Compressed Regolith Brick (CRB): a Proposal to Study the Feasibility of Producing in Situ CRB Units for Construction on the Moon

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April 14, 2024

COMPRESSED REGOLITH BRICK (CRB): A PROPOSAL TO STUDY THE FEASIBILITY OF PRODUCING IN SITU CRB UNITS FOR CONSTRUCTION ON THE MOON

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The Moon's proximity to the Earth makes it an ideal place for research and development of technologies needed for space exploration. It is known that the lunar gravity is about 0.166g and the temperature varies from -233°C to +110°C. Successful construction on the Moon will require the development of new technologies, materials and specialised equipment that can operate in low gravity and extreme temperature conditions. Researchers at the European Space Agency states that "lunar bricks will be made of dust" and have made a brick using volcanic dust and a traditional ceramic brick manufacturing technology that involves crushing, compressing and burning. A proposal, developed in the USA, is based on the sintering of Lunar and Martian regolith to produce a material for the construction of extraterrestrial masonry structures. Both China and the USA are currently investigating 3D printing technology using lunar dust to construct buildings on the Moon. Nevertheless, it is important to note that lunar soil does not flow well and the above processes require water for binding or even oxygen for firing, resources which are limited under lunar exploration conditions. Based on the properties of regolith, which is widely available on the lunar surface, this paper proposes to investigate the feasibility of *in situ* producing 'compressed regolith bricks' (CRB). Regolith is characterised by low thermal conductivity, strong adhesive and cohesive properties, and the absence of free water and other volatiles, making it the most accessible in-situ thermal insulation and building material on the Moon. One of the key physico-mechanical properties of lunar regolith is that the cohesive forces between loose particles tend to stick them together, achieving a degree of cohesion that allows the soil to clump. Data from different Russian and US lunar missions show that the mechanical properties of the lunar soil are highly dependent on the degree of compaction, e.g., the increase in bulk density with depth shows its dependence on pressure. The specific gravity of lunar regolith particles is G = 3.1 g/cm^3, the average bulk density of the uppermost 15 cm layer is 1.5 g/cm^3. For production of CRB a target relative density D_R = 90% should be reached. The minimum value of the void ratio to reach should be approximately $\varepsilon_{min}^{CRB} = 0.10$ at a minimum compaction pressure of P = 2.2 MPa. The maximum density of the CRB would be approximately 2.8 g/cm^3. Based on these parameters, we propose further research on the production of compressed regolith bricks in combination with techniques previously studied.

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INTRODUCTION

Building on the Moon is one of mankind's greatest challenges of the space age. The Russian scientist K. E. Tsiolkovsky (1857-1935), regarded as the founding father of modern cosmonautics, envisaged that space exploration would consist of sending compact, folded dwellings and accessories from Earth by rocket, which would be assembled on arrival at their destination in the cosmos. The Moon's proximity to Earth and its extensively studied terrain, along with advancements in astronautics and reductions in spaceflight costs, make it a potential site for establishing a habitable space research base. Existing plans to build habitable bases on the Moon can be considered as a preliminary stage of human settlement in space, however, autonomous human habitation is a much more complex task and will require the resolution of several issues, such as the development of new technologies, materials and specialised equipment that can operate in lunar conditions. The current state of 21st century science, which includes the rapid development of robotic construction technologies, 3D printing and new materials, suggests that there is a good chance of successfully implementing construction plans on the Moon or Mars. Furthermore, the Moon's proximity makes it an ideal place for research and development of technologies needed for space exploration.

At the beginning of the 21st century, the discovery of ice deposits at the lunar poles stimulated the start of the "second lunar race" between the United States (Artemis programme), the European Union (Terra Novae 2030+ Programme), China (China's Lunar Programme), Russia (Russian Lunar Programme), Japan and India. The American National Aeronautics and Space Administration (NASA) through the Artemis lunar exploration program aims to land the first woman and the next man on the Moon by 2024. NASA's goal is to develop an Artemis Base Camp at the Moon's South Pole to support longer expeditions on the lunar surface. This base camp will include a lunar foundation habitation module, power systems, and in-situ resource utilisation systems.[1] The European Space Agency (ESA), through its Terra Novae 2030+ programme, plans to organise expeditions and build infrastructure facilities on the Moon after 2030.[2] China aims to establish a habitable scientific base on the Moon between 2040 and 2060 through its Chang'e lunar programme.[3] In 2021, China and Russia reached an agreement on the construction of an International Lunar Station. The Russian lunar programme (Luna-Resurs-1) includes the Luna-25, Luna-26, Luna-27 and Luna-28 missions, and aims to build a habitable base on the Moon by 2031-2035.[4,5] The Japanese Aerospace Exploration Agency planned to develop technology for a lunar base after 2025 and then launch a habitable station on the Moon. The Indian Space Research Organisation (ISRO) launched the Chandrayaan lunar programme in 2008 and is now working with the Japan Aerospace Exploration Agency (JAXA) on the joint Lunar Polar Exploration Mission (LUPEX) or Chandrayaan-4.[6,7]

In this context, ESA proposes a future lunar base that should first be unfolded from a tubular module transported by rocket from Earth and then an inflatable dome could be extended from one end of this cylinder to provide a support structure for construction. Once assembled, the inflated domes should be covered with a layer of 3D-printed lunar regolith to protect the occupants from space radiation and micrometeoroids. Thus, a multi-dome lunar base can be constructed (Figure 1).

