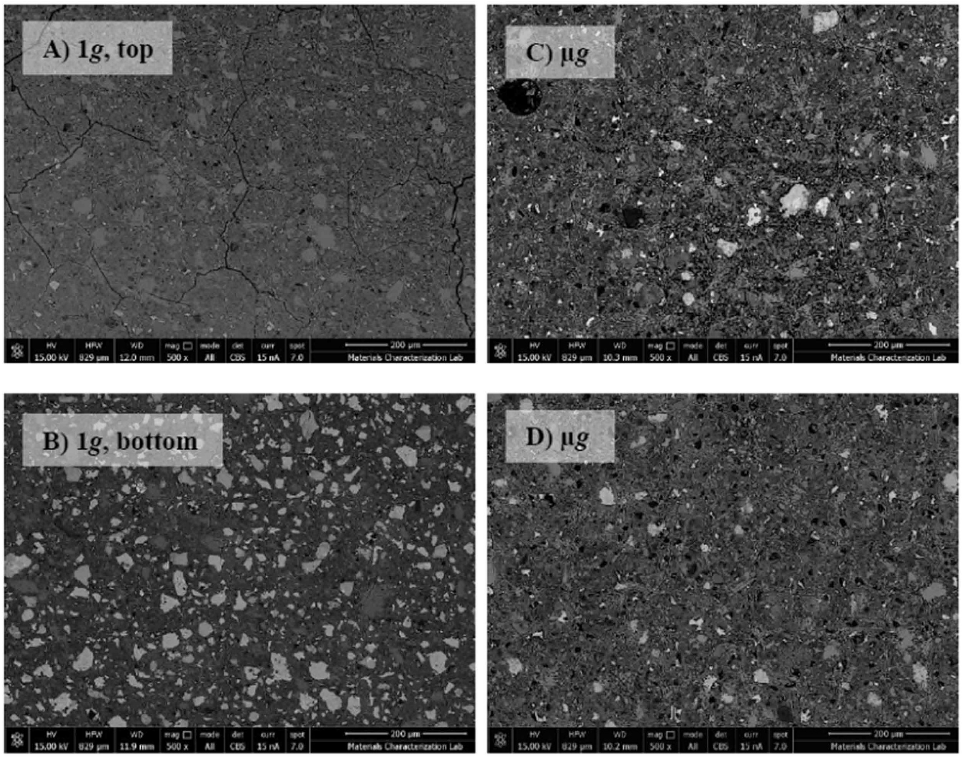

Fig. 12. Microscopic structures of Portland cement: (a-b) fewer microcracks and bubbles at 1 g and (c-d) increased microcracks and bubbles in microgravity [35].

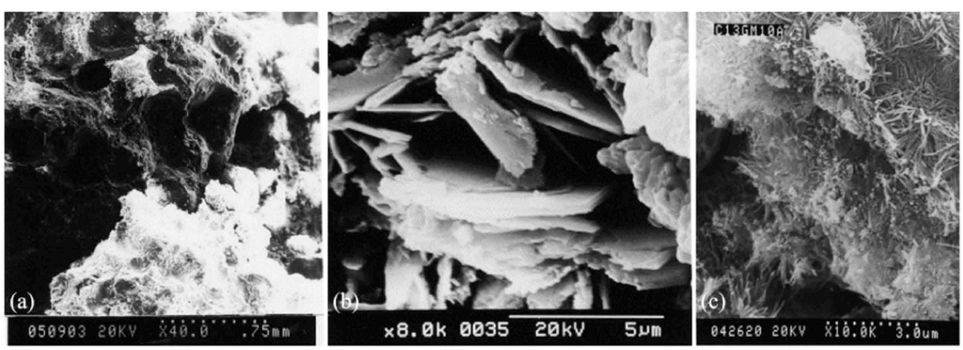

Fig. 13. Mortar microstructures: traditional methods result in (a) large pores and (b) unreacted calcium hydroxide, and (c) DMSI with minimal calcium hydroxide and abundant C-S-H gel [118].

compared to traditional wet-mix methods. Mortars (a) and (b), prepared traditionally, exhibit large pores and unreacted calcium hydroxide, respectively, while mortar (c), made with the DMSI method, exhibits less calcium hydroxide and more calcium silicate hydrate (C-S-H) gel, underscoring DMSI positive effect on mortar microstructure. Further studies by Lin et al. [116] emphasized the feasibility of DMSI for lunar infrastructural development and advocated for the utilization of solar energy in the concrete preparation on the lunar surface. Insights from O'Gallagher [117] complement findings by Lin, emphasizing the viability of using solar energy for concrete production on the Moon, where solar energy can achieve the high temperatures necessary for calcination.

The preparation of calcium aluminate concrete on the Moon or Mars can utilize local mineral resources. Lin [105] noted that anorthite, an aluminium-rich mineral found on the Moon, can serve as a raw material for calcium aluminate cement. Heating anorthite to high temperatures through calcination produced the cement, which can then be processed into concrete using the DMSI method. Similarly, the refinement of silicate minerals such as feldspar, pyroxene, and olivine found in Martian soil can facilitate the extraction of aluminium. High-energy processes involved in calcination and DMSI are anticipated to utilize solar energy for power.

3.4. Sulfur concrete

Sulfur concrete was emerged in the 20th century and has been recognized for its suitability in extraterrestrial settings like the Moon and Mars [119]. The significance of this material stems from its ability to be prepared without water, which is crucial in environments where water is scarce. Unlike conventional concrete, which hardens through a hydration process, material solidifies as sulfur crystallizes upon cooling [29,120]. Notably, sulfur concrete exhibits robust mechanical performance and can be further enhanced with fibres and additives [70]. Its unique composition and hardening mechanism render it an excellent choice for construction projects on extraterrestrial bodies.

Sulfur concrete, utilizing sulfur as a binding agent and lunar or Martian regolith as aggregate, presents a resource-efficient alternative to conventional concrete. The sulfur needed for this composite material is derived from the abundant sulfide and sulfate minerals found on the lunar and Martian surfaces. Barkatt et al. [121] noted the considerable sulfur deposits within crust and mantle of the Mars, characterized by a high presence of sulfates and sulfides, as visually represented in Fig. 14. This figure depicts sulfur distribution, with warmer colors denoting areas of higher concentration, particularly marked by red and yellow regions. The extraction methods suggested including chemical or electrochemical methods capable of oxidizing or decomposing sulfides, offering by-products beneficial for Martian expeditions. On the Moon, extracting sulfur requires heating sulfide minerals such as pyrite to about 1100 °C to release sulfur. This step was crucial for making sulfur concrete and supported the ISRU strategy needed for building and maintaining lunar infrastructure [122,123].

Aggregates are essential in sulfur concrete, often incorporating lunar or Martian soil simulants that mimic space soils. Lunar aggregates typically consist of basalt and glass microspheres, while Martian ones include silicate minerals and iron oxides. Combined with sulfur, these materials form durable and adaptable sulfur concrete for extraterrestrial use. Toutanji et al. [125,126] suggested using a mix ratio of 35% sulfur and 65% aggregate to achieve a high mechanical strength of 32 MPa, while the alternative method introduced by Grugel [29], utilizing a silica binder mixture of 25% sulfur, 20% silica, and 55% aggregate, exhibited potential for achieving compressive strengths ranging from 40 to 50 MPa. Toutanji et al. [40] found that incorporating a suitable amount of silica dioxide to sulfur concrete can effectively enhance its compressive strength. Fig. 15 presents a microscopic comparison of sulfur concrete: (a) with Martian soil showing smaller particles and dense packing owing to metal-sulfur reactions, and (b) with Earth sand, exhibiting larger voids and particle sizes. The interaction between Martian soil and sulfur leads to the creation of sulfates, which in turn, boosts the strength of the concrete.

In the context of enhancing sulfur concrete mechanical performance, fibre reinforcement is a pivotal strategy. Metal fibres are integrated to elevate compressive strength and ductility, while glass fibres, particularly those sourced from lunar soil, are used to augment the flexural-tensile strength. The application of glass fibres derived from the Moon, integrated longitudinally into the sulfur concrete matrix by Meyers et al. [70,88,128], evidently improved its mechanical strength and ductility, as illustrated in Fig. 16.

Sulfur concrete, while aligning with the principle of using local resources for space exploration, faces significant challenges in the vacuum and extreme temperature variations in space. In a vacuum, sulfur concrete may encounter volatility issues due to the ease of sulfur sublimation at low pressures, potentially reducing its structural strength and long-term durability. Grugel et al. [129] prepared sulfur concrete and found remarkable sublimation in vacuum conditions after 60 days, estimating a loss of about 1 cm in thickness every 4–6 years at room temperature. Fig. 17 displays the microstructural changes in sulfur concrete under vacuum over time. Initially, as shown in Fig. 17(a), the material is dense with few voids. After 8 days in vacuum, more porosity appeared due to sulfur sublimation, indicating the onset of material degradation as depicted in Fig. 17(b). By 58 days, Fig. 17(c) illustrates a heavily altered microstructure characterized by extensive porosity and cracks, aligning with findings by Grugel and Toutanji of significant sulfur loss, which can lead to a substantial reduction in material thickness over years.

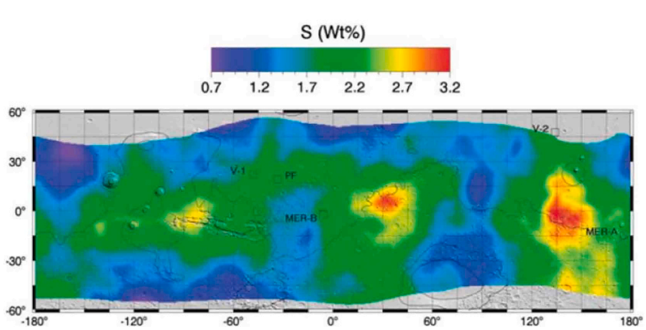

Fig. 14. Sulfur concentration map of Mars [124].

