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In-situ resources for infrastructure construction on Mars: A review

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A B S T R A C T

It is widely proposed that Mars will be the next destination for human to expand colonization. However, building up a habitat requires collective work from multiple disciplinaries of which engineering is an indispensable part. Similar to infrastructure construction on the earth, the technical issues of raw material, space construction technologies has to be addressed before human inhabitation. Based on the history of Mars exploration missions and a series of current Mars exploration results, this paper introduces the environment conditions on Mars, reviews the research of the in-situ resources which can be further utilized for infrastructure construction on Mars and proposes feasible infrastructure construction technologies. This paper provides an overview of in-situ construction material resources, possible construction methods and requirements for materials in extreme environment, which can be a valuable reference for future Mars exploration and possible infrastructure construction on the Mars.

Contents

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Introduction

Background

Mars is one of the planets in the Solar system and the fourth planet from the Sun. Due to the fact that the rotation period of Mars and the tilt of the rotational axis relative to the ecliptic plane are similar to those of earth, its days and seasons are much similar to those of Earth (David Alderton, 2021; Ziyuan and Fugen, 2012; ESA, 2010). These characteristics of Mars and its unique topography and landforms have aroused strong interest in Mars exploration and the possibility of future Martian immigration. So far, Mars is the planet most understood by humans other than the Earth. More than 30 probes had reached Mars and conducted detailed surveys on Mars to obtain a large amount of valuable data and images (Ziyuan and Fugen, 2012). In the future, the Mars exploration missions of various countries worldwide will continue to advance, aiming to further explore the external environmental conditions and internal structure of Mars, and lay the foundation for further realization of human mission to Mars.

History of exploration of Mars

Mars exploration started in 1960 when the Soviet launched the first probe Mars 1960A, which failed but marked as the beginning of human exploration of the Red Planet. In 2011, Ouyang et al. (Ziyuan and Fugen, 2011) summarized the Mars missions from the 1960s to 1990s. During that period, Mars exploration mainly took place in the United States (8 launches, 6 success) and the Soviet (15 launches, 1 success). In 1971, the Mariner 9, part of the National Aeronautics and Space Administration (NASA) Mariner Program, successfully entered orbit around Mars for the first time, took high-resolution photographs of satellites of Mars for the first time, and worked in Mars orbit for nearly a year (NASA, 2011). At the end of the 20th century, the U.S. "Mars Pathfinder" was one of the most successful Mars exploration missions in history, this mission carried in-depth analysis on the Martian atmosphere, climate, and geology and the composition of its rocks and soil (Cook and Spear, 1998; Thomas et al., 2011).

In the 21th century, with the progress and innovation of space science and technology, Mars exploration has received more attention. Many countries have made or are planning their programs towards Mars, among which are the U.S., Russia, European Space Agency (ESA), China, Japan and India (Wikipedia Exploration of Mars, 2021; Wikipedia SpaceX, 2021; National Geographic, 2009). In the early 2000s, the U.S. and ESA carried out their missions to Mars respectively. April 7, 2001, the U.S. launched the Odyssey, which is still in orbit, using spectrometers and a thermal imager to detect evidence of potential water and ice, as well as studying the geology and radiation on Mars (Wilson et al., 2018). In 2002, Odyssey firstly discovered that there may be abundant ice in the near-surface layers of Mars. In 2004, ESA also announced that its "Mars Express" probe had discovered the presence of frozen water in the south pole of Mars (Encrenaz and Sotin, 2005). Till Sept 2020, a discovery is reported based on MARSIS radar studies, of a three more subglacial lakes on Mars (Lauro et al., 2021). In 2004, the US President George W. Bush. proposed human exploration to Mars as the ultimate goal of future space exploration. In the U.S., currently there are multiple active plans and programs to put humans on Mars within the next ten to thirty years: In 2002, Elon Musk established the SpaceX, aiming at reducing the cost of space transportation and developing a rapid reusable launch system (Wikipedia Exploration of Mars, 2021; Wikipedia SpaceX, 2021). On 30 May 2020, SpaceX successfully launched two NASA astronauts into orbit on a Crew Dragon spacecraft, making it the first private company to send astronauts to the International Space Station (ISS). However, because of the current COVID-19 pandemic, proper quarantine procedures were taken to prevent the astronauts from bringing COVID-19 aboard the ISS (Masunaga, 2020). In 2015, NASA issued its official plan for human exploration and colonization of Mars, which was named as "Journey to Mars", as shown in Fig. 1. The plan operates through three distinct phases including Earth Reliant, Proving Ground and Earth Independent. In 2016, China launched its first Mars exploration mission, and successfully delivered the Tianwen-1 directly into the Earth-Mars transfer orbit in 2020. The Tianwen-1 entered Martian orbit successfully in February 2021 and will study the magnetosphere and ionosphere of Mars along with other climate characteristics (Zou et al., 2021).

Till February 20th 2021, Mars is host to eleven functioning spacecraft: eight in orbit and three on the surface, as shown in Table 1, and the landing sites of various Mars rovers are presented in Fig. 2.

Objectives

It is widely proposed that Mars will be the next destination for human inhabitation. However, building up a habitat requires collective work from multiple disciplinaries, of which engineering is an indispensable part. Similar to urban construction, the technical issues including raw material development, space construction technology and intelligent maintenance must be addressed before human inhabitation. The objective of this paper is to review a series of current Mars exploration results and focus on the research about the in-situ resources which can be further utilized for infrastructure construction on Mars, feasible infrastructure construction technologies are proposed as well. This paper provides an overview of Mars in-situ engineering resources, possible construction methods and prospects which can be a valuable reference for future infrastructure construction on Mars.

