Development of Novel Blocks Using Martian Soil and Mycelium for Extraterrestrial Infrastructure Construction

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BRIEF. An investigation of the application of mycelium bricks in an extraterrestrial habitat construction setting and possibilities for substrate variants for mycelium brick growth.

ABSTRACT. Mycelium is the underground network of threads from which mushroom absorb nutrients from the environment. The purpose of this study is to develop lightweight, durable mycelium bricks to be cultured on spaceships en route to Mars and used to build habitation facilities on Mars. Possible waste materials from spaceship operation were used as the base substrate of the mycelium brick. A Martian regolith simulant was also incorporated into the bricks to observe any possible changes in performance in exchange for using up less Earth-derivative resources once land on Mars. Four fungi species (*Rhizopus oryzae*, *Ganoderma resinaceum*, *Pleorotus ostreatus*, and *Penicillium sp*.) were obtained and cultured in a medium containing various combinations of cellulose, paper towels, coffee powder, and sawdust to encourage the growth of mycelium in the bricks over the course of a week, with some bricks having Martian simulant incorporated into the substrate. The bricks were then baked to maintain the structures formed within the brick and improve structural integrity. The durability of each manufactured brick was tested and recorded according to the degree of destruction the brick had sustained. Among the bricks made solely using mycelium, the cellulose powder-paper mixture with *G. resinaceum* was the stongest for its potential energy absorption-to-weight ratio. For the bricks mixed with a Martian simulant, the cellulose powder-coffee ground-paper substrate with *G. resinaceum* had the highest energy absorption-to-weight ratio.

INTRODUCTION.

For decades, people have been exploring the possibility of colonizing Mars to create a new place for humans to inhabit [1]. Many obstacles have prevented that dream from being fulfilled. Bringing all resources necessary for human survival from Earth is difficult and inefficient. Space missions already require lots of mass in the form of significant resources for human survival and travel, such as food, water, and mission-imperative equipment. Therefore, it is imperative to focus not only on increasing the efficiency of cargo transport aboard spacecraft but also on lowering the number of trips required to accomplish migration and colonization, reducing mission costs and time. Supplies for construction weigh a considerable amount. Because weight is a luxury in space due to the exponentially increasing amounts of fuel needed to lift larger and larger masses, many of the materials necessary for construction must be produced in situ [2]. Currently, the main goal for establishing human habitation on Mars is reducing the cost and weight of shelter [3][4]. Many previous investigations and experiments have utilized 3D printing technology to build sustainable housing on other planets. These proposed 3D printers would use regolith, the rocky gravel-like substance found on the surface of bodies such as the Moon and Mars, mixed with plastics to form a filament with which the necessary parts for housing would be printed [5]. Although regolith is abundant on the surface of Mars, it is quite a troublesome material to work with due to its glass-like structure which adheres to many surfaces due to electrostatic charge. This property can cause problems when regolith contacts the vital mechanisms of the 3D printer, making 3D printing with regolith unreliable [6]. There have also been studies exploring the use of Martian regolith to create a form of cement. By mixing molten sulfur with Martian regolith, scientists were able to create a form of concrete that had a compressive strength higher than 50 MPa and could be recyclable by reheating the material [7]. However, due to the shrinking of sulfur in the concrete that occurs when temperatures drop, the structural integrity of the material can be compromised. Cracks form from a lack of support left behind by cavities unfilled by sulfur and create more stresses on the remaining regolith aggregate material as the concrete shrinks and stretches, especially with the drastic temperature changes common on Mars [8]. In addition, while sulfur may be an abundant resource on Mars, it still requires its own chemical plant to harvest and refine the raw sulfur mined from the Martian earth [9]. As a result, without prior infrastructure, sulfur concrete production would be severely limited. With these considerations, the recent discovery of mycelium bricks and their newfound utility in construction seems to be the most promising next step towards sustainable and efficiently made buildings on Mars [10]. Although fungi must be brought from Earth and require water and energy sources to kickstart their growth, fungi are naturally hardy creatures, not needing as much maintenance as other plants [11]. The fungi can also reproduce asexually, reducing the risk of mutation in the building material [12]. Furthermore, the final mycelium bricks weigh a tenth of what a similar volume of concrete would, allowing the building material to be utilized to construct buildings without the need for heavy and costly machinery [13]. Similarly, the simplicity of growing fungi bypasses the need for machinery, which sulfur-based concrete, with the need for sulfur refineries on Mars, and 3D printed housing, cannot be created without the presence of a printer. Mycelium bricks have a greater strength-to-weight ratio than concrete [14]. Out of the four fungi species to be experimented on, *P. ostreatus, G. resinaceum, R. oryzae,* and *Penicillium s.p.*, bricks that contain the fungi *R. oryzae* may prove to be the most effective fungi in creating mycelium structures with the limited resources provided due to their resilience in less optimal conditions. However, mediums containing coffee grounds and cellulose powder may perform best in providing both phosphorous and cellulose for the fungi to break down into energy necessary for growth.

MATERIALS AND METHODS.

Materials Preparation.

A total of 4 different species of fungi were utilized in the experiment. Two species of fungi were obtained from the Korean Collection for Type Cultures (KCTC), one was bought from an online agricultural market, and one was obtained naturally through pre-existing spores within coffee grounds. Coffee grounds, due to their high levels of phosphorus, nitrogen, potassium, and other trace minerals, are an ideal environment for cultivating fungi such as *Penicillium sp.* and *Aspergillus sp.* Although the chance of contamination from an *Aspergillus sp.* also residing in the coffee grounds was quite high, it seemed that Penicillium sp. took dominance within the closed system in the end, isolating itself as the sole species of fungi present in the culture.

Growth of Fungi.