Figure 1. ESA/Foster + Partners proposal for Multi-dome Lunar Base. (Source: ESA)[8].

NASA's Marshall Space Flight Centre formulated the Moon-to-Mars Planetary Autonomous Construction Technology project (MMPACT) to address the lunar surface construction. One of the goals of the MMPACT project is to develop and build infrastructure on the lunar surface by constructing landing pads, habitats, shelters, roads, berms and blast shields using lunar regolith-based materials.[9] Researchers at the European Space Agency (ESA) argue that "lunar bricks will be made of dust" and have made a brick using volcanic dust from a region near Cologne, Germany, which they claim is a good match for lunar dust (Figure 2-A). The technology they propose involves making burnt bricks from regolith. Another proposal developed by European scientists is to produce 3D printed bricks by sintering lunar regolith layer by layer using concentrated sunlight (Figure 2-B).[10] A proposal, developed at the Department of Mechanical and Aerospace Engineering of the University of Central Florida in the USA, is based on sintering specimens of Lunar or Martian regolith moulded using a saltwater binder to produce without compression a material for the construction of extraterrestrial masonry structures (Figure 2-C)[11]. About 50 years ago, I.I. Cherkasov at the Moscow State University of Civil Engineering conducted similar tests on samples of ground basalt thermally reinforced with mineral additives under moderate heating at 340-360°C, obtaining a stone-like material with properties similar to concrete or brick.[12] In this line, the Indian Institute of Science has proposed a brick from lunar regolith via sintering.[13] Another proposal developed in the USA is the production of 'solar bricks' with a low-density thermoplastic polymer binder and 150°C heat treatment by solar radiation (Figure 2-D)[14]. Selective laser melting of lunar regolith has been studied in Germany.[15] Furthermore, both China and the USA are currently exploring the possibility of using lunar dust-based 3D printing technology to construct buildings on the Moon. Nevertheless, it is important to note that lunar soil does not flow well and some of the above processes require water for binding or even oxygen for firing, resources which are limited under lunar exploration conditions. Therefore, the idea of developing compressed regolith bricks in combination with techniques previously studied takes on an important technical significance.

Figure 2. Existing regolith building materials: A) 140 mm long brick made of regolith simulant (source: ESA website). B) 3D printed brick made by sintering lunar regolith simulant layer-by-layer using concentrated sunlight, (Meurisse *et al.*, 2018)[10]. C) Microscopic image of the Lunar sample sintered for 1 h at 1000°C collected at 200X magnification, (Warren *el al.*, 2022)[11]. D) Cylindrical sample of a solar brick made of "fake" lunar soil (Varela *et al.*, 2017)[14].

The successful construction on the Moon will require the development of new technologies, materials and specialised equipment that can operate basically in low gravity and extreme temperature conditions. Given that the properties of regolith have been studied over the last 60 years, it is considered to be the most available, accessible and suitable in-situ thermal insulation and construction material on the Moon due to its low thermal conductivity, strong adhesive and cohesive properties, and the absence of free water and other volatile substances. [16,17]

On the other hand, history shows that mudbrick is the earliest man-made building material on the Earth and it is used for over 10000 years. This was followed by the production of fired bricks around 4000-5000 years ago.[18–20] Since then, ceramic bricks have become the most widely used building material in the world. Despite the modernisation of the production processes of the ceramic brick, the basic technology of its production, which includes moulding and firing, has remained practically unchanged. In the 1950s, Raul Ramirez, a Latin American engineer, developed a simple process for producing pressed blocks of raw earth by mechanical compression under high pressure. and made the first Compressed Earth Block (CEB) using the CINVA-Ram manual press developed by Ramírez for this purpose.[21–24] Compressed Earth Blocks (Figure 3) are produced by mechanically compacting raw earth (soil) in a steel mould and immediately demoulding. The recommended maximum soil particle size is 5 mm and the minimum compaction pressure is 2 MPa, although pressures of 10–20 MPa are often used for compaction.[21,25–27] These pressures reduce the original volume of soil by about half. To enhance the physical and mechanical characteristics of the blocks, stabilised soil can be utilised. Stabilisation can be achieved through granulometric or chemical techniques, or a combination of both. Granulometric stabilisation involves the addition of sand, which is responsible for the internal structuring.[28] But, the chemical stabilisation using Portland cement or lime as a binder (up to 15% of the block's dry mass) is the most commonly used method, and the resulting block is known as Compressed Stabilised Earth Block (CSEB).[29–32] Different studies show that the compressive strength of Compressed Earth Block (CEB) ranges up to 7 MPa for unstabilised earth, and up to 20 MPa for chemically stabilised earth.[21,26,29,32–35] However, it is important to note that the main effect of chemical stabilisation is to prevent water attack, which is not a problem in the absence of free water in lunar conditions. It should also be noted that increasing the compaction pressure to 20 MPa increases the compressive strength of the CEB and reduces its mass loss.[27]

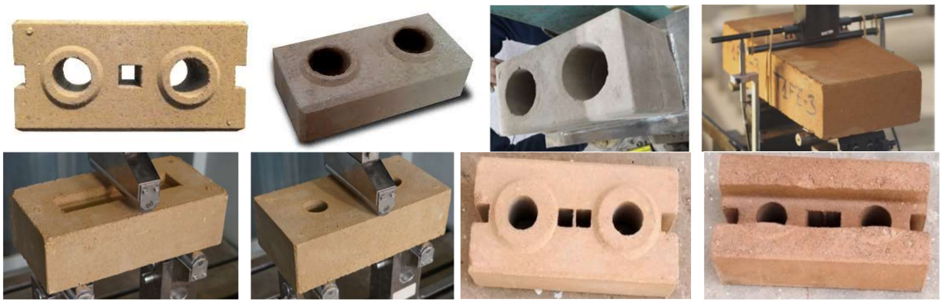

Figure 3. Different shapes of Compacted Earth Blocks (CEB). (Sources: Cabrera *et al.*, 2020 [27]; Ruiz *et al.*, 2018 [28]; Cottrell *et al.*, 2021 [15]; Al-Jabri *et al.*, 2018 [30]).