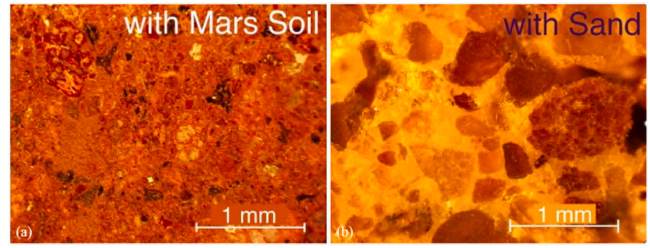

Fig. 15. Microstructural of sulfur concrete with (a) Martian soil and (b) regular sand [127].

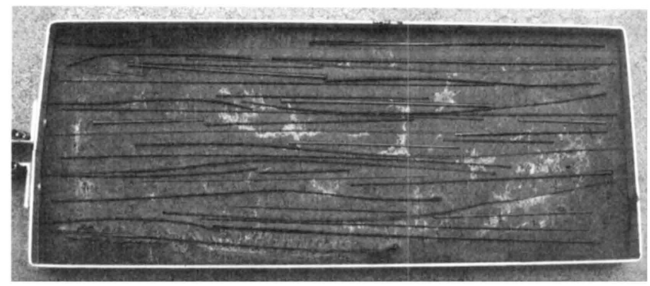
Fig. 16. Longitudinal glass fibre reinforcement in sulfur concrete [70].

Furthermore, extreme temperature variations pose another major challenge for sulfur concrete in space. Its performance may be significantly affected at very low or high temperatures. For example, at very low temperatures, it may become brittle and prone to cracking, while at high temperatures, sulfur may melt or soften, compromising the concrete structural stability. With a melting point of about 120 °C, similar to the Moon equatorial maximum temperature, sulfur concrete is impractical for use in these regions. Grugel [130] investigated the integrity of sulfur concrete under simulated lunar extreme temperatures, illustrating that samples subjected to temperature cycling exhibited at least five times lower strength than those not cycled. Fig. 18 contrasts the condition of sulfur concrete before and after exposure to extreme temperatures. Initially, as seen in Fig. 18(a), the concrete was smooth and crack-free post-casting. After 80 temperature cycles, as shown in Fig. 18 (b), it exhibited large and prominent cracks, evidencing the substantial structural impact from simulated lunar thermal extremes.

3.5. Sorel concrete

Sorel concrete, characterized by its composition of magnesium oxide (MgO) and magnesium chloride ($MgCl_2$), exhibits robust mechanical properties without necessitating hydration [131]. The formation of strong magnesium oxychloride occurs through the interaction of MgO powder with $MgCl_2$ solution, requiring water solely for achieving the desired consistency and affecting curing. Its advantages include corrosion resistance, rapid setting, thermal stability, and energy-efficient production, rendering it apt for Martian construction. However, its water requirement and vulnerability to water damage pose considerations for its extraterrestrial application [132].

Experiments conducted by Temiz et al. [133] demonstrated that Sorel concrete exhibited high strength, with compressive strengths of 54 MPa at 7 days and 73 MPa at 28 days, and flexural strengths of 8.5 MPa at 7 days and 11.5 MPa at 28 days. These values were 4–5 times higher than those of OPC. Lauermannova et al. [134] further advanced

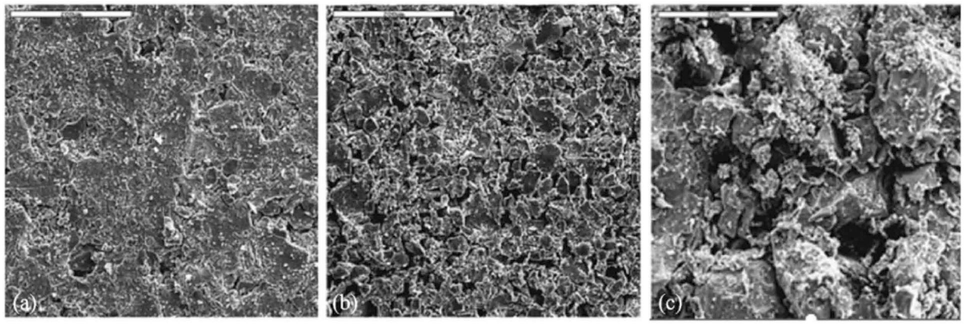

Fig. 17. Impact of vacuum exposure on sulfur concrete: (a) As-cast, (b) 8 days in vacuum, and (c) 58 days in vacuum [129].

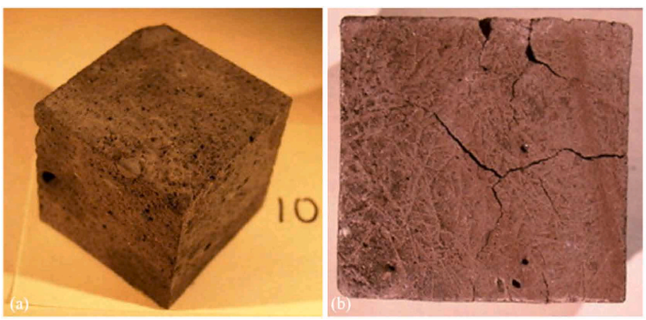

Fig. 18. Sulfur concrete (a) Just after casting (b) After 80 temperature cycles [130].

this by incorporating graphene into Sorel cement with lunar regolith, enhancing its mechanical properties. Even after temperature cycling between −58 °C and 150 °C to replicate lunar conditions, the Sorel mortar retained its integrity, with only a slight decrease in mechanical strength and minimal structural change. Fig. 19 displays the Sorel

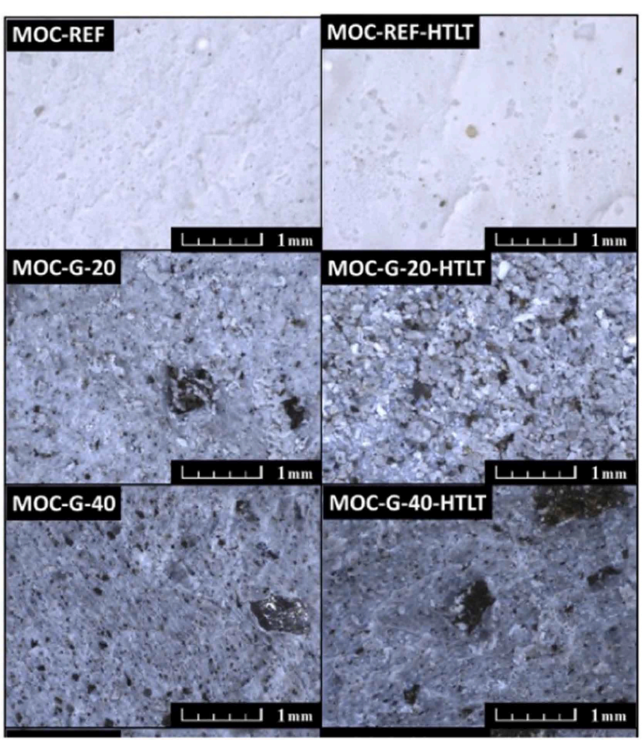

Fig. 19. Microstructure of the Sorel mortar before (left) and after (right) the thermal treatment [134].

mortar samples before and after the thermal cycling. The left side depicts the original microstructure, while the right exhibits increased porosity and coloration changes in samples, indicating thermal stress effects post-cycling.

Werkheiser et al. [135] outlined a process for in-situ production of Sorel concrete on the Mars and the Moon, highlighting the extraction of MgO and $MgCl_2$ from magnesium carbonate. They suggested using lunar apatite for chloride extraction, advocating for the use of local minerals to support extraterrestrial construction. Complementing this, Yang et al. [136] demonstrated the viability of using serpentine, treated with hydrochloric acid, to extract silica and magnesium - key components for creating a high-strength magnesium chloride concrete utilizing by-product acids. Building on these methodologies, Osio-Norgaard et al. [137] investigated the sintering of Sorel cement with lunar regolith, confirming improved mechanical properties and reduced porosity, which aligned with the requirements for 3D printing in lunar conditions, while also presenting a method for water recovery, integral for sustainable extraterrestrial habitation.

3.6. *Magnesia silica concrete*

Magnesia silica concrete, a mixture of magnesium oxide, silicon dioxide, aggregates, and sometimes additional additives, sets through the reaction between MgO and SiO_2, synthesizing magnesium silicate hydrate (M-S-H) gel. This gel is analogous to C-S-H in Portland cement, both crucial for their concrete strength and durability. Despite differences in composition, M-S-H and C-S-H have comparable microstructures and are integral to the cementitious qualities and overall performance of their respective concretes. Scott et al. [138] compared the phase evolution and microstructure of Portland cement and MgO:Si paste. Upon 28 days, Portland cement demonstrated enhanced C-S-H and calcium hydroxide (C-H), signifying increased the crystallinity and strength. The MgO:Si paste similarly displayed a maturing microstructure with prominent MSH peaks, indicating comparable hardening despite distinct compositions, crucial for the cement performance, as shown in Fig. 20.