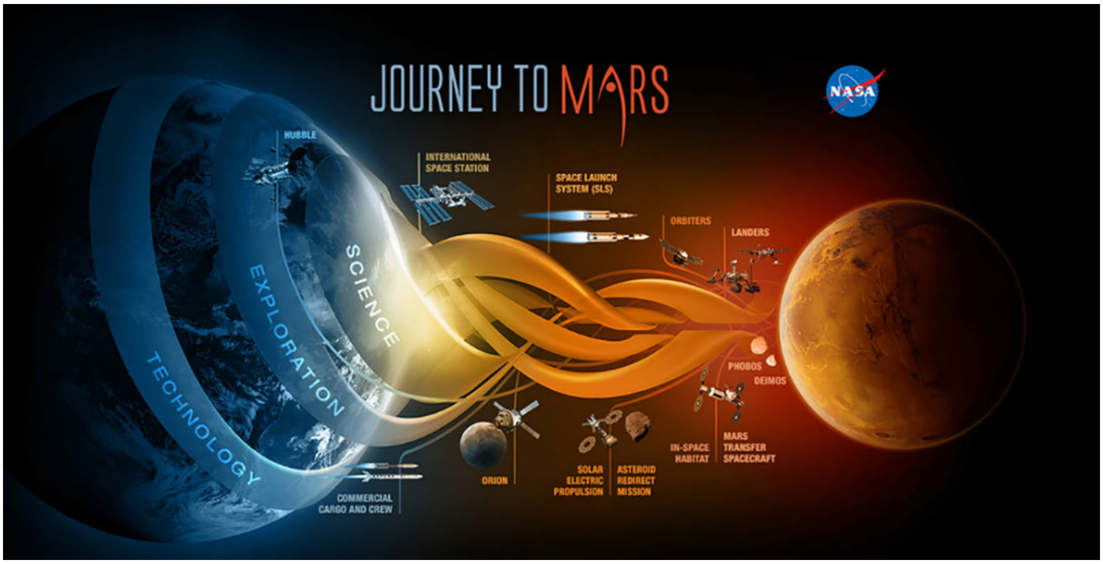

Fig. 1. Journey to Mars by NASA (NASA).

Table 1
List of current spacecraft towards Mars.

Name	Location	Nationality	Launched Date	Status
Mars Odyssey	In orbit	United States	2001.04.07	Operational 2001–2025.
Mars Express	In orbit	ESA	2003.06.02	Operational 2003–2026.
Mars Reconnaissance Orbiter	In orbit	United States	2005.08.12	Operational
Mars Science Laboratory Curiosity	Surface	United States	2011.11.26	Operational
Mars Orbiter Mission	In orbit	India	2013.11.05	Operational
MAVEN	In orbit	United States	2013.11.18	Operational
ExoMars Trace Gas Orbiter	In orbit	ESA/Russia	2016.03.14	Operational
InSight	Surface	United States	2018.05.05	Operational
Al-Amal	In orbit	United Arab Emirates	2020.07.20	Operational
Tianwen-1	In orbit	China	2020.07.23	Operational
Perseverance rover	Surface	United States	2020.07.30	Operational

Note: By February 20th 2021, in order of launched date.

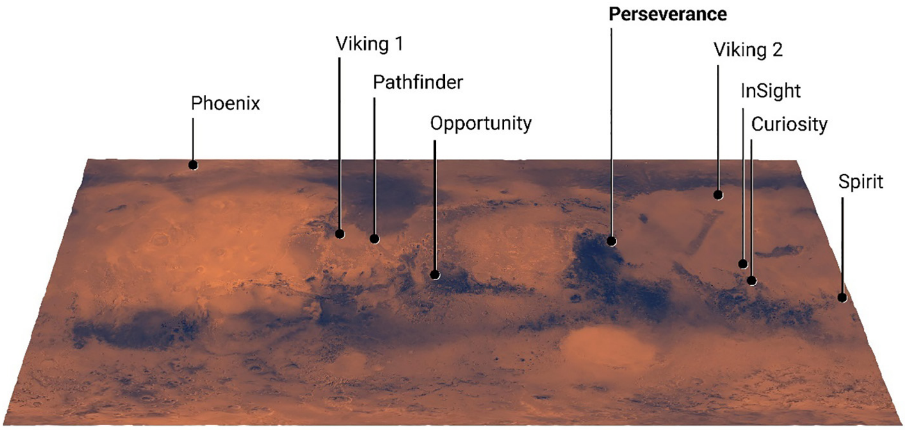

Fig. 2. Mars landing sites in history (Till 16th, December 2020) (Photojournal, 2020).

Mars environment

Landforms and geology

Kamps et al. (2020) calculated the Martian surface type map based on compact reconnaissance imaging spectrometer (CRISM) multispectral mapping mode data through clusters method. Fig. 3 presents the Martian surface is mainly composed of dust covered region (yellow) and southern highlands (pink). The main landforms include plain, basin, volcano, mountains, canyons and etc. Putzig and Mellon (2007) used improved thermal model and thermal inertia derivation algorithm to process temperature emissivity separation (TES) of three Mars years, and they found thermal behaviors of most regions dominated by geology layers. Duricrusts or desert over fines distributed in mid-latitudes while dust-covered rock, soils with shallow ice distributed in polar regions (Putzig and Mellon, 2007).

Bibring (2005) discovered the composition diversity in small scale on Martian surface based on the observation of OMEGA, and found mafic iron-bearing silicates in northern and southern crust, ices and frosts in the north polar cap, and thin carbon dioxide–ice on south polar. Odyssey discovered the Martian surface is dominated by basalt, some of which are rich in olivine (Christensen et al., 2003). The Mars rover InSight explored the structure beneath the surface, which is dominated by red dust, regolith below, and large chunks of rock below, shown in Fig. 4 (Golombek et al., 2020). It also detected Mars is a seismically active planet, but observed earthquakes of magnitude was less than 4 mW (Banerdt et al., 2020).

Atmosphere composition

The composition of the atmosphere of Mars is different from that of Earth. In Table 2, the atmosphere of the earth is dominated by 78.08% nitrogen (N_2) and 20.59% oxygen (O_2), while the atmosphere of Mars is composed of only 2.59% nitrogen

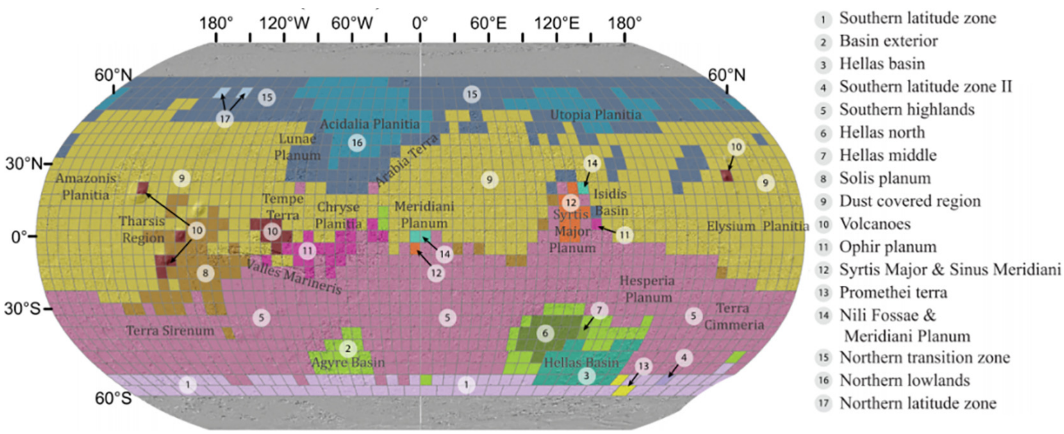

Fig. 3. Global surface types based on hierarchical clustering analysis (Viviano-Beck et al., 2014).