In view of the above, and based on more than half a century of experience in the production of compressed earth blocks (CEB) and the principle of in situ resource utilization (ISRU), this paper proposes to investigate the feasibility of producing Compressed Lunar Regolith Bricks (CRB) in situ. Further studies in this line should also consider the combination of CBR production technology with other techniques that have been investigated so far, such as sintering, the use of low-density thermoplastic polymer binders as stabilisers, etc.

APPLICATION OF COMPRESSED REGOLITH BRICKS (CRB) FOR CONSTRUCTION ON THE MOON

The In-Situ Resource Utilisation (ISRU) of lunar regolith for construction and protection of lunar infrastructure has been widely studied. The main objective of this idea is to use the lunar regolith both for the construction of habitable modules for a lunar base and its protection against radiation, temperature gradients and micrometeorite impacts. Different projects propose the construction of habitable structures on the Moon, whether buried, partially buried or on the surface. For instance, the Zvezda lunar base project, developed by the USSR from 1964 to 1974, proposed the construction of habitable modules buried in trenches and covered with regolith (Figure 4-a)[36]. The Xuanwu lunar base project developed in China proposes masonry structures on the lunar surface (Figure 4-b)[37]. The proposal for laser welding of blocks has also been developed for the construction of masonry structures on the lunar surface (Figure 4-c)[38]. A proposal for an ISRU facility on the Moon includes semi-buried structures (Figure 4-d)[36]. The European Space Agency's proposal for a lunar base includes semi-buried and regolith-covered structures (Figures 4-e, 4-f)[8].

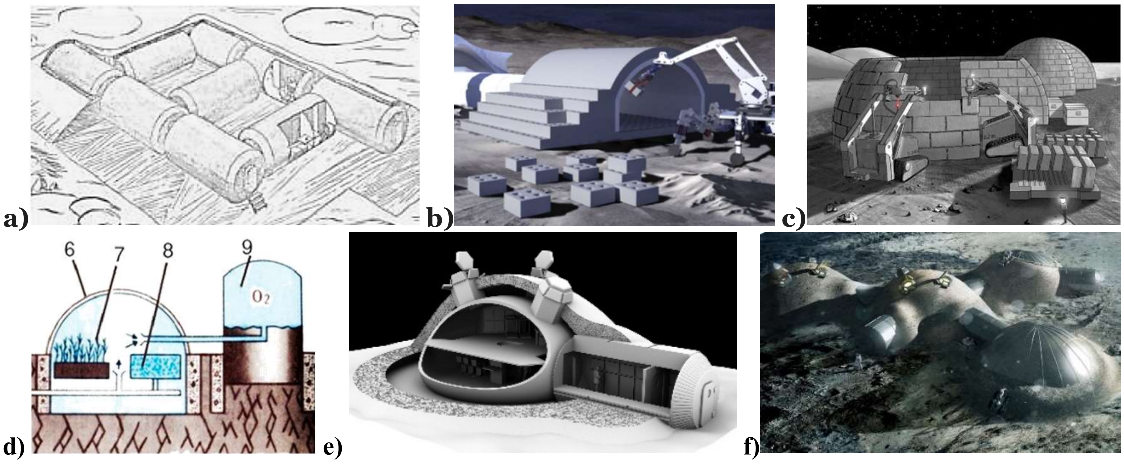

Figure 4. Different proposals for buried, partially buried or on-surface construction of habitable structures on the Moon. Sources: (S. Haeuplik-Meusburger and O. Bannova, 2023)[36]; (C. Zhou *et al.*, 2019)[37]; (K. Farries *et al.*, 2023)[38]; (ESA)[8].

Due to the magnitude of lunar gravity (6 times less than Earth gravity), the conditions for human habitability on a lunar base require a pressurised environment with breathable air. For this reason, the stresses developed in the habitable structures of the lunar base will be generated mainly by the service loads due to internal pressurisation, and to a much lesser extent by the gravitational loads of the structural and non-structural elements. Therefore, regardless of the type of construction (surface, partially buried or buried), the structure will be subject to significant tensile stresses due to the difference in internal and external pressures. These tensile stresses can be absorbed by an internal inflatable structure that can be transported from the Earth (as was envisaged by K.E. Tsiolkovsky), while the external revetment with compacted regolith bricks (CRB) will provide protection against radiation, temperature gradients and micrometeorite impacts. They can also be used to construct floor structures or retaining walls in the case of buried or partially buried structures (Figure 5).