Magnesia silica concrete has emerged as a promising material for space applications, especially for Martian infrastructure, due to its unique properties and compatibility with Martian resources. Studies by Simoni et al. [139] and Li et al. [140] laid the foundation for understanding the hydration process and the critical role of the MgO to silica fume ratio. The optimal formation of M-S-H gel, achieved with less than 50% MgO, underscored the importance of this gel for the concrete stability and strength, highlighting the potential for tailoring material properties to meet the demands of space conditions. Scott et al. [138] revealed that Mars serpentinization processes could produce MgO, a potential binder for magnesia silica concrete with strengths over 20 MPa, and that hydrogen, a serpentinization by-product, could serve as an energy source on Mars. Dhakal et al. [141,142] developed a MgO-based binder from Martian regolith, achieving compressive strengths of 20 MPa and 40 MPa after 28 and 90 days, respectively,

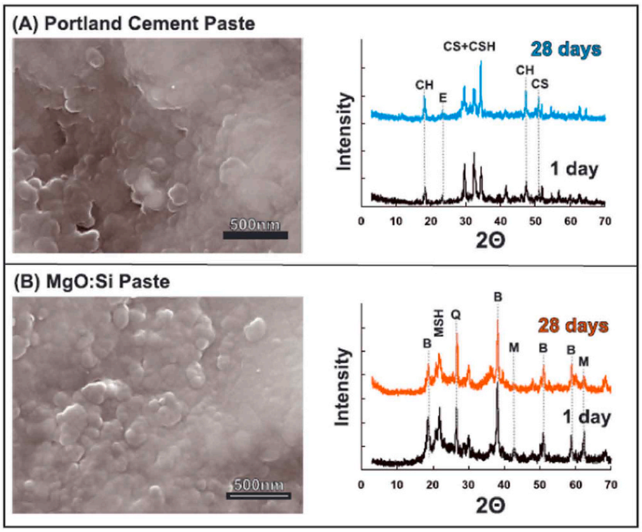

Fig. 20. Similar microscopic structures of C-S-H and M-S-H observed under an electron microscope (left) and X-ray diffraction (right) [138].

suggesting that the magnesia silica cement could match the performance of traditional Portland cement for Martian construction. Scott et al. [143] combined a magnesium-based binder with three different Martian regolith simulants and evaluated the mechanical characteristics of the mortar. The results indicated that the compressive strength of this cement was comparable to that of Portland cement. The research by Scott et al. [143] studied the mechanical performance of magnesium-silicate mortar for potential use in Martian construction, focusing on the impact of various water-to-binder ratios and curing conditions. As shown in Fig. 21, the reduced water-to-cement ratio led to an increased compressive strength, which was further optimized through the air or sealed curing rather than the water curing.

3.7. Polymer concrete

Polymer concrete represents an advanced composite material wherein polymer constituents enhance the intrinsic properties of conventional concrete. Polymer concrete is composed of aggregates bonded together by polymers. The most commonly used polymers are epoxy resins and polyesters [144]. Polymers significantly enhances the concrete compressive strength, durability, and environmental stressors resistance, making it an excellent candidate for space applications by virtue of the mechanical performance, thermal cycling resilience, and radiation shielding [145–147]. The low mass of the material also meets the strict payload limits associated with space missions. However, the use of polymer concrete in space is limited by its higher cost in

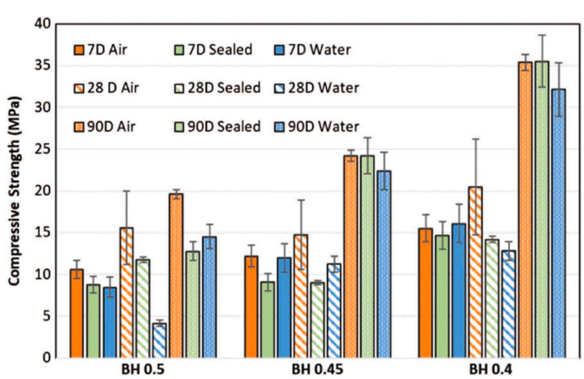

Fig. 21. Compressive strength of magnesia silica mortar under different curing conditions [143].

comparison with traditional cement-based materials and the complex on-site manufacturing and curing processes within the space environment, posing significant technical challenges.

Bedi et al. [148] noted that the epoxy resin polymer concrete exhibits significantly better mechanical properties and durability compared to polyester resin concrete. The recommended resin dosage by researchers generally ranged between 10% and 20% of the polymer concrete weight. Addition of glass fibres improved post-peak behaviour of polymer concrete, enhancing its strength and toughness. Caluk et al. [149] studied the impact of epoxy resin dosage on the strength of polymer concrete in lunar environments, finding that 18% epoxy content was most suitable for lunar polymer concrete, achieving a compressive strength of 123 MPa. Although tensile strength increased with higher dosages, it also exhibited greater brittleness. Bao et al. [150] explored the feasibility of constructing lunar infrastructure utilizing composite materials with extremely low binder concentration in a simulated lunar environment. The results revealed that the optimal curing temperature was 60 °C, achieving compressive strength and flexural strength of 156.2 MPa and 103.4 MPa, respectively.

Lee et al. [151,152] studied the use of polyethylene polymer concrete for lunar construction, discovering that bottom-up heating accelerated the solidification with a minor reduction in strength, achieving a compressive strength of 12.6 MPa under simulated lunar conditions. Koh et al. [153] indicated that preheating concrete to mimic lunar thermal conditions greatly speeds up the hardening process, resulting in solidification within 4–5 h. In contrast, unpreheated samples required approximately 11 h to commence hardening. This finding underscores the critical role of thermal environments in enhancing the performance of construction materials tailored for lunar applications, as illustrated in Fig. 22.

Chen et al. [154] focused on fabricating lunar infrastructure materials by integrating lunar soil simulant with polymer binders, yielding an inorganic-organic composite (IOM) that exhibited flexural strengths of 30–40 MPa and a range maintained across extreme temperatures from −200 °C to 130 °C. Su et al. [155] studied the fatigue behaviour of the IOM using JSC-1a lunar simulant, revealing superior fatigue performance under higher stress amplitudes, as compared to traditional reinforced concrete. Oh et al. [156] further adopted this approach with an impact moulding process that produced IOMs with flexural strengths between 12–16 MPa, suggesting that strength increases in proportion to the energy of impact used in the moulding process. In parallel, Zaccardi et al. [37] assessed the polyethylene mixed with Martian soil simulant for 3D printed structures, finding that an increase in polyethylene content significantly improved the radiation shielding effectiveness. Fig. 23 displays the effectiveness of polyethylene and Martian regolith composites in shielding against space radiation, including galactic cosmic rays (GCR) and solar particle events (SPE). The data compared the radiation absorption of these composites with varying Martian regolith contents to that of aluminium and pure polyethylene, showing that the increased polyethylene content improved protection.

Additionally, researchers proposed a new bio-based polymer. Biggerstaff et al. [157] studied a lunar regolith simulant bound with bovine blood protein, finding that drying correlated with strength development, achieving compressive strengths up to 34 MPa. Roberts et al. [158] furthered this by mixing human serum albumin with regolith simulants, noting that the addition of urea increased the compressive strength from 25.0 to 39.7 MPa. These materials gain their strength from the protein undergoing structure reformation into β-sheet layers upon dehydration, a process akin to the way spider silk adheres. This highlights the potential of bio-based polymers in building durable habitats in extraterrestrial environments.

3.8. Geopolymer concrete

Geopolymer concrete, leveraging industrial by-products, forms a binder through silicates and aluminates reacting in alkaline solutions,

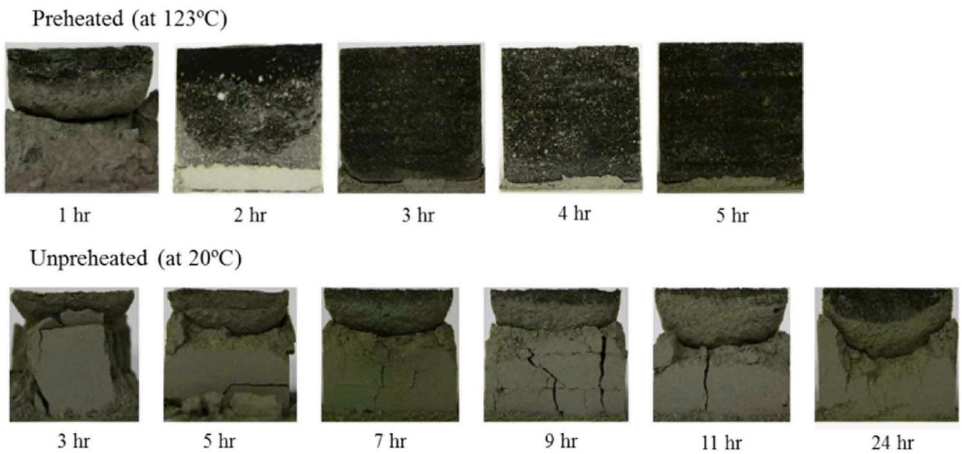

Fig. 22. Preheated and unpreheated polyethylene polymer concrete [153].