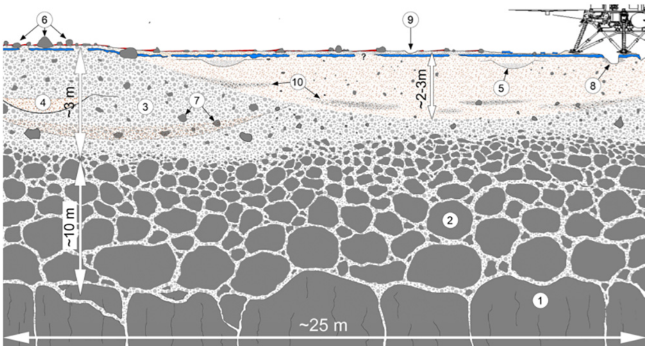

Fig. 4. Interpretive cross section of the shallow subsurface beneath the InSight lander (Golombek et al., 2020).

Table 2
Major atmospheric compositions in Mars and Earth.

Major atmospheric compositions	Mars (%)	Earth (%)
CO_2	95.1	M*
N_2	2.59	78.08
Ar	1.94	M*
O_2	0.16	20.95
CO	0.06	M*

Note: M* means the composition is minor.

and 0.16% oxygen. The largest proportion of gas is carbon dioxide (CO_2), which is continuously transformed between the dry ice and gas during the temperature variation. At the same time, due to the gravity on the surface of Mars is only 38% of that of the earth, more gas escapes. This resulted in the low average pressure on Mars, 0.636 kPa, while on the earth it is 101.325 kPa (Williams, 2004). Due to the seasonal CO_2 condensation at the polar regions, the Martian pressure varies 20% in each year (Leovy, 2001).

Climate

The distance between Mars and the Sun is 2.28 million kilometers, which is 1.5 times the distance between the sun and the Earth. Thus, 586.2 W/m^2 solar radiation received by Mars is less than 1361.0 W/m^2 solar radiation received by the earth (Leovy, 2001). This leads to the average temperature of Mars is lower than that of the earth, and the temperature difference is huger, relatively. The average temperature on the surface of Mars is −63 °C with a maximum daily temperature difference of 60 °C, while the average temperature on Earth is 15 °C with a maximum daily temperature difference of 30 °C (Williams, 2004).

In-situ resources for infrastructure construction on mars

In-situ resource utilization (ISRU) is the practice of collection, processing, storing and use of materials found or manufactured on other astronomical objects that replace materials originated from Earth. Research have shown that ISRU can provide materials including water, rocket propellant and construction materials (Sanders and Larson, 2011; Naser, 2019a, 2019b; Starr and Muscatello, 2020). Civil engineering and surface construction is one of the main areas of ISRU. This part mainly discusses the research on construction materials and their possible utilization.

Martian soil

Definition

Both multi-source remote sensing detection and in-situ detection data show that the surface of Mars is covered with a large amount of unconsolidated or weakly consolidated weathered material. Currently, the definition of this material varies, mainly including: regolith, aeolian or fluvial deposit, sediment, dust, and soil. In 2020, Certini et al. (2020) emphasized the need to unify the current terminology from the perspective of the composition and formation of Martian soil and considered it appropriate to use the term "soil" in preference to denote unconsolidated sediments on Mars. However, since limited information is known to draw a sufficiently representative picture on Mars, the detailed classification of the soil needs further research. The Martian soil, as shown in Fig. 5 would presumably be applied as aggregates of construction materials after being sifted. So far, no Martian samples have been returned to Earth, however the soil has been studied remotely with the assistance of rovers and orbiters (see Fig. 6).

Fig. 5. Martian soil (Photographed by NASA's Curiosity Mars rover, 2014) (Photojournal, 2014).

Fig. 6. Martian soil simulant: JSC MARS-1A developed by NASA's Marshall Space Flight Center (MSFC).

Martian soil simulants

Martian soil can be utilized on Mars only after it is synthesized on Earth for testing and development. Therefore, researchers are focusing on simulating Martian soil based on the analysis from the various Mars spacecraft. On the one hand, the simulated soil can be used to meet scientific research needs: such as astrobiology experiments, international space station experiments, wind tunnel experiments, infrastructure development, etc. On the other hand, it can be applied for the landing, moving and drilling test experiments of the probe on the surface of Mars.

Traditional formation methods of Martian soil simulants include whole-rock simulation and single mineral simulation. The whole-rock simulation method usually selects rocks with similar mineral and chemical composition as the simulated soil. The single mineral simulation method selects a single mineral as the raw material, or selects different minerals as the raw material according to the material composition of the simulated soil. After drying, the raw materials are crushed and screened into semi-finished products of different sizes, and then mixed according to the characteristics of the simulated objects. In 2011, Gouache et al. (2011) from ESA replicated three types of soil on the Martian surface using commercially available terrestrial materials, the soil were further tested to determine their physical characteristics. In 2017, Chow et al. (2017) demonstrated that Martian soil simulant Mars-1a can be directly compressed at ambient into a strong solid without additives, highlighting a possible aspect of complete Martian in-situ resource utilization. In 2018, Scott and Oze (2018) produced Martian soil simulant representative of material identified in the Columbia Hills region of Gusev Crater using olivine basalt and volcanic glass from Banks Peninsula, New Zealand. In 2020, Liu et al. (Hansheng et al., 2020) systematically reviewed the research progress of typical simulated Martian soil worldwide, and proposed that it is necessary to further develop various types of Martian soil for both research and engineering use.

The United States, ESA and Russia are more advanced in the soil formation technologies, while China is still in its infancy. Currently, there are more than 40 types of Martian soil simulants covering different parts on the surface of Mars. In addition to the typical basaltic, they also include acidic, alkaline, clayey, mudstone, perchlorate, chloride, sulfate, carbonate, hematite and other pyrogenic regolith (Xingjie et al., 2016). A number of Mars sample-return missions (MSR) are being planned by the U.S., Russia, China and Japan (Chang, 2020; Yan et al., 2018), which would allow actual Martian soil to be returned to Earth for more advanced analysis.

Basalt

Basalt is also a common rock on the surface of Mars. Basalt is a type of igneous rock formed from the cooling of lava rich in magnesium and iron exposed at or very near the surface of a terrestrial planet (Craddock and Golombek, 2016; Kading and Straub, 2015). In 2000, Bandfield et al. (2000) applied the TES data of the Mars Global Probe (MGS) to determine the composition and distribution of the low albedo area on Mars, and proposed that the area was consisted of basalt composed of plagioclase and clinopyroxene and andesite composed of plagioclase and volcanic glass, as shown in Fig. 7. In 2007, Rogers and Christensen (2007) categorized the rocks on the surface of Mars into 4 categories: lime-ash basalt rich in high silica glass, pyroxene basalt containing olivine, lime-ash basalt containing olivine and lime-ash basalt using TES. In 2015, Kading and Straub (2015) described a prospective mission that the structures could be constructed utilizing 3D printing of the common Martian in situ resource basalt.