Freestanding structures can be designed on the basis of shell theory, considering that there are optimal shapes for shell structures under the action of specific loads.[39] In addition to the classic shapes of spherical, cylindrical or parabolic domes, certain analytical surfaces can be studied, such as: conoids with circular, parabolic or catenary directrix; velaroidal surfaces; ellipsoids; hyperbolic paraboloids; and torses (Figure 6).[40–43]

The construction of CRB masonry structures on the Moon will require the development of automated processes for lunar regolith collection and CRB unit production, as well as robotic brick cladding. Robotic construction techniques for freestanding shell structures are being investigated and there are results that may be applicable to lunar conditions (Figure 7).[44]

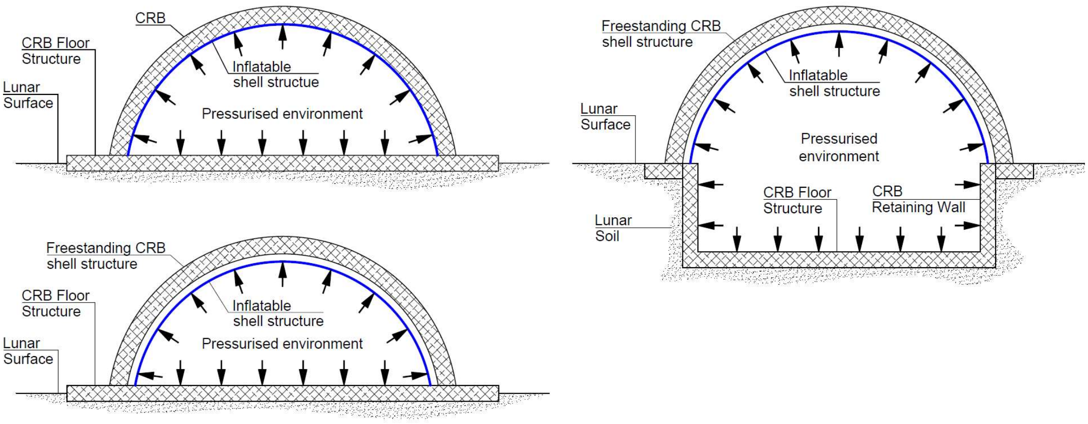

Figure 5. Schematic representation of the internal pressure acting on the structure. Left: surface structures; right: partially buried structure.

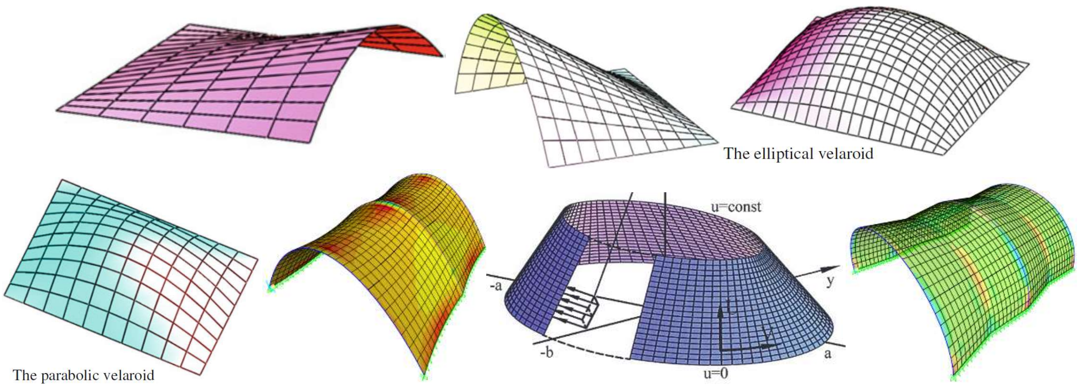

Figure 6. Some analytical surfaces.[40,42,43]

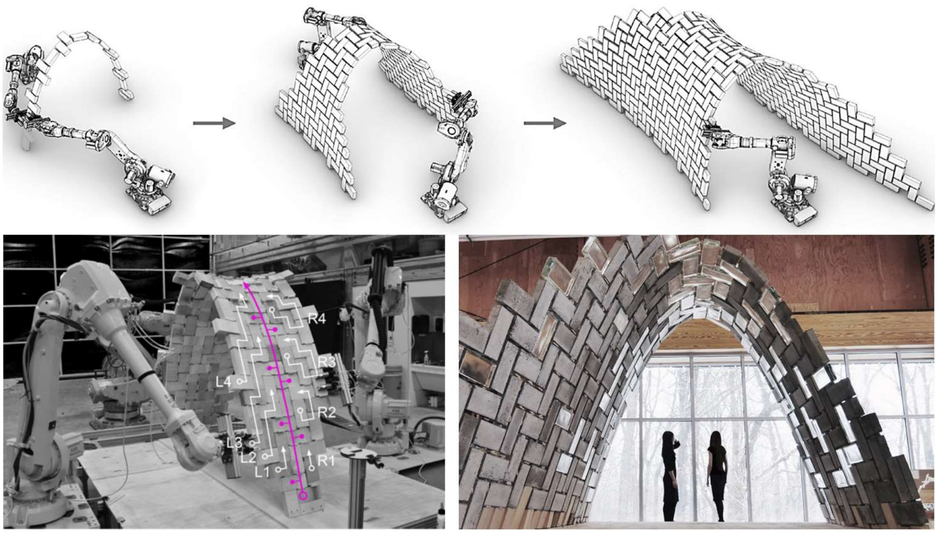

Figure 7. Robotic construction of brick shell. (Source: Parascho S. *et al.*, 2020)[44]**.**

PROPOSAL FOR THE DEVELOPMENT OF COMPRESSED REGOLITH BRICKS (CRB)

It is known that on the Moon the temperature ranges from -233°C to +110°C, the gravity is about 0.166*g*, the atmosphere is considerably less dense than the Earth's atmosphere, the pressure at the lunar surface is about 3×10^{-15} atm, and there is quiet seismic activity.[14,45,46] However, recent studies in the vicinity of the Chandrayaan-3 landing site in the lunar south high latitudes reveal potential shallow "moonquakes".[47] Below we will analyse an initial proposal that considers only the actions due to gravity and service loads of probable future structures on the Moon. In the future, once the feasibility of the present proposal has been established, studies should be extended to consider other parameters, including probable seismic actions.