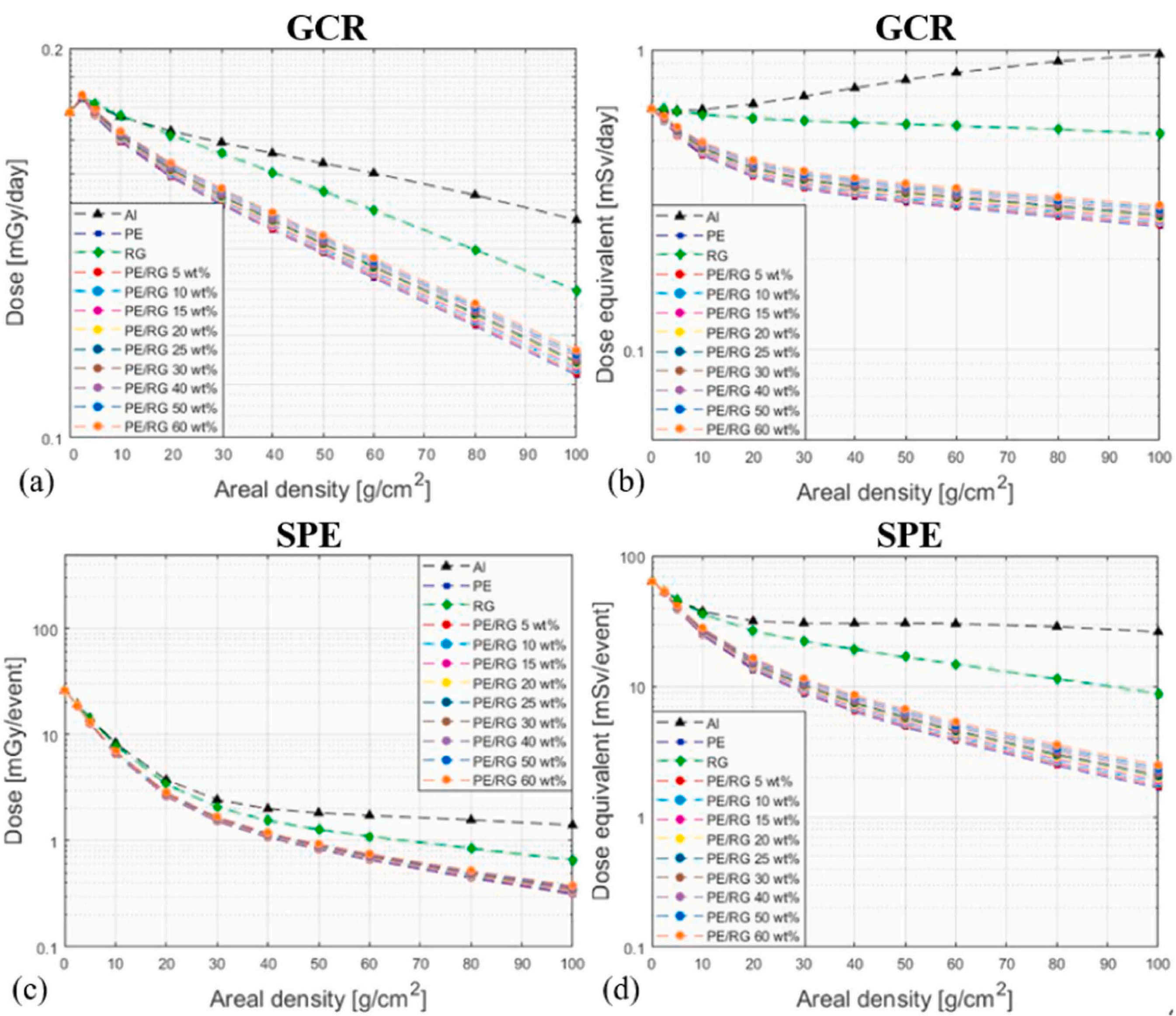

Fig. 23. Radiation shielding efficiency of polyethylene/regolith composite materials against (a-b) GCR, and (c-d) SPE [37].

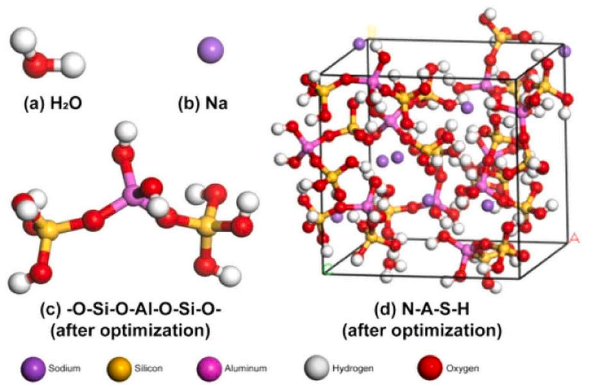

Fig. 24. Structures of (a) H_2O, (b) Na, (c) Aluminosilicate, and (d) N-A-S-H [18].

producing sodium aluminosilicate hydrate (N-A-S-H) as shown in Fig. 24. This process, occurring at ambient temperatures, creates a durable, fire-resistant matrix with excellent adhesion. Its molecular structure contributes to the concrete mechanical strengths, offering a low carbon footprint and the possibility of using local materials. This makes geopolymer concrete an eco-friendly option for space construction, supporting the use of in-situ resources to minimize the dependence on Earth-based supplies. Additionally, geopolymer concrete requires significantly less water than conventional concrete, enhancing its suitability for space applications where water is scarce, aligning with sustainable extraterrestrial colonization efforts.

Lunar regolith, rich in minerals such as olivine, pyroxene, and silica, is ideal for geopolymers. Mills et al. [159] optimized silicates and aluminates to enhance cement strength. Hou et al. [160] explored the thermal instability of N-A-S-H gel in lunar geopolymers at high temperatures, revealing structural vulnerability. In contrast, Kupwade-Patil et al. [161] identified a crucial Si:Al ratio of 2:1 for thermal resistance and performance in lunar geopolymers. Xiong et al. [18] achieved an optimal compressive strength of 58.5 MPa in geopolymers made from lunar soil simulants by fine-tuning the mix ratios and curing at 60 °C, with these geopolymers exhibiting stable or improved strength after the temperature cycling akin to lunar conditions. Contrasting findings by Pilehvar et al. [162] indicated the strength reduction in vacuum-cured geopolymers at ambient temperatures due to the rapid water loss and cracking. However, Zhou et al. [163,164] found that curing lunar geopolymer concrete in vacuum at high temperatures increases its strength. Their development of BH series lunar simulants demonstrated this with Al_2O_3 and Metamax additions, significantly boosting mechanical strength.

The incorporation of superplasticizers, including those synthesized from urea in human urine, is crucial in advancing lunar geopolymer technology. Pilehvar et al. [165] demonstrated that the urea not only enhanced the workability and setting times but also, under specific conditions, can improve the compressive strength of geopolymers, making it a viable option for 3D printing applications within the scope of ISRU. Wang et al. [166] investigated the utilization of lunar glass tektite in geopolymer production, affirming its suitability for lunar construction due to its satisfactory properties and temperature resilience. Additionally, they developed a novel water recovery process for lunar geopolymer concrete manufacturing, proposing a closed-loop system that recycled water, crucial for the self-sufficient production of construction materials on the Moon. Fig. 25 illustrates the method of producing geopolymer concrete on the Moon by sieving lunar soil into powder, then mixing it with water and an alkali to create a paste. The paste was moulded and cured in a vacuum, with water vapor recycled through a condensation system. Furthermore, Shao et al. [167] investigated the utilization of lunar soil-derived geopolymers for producing concrete with high strength, suitable for lunar conditions. Their microstructural

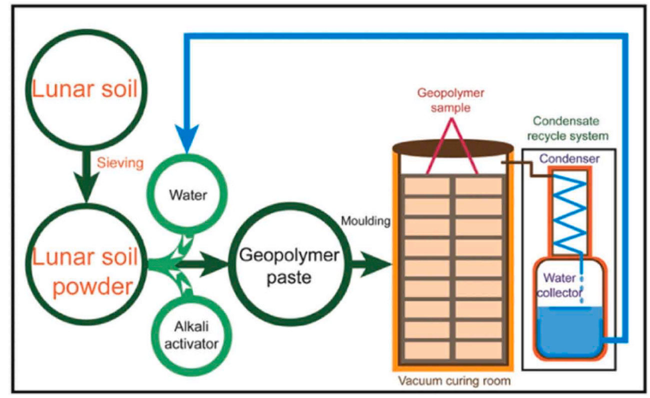

Fig. 25. Closed-loop water recovery system for lunar geopolymer production [166].

analysis revealed that concrete derived from the LHS-1 simulant displayed greater structural density, characterized by denser amorphous gels and a reduction in microcracks. In addition, it was demonstrated that the optimal proportion of lunar simulants with granulated blast-furnace slag, silica fume, and fly ash could yield compressive strengths of more than 100 MPa at 28 days, respectively. This development of high-strength lunar concrete constitutes an important advancement in the field of space construction materials.

The application of geopolymer concrete on Mars leverages the planet abundant silicate and aluminate minerals, crucial for its eco-friendly production. This approach emphasizes utilizing Martian soil and rocks, with ongoing exploration into 3D printing methodologies. Alexiadis et al. [168] highlighted that the Martian geopolymer concrete demonstrated promising mechanical strengths, essential for Martian infrastructure but necessitating further optimization against environmental challenges. Concurrently, Mills et al. [159] identified the reduction in strength due to Martian's iron and magnesium content at elevated temperatures, underscoring the need for adapted processing techniques. Ma et al. [169] developed a 3D printing geopolymer from Martian soil, reinforced with basalt fibres, achieving a high compressive strength of 32.2 MPa. This demonstrated the potential for durable construction on Mars and highlighted the need to refine material properties and printing processes for effective space building solutions.

4. Comparative analysis of different lunar and Martian concretes

This section conducts a comprehensive comparative analysis of various space concretes, focusing on the key performance metrics such as compressive and flexural strengths. The study encompasses a broad spectrum of concrete types ranging from traditional concrete to innovative alternatives like sulfur concrete, polymer concrete and geopolymer concrete. Tables 5 and 6 respectively summarize the existing literature on the compressive and flexural strengths of space concretes and provide a detailed comparison of key performance parameters for different types of lunar and Martian concretes. These tables lay the groundwork for discussions in this section and assist in proposing the appropriate concrete for space construction, considering the distinct challenges posed space environments.

Integrating insights from Tables 5 and 6 of the comprehensive review on space concrete innovations emphasize the critical selection of concrete materials tailored for the unique and extreme conditions of extraterrestrial environments. This selection process is paramount for the development of sustainable construction projects on space, focusing on adaptability of materials to severe temperatures, radiation levels, vacuum exposure, and their ability to maximize the use of local resources through ISRU.

Table 5
Summary of compressive and flexural strengths of space concrete.

