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# Advances in Solidification Technologies of Lunar Regolith-Based Building Materials Under Extreme Lunar Environments

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**Abstract**

With the launch of the Artemis program and the International Lunar Research Station project, the construction of lunar bases has emerged as a global research focus. In situ manufacturing technologies for robust lunar regolith-based building materials are critical to ensuring building safety under the Moon's extreme environmental conditions. This paper reviews the relevant advancements in two areas: solidification technologies for lunar regolith-based construction materials and simulation techniques of extreme lunar environments. This review reveals that, although significant advancements have been made in solidification technologies, the development of lunar environment simulation technologies, particularly for 1/6 g gravity, has lagged, thereby hindering the assessment of the in situ applicability of these solidification methods. To address these limitations, this paper introduces a newly developed comprehensive lunar extreme environment simulation system based on superconducting magnetic suspension technology and its potential applications in lunar regolith-based construction material solidification. This review highlights the current progress and challenges in solidification techniques for lunar regolith-based building materials, aiming to enhance researchers' attention to the extreme environmental conditions on the lunar surface.

**Keywords:** lunar base construction; lunar regolith solidification; lunar environment simulation; safety performance evaluation methods

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## 1. Introduction

As Earth's closest natural satellite, the Moon is abundant in helium-3 and various rare metal resources [1–4], with potential for water ice in its polar regions [5–7]. These factors make the Moon an ideal testing ground for space exploration. The development and utilization of the Moon have now become a global consensus. Many countries, *e.g.*, the United States [8], China [9], the European Union [10], Russia [11], Japan [12], the United Kingdom [13], India [14], and Israel [15], along with commercial entities like Intuitive Machines, Moon Express, and SpaceX, are all entering the field of lunar development. Among these initiatives, both America's Artemis program [16] and China's International Lunar Research Station (ILRS) project [17] plan to implement in situ resource utilization on the Moon.

The extreme lunar environment poses significant challenges to lunar exploration activities. The temperature on the lunar surface ranges from approximately −180 °C to

127 °C, with a vacuum of $10^{-14}$ Torr and a gravity field of about 1/6 g [18]. Furthermore, the Moon is continuously subjected to high-energy cosmic radiation, meteorite impacts, micrometeorite abrasion, and lunar dust erosion, creating an extremely harsh environment [19], as illustrated in Figure 1. Consequently, previous lunar exploration missions have encountered numerous engineering challenges. For instance, the Apollo astronaut experienced cardiac damage [20,21]; the Apollo 15 mission faced drill jamming and severe bit wear [22]; the Apollo 16 lunar rover suffered from battery cooling malfunctions [23]; Apollo 17 astronauts were exposed to dust abrasion [24]; the Soviet's Luna 20 mission encountered power shortages and drill jamming [25]; the Chinese Yutu series lunar rovers exhibited fragile performance at night; and India's Chandrayaan-3 mission was declared a failure two weeks after landing. These issues have posed significant challenges to the sustainable development of lunar exploration. To ensure astronauts and lunar equipment can be effectively placed, resupplied, and repaired during long-term missions, there is an urgent need to establish protective infrastructure on the Moon. Therefore, the development of lunar base construction technologies is a frontier scientific issue [26–30].

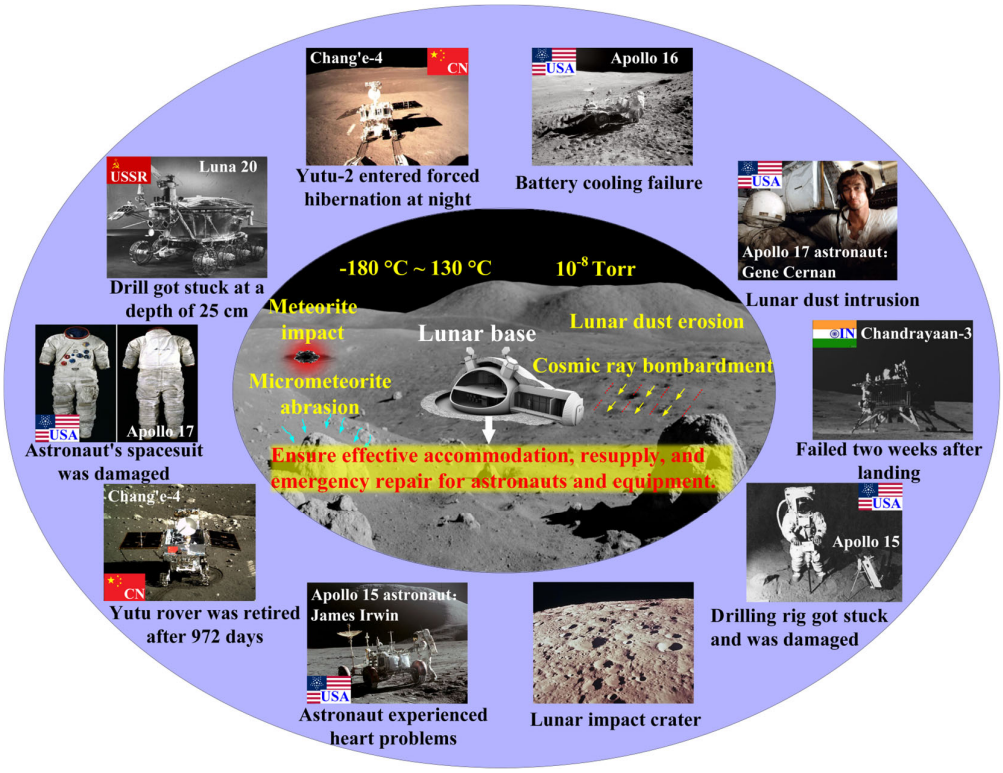



**Figure 1.** Overview of the extreme lunar environment and challenges faced by lunar exploration.

Due to the limitations of Earth–Moon transportation costs [31], developing robust lunar regolith solidification technology is a necessary step for enabling large-scale lunar infrastructure. To support this goal, assessing the reliability of solidification and the long-term safety of lunar regolith-based building materials under extreme conditions is critical. This paper reviews the relevant progress and challenges in two key areas: lunar regolith-based material solidification technologies and technologies for simulating extreme lunar surface environments. The review highlights that current simulation technologies for replicating the extreme lunar environment are still in their infancy, making it difficult to evaluate the in situ applicability of existing solidification methods. To overcome this challenge, we have recently developed a comprehensive lunar environment simulation system, with its principles and research plan outlined. We hope this review will draw attention from researchers to the details of lunar extreme environments and the in situ production conditions for lunar