Lunar regolith is the most accessible in-situ material for the production of compressed bricks on the Moon, due to its strong adhesive and cohesive properties. In addition, its low thermal conductivity makes it a good material for thermal insulation. Nonetheless, the main limitation for experimental investigation of the proposal is related to the scarcity of lunar regolith samples. In total, only about 380 kg of lunar soil were brought back to Earth by lunar stations.[12] US and USSR lunar stations provided samples of lunar soil to scientists in both countries on an equal exchange basis. For research purposes, the consumption of lunar material was carried out with extreme economy. The study of lunar soils under laboratory conditions on Earth was carried out in special chambers filled with helium or in a vacuum at a temperature of +20°C to +140°C.[48] Studies showed that regolith, despite its similarity to some terrestrial soils, has properties that are not characteristic of terrestrial soils. For instance, regolith samples returned by the Luna-16 and Apollo missions contained glassy silicate particles in the form of regular droplets or spheres with diameters of 0.05-5 μm and 40-480 μm were found, which are not found in terrestrial soils. The presence of these spheres raised the question of their influence on soil compaction. The dusty soils of the Moon have a tendency to form clumps that are indistinguishable from rocks in photographs. This property was attributed to the presence of cohesion documented in field tests on the Moon. However, under laboratory conditions on Earth, it is not possible to reproduce the cohesion of water-free dusty soils unless the van der Waals forces in the contacts are replaced by some other forces.[12]

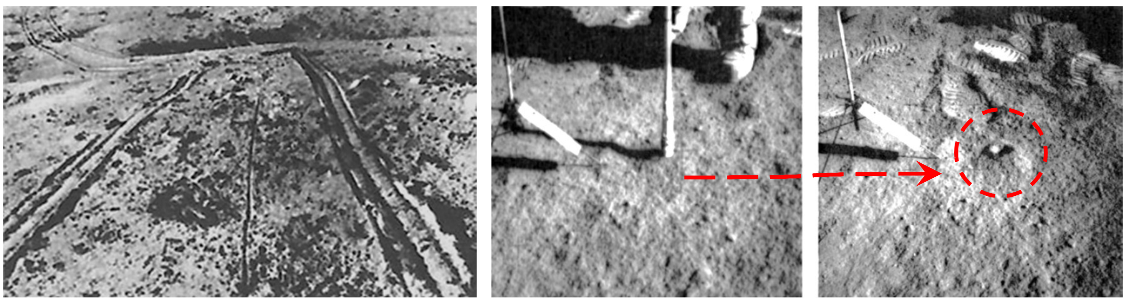

Figure 8. Clumping of lunar soil. A) Lunar surface after the passage of the Lunakhod-1 (Source: Cherkasov & Shaverv, 1975)[49]. Collection of a deep core sample of lunar soil by Apollo 15 mission: B) core tube driven to a final depth of 68 cm; C) neat open hole remaining in lunar surface material after withdrawal of the core tube. (Source: Carrier W.D. *et al.*,1991)[50].

In this sense, one of the key physico-mechanical properties of lunar regolith considered in the present proposal is that the cohesive forces between the loose particles manifest themselves in their ability to stick together and achieve a degree of cohesion that allows the soil to clump and support vertical walls of a small height.[16] According to the cosmonauts' observations, the pressure of the Lunokhod chassis induced some compaction of the regolith and its lateral bulging. When crushed, the soil clumps and forms a steep slope of fine-grained material with non-crumbling walls (Figure 8-A).[16,49] In addition, during the collection of a 68 cm deep core sample of lunar soil by the Apollo 15 mission, it was documented that a neat, round hole was left in the lunar surface after the core tube was withdrawn after approximately 50 hammer blows, as well as well-formed footprints from the astronaut's boots (Figure 8-B and 8-C).[50] This behaviour indicates the presence of significant cohesive forces in the lunar soil.

Key physico-mechanical properties of lunar soil (lunar regolith)

Data from different Russian and American lunar missions show that the mechanical properties of the lunar soil are highly dependent on the degree of compaction and the variation of bulk density with depth is related to its dependence on pressure. Leonovich, A. K. *et al.* (1973)[51] claims that the most probable values for lunar soil in natural state is a coefficient of porosity $\varepsilon = 0.9$ and a bulk density of $\rho = 1.6$ g/cm^3 with a particle specific gravity of $G = 3$ g/cm^3. However, Mitchell *et al.* (1974)[52] proposes that the "best estimate" values are $\rho = 1.5$ g/cm^3 and $G = 3.1$ g/cm^3.[16,50,53] The soil particle specific gravity (G) is defined as the ratio of its mass to the mass of an equal volume of water at 4°C. The bulk density of a soil (ρ), as a function of the porosity (n), the specific gravity of its particles (G), and the density of water at 4°C ($\rho_w = 1$ g/cm^3), is assumed to be defined by the Equation (1):

$$\rho = \rho_w G(1 - n) \tag{1}$$

Table 1 summarises some of the estimated bulk density values determined since the early lunar exploration missions.[54]