Type of concrete	Compressive strength	Flexural Strength	Reference
Portland concrete	30.0 MPa	-	Neves et al.[109]
	45.0 MPa	-	Collins et al.[34]
	5.8 MPa (Wet-mix) 24.3 MPa (DMSI)	–	Horiguchi et al. [26]
	35.6 MPa (Mars) 37.1 MPa (Moon)	–	Edmunson et al. [170]
Calcium aluminate concrete	75.0 MPa	-	Lin et al.[106]
	69.0 MPa (DMSI)	-	Lin et al.[114]
Sulfur concrete	33.8 MPa (Non-reinforced)	3.7 MPa	Omar[171]
	43.0 MPa (2 % metal fibre)	-	
	35.0 MPa (without thermal cycle) 7.0 MPa (with thermal cycle)	–	Toutanji et al. [125]
	47.0 MPa (without thermal cycle)	-	Grugel[130]
	8.0 MPa (with thermal cycle)	-	
	31.0 MPa	-	Toutanji et al.[39]
	3.5 MPa (20 wt% sulfur)	1.0 MPa (20 wt% sulfur)	Shahsavari et al. [172]
	13.0 MPa (30 wt% sulfur)	3.0 MPa (30 wt% sulfur)	
	7.0 MPa (40 wt% sulfur)	2.5 MPa (40 wt% sulfur)	
	5.8 MPa (50 wt% sulfur)	2.6 MPa (50 wt% sulfur)	
	46.6 MPa (35 wt% sulfur) 65.0 MPa (40 wt% sulfur)	–	Roqueta et al. [119]
	17.4 MPa (High microwave power)	-	Li et al.[173]
	11.9 MPa (Low microwave power)	-	
Polymer concrete	12.9 MPa (polyethylene)	-	Lee et al.[174]
	5.0 MPa (10 % polypropylene)	1.4 MPa	Garnock et al. [175]
	-	30.0 MPa (Epoxy resin)	Chen et al.[154]
	-	39.9 MPa (Epoxy binder)	Su et al.[155]
	-	12.0 MPa (Epoxy binder)	Oh et al.[156]
Geopolymer concrete	26.7 MPa (Na-geopolymer pastes)	-	Wang et al.[166]
	26.5 MPa (After 30 freeze-thaw cycles)	-	
	35.8 MPa (Na-Si-geopolymer pastes)	-	
	32.0 MPa (After 30 freeze-thaw cycles)	-	
	50.4 MPa (Volcanic ash)	-	Wang et al.[176]
	45.5 MPa (After 30 freeze-thaw cycles)	-	
	19.9 MPa (Lunar average daytime heat)	-	Davis et al.[177]
	9.8 MPa (Vacuum)	-	
	8.2 MPa (Heat and vacuum)	-	
	18.4 MPa (Lunar - 8 M)	13.0 MPa	Alexiadis et al. [168]
	2.5 MPa (Mars - 8 M)	3.6 MPa	
	10.0 MPa (Lunar ambient curing)	-	Mills et al.[159]
	35.0 MPa (Lunar - 600 °C 1 h)	-	
	3.8 MPa (Lunar vacuum curing)	-	
	0.4 MPa (Lunar - 80 °C 3d)	-	
	14.8 MPa (Mars ambient curing)	-	
	15.0 MPa (Mars - 600 °C 1 h)	-	
	7.0 MPa (Lunar vacuum curing)	-	
	1.0 MPa (Lunar - 80 °C 3d)	-	
	26.7 MPa (NaOH)	-	Wang et al.[178]
	26.5 MPa (After 30 freeze-thaw cycles)	-	
	35.8 MPa (Na_2SiO_3)	-	
	32.0 MPa (After 30 freeze-thaw cycles)	-	
Magnesia silica concrete	27.0 MPa	-	Scott et al.[138]
	20.0 MPa	-	Dhakal et al.[141]
Sorel concrete	76.8 MPa (graphene added)	21.5 MPa	Lauermannova et al.[134]
	68.2 MPa (cyclic heating and freezing)	21.3 MPa	

Notes: “M” denotes molarity, and “wt%” denotes weight percent.

Among the various contenders, geopolymer concrete has been identified as particularly suited for the challenges of Martian and lunar construction. Unlike traditional concrete options, which are heavily reliant on water and subject to lengthy curing processes, geopolymer concrete presents a compelling alternative with its low water demand and rapid curing capabilities. These attributes are critically advantageous given the scarcity of water and the operational constraints imposed by human and robotic activities on Mars and the Moon. Furthermore, the excellent chemical stability of geopolymer concrete is a significant asset, ensuring structural integrity against the chemically reactive surfaces encountered in these extraterrestrial settings. Its high mechanical strength provides the necessary resilience against the myriad pressures and stresses space structures are expected to withstand. Perhaps most importantly, the ISRU compatibility of geopolymer concrete represents a substantial leap forward in sustainable extraterrestrial construction, allowing for the use of local materials and significantly curtailing the logistical and economic burdens associated with transporting construction materials from Earth.

Magnesia silica concrete offers certain advantages, including a moderate water demand and acceptable curing times, which might seem beneficial at a glance. However, the practicality of employing this material in space construction is tempered by significant concerns regarding the availability of water resources on Mars and the Moon. Additionally, the energy-intensive nature of producing Magnesia silica concrete may not be compatible with the energy limitations inherent to extraterrestrial environments, presenting a substantial challenge to its adoption.

Sorel and sulfur concrete stand out for their minimal to non-existent water requirements and rapid hardening properties, alongside their low energy consumption during the curing process. These characteristics render them particularly appealing for the resource-constrained settings of Mars and the Moon. The adaptability of Sorel concrete to a variety of conditions and the exceptional performance of sulfur concrete in non-equatorial regions of the Moon underscore their potential utility in specific applications. However, the successful implementation of these materials will necessitate thorough consideration of their durability and

Table 6
Comparison of different space concrete.

Concrete categories	Material composition	Water requirement	Setting time	Chemical stability	Lack of resources	Energy demand	Mechanicalproperty	Suitable planet
Portland	Limestone and clay	High	Slow	Poor (SA)	Limestone and water	High	Good	No
Calcium aluminate	Limestone and bauxite	High (Wet-mix)Low (DMSI)	Moderate	Moderate	Limestone and water	High	Good	Moon
Magnesia silica	MgO and silicate	Moderate	Moderate	Moderate	Water	Moderate	Good	Mars and Moon
Sorel	MgO and $MgCl_2$	No	Fast	Moderate (WS)	No	Low	Good	Mars and Moon
Sulfur	Sulfur and fillers sand	No	Fast	Moderate (HT)	No	Low	Moderate	Mars
Polymer	Epoxy resins, polyethylene etc.	No	Fast	Good	Polymers	Moderate	High	Mars and Moon
Geopolymer	Silicate and aluminate minerals	Low	Fast	Good	Alkali activator	Low	High	Mars and Moon

Notes: "SA" denotes sulfate attack, "WS" denotes water sensitivity, and "HT" denotes high temperature.

their capacity to resist the environmental stresses peculiar to space. Conversely, conventional concrete materials such as OPC and calcium aluminate concrete are beset with challenges when considering the space environments. The high-water consumption, reliance on energy-intensive production processes, and poor stability under space conditions severely limit their suitability for extraterrestrial construction. Similarly, polymer concrete, despite exhibiting impressive mechanical properties and chemical stability, is hampered by its dependence on Earth-sourced polymers and a moderate energy profile, which could constrain its application in space settings.

In conclusion, the selection for concrete materials suitable for space construction is an intricate task that demands a comprehensive evaluation of their properties, the performance under the extreme conditions of space, the compatibility with ISRU principles, along with the overall contribution to the sustainability of construction projects on Mars and the Moon. Geopolymer concrete, with its array of benefits tailored to meet the stringent requirements, is recommended as the prime material for future space construction initiatives. Moreover, sulfur concrete also provides promising prospects, with each presenting unique advantage that can be harnessed to overcome specific challenges in extraterrestrial environments.

5. Design principles and challenges of space concrete structures

Extending from the exploration of diverse space concrete materials, the progression towards their application in architectural framework exemplifies the transition from theoretical material selection to its pragmatic deployment. This highlights the imperative of leveraging ISRU and innovative manufacturing methodologies for the development of space habitat structures [179–181]. Thus, this section explores the design principles, fabrication technology of space concrete structures. Furthermore, the advancements were summarized in the design of space concrete structures, including case studies and numerical simulations.

5.1. Design of space concrete structures

In the field of space habitation, academic efforts delineate a spectrum of architectural solutions, from prefabricated modules to inflatable structures and resource-integrated concrete edifices, tailored to mitigate the diverse challenges of the space environment. These pioneering designs are important steps towards establishing a sustainable human presence and effectively utilizing resources in outer space. Current scholars emphasize the need to establish sustainable and resilient space habitats. Bernold et al. [182] discussed structural concepts for lunar habitats, emphasizing the use of local resources to construct durable and sustainable structures. They addressed lunar environmental challenges, such as radiation, temperature extremes, and regolith properties, proposing innovative solutions. Naser et al. [183] highlighted the need to overcome material development challenges and modernize structural engineering principles, including the use of in-situ resources, automation, and self-diagnostics to ensure resilience and sustainability. Similarly, Dyke et al. [184] stressed designing resilient space habitats capable of autonomously adapting to extreme conditions, advocating for systems that can sense, anticipate, and recover from disruptions using integrated technologies like robotics and decision-making algorithms.

Jablonski et al. [179] segmented lunar structure development into three phases: Phase I focused on building shelters for the equipment; Phase II expanded to developing temporary habitats for humans; Phase III culminated in establishing permanent bases for the long-term habitation and resource utilization. Current research primarily focuses on the development of the second and third phases of lunar structure construction - the creation of temporary human habitats and the establishment of permanent bases for prolonged living and resource utilization in space. Toklu [185] highlighted the complex challenges in creating habitable environments in space due to the extreme temperatures, radiation, low atmospheric pressure, meteoroid impact, gravity, lunar dust, and seism. Cohen et al. [186] introduced a three-phase framework for space habitats. In the first phase, the framework utilized the pre-integrated modules based on existing technology on Earth. The second phase shifted towards the use of prefabricated inflatable structures, aimed at enhancing habitability while reducing mass. The third phase advanced to construction using in-situ resources, with the goal of achieving self-sufficiency and sustainable development for space colonization. Ordway III et al. [187] conceptualised a lunar outpost composed of pre-integrated cylindrical modules, intended for subterranean assembly on the Moon. The modules were made on Earth in advance and taken to the Moon for assembly. Fig. 26(a) illustrates the construction of the lunar outpost, with a vehicle installing pre-integrated modules into a trench 0.91 m beneath the lunar surface. As shown in Fig. 26(b), Benaroya [188] introduced a concept for a lunar base engineered to transport materials. The design integrated four large horizontal cylinders housing the habitat, maintenance, supply packaging, and a loading facility for a lunar mass driver - an electromagnetic launcher for dispatching soil packages into space.