regolith-based building materials, ensuring that the proposed technologies are suitable for the harsh lunar surface environment.

## 2. Solidification Technologies of Lunar Regolith-Based Building Materials

In the past few decades, dozens of stabilization technologies for lunar regolith-based building materials have been proposed. Bao et al. [32] classified these technologies into four categories based on their curing principles: reaction solidification, sintering/melting solidification, bonding solidification, and confinement formation. This section provides an overview of the underlying principles and developmental progress of the major solidification technologies, along with a discussion of their advantages and constraints.

### *2.1. Reaction Solidification*

Reaction solidification achieves material hardening by forming chemical bonds through reactions between lunar regolith and specific additives. Therefore, a thorough understanding of the chemical composition of lunar regolith is essential. Lunar regolith is an assemblage of granular particles formed through the long-term exposure of lunar bedrock to extreme processes, including billions of years of meteoroid impacts, micrometeorite abrasion, cosmic ray bombardment, and intense diurnal temperature fluctuations [1]. Its primary constituents include mineral fragments (e.g., olivine and ilmenite), pristine crystalline rock debris (e.g., anorthosite and basalt), breccia fragments (e.g., impact melt rocks and microbreccias), glassy materials (e.g., glass beads and shards), and agglutinates—heterogeneous particles formed by the cooling and solidification of fine debris.

Table 1 summarizes the chemical compositions of lunar regolith samples from Apollo and Chang'e series missions, as well as some representative lunar regolith simulants. Previous studies have shown that silica- and alumina-based oxides are the chemically active components during reaction-based solidification. In Table 1, the combined mass fraction of $SiO_2$ and $Al_2O_3$ in all five real lunar regolith samples exceeds 50%, indicating a high potential for chemical reactivity in the presence of suitable additives.

**Table 1.** Chemical composition (wt%) of partial lunar regolith and lunar regolith simulants.

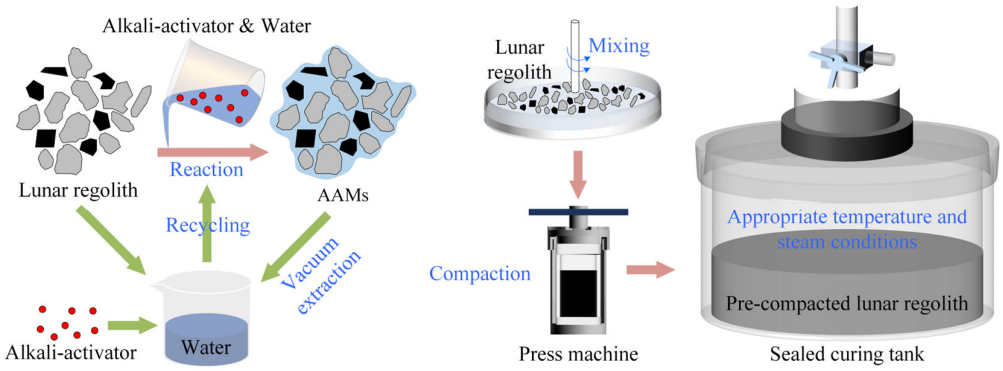
| Oxide | Apollo12 | Apollo14 | Apollo15 | Apollo16 | Chang'e-5 | JSC-1 | CUMT-1 | BH-1 |
|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 42.20 | 46.30 | 48.10 | 46.80 | 42.20 | 47.71 | 42.68 | 43.3 |
| $TiO_2$ | 7.80 | 3.00 | 1.70 | 1.20 | 5.00 | 1.59 | 1.31 | 2.90 |
| $Al_2O_3$ | 13.60 | 12.90 | 17.40 | 14.60 | 10.80 | 15.02 | 15.20 | 16.50 |
| FeO | 15.30 | 15.10 | 10.40 | 14.30 | 22.50 | 10.79 | 26.76 | 16.70 |
| MnO | 0.20 | 0.22 | 0.14 | 0.19 | 0.28 | 0.18 | 0.11 | 0.30 |
| MgO | 7.80 | 9.30 | 9.40 | 11.50 | 6.48 | 9.01 | 3.44 | 3.00 |
| CaO | 11.90 | 10.70 | 10.70 | 10.80 | 11.00 | 10.42 | 5.62 | 8.80 |
| $Na_2O$ | 0.47 | 0.54 | 0.70 | 0.39 | 0.26 | 2.70 | 3.23 | 3.80 |
| $K_2O$ | 0.16 | 0.31 | 0.55 | 0.21 | 0.19 | 0.82 | 0.00 | 3.30 |
| $P_2O_5$ | 0.05 | 0.40 | 0.51 | 0.18 | 0.23 | 0.66 | 0.13 | 0.70 |

Notes: Data for Chang'e-5 are from [33]; Data for Apollo12, Apollo14, Apollo15, Apollo16, JSC-1 and BH-1 are from [34]; Data for CUMT-1 are from [35].