Table 1. Estimates of lunar soil bulk density. (Source: Mitchell, J. K. *et al.*, 1972)[54]

Mission	Investigator	Bulk density ρ (g/cm^3)
Luna 13	Cherkasov *et al.*, 1968	0.8
Surveyor III and IV	Scott and Roberson (1967, 1968)	1.5
Apollo 11	Costes & Mitchell, 1970	1.57 – 1.75
Apollo 11	Costes *et al.*, 1971	1.81 – 1.92
Apollo 12	Houston & Mitchell, 1971	1.55 – 1.90
Apollo 12	Carrier *et al.*, 1971	1.70 – 1.90
Luna 16	Vinogradov, 1971	1.2
Lunakhod 1	Leonovich *et al.*, 1971	1.50 – 1.70
Apollo 14	Carrier *et al.*, 1972	1.45 – 1.60
Apollo 15	Mitchell *et al.*, 1972	1.35 – 2.15

Based on Equation (1), the porosity of the lunar soil can be determined by Equation (2) using the specific gravity of lunar soil particles $G = 3.1$ g/cm^3 (proposed by Mitchell *et al.*, 1974)[52].

$$n = 1 - \frac{\rho}{\rho_w G} = 1 - \frac{\rho}{3.1} \tag{2}$$

Porosity (n) and the coefficient of porosity (void ratio, ε) are related as follows:

$$n = \frac{\varepsilon}{1+\varepsilon}\ ;\ \ \varepsilon = \frac{n}{1-n} \tag{3}$$

The maximum void ratio (ε_{max}) corresponds to the maximum porosity (n_{max}) or minimum bulk density (ρ_{min}), and the minimum void ratio (ε_{min}) corresponds to the minimum porosity (n_{mi}) or maximum bulk density (ρ_{max}). Mitchell *et al.*, (1974)[52] tentatively proposed the void ratio values (porosity coefficients) $\varepsilon_{max} = 1.7$ and $\varepsilon_{min} = 0.7$ for lunar soil.[53]

The bulk density may change in wide limits and in dependence on the spatial assemblage of grains without their deformation or destruction. For a granular lunar soil, the degree of particle packing is defined by the relative density (D_R):

$$D_R = \frac{\rho_{max}}{\rho}\frac{(\rho-\rho_{min})}{(\rho_{max}-\rho_{min})} \times 100\% \tag{4}$$

where ρ is the bulk density of lunar soil, ρ_{min} and ρ_{max} are the minimum and maximum values of the bulk density respectively.

In function of the void ratio (porosity coefficient) or the porosity, the relative density can also be defined by:

$$D_R = \frac{(\varepsilon_{max}-\varepsilon)}{(\varepsilon_{max}-\varepsilon_{min})} \times 100\% = \frac{(1-n_{min})}{(1-n)}\frac{(n_{max}-n)}{(n_{max}-n_{min})} \times 100\% \tag{5}$$

The in situ relative density of the lunar regolith in the upper 15 cm layer is about 63–65%, which corresponds to medium to high density (consistency), but increases to over 90% (very dense) below 30 cm depth.[16,17,50,52,54] The empirical hyperbolic relationship between the bulk density of the lunar soil and depth (z) is described by Equation (6)[50] and shown in Figure 9.

$$\rho = 1.92\frac{z+12.2}{z+18} \tag{6}$$

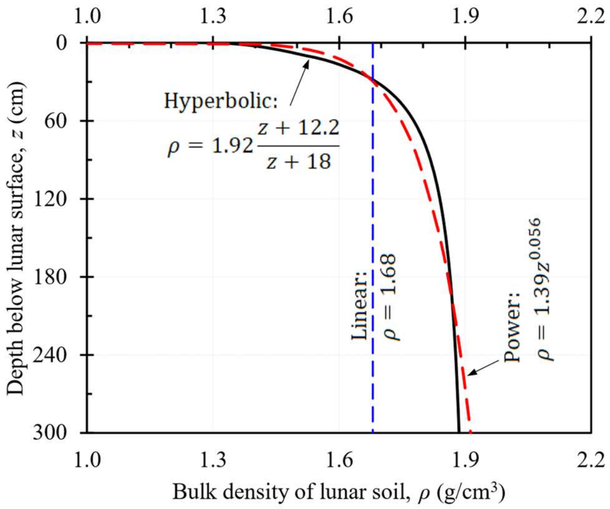

Figure 9. Bulk density of lunar soil as a function of depth below the surface. (Modified after Carrier W.D. *et al.*, 1991)[50].

