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Materials and design concepts for space-resilient structures

Mohannad Z. Naser [a,*], Alaa I. Chehab [b]

[a] Civil and Environmental Engineering, Michigan State University, East Lansing, MI, United States
[b] Civil and Environmental Engineering, Wayne State University, Detroit, MI, United States

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ABSTRACT

Space exploration and terraforming nearby planets have been fascinating concepts for the longest time. Nowadays, that technological advancements with regard to space exploration are thriving, it is only a matter of time before humans can start colonizing nearby moons and planets. This paper presents a state-of-the-art literature review on recent developments of "space-native" construction materials, and highlights evolutionary design concepts for "space-resilient" structures (i.e., colonies and habitats). This paper also details effects of harsh (and unique) space environments on various terrestrial and extraterrestrial construction materials, as well as on space infrastructure and structural systems. The feasibility of exploiting available space resources in terms of "in-situ resource utilization" and "harvesting of elements and compounds", as well as emergence of enabling technologies such as "cultured (lab-grown)" space construction materials are discussed. Towards the end of the present review, number of limitations and challenges facing Lunar and Martian exploration, and venues in-need for urgent research are identified and examined.

1. Introduction

Humans are explorers by nature. Our curiosity continues to grow as, since the lunch of Apollo 11 Mission in 1961, we managed not only to explore nearby moons and planets, but also number of galaxies in search of an Earth-like destination that would be suitable for human colonization. In concurrence to searching for a prospect plant (or moon), modern concepts such as "Terraforming" (Earth-shaping) of space bodies have emerged. Terraforming is defined as the process of deliberately modifying a space body's atmosphere in terms of temperature, topography, or ecology to engineer an environment similar to that of the Earth [1]. Unfortunately, terraforming of a typical-sized plant (such as the Moon or Mars) can take thousands of years; and without a significant scientific breakthrough, terraforming of space bodies may not be practically possible [1]. Hence, most of the current research efforts are mainly directed towards further exploring of nearby planets and moons.

Due to their proximity to Earth, number of studies have pointed out the possibility of human life on the Moon and more recently on Mars without the need for terraformation [1,2]. These studies also agree on the fact that in order to provide a safe environment to humans, habitats (bases) not only need to withstand extreme space environment, but also need to be properly fabricated; preferably using in-situ space resources. Interestingly, analysis on lunar and Maritain soils has demonstrated that they contain an abundance of substances and elements that could potentially be used to produce construction materials [3,4]. Thus, number of studies have emphasized the importance of using in-situ materials [3,5,6]. This emphasis is triggered by the fact that it can cost up to $20, 000 to transport one kilo-gram of materials from Earth to Moon; a cost that can exponentially scale in the case of Mars [5]. Although utilizing space-native raw materials seems promising and promotes development of independent and sustainable space habitats, however characterization, processing, and fabrication of such materials under microgravity as well as hard vacuum conditions continues to be challenging [7,8].

Therefore, parallel studies were carried out during the last 50 years to advance our state of knowledge, in terms of material science and structural design, to allow development of space-native construction materials and space-resilient habitats [9–12]. Some of these studies have led to the development of advanced and specifically tailored construction materials ranging from derivatives of classical composites and metals/alloys, to those inspired by nature (bio-inspired materials, comprising of Earth or space native raw elements and compounds), and/or designed to possess special features such as self-healing and sensing abilities, [13–15]. Although other types of materials are currently being developed, researchers seem to converge on the fact that among all available construction materials, composite materials (such as concrete) could be the most suitable material for fabrication of space structures since, unlike

* Corresponding author.
E-mail addresses: nasermoh@msu.edu (M.Z. Naser), alaa.chehab@wayne.edu (A.I. Chehab).

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other construction materials, the performance of concrete under extreme conditions, i.e., radiation, elevated temperature, etc., has been well documented in terrestrial applications [3,16–18].

Whether human habitats are built using traditional, advanced, or space-native construction materials, these habitats, much like Earth-based structures, need to protect their occupants and provide them with a safe environment to live and function. Despite recent advancements in structural engineering, there is virtually no design or construction precedents for space habitats [19]. Given the extreme and harsh environmental conditions associated with the Moon and Mars, the design of safe space-resilient structures seem to be a unique challenge that requires in-depth investigation and interdisciplinary efforts. This is one of the main motivations behind this work.

This paper is also inspired by the National Aeronautics and Space Administration (NASA) recent announcement that Geodesy and Heat Transport (InSight) mission is scheduled to launch on May 2018, and for Mars landing on November 2018 [20]. This announcement also included a target deadline to send manned mission to Mars by 2030, and to start building future human habitats soon after. In essence, these announcements have started an inertia directed towards developing new materials, structural systems, and technologies to enable space exploration and colonialization within the next 10–15 years.

In support of these efforts, this paper presents a comprehensive survey that summaries past and most recent research findings, as well as identifies current limitations and technological needs associated with space colonization. More specifically, the present review addresses the effect of extreme and harsh space environments on properties of various construction materials. This review also explores feasibility of using available space resources to allow development of space construction materials and fabrication of structural components. Furthermore, structural–related design principles and number of concepts for “space-resilient” structural systems and infrastructure are highlighted. This review also highlights number of issues and challenges facing space exploration and venues in-need for urgent research.