#### 2.1.1. Alkali-Activated Solidification

This method represents the most extensively studied chemical solidification technique, in which alkaline activators react with aluminosilicate components in the regolith via a dissolution–repolymerization mechanism to form alkali-activated materials (AAMs), as illustrated in Figure 2a. Extensive studies have been conducted to explore and optimize this solidification approach. Alexiadis et al. [36] and Geng et al. [37] reported that the presence

of amorphous aluminosilicates in lunar regolith facilitates alkali activation. Ma et al. [38] demonstrated that the addition of fiber aggregates during the alkali activation process significantly improves compressive strength. Zhou et al. [39] found that the lunar vacuum environment enhances the reaction quality of alkali activation. Zhang et al. [40], Zhou et al. [41], and Gu et al. [42] showed that activator concentration and curing temperature are key parameters affecting the solidification performance. Yao et al. [43–45] investigated the alkali-activated solidification behavior under lunar-like temperature and vacuum conditions from a microscale perspective.




(a) Alkali-activated solidification (b) Hydrothermal solidification

**Figure 2.** Schematic diagram of reaction solidification methods for lunar regolith-based construction materials.

This technique has demonstrated excellent reactivity and environmental adaptability in various silico-aluminous materials, including clays [46,47], tailings [48,49], and industrial solid wastes [50,51] on Earth. The high content of aluminosilicate oxides in lunar regolith renders it highly compatible with alkali-activated systems. Additionally, the alkali activation process has a low water demand, with up to 98.61% of the water being recoverable for reuse [52]. These advantages make it a promising candidate for in situ lunar construction applications and have attracted considerable research attention in recent years.

#### 2.1.2. Hydrothermal Solidification

This method utilizes silicates from lunar regolith as the primary reactive material. It achieves solidification under a saturated steam pressurized environment [53–57], as shown in Figure 2b. The microstructure of the hydration products can be effectively controlled by adjusting temperature and moisture content. Such a technique mitigates the adverse effects of ultravacuum conditions on the concrete curing process, producing solidified materials with compressive strengths ranging up to 70 MPa [58]. However, the method is highly dependent on water, and its stringent curing conditions are challenging to maintain under lunar surface environments, thereby posing significant bottlenecks for large-scale application.

Generally, reaction-based solidification methods offer the advantage of rapid curing rates. Nevertheless, several limitations hinder their broader application, including the requirement for considerable amounts of additives, reliance on specific temperature and pressure conditions during curing, and the limited durability of the newly formed chemical bonds under the harsh lunar environment. These challenges necessitate further research to improve the practicality and longevity of such methods for lunar in situ resource utilization.

### *2.2. Sintering/Melting Solidification*

Electric and solar thermal heating are two primary approaches for the in situ solidification of lunar regolith into building materials. Theoretically, both methods can enable direct

3D printing and modular printing of structures. Each method offers distinct advantages and limitations in terms of energy use, process control, and material performance, as shown in Figure 3.

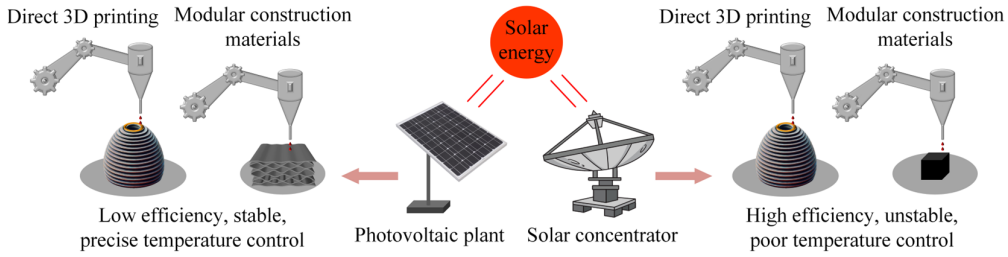



**Figure 3.** Schematic diagram of sintering/melting solidification methods for lunar regolith-based construction materials.

Electric heating provides precise and stable temperature control, e.g., electric resistance sintering [59–61], microwave sintering [62,63], and laser melting [64,65], often resulting in sintered products with superior densification, uniformity, and mechanical strength. Additionally, it is adaptable to various component geometries and manufacturing processes. However, its practical application on the Moon is constrained by the requirement for a reliable and continuous high-power energy supply, which poses significant engineering challenges under lunar conditions. The associated system complexity also contributes to higher operational demands. In contrast, solar thermal heating directly utilizes the abundant solar radiation on the lunar surface, offering a sustainable and resource-efficient solution for high-temperature solidification [66–69]. Nevertheless, this method suffers from limited controllability due to the lunar day-night cycle and natural fluctuations in solar irradiance, making complex thermal management difficult and often resulting in less consistent product quality compared to electric heating.

In terms of energy consumption, Bao et al. [32] estimated that heating one ton of lunar regolith to 1000 °C—neglecting system losses—requires at least 233 kWh of electrical energy. This is approximately equivalent to the output of a 100 $m^2$ photovoltaic array operating for six hours during a lunar day. Therefore, regardless of the specific sintering method employed, the integration of dedicated solar power infrastructure is essential. Most experimental studies report peak sintering temperatures in the range of from 900 °C to 1400 °C [32], with minimal variation among different sintering techniques. However, studies have demonstrated that vacuum conditions can significantly reduce the required peak temperature while simultaneously enhancing the compressive strength of the sintered products [61,70]. Given the ultra-high vacuum environment on the Moon, this effect could facilitate sintering and solidification processes at lower power input and energy consumption.