Basalt could be widely applied in construction (e.g. as building blocks or in the pavement materials), making cobblestones and decorative crafts. Heating and extruding basalt produces stone wool, which is a type of thermal insulation material. However, similar to Martian soil, work must be conducted on the characterization of several basalt composition from Mars on land to better understand its utility in the Martian environment.

Volcanic ash

There are many volcanic landforms on Mars. Large shield volcanoes are mainly distributed in the Tharsis Bulge and Elysium Bulge highlands. In an explosive volcanic movement, solid rocks and molten slurry are broken down into fine particles to form volcanic ash. The reason why Mars is red is that a large amount of iron-containing volcanic ash cover the surface of the planet in ancient times, and turned red after oxidation. The "Mars Express" probe photographed volcanic ash deposits on the Meridiani Planum, as shown in Fig. 8, mainly composed of pyroxene and olivine ores. Volcanic ash can react with lime (CaO) at room temperature and in the presence of water to form hydrates with hydraulic gelling ability. Therefore, it can be used as a mixing material for cement and an admixture for concrete after grinding.

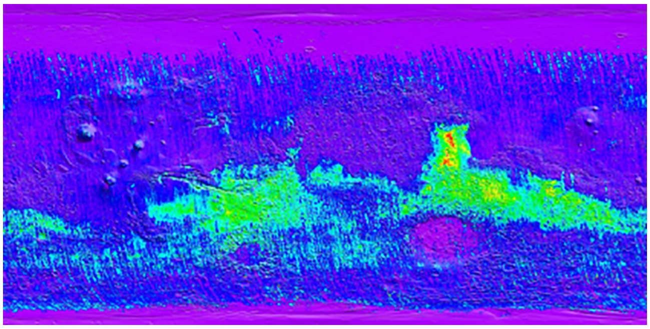

Fig. 7. Basalt distribution on southern highlands (represented in green) (Bandfield et al., 2000).

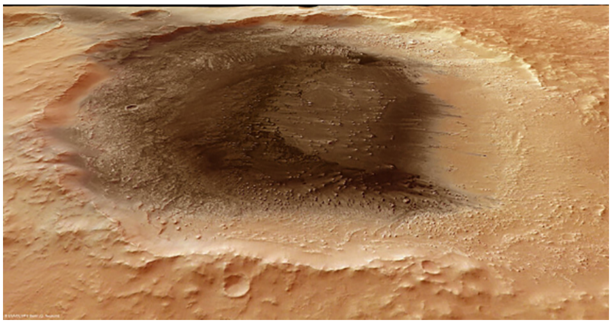

Fig. 8. Volcanic ash deposits on Mars's Meridiani Plain (ESA, 2010).

Compared with Portland cement, pozzolan cement (cement with volcanic ash) has a small specific gravity, lower hydration heat, better corrosion resistance but greater water demand and shrinkage and poorer frost resistance (Djobo et al., 2017). Environmental conditions have a significant impact on the hydration and strength development of pozzolan cement, and the humid environment is conducive to the strength development of cement. Pozzolanic cement is generally suitable for concrete projects in underground, water and humid environments, but not suitable for dry environments, freeze–thaw cycles, alternating dry and wet conditions, and projects that require high early strength.

Martian concrete

The successful application of concrete on Mars need a comparative review of existing in-situ resources. To make concrete in the Martian environment, the first thing is to explore potential raw materials for the production of concrete including binder, water and aggregates. As introduced previously, Martian soil can be used as aggregates. Since recent explorations have shown that ice exists on Mars, therefore water can be condensed or recovered (Rickman et al., 2019; Lauro et al., 2021). As for feasible binder solutions, cement is commonly used as the binder on earth, the main chemical components of Portland cement are calcium oxide, silicon dioxide, iron oxide, aluminum oxide and water. Cement can harden in the air or in water, and can firmly bond sand, stone and other materials together, which makes it favorable construction materials. Therefore, if similar material could be found in space, concrete production would be possible.

Since 2006, the NASA team has been investigating many types of binders including sulfur and polymer and mixed them with regolith in space, for additive construction applications (Sanders and Larson, 2011). In 2016, Wan et al.(2016) combined regolith and molten sulfur binder to develop Martian concrete, and found that this concrete had higher strengths and was more feasible for construction under atmospheric pressure and temperature range on Mars. NASA now has broadened its scope to include other binders, such as sulfur, polymer, that can be produced on planetary surfaces. In 2017, Ordonez et al. (2017) developed Ordinary Portland Cement (OPC) and the magnesium-oxide-based Sorel cement using binders to test their hypervelocity impact resistance, the results showed that aggregate makeup affected the resistance of the material to impact. Additively-emplaced planetary construction materials like non-vesicular crushed basalt should be developed as aggregate. In 2018, Scott and Oze (2018) pointed out that olivine hydrolysis (i.e., serpentinization) and related products including magnesite ($MgCO_3$) could be developed to produce a type of Mg-based cement and molecular hydrogen (H_2) as an energy resource. Reches (2019) systematically listed potential applicable binder types existing on Mars including bassanite or gypsum, opal and ferric sulfate etc. Fig. 9 presents the concrete formulations illustrating the binder, aggregates made therefrom in Reches's review (Reches, 2019). Processing and curing methods for Martian concrete were also proposed for the low-temperature, low-gravity, low-pressure conditions on Mars (see Fig. 10).

It can be referred that there is a lot of on-going research on the formation of concrete using lunar regolith. Binder alternatives include resins, epoxies and polymer matrices. Also, there is a type of concrete derivative developed using geopolymers. Geopolymers are materials produced through reaction between an aluminosilicate precursor and alkaline solution. The