Roberts [189] presented a concept of lunar base habitats with an external structure of a spherical inflatable envelope, crafted from robust multi-layer fabric potentially including materials like Kevlar. The internal framework, aimed at maintaining habitat structure while offering habitable space, could incorporate space concrete made from lunar in-situ resources. Fig. 27(a) illustrates the cross-section of a spherical inflatable habitat, exhibiting multiple levels for crew quarters and operations, integrated with a structural rib and lightweight modular flooring. Fig. 27(b) depicts the habitat enveloped in lunar regolith for radiation shielding and thermal insulation. Schänzlin et al. [190] noted that the use of concrete structures on the lunar surface might reduce the need for approximately 3 m of regolith shielding. Meanwhile, Ganapathi

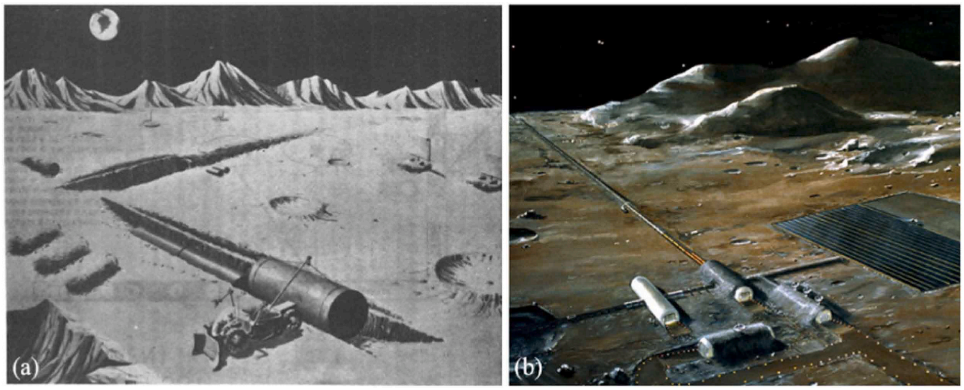

Fig. 26. (a) Lunar outpost construction [187] and (b) lunar supply base [188].

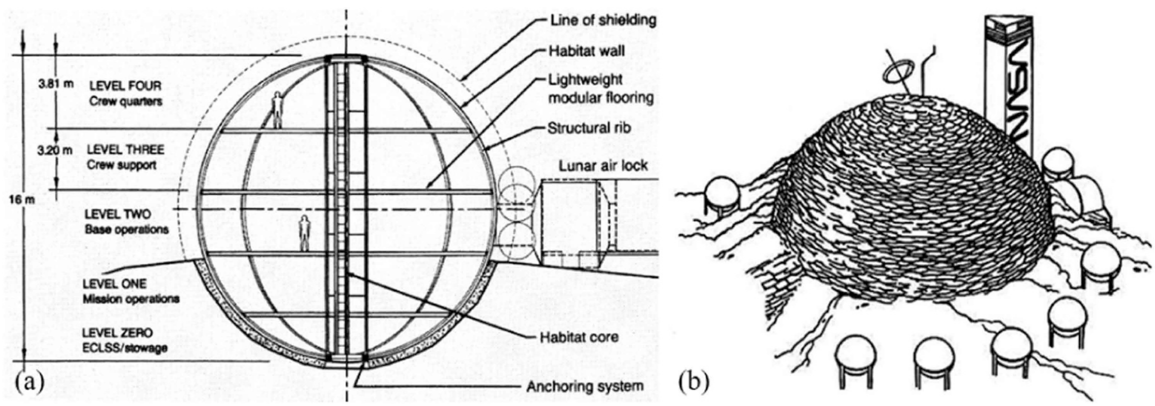

Fig. 27. (a) Cross-sectional view of spherical inflatable habitat [192] and (b) spherical inflatable habitat covered with regolith shielding [189].

et al. [191] developed on a cylindrical inflatable with a high-strength pneumatic envelope and an internal framework designed for easy transport and rapid assembly. The habitats offered ample internal space and robust construction, capable of supporting a 12-person crew. They were characterized by their modular design and space-efficient layout, which guaranteed their adaptability to the lunar environment (Fig. 28).

Moore et al. [193] conceptualized a multi-level lunar base structure featuring logistics modules on the top level and inflatable modules for habitation and laboratories on lower levels. The habitation inflatables were integrated in a rigid frame for stability, all resting on a foundation providing insulation and protection from the lunar environment. Benaroya et al. [194] presented a NASA conceptual lunar base as depicted in Fig. 29(a). This base featured a main habitat with a dome shape, additional cylindrical modules, and large solar panels. The design aimed for self-sufficiency, long-term survival in outer space and efficient energy production. Zhou et al. [195] proposed the Xuanwu lunar base as depicted in Fig. 29(b), using an autonomous robotic system for in-situ construction with materials derived from the lunar soil. The design integrated cultural elements and aimed for sustainability and protection against lunar extreme environments, which could revolutionize lunar construction and facilitate long-term habitation.

The preceding section describes the structures of lunar bases, which predominantly consist of hybrid structures with a portion employing concrete construction. Most of these structures are intended for

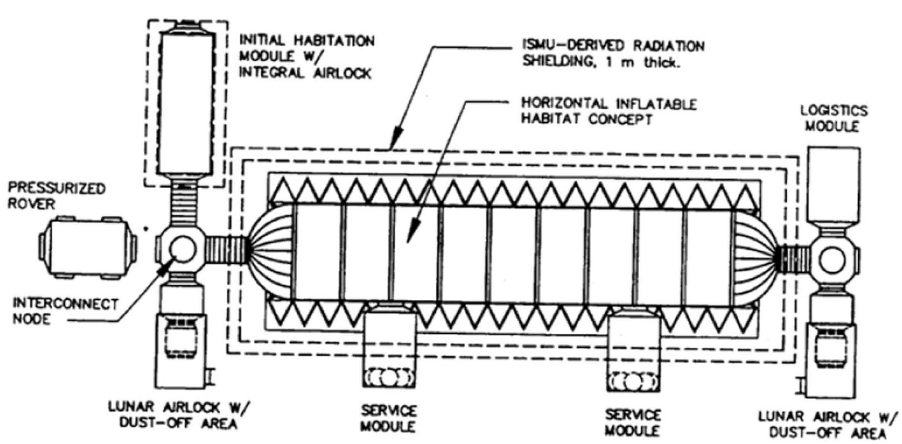

Fig. 28. Cross-sectional view of a cylindrical lunar habitat [191].

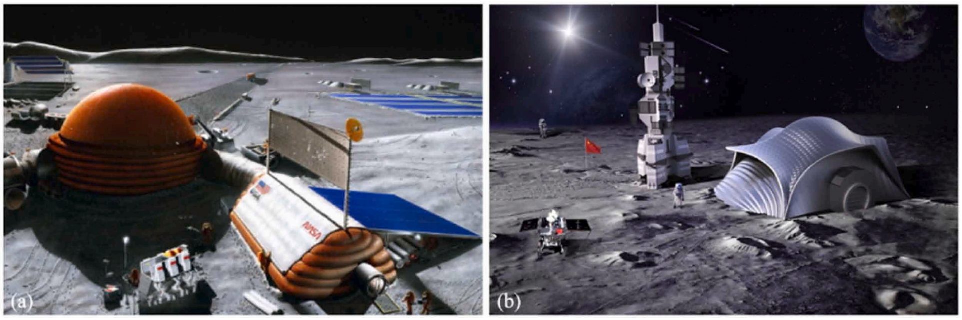

Fig. 29. Conceptual design of lunar base proposed by (a) NASA [196] and (b) Xuanwu [195].

deployment as space outpost stations, relying on templates from Earth or assembly on the lunar surface. How to manufacture permanent durable concrete structures primarily utilizing local resources is a critical issue that needs to be addressed. Lin et al. [197] pioneered the concept of utilizing precast prestressed concrete for lunar base structures, demonstrating the feasibility of large-scale construction on the Moon using mostly in-situ materials. As depicted in Fig. 30, it is evident that their design included a three-story concrete structure with a floating foundation. This base supported internal atmospheric pressure and provided large workspaces for scientific and industrial activities. Meyers et al. [70] investigated three lunar habitat designs using in-situ concrete. The first design was a hemispherical structure which evenly distributed internal pressure and anchors against lunar gravity, ideal for small crews on short missions (Fig. 31(a)). The second design was a cylindrical habitat, countered uplift without external anchors by using a weighted wedge and tension cables for stability and access to internal space, detailed in Fig. 31(b). The final design utilized an arched-panel configuration that capitalized on the compressive strength of lunar concrete. This was reinforced by tension cables on the exterior, ensuring the safe containment of internal pressures and durability of the habitat structure (Fig. 31(c)). In summary, hemispherical designs needed significant anchoring, while cylindrical and arched-panel structures used tension cables for better pressure and thermal stress handling.