Based on whether the structure is formed in a single step, sintering solidification can also be classified into two approaches: direct 3D printing and modular sintering. Direct 3D printing offers a more efficient pathway for constructing lunar habitats. However, it presents significantly greater technical challenges compared to prefabricated sintering. This is because large-scale printing is required to achieve practical engineering relevance, which demands higher mechanical power and entails more complex thermo-mechanical control systems. Moreover, previous studies have shown that sintering lunar regolith directly under vacuum conditions can lead to the intense formation of pore structures due to the escape of volatile components [71], posing serious challenges to the material quality of high-temperature fused 3D-printed components. In contrast, modular sintering allows for better control over the initial regolith density, applied pressure, and thermal gradients during the sintering process, thereby improving the quality and uniformity of the final

products [61]. However, since modular components still require secondary assembly to form full-scale structures, the mechanical integrity of inter-module connections becomes a critical factor for the overall structural performance.

Compared to other solidification methods, the advantages and disadvantages of the sintering/melting approach are the most pronounced. Its primary advantage lies in being the only method that enables the solidification of lunar regolith into building materials without the need to transport chemical binders or reactants from Earth. However, this approach also presents the highest equipment complexity and faces significant challenges in heat dissipation under the Moon's ultra-high vacuum environment. Therefore, research on this method should focus on the adaptability of melting systems to extreme lunar conditions and the heat dissipation behavior of molten regolith in a vacuum. If these two key technical challenges can be overcome, sintering/melting solidification holds strong potential as an efficient solution for large-scale lunar infrastructure construction.

### *2.3. Bonding Solidification*

This method solidifies lunar regolith by bonding loose particles using adhesives, as shown in Figure 4. The binders are generally classified into two categories: inorganic [72–74] and organic [75–77]. Common inorganic binders include sulfur and inorganic cementitious inks, while organic binders consist of polymeric materials and biobased substances. They generally do not chemically react with the lunar regolith components, though minimal and weak reactions may occasionally occur.

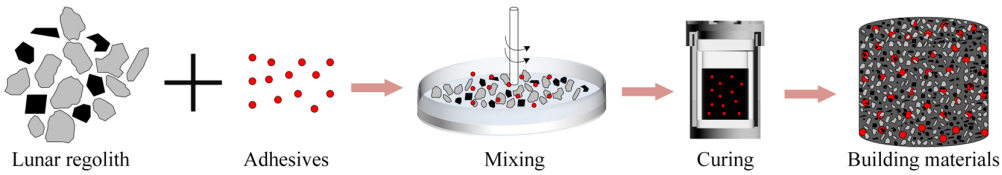



**Figure 4.** Schematic diagram of bonding solidification methods for lunar regolith-based construction materials.

The main advantage of the bonding solidification method is that it does not require the lunar regolith to participate in chemical reactions. Solidification is predominantly achieved through physical or chemical reactions of the binder itself, making the process highly efficient and controllable. However, the limitations of this method lie in the relatively low bonding strength and poor durability of the adhesives under the extreme lunar conditions, such as high vacuum and large temperature fluctuations. Moreover, adhesives often require complex in situ extraction processes or incur high Earth-to-Moon transportation costs.

### *2.4. Confinement Formation*

This method achieves the solidification of building materials by filling bulk lunar regolith into specially designed fabric bags [78–82], as shown in Figure 5. Existing studies have shown that extreme lunar conditions, *e.g.*, intense thermal cycling, strong radiation, and micrometeoroid abrasion, can accelerate the aging of fabric bags, ultimately leading to structural failure. Therefore, the durability of fabric bags is a critical factor determining the long-term performance of such building materials in the harsh lunar environment.

Among the four solidification approaches, this is the only purely physical method. Its advantages include rapid solidification and high efficiency in structural assembly. However, its limitations lie in the limited durability of the regolith bags under micrometeoroid abrasion and the difficulty in constructing complex architectural forms.

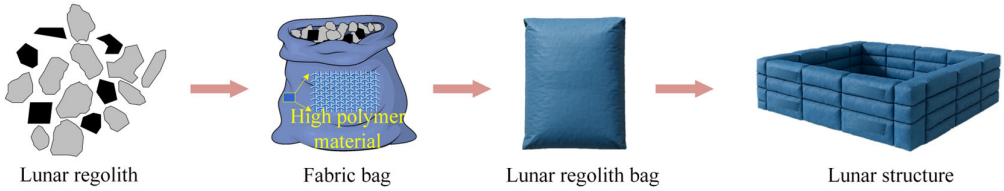



**Figure 5.** Schematic diagram of confinement formation methods for lunar regolith-based construction materials.

### *2.5. Discussion of Solidification Technologies*

The selection of lunar regolith solidification methods should comprehensively consider factors such as in situ curing reliability, durability under extreme lunar conditions, Earth-to-Moon transportation costs, and engineering complexity in the lunar environment. The four mainstream approaches each present distinct advantages and limitations across these dimensions.

Reaction solidification methods, particularly alkali activation, benefit from compatibility with the aluminosilicate-rich composition of lunar regolith and offer low water demand, making them promising for long-duration lunar missions. However, their dependence on transported activators and vulnerability of chemical bonds under severe lunar thermal and radiation conditions may limit their long-term reliability. Hydrothermal solidification demonstrates strong material performance but is severely constrained by its water demand and pressurization requirements, which are difficult to meet on the Moon.

Sintering/melting technologies require no terrestrial inputs, thus minimizing Earth-to-Moon transportation costs. Furthermore, the resulting construction materials typically demonstrate enhanced strength and durability relative to those produced by the other three approaches. These advantages underscore the considerable potential of this method for future in situ lunar infrastructure development. Nevertheless, the reliance on stable energy supply (electric) or fluctuating solar input (solar thermal), along with challenges in vacuum heat dissipation and system complexity, restricts their operational feasibility at scale.