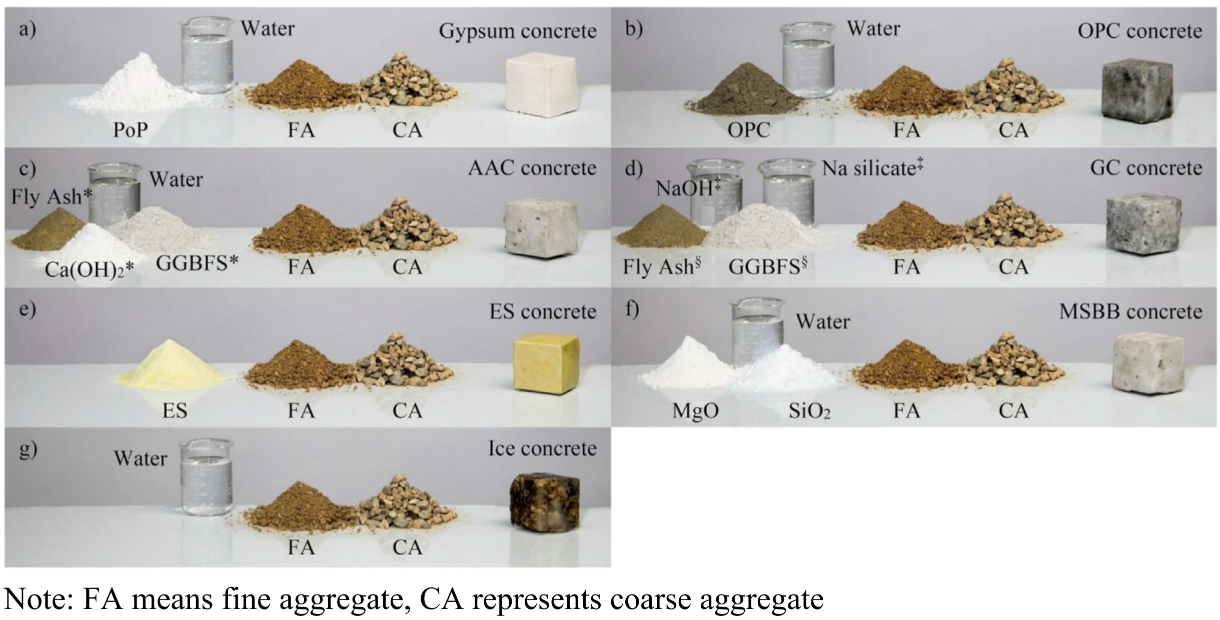

Fig. 9. Applicable compositions of Martian concrete (Reches, 2019) (From left to right are binders, aggregates and molded concrete specimens). Note: FA means fine aggregate, CA represents coarse aggregate.

Fig. 10. Mars Observer with solar pannels in Mars Orbit (JPL).

research of Montes et al. (2015) showed that geopolymer binders could be produced from regolith and such binders could reach a compressive strength ranging from 16.6 to 33.1 MPa. A similar research could be conducted to investigate the potential of the Mars regolith to be used as source material for geopolymerization.

Metals and alloys

In 2009, Fairen et al. (2009) modeled the freezing and evaporation processes of Martian fluids from the weathering of basalts, and found a significant fraction of Si, Fe, S, Mg, Ca, Cl, Na, K and Al remain in the liquid state under cold temperatures (below 273 K). In 2018, Naser and Chehab (2018) proposed that while metals are not readily available on Mars, the elements existing could be mined and used to produce metals and alloys. In 2019, Naser (2019a) and Naser (2019b) further listed that among the various metals, magnesium, iron and aluminum are suitable for use in early development on the Mars due their mechanical properties and usage in steel-based terrestrial construction.

Energy sources

In fact, many in-situ resources exploiting and processing activities involve complex mechanical operations and energy conversions, and most of them use electricity as main energy source. According to Wang et al.'s (Lingyun et al., 2020) review, the advanced energy technologies applied in Mars exploration currently are the isotopic thermoelectric generator and solar panels. Most of the operational Mars rover and probes use solar energy and nuclear power as energy sources (Lu and Xianghua, 2020). In addition, intelligent power distribution and management and energy storage technology have gradually received more attention.

1. Isotopic thermoelectric generation: The thermoelectric conversion effect is used to convert the decay heat of radioisotopes into electricity. Despite the low efficiency and high cost, this energy generation method has a high energy-quality ratio and long service life. Since this method will not be affected by the external environment, since it has been successfully applied in military reconnaissance satellites and communication satellites. It remains the nuclear power source of choice for interstellar missions such as the lunar surface and deep space. At present, the United States is still the leader in the field of isotope thermoelectric generation.
2. Solar panels: Refers to a power system that uses single solar cell to form a square array to convert light energy into electricity. The two main fuctions of solar panels on spacecraft are providing power to run the sensors and to propel spacecraft (namely solar-electric propulsion). To date, solar power has been widely applied for spacecraft operating around the Mars, e.g. Mars Global Surveyor and Mars Observer. At present, solar energy is only used to provide energy for various Mars probes. In the future, will it be possible to directly focus sunlight and convert solar energy into power for mechanical manufacturing? In 2017, ESA applied concentrator combined with 3D printing to develop the lunar soil bricks at 1000 °C, verifying the feasibility of solar 3D printing engineering materials (Meurisse et al., 2018b). Could similar research be done on Mars? Gu et al. (Caixin et al., 2018) calculated the distribution of solar energy during each Martian revolution, and took into account factors such as atmospheric scattering and sandstorms. They believed that the dust storms on the Martian surface would easily cover the solar panels, leading to a significant reduction in the efficiency of power generation. This problem could be tackled firstly by studying the application of solar energy in the desert on the Earth.

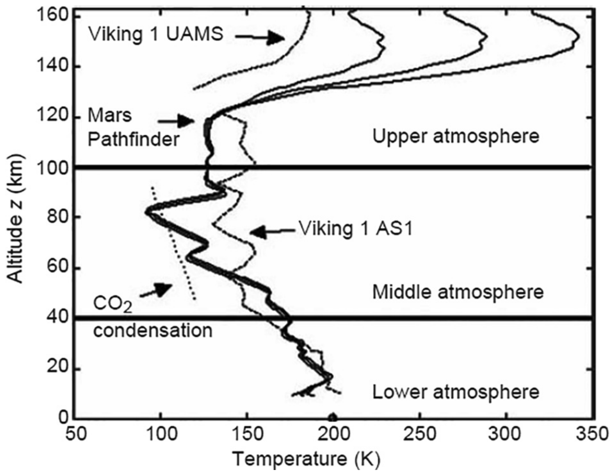

Fig. 11. Martian atmosphere temperature profiles measured by Mars rovers (Barlow, 2008).

3. Potential in-situ energy support strategies: Relying on solar cells or isotopic thermoelectric generators will not provide sufficient and continuous energy supply. Therefore, only the development of in-situ energy supply technology is the key to the implementation of various tasks on the surface of Mars. Xie et.al (Heping et al., 2020a, 2020b) took the advantage of the temperature difference between the lunar regolith and rock constant temperature layer and the lunar surface and proposed a conceptualization of in-situ energy support technology. In their research, lunar thermoelectric materials thermovoltaic power generation technology and magnetic levitation power generation technology were developed to continuously convert the radiant energy on the lunar surface during the day and the heat energy on the lunar soil at night into electricity. Similarly, the surface temperature on Mars varies greatly. For example, the daily temperature of the Viking landing site can vary up to 100 °C (Ziyuan, 2012). At the same time, due to the thin atmosphere of Mars, it is difficult to transfer the heat of solar radiation through atmospheric movement, resulting in a large difference between the air temperature and the ground temperature (Barlow, 2008), as shown in Fig. 11. If this temperature difference can be utilized, it can also be used as an in-situ energy source.