2. Background on extraterrestrial exploration

Serious consideration was directed towards space exploration in the early 1900s due to the pioneering work of Tsjolkoysky [21] and Goddard [22]. Soon after that and during the Second World War (WWII), the Germans managed to launch the first rocket to ever reach the space (namely, V-2 rocket). After the end of WWII, the United States and the Soviet Union started their individual space programs. In 1957, the Soviets launched Sputnik 1, the first satellite, into space. Encouraged by the early Soviet success, the United States reorganized and expanded its space exploration efforts in 1958 with the commencement of NASA which began conducting space missions shortly after its establishment.

In April 12, 1961, Yuri Gagarin became the first human to orbit the Earth. Twenty-three days later, Alan Shepard Jr. became the first American to travel to space. After these successful missions, a series of major events took place. For example, the Soviets placed the first spacecraft that carried more than one person in orbit in 1964 and Russian cosmonaut Alexei Leonov became the first person to step outside a spacecraft in 1965. The space race reached its climax in 1969 when Neil Armstrong was the first man to land on the Moon. Since 1969, nearly twelve landings have been made on the Moon surface by the Soviets and the Americans, along with plentiful scientific operations.

In the mid-1990s, the discussion on space exploration was divided between those who wished to pursue Moon exploration and others who sought out shelter on Mars or nearby Earth-analog exoplanets. While it is clear that lesser energy, time, cost and technology are required for transportation to (and from) the Moon, it is of equal importance to note few major differences between Moon, Mars, and habitatable exoplanets i.e., Kepler-452b and Proxima- Centauri b (see Table 1). For example, one lunar day equals about twenty-seven days on Earth, while one sidereal day on Mars takes 24 h and 37 min [23]. Further, the gravity on Mars is double of that on the Moon, and Mars also has a better atmosphere which can provide better environment for shielding from space radiation. For brevity, the present paper does not address major differences between Moon, Mars, or exoplanets nor on discusses the alternative space bodies that are appropriate for human colonization, but rather directs interested readers to the following references [24–26].

2.1. Space environment

The outer space holds a multitude of environments and load actions that are primarily different than those on Earth such a high-energy charged particles, ultraviolet (UV) irradiation, meteoroids, orbital debris, etc. [30]. These actions can adversely affect behavior of construction materials and can also change fundamental aspects of loading and mechanics. In general, there are three main differences between Earth, Lunar and Martian environments. These differences pose critical challenges and are often grouped under 1) lack of atmosphere; 2) extreme radiation; and 3) differences in gravity.

For a start, the atmosphere of Earth is composed of a specific mixture of gases, primarily Oxygen (21%) and Nitrogen (78%), with very small amounts of Carbon Dioxide, Neon, etc. Unlike Earth, the Moon has a much smaller size (and correspondingly lower gravity) and technically does not have an atmosphere. On the other hand, the atmosphere of Mars is about 100 times thinner than the Earth, and mainly consists of Carbon Dioxide, Nitrogen and Argon [31]. This very thin atmosphere of the Moon and Mars forms a weak shield against meteorites and micrometeorites impact. Lindsey [32] noted that micrometeorites can reach a speed of 20–70 km/s. The impact effect of similar particles was studied by Toutanji et al. [33], wherein projectiles with a mass of 1.4×10^{-4} g were fired into representative specimens made of concrete at a speed of 5.9 km/s. The impact of such particles caused damages in the form of craters with 13 mm diameters. Such experiments, together with those carried out by Nealy et al. [34], demonstrate the devastating effects of meteorites impact, need for considerable protection measures from large–sized meteorites, and emphasize the use of durable and resilient construction materials.

The lack of atmosphere can cause other phenomena such as temperature fluctuations and low pressure. For example, temperature fluctuates on the Moon between −173 and 127 °C, while it remains particularly freezing on Mars at about −57 °C. The lack of atmosphere can also amplify adverse effects of vacuum. For a comparison, the hard vacuum of space has a magnitude ranging from 3×10^{-13} kPa on the Moon to 0.7 kPa on Mars (as compared to 101.3 kPa on Earth). Vacuum conditions can cause materials to outgas (releasing volatiles). Kanamori et al. [35] studied the long-term exposure of mortar to vacuum. Despite the fact that some vacuum-exposed mortar specimens achieved higher strength than

Table 1
Key differences between Earth, Moon, Mars, and other exoplanets [27–29].

Parameter	Earth	Moon	Mars	Kepler-452b	Proxima- Centauri b
Total Mass Compared to Earth (%)	–	1.2	10.7	190	80–110
Approximate Distance from Earth (km)	–	3.84×10^5	2.25×10^8	1.32×10^{16}	3.9×10^{13}
Day Period (hrs)	23.9	655.7	24.7	–	–
Revolution Period (days)	365.3	27.3	686.9	384.8	11.2
Average Surface Temperature (°C)	13	−30	−57	−8	−39
Atmospheric Pressure (kPa)	101.3	negligible	0.7	unknown	unknown