Bonding solidification methods offer high process controllability and exhibit low dependency on the chemical composition of the regolith weathering layer. However, due to the potential degradation or failure of adhesives under lunar environmental conditions, their long-term stability remains questionable. Similarly, confinement formation methods offer a highly efficient solution for emergency shelters or temporary infrastructure. However, this method is incapable of supporting the construction of complex architectural structures, and the durability of the fabric bags is challenged by micrometeoroid abrasion and cosmic radiation on the lunar surface.

Overall, current understanding of the advantages and limitations of the four mainstream solidification approaches is primarily based on experimental results from ground-based or thermal-vacuum environments. However, these experimental conditions generally do not account for the influence of the Moon's 1/6 g gravity, which limits the accuracy of assessing the in situ applicability of each method.

## 3. Lunar Environment Simulation Technologies

Lunar regolith-based building materials are subjected to harsh environmental conditions during both in situ solidification and long-term service, including ultra-high vacuum, extreme thermal cycling, and reduced gravity. Accurately simulating these three types of environments on Earth is crucial for evaluating the in situ applicability of building materials [83]. The following section summarizes and discusses recent technological advances in this area.

### *3.1. Thermal Vacuum Simulation Technology*

In aerospace engineering, the extreme temperatures and vacuum conditions are collectively referred to as the thermal-vacuum environment. Vacuum conditions are typically achieved using vacuum pumps, while extreme temperature environments are generated via thermal flux and heat sink systems, as shown in Figure 6. Many research institutions, including the Austrian Academy of Sciences [84], the Spanish National Research Council [85], NASA's Marshall Space Flight Center [86], Canadian Space Agency [87], the German Aerospace Center [88], and the Physical Research Laboratory of India [89], have developed lunar thermal-vacuum environment simulation chambers.

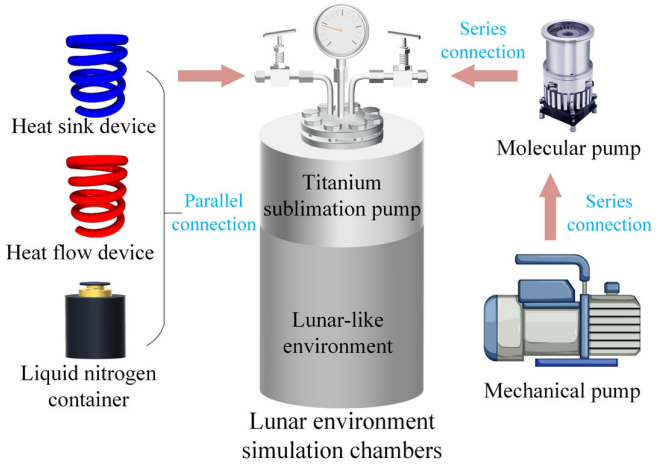



**Figure 6.** Working principle of lunar thermal-vacuum environment simulation chamber.

Previous studies have shown that the vacuum level is primarily determined by the chamber volume and whether the chamber contains lunar regolith simulant. Compared to unloaded conditions, the outgassing of lunar regolith simulant can reduce the vacuum level by more than two orders of magnitude. For instance, under comparable pumping conditions using five vacuum pumps, Johnson et al. [90] achieved a vacuum level of $10^{-8}$ Pa in a chamber with a volume of 8.8 $cm^3$, while Zhang et al. [91] reached only $10^{-1}$ Pa in a 4.3 $m^3$ chamber. In addition, creating low-temperature conditions is significantly more challenging than generating high temperatures. According to Zhang et al. [91], cooling from room temperature to −20 °C required 32 h, whereas heating to 80 °C took only 50 min.

### *3.2. 1/6 g Gravity Simulation Technology*

Three approaches can simulate the Moon's 1/6 g gravity on Earth: parabolic flight, drop towers, and magnetic levitation-based gravity compensation, as illustrated in Figure 7.

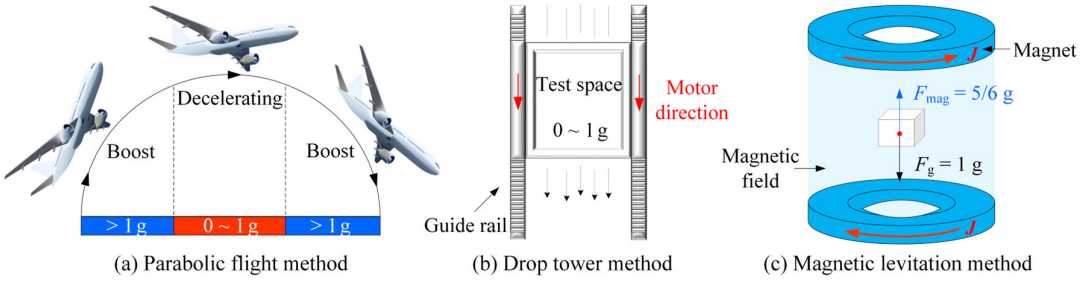



**Figure 7.** Working principle of lunar thermal-vacuum environment simulation chambers.

Parabolic flight generates reduced gravity by flying an aircraft along a specific parabolic trajectory. The concept is believed to have been first proposed by the German

physicist Haber in the early 1950s [92]. Representative reduced-gravity aircraft include the United States' Zero-G aircraft [93], Russia's Ilyushin Il-76 [94], and Canada's Falcon 20 [95]. However, these aircraft can only simulate 1/6 g gravity for approximately 25 s, which is insufficient for the timescale required for the solidification of building materials. Similar to parabolic flights, the drop tower method simulates reduced gravity by allowing experimental payloads to undergo controlled deceleration, thereby creating a partial gravity environment. Representative facilities include those at the Chinese Academy of Sciences [96], NASA Lewis Research Center [97], the Center of Applied Space Technology and Microgravity in Germany [98], and the JAMIC drop tower in Japan [99]. However, the achievable duration of 1/6 g environment in drop towers is generally shorter than that in parabolic flights due to height limitations.