Designing habitats on Mars involved confronting challenges similar to those on the Moon, such as extreme temperature variations, radiation protection, and atmospheric pressure differences. Cohen [198] focused on applying architectural principles in extreme environments, highlighting considerations such as radiation shielding, pressure management, and local resource utilization in habitat design (Fig. 32). Bell et al. [199] emphasized the aspects of launching, scalability, and functional design of Mars habitat modules, noting the necessity for efficient transportation on Mars. Research by Cadogan et al. [200] into habitat structures presented a promising approach for Martian exploration, allowing the rapid deployment to provide ample living space. These structures had to be robust enough to resist external challenges, including micrometeorite impacts and extreme temperature fluctuations. Polsgrove et al. [201] concentrated on transiting habitat design for Mars missions, addressing the need to provide liveable and workable

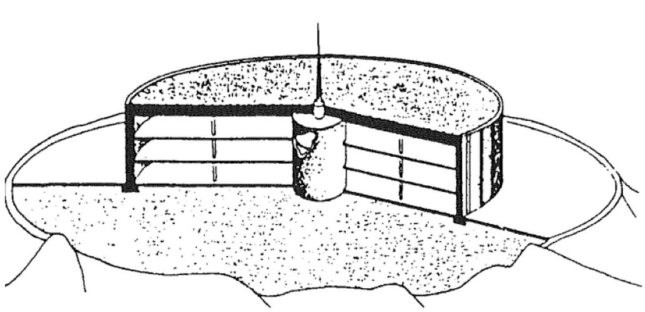

Fig. 30. Conceptual design of a precast prestressed concrete lunar base [197].

spaces that protected astronauts from various risks of the space environment during the lengthy journey to Mars. Anerdi et al. [202] conducted a 3D finite element analysis and found that introducing rapidly cultivable hemp fibres into Martian regolith-based concrete significantly enhanced its flexural strength and thermal properties. This suggests that using Martian-cultivable plant fibres in construction could lead to more durable and efficient structures.

5.2. Fabrication method for space concrete structures

5.2.1. 3D printing technology

3D printing of concrete structures emerges as a pivotal innovation in space exploration, utilizing in-situ materials such as lunar and Martian soil to erect durable infrastructures. This approach notably diminishes the dependence on Earth-based resources by capitalizing on the precision of 3D printing to minimize waste and enhance efficiency in environments where resources are scarce. The rapid-setting and energy-efficient characteristics of 3D-printed concrete structures align seamlessly with the rigorous energy constraints of space missions, while their stability ensures resilience against the volatile conditions of extraterrestrial terrains. This breakthrough is crucial in propelling the development of sustainable habitats and facilities on other planets, representing a substantial advancement in the construction of space infrastructures.

Several researches highlight the advancements in 3D printing technology for space construction. Khoshnevis et al. [72,124,203] developed Contour Crafting, a 3D printing technology using a robotic arm for sulfur concrete extrusion, aimed at construction on lunar and Martian surfaces, as shown in Fig. 33(a). This method enabled on-site construction, incorporating micro-vibration technology to improve the surface quality of the extruded concrete. Meanwhile, Cesaretti et al. [204] studied the D-shape 3D printer for rapid prototyping with lunar soil, shown in Fig. 33(b), capable of fabricating complex structures in space environments. Expanding on this, Jakus et al. [205] created inks from lunar and Martian regolith simulants for room temperature printing, causing materials with rubber-like properties and 20-40% porosity, emphasizing the potential for ISRU in space construction. Moreover, research by Osio-Norgaard et al. [137] studied the creation of Sorel cement using powder binder jet printing on lunar soil. This study demonstrated the potential of 3D printing on the Moon. Despite exhibiting lesser strength than direct sintering, this advancement marked significant progress in building methods beyond Earth.

The nascent domain of 3D printing for space concrete centres on leveraging extraterrestrial soil and innovative additives to bolster the mechanical characteristics of the constructed materials. Montes et al. [38] demonstrated that the strength of JSC-1A lunar simulant polymer cement, synthesized through 3D printing, could reach up to 16 MPa. Zaccardi [37] developed a Martian simulant polymer (polyethylene) cement that achieved a tensile strength of 4 MPa and a flexural strength of 7.5 MPa. Ma et al. [169,206] produced HIT-MRS-1 Martian simulant polymer cement with a compressive strength between 9.3–32.2 MPa.

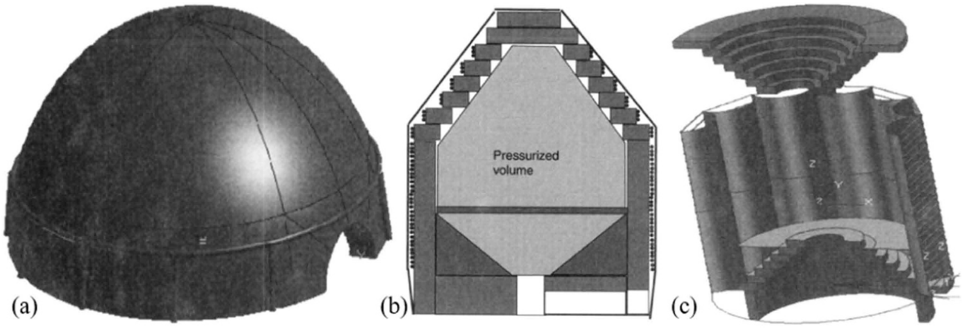

Fig. 31. (a) Hemispherical, (b) cylindrical, and (c) arched-panel lunar habitat [70].

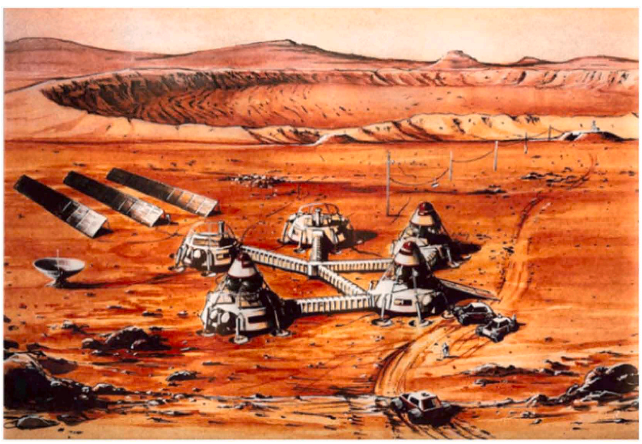

Fig. 32. Conceptual design of Martian base [198].

Khoshnevis et al. [72] fabricated Martian soil sulfur concrete reaching a strength of 31 MPa, and Pilehvar et al. [165] used urea as a superplasticizer to improve the flowability of 3D printed geopolymer, with the extrusion method resulting in a geopolymer cement strength of up to 13 MPa.

The transition from early successes to the practical implementation of 3D printing for habitat construction in extraterrestrial environments encapsulates a myriad of challenges, transcending mere material properties. Microgravity, intrinsic to space conditions, poses formidable barriers to material processing and the efficacious deployment of 3D printing technology. Additionally, logistical complexities related to the transport and operation of large-scale 3D printers in space highlight the imperative for sustained innovation and exhaustive research. Overcoming these obstacles is paramount for evolving 3D printing from an experimental concept to a practical, cost-efficient strategy for establishing habitats in extraterrestrial locales.

Building on these technology advancements, the exploration of 3D printing method for habitat construction on planetary surfaces represents a significant leap forward. Fiske et al. [207] used Contour Crafting technology for the direct construction on the planet surface. This approach facilitated the rapid construction of various concrete structures, from simple walls to complex living unit. Ultimately, as depicted in Fig. 34(a), these 3D-printed structures not only provided excellent sealing and structural performance but also effectively protected against external environment and cosmic radiation. Giovanni et al. [204] utilized D-shape technology and lunar materials to build complex habitats and workspaces on the Moon. The structure shown in Fig. 34(b) highlighted the potential of 3D printing for rapidly manufacturing large structures suited for extraterrestrial environments. Ulubeyli [41] assessed the feasibility of using robotic swarms for constructing lunar habitats with 3D printing technology on the Moon. The study highlighted the complexity of preparing, transporting, and printing in-situ materials under microgravity and vacuum conditions, focusing the necessity for technological advancements. Furthermore, space construction can leverage lunar and Martian lava tubes and craters. Lava tubes provide natural radiation protection and climate stability and craters offer radiation shielding and water ice resources. The features enable efficient habitat integration with the extraterrestrial environment [208, 209].

5.2.2. Automated robot technology

In space exploration and colonization, automated robots play an important role. They construct concrete structures in severe environments, such as those with microgravity and high radiation. These robots use 3D printing technology and local materials like lunar or Martian soil, and the binders are incorporated into these soils to print structures directly. This method significantly reduces the need to transport building materials from Earth and can create both simple habitats and complex structures. Robots have real-time monitoring capabilities for construction quality, which ensures the safety for long-term habitation.

Samid et al. [210] explored robot automation technologies for lunar

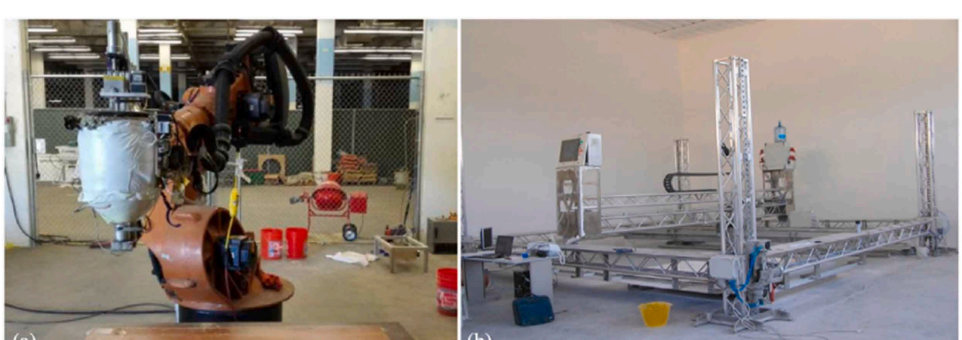

Fig. 33. (a) Contour Crafting 3D printer [124] and (b) D-shape 3D printer [204].