In addition, the detection results of the surface wind speed on Mars by multiple Mars probes such as Viking, Mars Pathfinder, and Curiosity found that the wind speed on the Martian surface was generally 2–7 m/s, but 40 m/s storms were also recorded (Savijarvi et al., 2020). Differences in atmospheric pressure and temperature along the longitude of Mars can cause huge dust storms on the planet's surface. Dust and dust storms on the surface of Mars can seriously affect Mars exploration and solar energy utilization, but on the other hand, they are also potential wind resources.

The utilization of Martian wind resources is mainly to convert part of the kinetic energy of moving atmospheric particles into electricity, thermal energy or mechanical energy. Zhang et al. (Ning et al., 2020) focused on a comprehensive analysis of the utilization of Martian wind resources, such as wind power generation and tumbleweed detectors. In the future, it is necessary to strengthen the detection of Martian atmospheric environment and wind conditions. To build wind power equipment on Mars, it is necessary to reduce the quality of the equipment as much as possible, and adopt new materials and new designs to enable the wind power system to adapt to the harsh climate conditions of Mars such as low temperature and dust storms.

Existing energy sources can be combined with in-situ energy support strategies on Mars to realize realize the stable and continuous output of energy, as shown in Fig. 12.

Possible construction technologies on mars

In-situ resources must be processed and constructed into infrastructure that people can use and live in. In 2019, Reches (2019) proposed a concrete structure made from Martian concrete, as shown in Fig. 13, which presented the fact that concrete as we have known it on Earth would not be always viable on Mars.

Processing technologies

Martian soil processing technologies can draw lessons from those of the lunar regolith. Researchers (Zhenping et al., 2019; Rui, 2020) have proposed a lot of soil in-situ processing method, including technologies under normal temperature such as alkali activation and lunar concrete, and high temperature technology such as combustion synthesis, steam dry mix-

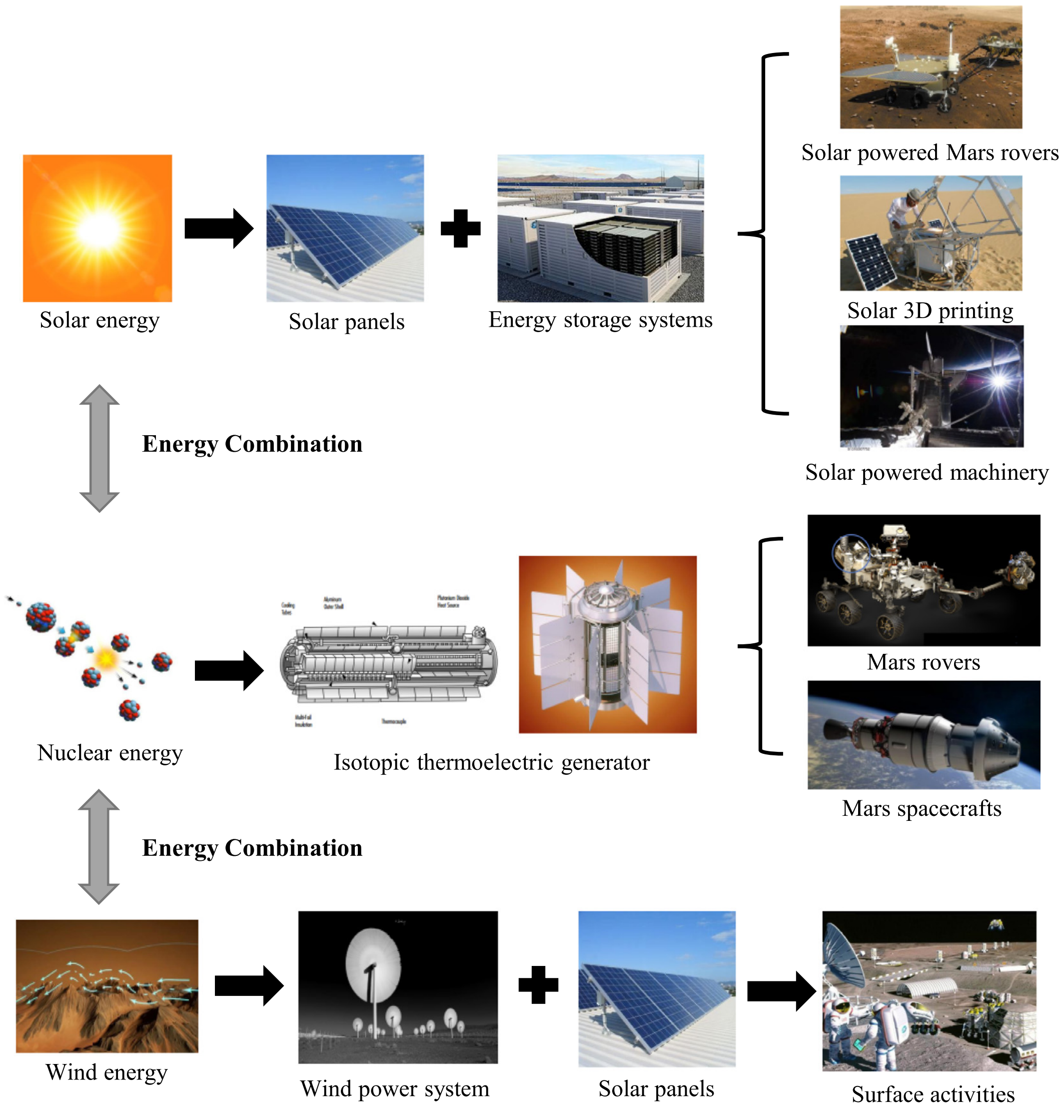

Fig. 12. Schematic diagram of in-situ energy support on Mars.