The magnetic levitation method achieves partial gravity by applying a precisely controlled magnetic force to counteract a portion of Earth's gravitational force in the vertical direction. Relevant studies have been conducted by Li et al. [100] and Sanavandi et al. [101]. Since both magnetic force and gravity are body forces, this technique enables stable and accurate simulation of the Moon's 1/6 g gravity. Nevertheless, the duration of such simulations is constrained by the thermal load generated in the magnet's resistive coils during operation.

### *3.3. Discussion of Lunar Environment Simulation Technologies*

Overall, replicating the extreme lunar environment on Earth for testing the in situ solidification and service performance of lunar regolith-based building materials still faces two major technical challenges. First, due to the high complexity of system integration, the development of thermal vacuum and low-gravity simulation technologies has largely progressed in isolation, preventing the creation of comprehensive experimental platforms that can simultaneously reproduce all critical lunar environmental parameters, *e.g.*, ultra-high vacuum, extreme thermal cycling, and 1/6 g gravity. Second, although the magnetic levitation method has shown promise in stably generating a reduced gravity field that mimics lunar gravity, its practical application is severely constrained by significant heat generation in superconducting or resistive magnetic coils, which limits continuous operation time.

The challenges above represent critical bottlenecks that hinder the long-duration and stable simulation of the Moon's extreme environmental conditions on Earth. Consequently, current research on lunar regolith solidification technologies is predominantly conducted under terrestrial gravity or thermal-vacuum conditions. However, these experimental settings fail to replicate the Moon's low-gravity environment, thereby limiting our ability to accurately assess its influence on key solidification processes such as material flow, chemical reactions, particle deposition, adhesion, and heat dissipation. As a result, the reliability of these solidification techniques under actual lunar conditions remains highly uncertain, particularly for methods that involve complex chemical reactions.

Moreover, existing studies generally lack thermal fatigue testing of the building materials under prolonged extreme lunar conditions characterized by large temperature fluctuations and high vacuum exposure. Without long-term performance data under this extreme environment, it is challenging to determine whether the proposed methods can meet the structural reliability and durability requirements for lunar surface infrastructure. Therefore, future research must prioritize the development of testing frameworks that incorporate lunar gravity analogs and simulate the full spectrum of lunar environmental extremes to validate and refine current solidification technologies.

## 4. Comprehensive Lunar Environment Simulation System

### *4.1. System Development Overview*

The system was originally developed to simulate the Moon's 1/6 g gravitational environment. Its conceptual inspiration traces back to Professor Geim's famous magnetic levitation experiment in which a frog was levitated using a strong magnetic field [102]. This experiment earned him the 2000 Ig Nobel Prize in Physics. The underlying principle was that magnetic forces could counteract gravitational forces, offering a novel pathway to simulate reduced-gravity conditions on Earth.

In 2010, Li et al. proposed the geotechnical magnetic-similitude-gravity model testing (GMMT) method to simulate unconventional gravity fields on extraterrestrial bodies [100]. After several years of refinement, an application-oriented system was successfully developed [103]. The apparatus consists of a central test module, a power supply system, and a cooling system, as shown in Figure 8. It provides a cylindrical experimental chamber with a diameter of 90 mm and a height of 160 mm. To enable lunar gravity simulation, the system must operate in conjunction with magnetically responsive materials. Hence, a specially formulated magnetic-sensitive lunar regolith simulant, named CUMT-1 lunar regolith simulant, was developed to interact with the magnetic field and enable the generation of controllable magnetic force [35]. This platform subsequently supported preliminary studies on the mechanical behavior of lunar regolith simulant under 1/6 g gravity conditions [104].

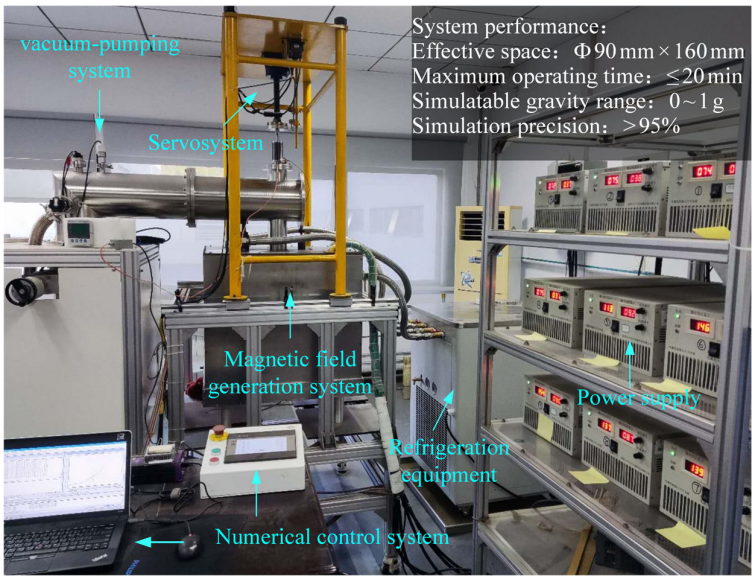



**Figure 8.** The second-generation extended magnetic gravity model testing system.

However, the system relied on copper windings to generate the magnetic field, which resulted in excessive heat generation and limited the operational duration to approximately 20 min. The significant thermal load also posed serious challenges for thermal management and prevented integration with thermal-vacuum environments. In 2020, under the supervision of Professor Li, the author redesigned the system with NbTi superconducting coils to overcome these limitations. This upgrade effectively eliminated the problem of resistive heating, enabling stable, long-duration reduced-gravity simulation. Moreover, by integrating this superconducting platform with a thermal vacuum chamber, we successfully established a simulation system capable of reproducing the Moon's extreme environmental conditions over extended periods. This system, referred to as the superconducting magnetic levitation lunar environment simulation system (SML-LESS), offers a more comprehensive and realistic testbed for lunar construction technologies.