The variation of density due to compaction pressure is a significant property of lunar regolith, as it determines all its other physical, mechanical, thermal and electromagnetic properties. The bulk density of the regolith in the upper 30 cm layer of the lunar surface increases sharply with depth. Nevertheless, at depths greater than 60 cm the bulk density increases slightly, probably due to the low value of lunar gravity. Consequently, the natural compaction of the lunar regolith at depth is insignificant. The average bulk density of the lunar regolith in the 10 cm layer is 1.5–1.6 g/cm^3 and the angle of internal friction is ~25°, but at 40–50 kPa (0.4–0.5 kg/cm^2) of compression the angle of internal friction and cohesion gradually reach a constant value and the deformation values converge towards the state of maximum compaction (Figure 10).[16,53]

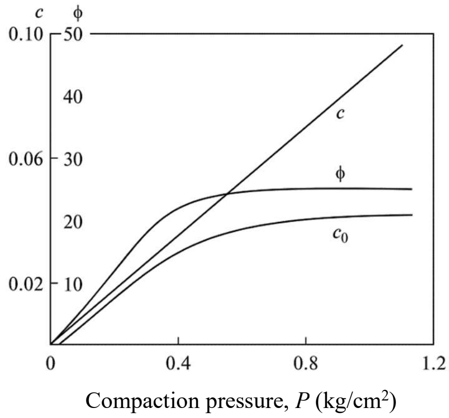

Figure 10. Dependence of the shear strength parameters on the normal compaction stress. Here *c* is the initial cohesion (kg/cm^2), ϕ is the angle of internal friction in degrees. (Source: E. Slyuta, 2014)[16].

V. V. Gromov studied a 20 g sample of the 100 mm top layer of the lunar soil returned by the Soviet mission Luna-20. The results of the compaction tests showed that the bulk density of the regolith sample in the loose state was 1.04 g/cm^3, which corresponds to a porosity coefficient of $\varepsilon = 1.88$, and after vibro-impact compaction the bulk density was 1.798 g/cm^3, which corresponds to a porosity coefficient of $\varepsilon = 0.67$ (considering a specific gravity of $G = 3$ g/cm^3).[49] Based on these results, he concluded that the equation of the compaction curve (Figure 11) is composed of two terms. In the range of compressive stresses from 0 to 0.4 kg/cm^2 the change of ε is mainly determined by the first term of Equation (7), and at higher values of P by the second member.

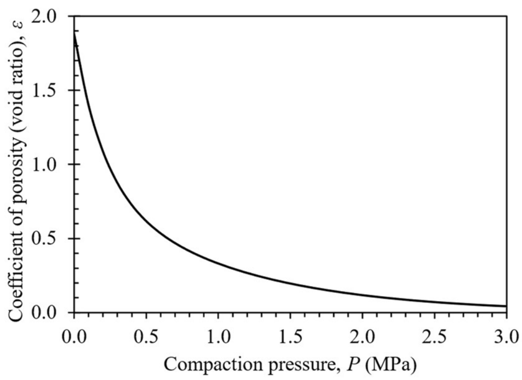

Figure 11. Compaction curve of lunar regolith. Dependence of void ratio on compaction pressure.

$$\varepsilon = 0.98e^{-0.5P} + 0.9e^{-0.1P} \quad (7)$$

where ε is the porosity coefficient and P is the compressive pressure in kg/cm^2.

Definition of compaction pressure for the elaboration of Compressed Regolith Bricks (CRB)

Loose regolith consists of aggregates formed by clumped grains. These aggregates are characterised by low strength and form a weak structure of the loose sample. After the application of compaction pressure, two processes occur: firstly, the aggregates join together and the overall porosity of the soil decreases significantly; secondly, the weak aggregates collapse and the individual grains are packed together, which also leads to a decrease in porosity. As I. Cherkasov (1975)[49] points out, at compaction pressures above 0.5 kg/cm^2 the regolith compaction occurs due to the destruction of aggregates at their contact points and the reduction of intergranular and subgranular porosity.

The main physico-mechanical properties considered as input data are: specific gravity of soil particles $G = 3.1$ g/cm^3, average bulk density of the uppermost 15 cm layer of the lunar regolith 1.5 g/cm^3, maximum void ratio ε_{max}=1.7, minimum void ratio ε_{min}=0.7 (W. Houston,).[53] Additionally: modulus of deformation 240 kPa, Poisson's ratio 0.2, shear strength 6 kPa (0.06 kg/cm^2), cohesion 1.6 kPa (0.016 kg/cm^2), angle of internal friction 46°.[16,17,54,55] Nevertheless, is important to note that recent experimental results from lunar samples collected by the Chang'e-5 mission show that the residual friction angle of lunar regolith under low confining pressure is predicted to be between 53° and 56° depending on the overall particle regularity and inter-particle friction coefficients.[56] Table 2 shows the minimum and maximum values of porosity and bulk density determined by equations (1) to (3).

Table 2. Porosity and bulk density of lunar regolith.

Void ratio (Porosity coefficient)	Porosity	Specific gravity G (g/cm^3)	Bulk density ρ (g/cm^3)
$\varepsilon_{max} = 1.7$	$n_{max} = 0.63$	3.1	$\rho_{min} = 1.148$
$\varepsilon_{min} = 0.7$	$n_{min} = 0.41$	3.1	$\rho_{max} = 1.824$

Studies on Compressed Earth Blocks (CEB) show that the higher the degree of compaction, the better the structural performance. The target degree of compaction for the production of CEB is usually between 83% and 90%. For the production of the regolith bricks, we consider that a relative density of 90% should be reached. It is estimated that this can be achieved by applying compaction pressures higher than those experienced by the regolith under natural conditions of low lunar gravity. The result will be a reduction in the void ratio of the loose regolith, the collapse of the natural aggregates at their contact points and the reduction of intergranular and subgranular porosity.