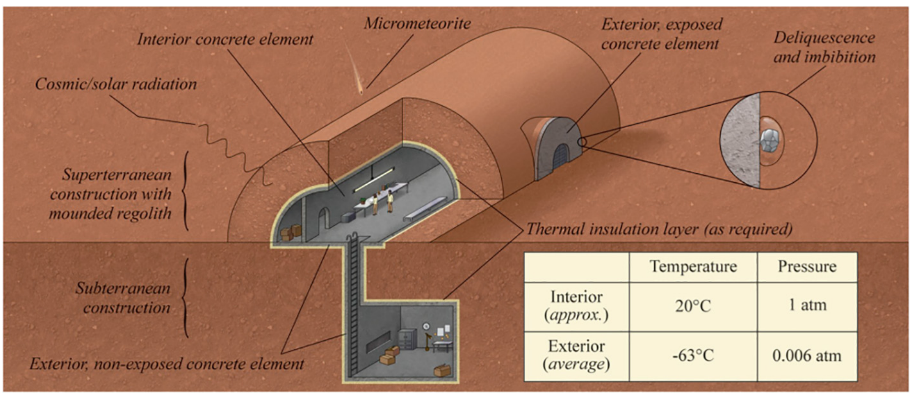

Fig. 13. Structures made from concrete with different key characteristics (Reches, 2019).

ing method and sintering method. There are also researchers (Lihua et al., 2011; Zhenping et al., 2019) proposed straregies including concrete with dry-mix/steam-injection (DMSI) method and sulfur concrete (which does not require water) as a non-hydraulic concrete-derivate construction material. Solar sintering can be considered as a dominant technology on the Mars due to the fact that lack of atmosphere allows higher degree of sunlight to reach the Mars surface. In 2018, Meurisse et al. (2018a) and Meurisse et al. (2018b) had formed lunar brick using solar energy and 3D printing, however the compression strength cannot meet requirements for construction on the Moon. In 2018, Naser and Chehab (2018) further summarized possible processing technologies of space construction materials.

3D printing

3D printing technology has been matured during the last ten years since its invention in 1970s, and additive construction is fulfilled by printing building structures in three dimensions. NASA and the United States Army Corps of Engineers (USACE) are pursuing additive construction for planetary surface infrastructure elements and concrete base housing and barriers, respectively. Therefore, 3D printing is of great significance in building human habitation in space. In 2014, NASA, and Made In Space Inc. (MIS), a US-based company, specializing in the engineering and manufacturing of three-dimensional printers for use in microgravity, cooperated to achieve the world's first space 3D printing. In 2015, Kading and Straub (2015) proposed that the 3D printer should be applied in a dome structure to maintain a pressurized working environment, as shown in Fig. 14. In 2017, ESA (Meurisse et al., 2018a, 2018b) used the concentrator equipment at the DLR (German Aerospace Centerin Cologne to prepare several lunar bricks layer by layer at 1000 °C, initially verifying the feasibility of 3D printing. Wang (Rui, 2020) reviewed the development of 3D printing technology for lunar regolith, and pointed out that energy conversion efficiency, extreme environmental conditions and manufacturing properties will be important research directions in the future.

Intelligent construction

In Kading's research (Kading and Straub, 2015), the IRSU was divided into two missions. One is an unmanned preparation mission which involved building the necessary infrastructure to support human life. Another is to send people to inhabit the infrastructures. Therefore, the intelligent and automated construction inevitably needs to be developed and applied. Taking into account the harsh conditions of the Mars, it is feasible to develop robots, fully automatic construction and engineering systems (equipment). These construction systems need to be able to investigate, update the structural design, and make real-time construction-related decisions. The use of intelligent autonomous robots for construction tasks on the Mars is very important for reducing the hazards of the harsh space environment to humans. Moreover, use of a swarm of robots, especially heterogenous robots with different specific functionality, might be a reasonable and natural way to mimic from human on the Earth (Tang et al., 2017, 2018, 2019)

At present, modern engineering construction on the earth can basically realize automatic control of machinery, includinglocation recognition of construction machinery, intelligent control of earthwork construction, intelligent paving, and compaction of roads, etc. These technologies are expected to be further implemented in the space environment. In fact, studies (Brooks et al., 1990) had paid attention to autonomous construction equipment and investigated the possibility of sending robots for space construction missions on the Moon. However, it should be noted that the robots and the machinery must be made from resilient materials as well.

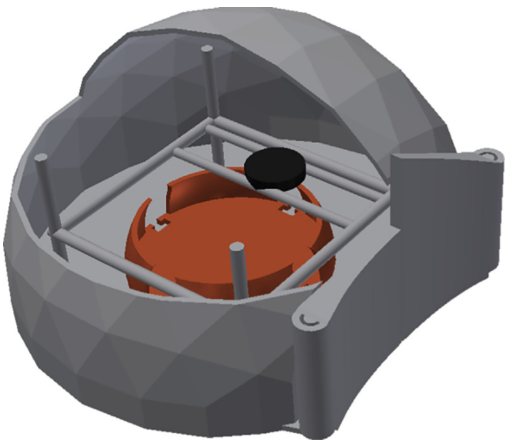

Fig. 14. 3D printer housed in the construction dome (Kading and Straub, 2015).

Challenges and opportunities

Current challenges

Construction materials and materials for energy conversion equipments in space must meet the following three requirements: resiliency, durability and economy.

- Resiliency: Construction materials are expected to perform in extreme environments of Mars with low pressure and cold temperature and other variable environmental conditions. For instance, the Martian temperature conditions require construction materials to be able to withstand high temperatures, low temperatures and large temperature differences, as well as meet the needs of human thermal insulation. In addition, meteorite impacts cannot be ignored. Currently, NASA's Additive Construction with Mobile Emplacement (ACME) project is investigating planetary construction materials and additively constructed materials for their resistance to hypervelocity impact.
- Durability: Materials used in additive construction have specific requirements such as the ability to be deposited in a specific predictable shape, the ability to support a superimposed layer after a period of time, the ability to bond to the layers above and below, and the ability to have structural integrity for use. Considering the harsh environmental conditions, it is necessary to ensure the strength of the material in the low temperature and low pressure environment, and to have the function of preventing strong ultraviolet radiation and solar radiation. A certain reflective material can be used to prevent the aging of the material and achieve duability.
- Economy: The reason for IRSU is that transportation from Earth to space is expensive and future research could consider the economic trade off between producing construction materials from in-situ resources on Mars and transporting necessary materials from the earth during the whole life cycle.