### *4.2. System Performance*

The SML-LESS system comprises two subsystems: a superconducting magnetic levitation module and a thermal vacuum generation module, as shown in Figure 9. The two subsystems can independently simulate individual extreme lunar environmental conditions or operate simultaneously to replicate integrated lunar environments. The system is capable of maintaining a long-duration, stable simulation of a 1/6 g gravitational field, an ultra-high vacuum down to $10^{-8}$ Torr, and extreme temperature variations ranging from −180 °C to 180 °C within a cylindrical test chamber with a diameter of 500 mm.

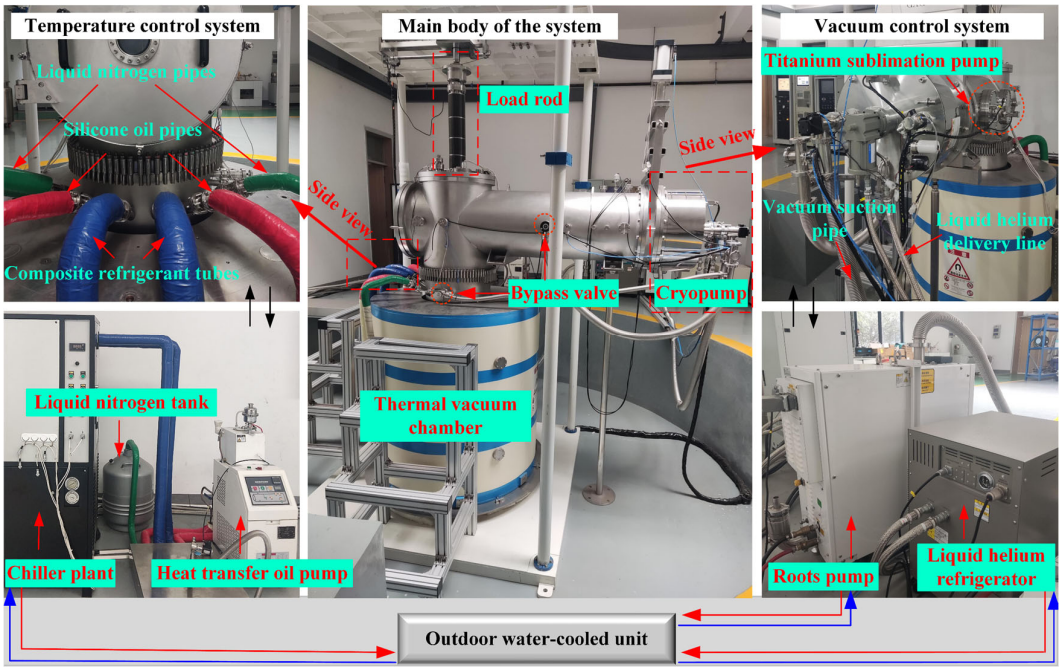



**Figure 9.** Overview of the SML-LESS system.

The 1/6 g gravity environment is created by the superconducting magnetic levitation subsystem. Its development focused on two main aspects: the design of the magnetic structure and the creation of the magnet's operational environment. For the magnetic structure, based on the Biot–Savart law and vector superposition principles, the magnetic field distributions around current-carrying uniform field coils and Helmholtz coils were derived. An initial configuration of superconducting coils was proposed accordingly, and the structure was further optimized using ANSYS 2024R2 simulations. The resulting design achieved a gravity distribution accuracy better than 96.23% for a 1/6 g field within the Φ500 × 500 mm volume. For the magnet's operational environment, a cryogenic refrigeration system was developed using an FJ-110 composite molecular pump unit and two GM helium compressors. This system successfully created an ultra-low temperature environment of less than 4.2 K, which is required to maintain the NbTi superconducting state. As superconductors exhibit zero electrical resistance, they do not generate heat as conventional copper conductors do. Consequently, the superconducting magnet can operate continuously without thermal limitations, ensuring a stable and sustained artificial 1/6 g gravity field.

The lunar-like thermal and vacuum environment is simulated by the thermal vacuum subsystem. A three-stage thermal control system, comprising silicone oil heating pipes, composite refrigerant tubes, and liquid nitrogen cooling pipes, enables precise temperature regulation across a ±180 °C range. A three-stage vacuum pumping system, consisting of a

roots pump, a cryopump, and a titanium sublimation pump, allows the vacuum level to be continuously adjusted from atmospheric pressure down to $10^{-8}$ Torr.

Due to the strong magnetic fields generated during operation, some sensitive components may be affected. To ensure functional independence and prevent interference between subsystems under high-density integration, the magnetic field distribution was calculated, and the spatial layout of sensitive components was optimized accordingly.

### *4.3. Future Application Plans*

Based on the SML-LESS system, we have preliminarily achieved stable long-term simulation of lunar-like conditions, including 1/6 g gravity, high vacuum, and extreme temperatures. Moving forward, zero-gravity solidification experiments will be carried out using the SML-LESS system. The results will be systematically compared with existing space station-based zero-gravity 3D printing experiments to assess the method's reliability and applicability. On this basis, we plan to utilize this system to conduct experiments on the solidification of lunar regolith-based building materials and to evaluate their long-term durability under extreme lunar environmental conditions.

Solidification tests. Given the limited robustness and reliability of current lunar equipment under extreme lunar environmental conditions, large-scale, single-step in situ 3D printing is unlikely to be achievable in the near term. A more pragmatic solution is to adopt modular construction methods. Accordingly, the solidification tests will primarily focus on the modular production techniques of building materials based on lunar regolith.