Considering the CRB unit as an ideal material (without voids), the maximum density should be equal to the value of specific gravity (G) of regolith particles, and the equivalent density would be $D_R = 100\%$. Therefore, assuming $\rho_{max} = 3.1$ g/cm^3 and $\rho_{min} = 1.5$ g/cm^3 (average bulk density) as the minimum density, the minimum value of the void ratio to reach a tentative target relative density $D_R = 90\%$ should be approximately $\varepsilon_{min}^{CRB} = 0.10$. According to Equation (7), a minimum compaction pressure of $P = 2.2$ MPa is required to achieve this value of void ratio (Figure 12). Thus, the maximum density of the CRB would be approximately 2.8 g/cm^3.

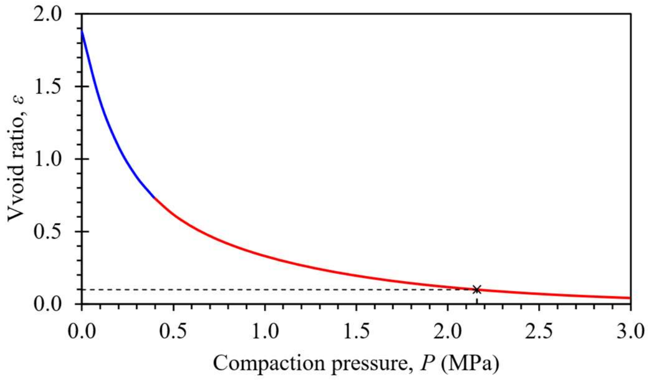

Figure 12. Dependence of void ratio on compaction pressure. A void ratio of 0.1 requires a compaction pressure of 2.2 MPa.

Proposal for future experimental investigations on Compressed Regolith Bricks (CRB)

On the basis of the above, it is proposed to carry out further experimental investigations to determine the feasibility of the production of compacted regolith brick units. The experimental investigations should study the behaviour of CRB produced by:

a) confined compaction of loose regolith in rigid moulds without the use of binding materials,
b) combination of confined compaction of loose regolith in rigid moulds and sintering at high temperatures (T > 1000 °C),
c) simultaneous combination of confined compaction of loose regolith in rigid moulds and sintering at intermediate temperatures (150 °C < T < 500 °C),
d) simultaneous combination of confined compaction of the regolith with the addition of thermoplastic binders and sintering at different temperature levels.

In addition, further research should be conducted on:

a) automation of lunar regolith collection and CRB unit production,
b) automation of construction using robotic bricklaying methods.

Once the feasibility of their production has been determined, research should focus on the study of stress-strain behaviour of CRB units, the bonding materials, block connection mechanisms, and the behaviour of the CRB masonry structures. These structures, given their likely shape, can be subject to normal and shear stresses, which mainly influence the contact interfaces. The influence of the contact interfaces (brick/brick or brick/bonding agent) should be considered when assessing the overall structural behaviour. The detailed micro-modelling of masonry could be a suitable approach for the structural analysis.[57,58]

CONCLUSIONS

The In-Situ Resource Utilisation (ISRU) of lunar regolith for construction on the Moon has been extensively studied by a number of scientists. The main objective of this idea is to use the lunar regolith both for the construction of habitable modules for a lunar base and its protection against radiation, temperature gradients and micrometeorite impacts.

Lunar regolith is the most accessible in-situ material for the production of compressed bricks on the Moon, due to its strong adhesive and cohesive properties. In addition, its low thermal conductivity makes it a good material for thermal insulation.

The key physico-mechanical property of lunar regolith for CRB production is the cohesive force between the loose particles, which stick they together and allows the soil to clump.

At compaction pressures above 0.5 kg/cm^2 the regolith compaction occurs due to the destruction of aggregates at their contact points and the reduction of intergranular and subgranular porosity. The specific gravity of lunar regolith particles is $G = 3.1$ g/cm^3, the average bulk density of the uppermost 15 cm layer is 1.5 g/cm^3, the maximum and minimum void ratios are ε_{max}=1.7 and ε_{min}=0.7. The modulus of deformation at natural state is 240 kPa, Poisson's ratio is 0.2, the shear strength is 6 kPa, the cohesion is 1.6 kPa, and the angle of internal friction is 46°. Although experimental results from lunar samples collected by the Chang'e-5 mission show that the residual friction angle of lunar regolith under low confining pressure is between 53° and 56°.

For production of CRB units, we consider that a target relative density $D_R = 90\%$ should be reached. The minimum value of the void ratio to reach this target relative density should be approximately $\varepsilon_{min}^{CRB} = 0.10$ at a minimum compaction pressure of $P = 2.2$ MPa. The maximum density of the CRB would be approximately 2.8 g/cm^3.

The results of the present investigation show that there is a high probability that in situ production of compacted regolith bricks (CRB) for construction on the Moon is feasible. Therefore, we recommend to carry out further experimental investigations on the production of CRB units by: confined compaction of loose regolith in rigid moulds without the use of binding materials; combination of confined compaction of loose regolith in rigid moulds and sintering at high temperatures (T > 1000 °C); simultaneous combination of confined compaction of loose regolith in rigid moulds and sintering at intermediate temperatures (150 °C < T < 500 °C); simultaneous combination of confined compaction of the regolith with the addition of thermoplastic binders and sintering at different temperature levels.

ACKNOWLEDGMENTS

The author acknowledges the RUDN University for funding the publication of this work.

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