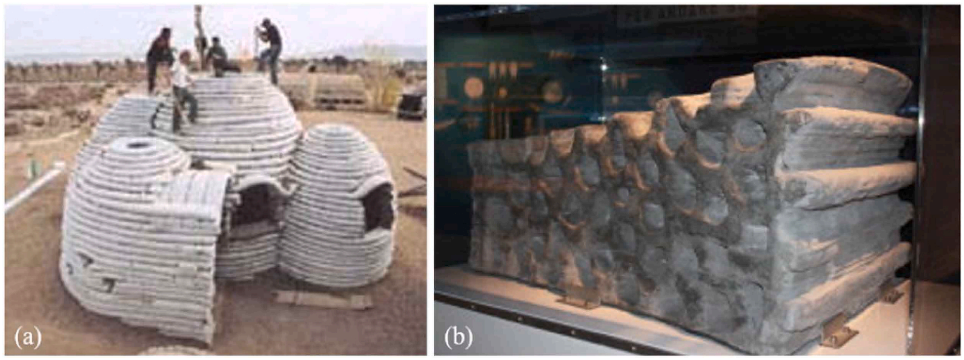

Fig. 34. (a) Contour Crafting printed [207] and (b) D-shape printed lunar structures [204].

base construction using in-situ resources, highlighting autonomous multi-robot excavation solutions enhanced by machine learning for efficiency and cost reduction. Furthermore, Smitherman et al. [211] proposed a conceptual design for developing lunar walking habitats using existing robotics technology and International Space Station hardware. The studies highlighted the potential of robotics method in future lunar exploration architectures. Thangavelautham et al. [212] explored the significant advantages of using automation robotics for constructing a lunar mining base. By employing 300 infrastructure robots and leveraging 3D printing technology, the approach dramatically reduced energy requirements by fifteen times and accelerated the construction process equally. Moreover, Thangavelautham et al. [213] introduced the Artificial Neural Tissue (ANT) method for autonomous multirobot excavation for lunar base fabrication, exhibiting autonomous robots excavating according to a 3D blueprint with minimal supervision. Zhou et al. [195] proposed an automated robotic construction system named the Chinese Super Mason (CSM), specifically designed for constructing lunar habitats. As depicted in Fig. 35, the CSM system utilized lunar soil as the primary construction material and operated through a six-axis robotic arm and a dry mix autoclaving fabricator, demonstrating the potential for automated construction in extreme environments. In addition, Huntsberger et al. [214] discussed the critical role played by robust robotic systems in Mars exploration, focusing on infrastructure deployment, servicing power systems, and site preparation for human habitats. Their research emphasized the importance of autonomous, cooperating robots in addressing the technological issues of pre-human missions.

5.3. Numerical simulation of space concrete structures

Despite progress in space concrete research, the actual construction of extraterrestrial structures is not yet feasible, with current initiatives largely confined to the numerical simulations. These simulations aim to understand how these materials perform under the harsh conditions of space, helping researchers to design future habitats and facilities that could one day resist the extreme environments. Steiner et al. [48,50] explored the multilayer materials for thermal and impact shielding in lunar habitats, assessing their resistance to extreme environments for efficient layer selection using heat equations and static loads. Mottaghi et al. [47] proposed an igloo-shaped magnesium alloy structure with regolith sandbags, confirming its thermal effectiveness against lunar temperature fluctuations through analysis. Furthermore, Shahriar et al. [216] developed a MATLAB computational framework, focusing on the resilient design of dome-style structures made of space concrete against impacts and other hazards through the cyber-physical testing. Kitching et al. [215] introduced a method to space habitat design that was driven by resilience, emphasizing the use of safety controls to navigate a complex matrix of hardware, software, and human interactions within harsh space environments. As illustrated in Fig. 36, the innovative method leveraged a state-and-trigger model to identify disruptions, hazardous states, and safety controls, applying this model to early-stage Martian habitat designs. Gino et al. [217] demonstrated a strain-based method for assessing global resistant safety factors in non-linear numerical analyses (NLNAs) of reinforced concrete structures. This method offered insights for designing space habitats by enhancing predictions of performance and durability under extreme conditions, addressing

Fig. 35. Construction process of the CSM [195].

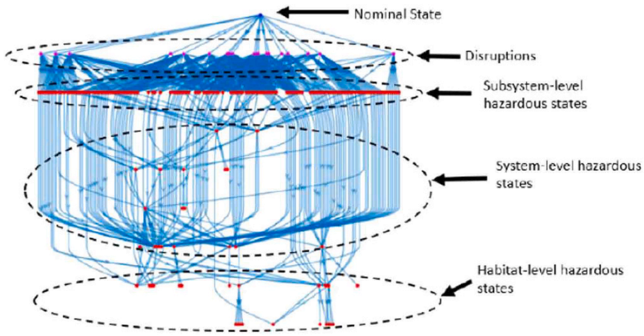

Fig. 36. Martian habitat structural integrity analysis network [215].

challenges like microgravity and radiation, therefore improving safety and resilience.

6. Conclusion and prospect

The review provides a comprehensive exploration of the key considerations and innovations necessary for developing concrete suitable for the construction in extraterrestrial environments, such as those observed on the Moon and Mars. This includes a detailed examination of the unique challenges presented by such environments, the exploration of innovative solutions to these challenges, and the emphasis on sustainable practices. Here's an expanded conclusion of the points highlighted in the review:

1) Challenges: The review elaborates on the extreme environmental conditions that pose significant challenges to traditional construction methods and materials. These include severe temperature fluctuations, which can compromise the integrity of conventional construction materials; the vacuum of space, which affects material properties and curing processes; microgravity, which impacts the mixing and settling of concrete; radiation, which can degrade materials over time; and the scarcity of resources, which limits the availability of traditional building materials. These challenges necessitate a rethinking of construction materials and methods for construction in space.
2) Innovative solutions: To address the scarcity of resources and the harsh environmental conditions, the review discusses innovative solutions such as the utilization of lunar and Martian soil as a base material for concrete, which could significantly reduce the need to transport materials from Earth. It also explores alternative binders that can be used in place of water, which is scarce on extraterrestrial bodies. Furthermore, the document highlights the potential of 3D printing technology as a method for constructing habitats and structures in space, allowing for the creation of complex shapes and structures that are optimized for the unique conditions of extraterrestrial environments.
3) Material research: The review delves into the research and development of various types of space concrete, examining how different compositions and binders can be tailored to meet the specific requirements of extraterrestrial construction like radiation and thermal cycling. Emphasizing the need for materials with sufficient mechanical strength and flexibility for space construction, geopolymer concrete emerges as a promising option. Its adaptability to harsh space environments and compatibility with ISRU strategies minimize Earth resource dependency, supporting sustainable exploration and habitation.
4) Structure research: The design principles, technological challenges, and adaptive strategies discussed highlight the complexity and innovation in developing space concrete structures for extraterrestrial habitats. Using in-situ resources and advanced manufacturing is central to creating sustainable, protective environments for space conditions.
5) Sustainability: Sustainability is underlined as a critical aspect of developing construction materials and techniques for extraterrestrial use. The review advocates for solutions that are not only effective in addressing the immediate challenges of space construction but also sustainable in the long term, ensuring that human activities in space do not deplete limited resources or cause irreversible harm to extraterrestrial environments. This includes the development of construction practices that minimize waste, the exploration of recyclable or reusable materials, and the consideration of the environmental impact of construction activities in space.

Based on the current review, space concrete technology is at a pivotal stage with significant potential for supporting human endeavours in space exploration and construction on celestial bodies such as the Moon and Mars. However, there are notable research gaps and challenges that must be addressed to advance this field:

1) Utilization of indigenous water resources: Utilizing indigenous water resources from the Moon and Mars is vital for concrete mixtures in space construction. Studies must explore the extraction, storage, and integration of water from ice deposits into cement formulations, addressing the challenges of operating in extreme conditions. This includes evaluating the impact on concrete properties, crucial for building durable structures in extraterrestrial environments and supporting long-term space habitation.
2) Development of high performance and ultra-high performance space concrete: Efforts should be directed to the development of high performance and ultra-high performance concrete formulations tailored for the extreme conditions of outer space. This includes enhancing strength, durability, and resistance to extreme temperature variations. Research should focus on optimizing material formulations and leveraging local resources to meet these elevated standards, ensuring reliability and long-term stability in the construction of space habitats and infrastructure.
3) Durability studies: Durability studies on space concrete are of great concern, focusing on its behaviour in the vacuum of space, resistance to extreme temperatures, solar and cosmic radiation, seismic activities, and micrometeorite impacts. Research should also explore its efficacy as a protective barrier against electromagnetic radiation, assess long-term stability and aging, and identify unique degradation mechanisms like outgassing or reactions with spaceborne chemicals.
4) Space structure research: Space structure research demands blending extensive experimentation with advanced analytics to surpass current limitations. This approach focuses on innovation in design and refinement of analytical methods to address the unique challenges of space, aiming for breakthroughs in efficiency, resilience, and suitability for extraterrestrial environments. Investigating the effect of low gravity and vacuum conditions on space structures is crucial for ensuring their durability and performance in extraterrestrial environments. Furthermore, integrating 3D printing technology into this research domain opens new horizons for constructing complex structures in space, dramatically transforming the potential for human habitation and exploration beyond Earth.
5) Safety analysis for space structures: At present, there is a lack of specific investigation into the required safety levels for spatial structures, including target probability of failure and design working life. This gap highlights the need for comprehensive safety analysis like that used for Earth structures, encompassing risk assessments, defined safety margins, redundancy strategies, and maintenance planning.
6) Energy and maintenance innovations: Innovative energy solutions and repair strategies are essential for the efficient manufacturing and sustainability of space concrete structures. Utilizing solar or nuclear power alongside advanced energy conversion technologies can

optimize concrete production. Moreover, space self-healing concrete technologies advance infrastructure maintenance by autonomously repairing damages, marking a significant leap towards sustainability.

CRediT authorship contribution statement

Chengqing Wu: Writing – original draft, Resources, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Jun Li:** Writing – review & editing, Investigation. **Ruizhe Shao:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Zizheng Yu:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation.

Declaration of Competing Interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In doing so we confirm that we have followed the regulations of our institutions concerning intellectual property.

We understand that the Corresponding Author is the sole contact for the Editorial process (including Editorial Manager and direct communications with the office). He is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs. We confirm that we have provided a current, correct email address which is accessible by the Corresponding Author and which has been configured to accept email from Chengqing.wu@uts.edu.au.

Data availability

Data will be made available on request.

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