Under on-site modular construction scenarios, the production and solidification of lunar regolith-based building material can be carried out within the lander module, where temperature and pressure conditions are controllable. However, the 1/6 g gravity environment cannot be altered. Therefore, the solidification tests will focus on accurately simulating the 1/6 g gravity. This will facilitate the investigation of potential gravity-related solidification phenomena and support the development of targeted strategies to enhance curing efficiency and material quality.

Based on these considerations, we plan to conduct reactive curing, adhesive curing, and melt-based curing experiments under 1/6 g gravity conditions. It is worth noting that maintaining a stable 1/6 g gravitational condition during the experiment requires not only a stable magnetic field but also consistent magnetic responsiveness of the building materials involved. To address this, we have recently developed a cobalt-doped magnetic-sensitive lunar regolith simulant, which retains stable magnetic properties even under vacuum melting conditions at 1100 °C. Furthermore, this simulant does not participate in chemical reactions such as alkali activation, thereby ensuring that all three curing methods can be tested under a reliably 1/6 g gravity environment.

Long-term durability tests. Different lunar structures impose distinct service performance requirements on building materials. Habitability modules demand materials that combine low thermal conductivity for effective insulation and high impact resistance to withstand micrometeoroid impacts. Landing pads and lunar roads primarily require high impact resistance. Subsurface structures mainly emphasize the compressive strength of the materials. During the assembly of modular building units, the mortise-tenon joints particularly rely on adequate flexural strength to ensure structural soundness. Considering that thermal conductivity, impact resistance, compressive strength, and flexural strength are key indicators for evaluating the service performance of lunar regolith-based construction materials, the next study will focus on the evolution of these four properties under long-term vacuum thermal fatigue conditions. The research framework is illustrated in Figure 10.

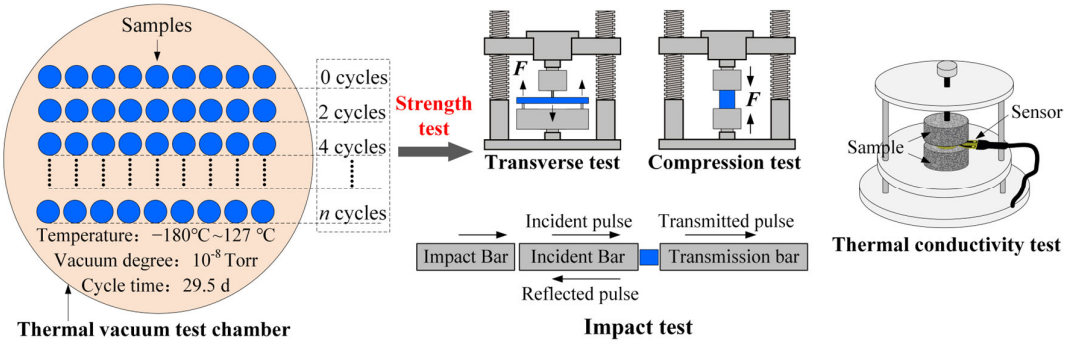



**Figure 10.** Research framework for the service performance of lunar regolith-based building materials.

In future work, we plan to systematically test the thermal conductivity and three key mechanical strength properties of building materials subjected to varying numbers of thermal fatigue cycles. These results will be integrated with material preparation process parameters to construct a technological parameter-service performance mapping matrix. The Pearson correlation coefficient will be employed to quantify the relationships between different processing parameters and specific performance indicators. On this basis, correlation verification experiments will be designed to investigate the independent contributions of individual parameters and to uncover potential synergistic regulation mechanisms.

Additionally, microstructural analysis will be incorporated to support a deeper interpretation of how multiple process parameters jointly influence material performance. This integrated approach is expected to enable the identification of dominant process parameters governing key service performance indicators, ultimately guiding the development of a preliminary performance regulation strategy for lunar regolith-based building materials.

## 5. Conclusions

This review summarizes recent advances in the development of building materials based on lunar regolith and compares the advantages and limitations of four mainstream solidification methods: reaction solidification, melting solidification, bonding solidification, and confinement formation. The main conclusions are as follows:

1. Reaction solidification offers the advantage of rapid curing; however, it requires substantial additives, depends on specific temperature and pressure conditions during curing, and the durability of the newly formed chemical bonds under the extreme lunar environment may face significant challenges.
2. Melting solidification directly utilizes lunar soil as a construction material without the need for additional Earth-supplied materials, leading to low preparation costs and high durability. Its major drawback lies in the challenges of thermal management in the ultra-high vacuum environment.
3. Bonding solidification provides an efficient and controllable curing process, yet it suffers from relatively low solidification strength and limited durability of bonding agents, particularly organic adhesives, under harsh lunar surface conditions.
4. Confinement formation achieves the fastest curing and allows for efficient reconfiguration. However, this method faces challenges in realizing complex architectural forms, and the durability of regolith bags is limited by micrometeorite abrasion and damage from cosmic radiation.
5. It is important to note that these conclusions are primarily drawn from existing ground-based or thermal vacuum experiments. The performance and applicability of these four methods under lunar gravity conditions remain inadequately validated. The absence of reliable and stable low-gravity simulation technologies rep-

resents a critical bottleneck for further in situ assessment and development of these solidification techniques.

To ensure the in situ reliability of the solidification technologies, future research should focus on the solidification behavior under 1/6 g gravity and the long-term service durability of building materials under extreme thermal-vacuum conditions. The newly developed SML-LESS system, capable of high-fidelity simulation of lunar gravity and thermal-vacuum environments, offers a promising platform for validating and optimizing solidification strategies. Its application may open new avenues for developing more reliable and efficient lunar construction technologies.

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