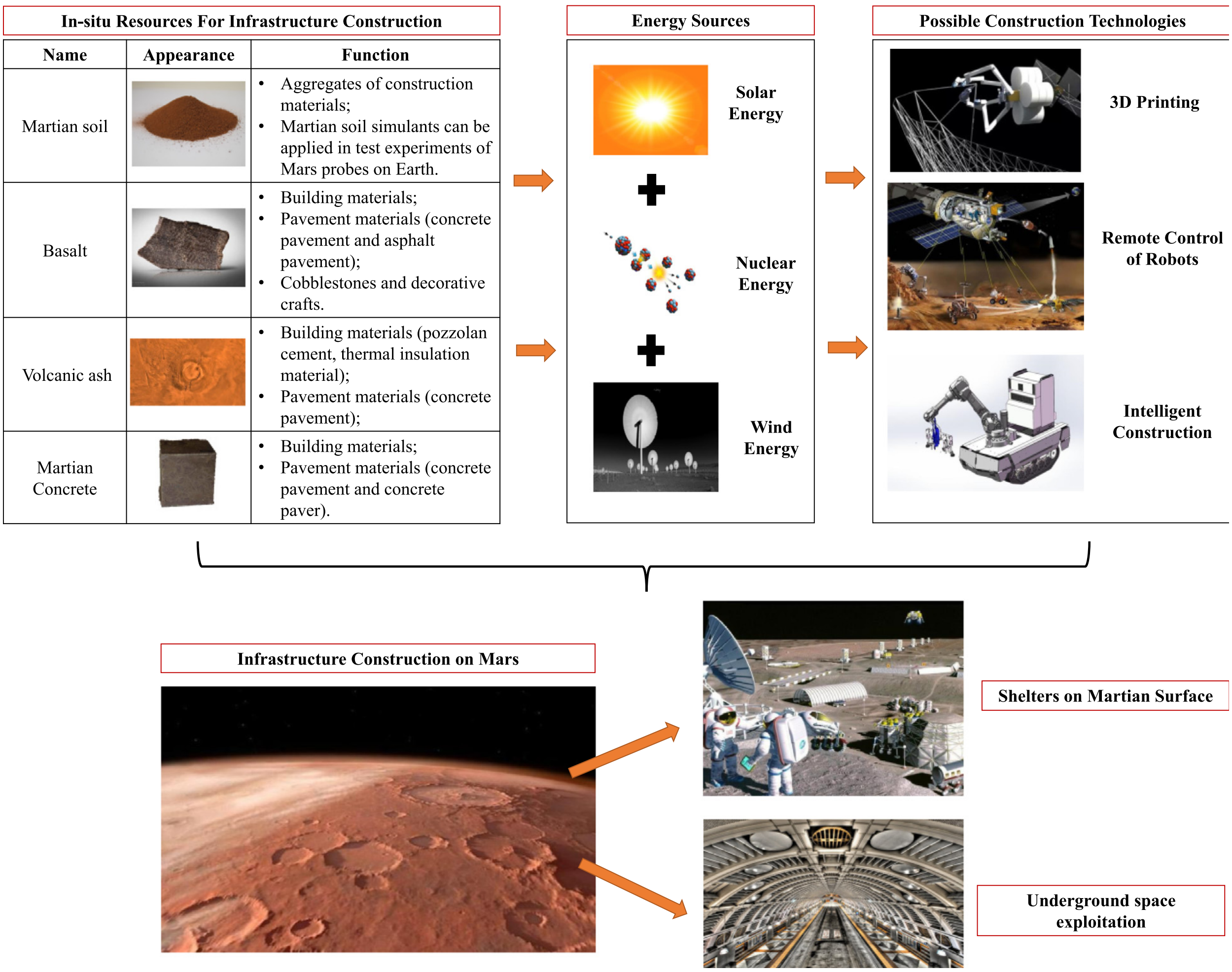

Fig. 15. Conceptualization of ISRU on Mars.

Future opportunities

The Martian soil, basalt and concrete material are among the most studied and feasible future construction materials for human mission to Mars. Meanwhile, the simulation of the Martian soil can also be applied for the synthesis and development of new materials for a wide range of industries on Earth. The concrete material along with its derivates are regarded with the highest potential for use in space construction. However, due to the limited research on Martian soil composition and environmental conditions, further work on ISRU for infrastructure construction is needed in the following aspects to exploit the potential of the journey to Mars, as shown in Fig. 15.

- Durable materials: Including further searching for in-situ resources which can be exploited and utilized on the surface of Mars, shallow underground layers, and deep underground spaces; research on material processing techniques suitable for the Martian environment; ensuring the strength of the material under low pressure and low temperature environment on Mars, and also resisting strong ultraviolet and solar radiation; ensuring the seismic resistance and impact resistance of building materials.
- Intelligent construction technologies: Including improving the efficiency of energy conversion; arranging machineries in space environment and ensuring the timeliness of remote control. At present, the space laser communication technology is widely studied to carry out the communication between the space shuttle and the ground.
- In-situ energy exploitation: Mars energy exploration is still in the self-sufficient stage. Nuclear energy and solar energy are the objects of development and utilization. In the future, energy sources that can be further developed as in-situ resources include nuclear energy, solar energy (thermal power generation) and wind energy. In view of the problem of Mars energy exploration, it is necessary to consider the deformation, aging and failure of the heat exchange components of the power generation system under extremely low temperature and alternating thermal load. The output of the power generation system may be discontinuous, which needs to be combined with energy storage technologies to realize the stable and continuous output of electricity. In the construction of the Mars habitat, energy requirements can be fulfilled with solar energy, nuclear energy and wind energy to provide a continuous and sufficient energy supply.
- Underground space exploitation: Below a certain depth of the lunar surface, the temperature remains constant, forming a constant temperature layer. Therefore, many researchers (Heping et al., 2020a, 2020b) have put forward a series of ideas for the utilization of the lunar constant temperature layer underground space. It is believed that with the continuous deepening of the exploration of Mars in the future, the development of the Martian underground space will also become the way to build human Mars colonies, including the Mars underground base, underground rail transit (based on electromagnetic technology), etc.

Conclusions

The discovery of water and possible life on Mars, the most Earth-like planet in the solar system, has stimulated the interest in further exploration of Mars. It's not clear whether Mars will be the next place for human to inhabit, while some assumptions and hypothesis may be necessary before the journey to Mars. Types of in-situ resources for infrastructure construction on Mars are proposed and relevant studies are reviewed in this paper. The conclusions are as follows:

1. In-situ resources including Martian soil, basalt and Martian concrete are among the most feasible future construction materials on Mars. However, these materials should endure low pressure, low temperature, large temperature difference and high space radiation, including Galactic Cosmic Rays and UV. As for Martian concrete, its molding process and maintenance methods under harsh environment conditions need in-depth study.
2. Nuclear energy and solar energy are the main objects of Mars energy exploration. In the future, energy sources that can be further developed as in-situ resources include nuclear energy, solar energy (thermal power generation) and wind energy. Energy combination and storage technologies are needed to realize the stable and continuous energy support.
3. Intelligent construction on Mars is inevitable since the damage of the Martian environment to human bodies remains a mystery. 3D printing can be applied to produce construction materials from in-situ resources on Mars. Robots with swarm robotics and automated management systems are needed to carry out the intelligent construction process, and human on Earth should be able to make real-time controls.
4. On the basis of finding the appropriate in-situ resources for construction and in-depth understanding of the Martian environmental conditions, the development of materials that fulfills the requirement of resiliency, durability and economy will be the following steps.

Conflict of Interest

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

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