The fungi obtained from the KCTC, *G. resinaceum* and *R. oryzae*, were inoculated into a Potato Dextrose Agar (PDA) medium. *G. resinaceum* spores were resuspended with 1 mL of distilled water, and 10 uL of the resuspended fungi spores were dropped on the PDA medium. The *R. oryzae* fungus was obtained as an already-inoculated medium with the fungi spores in it. A piece of medium in which the fungus was cultured was cut finely and placed on the PDA. The media inoculated with each fungus was incubated at room temperature for one week. To obtain the *Penicillium sp.* fungi, 1.5 kg of coffee grounds were transferred to a Styrofoam container and 500 mL of distilled water was added to the coffee grounds. After mixing the coffee grounds and water well, the mixture was incubated at room temperature for 12 days. To help distribute the fungi spores evenly throughout the coffee grounds, the mixture was mixed once every 4 days during the incubation period. *P. ostreatus* fungi obtained from the online marketplace were already in a sufficiently mature stage of growth, allowing for their immediate usage in growing the bricks.

Production of Materials for the Manufacture of Bricks.

The purpose of making bricks using fungi is to sufficiently cultivate fungi during the transit time to Mars. Therefore, the prepared medium must supply sufficient nutrients for fungi growth on its own. Generally, fungi break down cellulose or lignin to obtain nutrients. Four different materials—cellulose powder, coffee grounds, animal-grade sawdust, and paper towels—were used to produce the various mediums for the bricks. These materials were mixed in varying proportions shown in Table 1.

Table 1. The Composition and Proportion of Materials for Each Brick Type

Materials	Used Amount (Ratio)	Water
Co + Ce + Pa	150 g : 15 g : 37.5 g (10 : 1 : 1.5, Weight)	500 mL
Co + Pa	7 g : 7.5 g (1 : 2.5, Weight)	175 mL
Co + Ce	100 g : 10 g (10 : 1, Weight)	100 mL
Co + SD	500 mL : 500 mL (1 : 1, Volume)	250 mL

Co, Coffee Grounds; Ce, Cellulose Powder; Pa, Paper Towels; SD, Sawdust

Preparation of Mycelium Bricks.

G. resinaceum or *R. oryzae* grown on the PDA media were transferred into each beaker, and the medium in which fungi were cultured was cut into small pieces using a spoon. *Penicillium sp.* grown in coffee grounds was used as is because of their already homogenous state, and *P. ostreatus* was further processed into smaller pieces. Each fungus was divided into quarters and mixed with the prepared mediums. To ensure the sufficient growth of fungi in each material, the mixtures were incubated at room temperature for 2 days. To prepare the bricks containing simulated Martian soil, the mixture containing each material and each fungus was mixed with MMS-2 enhanced Mars Simulant (The Martian Garden, USA), a mixture of materials that recreates the chemical composition of Martian regolith, in a ratio of 1:1 to improve the structural stability of the bricks. To fabricate the bricks, each well in a 12 well plate was used as a formwork. The incubated mixture was put into each well and baked at 65˚C for 5 days to dry completely.

Testing Procedure.

To test the limits of the bricks' ability to withstand certain levels of force, each completely dried brick was placed within a petri dish. A metal weight was used to simulate the loads that bricks may have to face as a structural element in a habitat. There were a total of 5 weights in the experiment, each weighing 50 g, 100 g, 200 g, 500 g, and 1 kg. To drop the many metal weights from 20 cm above the floor, the height of the test bench was adjusted so that the tip of the weight was 20 cm away from the floor. After lining up the weights with the brick below, the weights were dropped, and the resulting aftermath was recorded using a photo. Structural failure was determined through an observation of the bricks post-weight-drop, formation of cracks within the bricks' structure serving as evidence of structural failure. The amount of force withstood by each brick was calculated using Newton's Law of Universal Gravitation (Eq. 1).

$$F = G\frac{m_1 m_2}{r^2} \quad (1)$$

where F = force, G = gravitational constant, m_1 = mass of object 1, m_2 = mass of object 2, and r^2 = distance between centers of the masses. Afterwards, all the weights and force tolerances, after being calculated, were averaged out and used as the results.

RESULTS.

Non-Martian Mycelium Brick Potential Energy Resistance (J) per Unit of Mass (g).

On Mars, the supply of energy that can be consumed in the transport of objects is limited, so the optimal material used for the construction of the Mars habitats must be both lightweight and durable. Among bricks using *R. oryzae, G. resinaceum,* or *P. ostreatus*, excluding *Penicillium sp*., bricks containing paper showed relatively high durability per weight. In addition, the durability of bricks containing coffee grounds was reduced, and even bricks containing cellulose, or sawdust showed low durability (Fig 1).

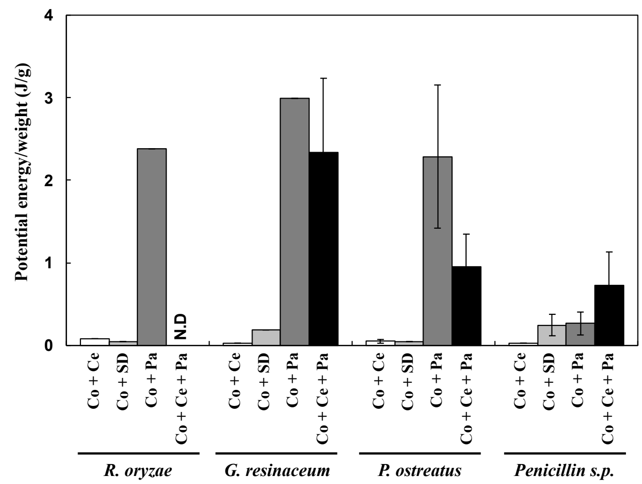

Figure 1. Point of structural failure in J/g of bricks not containing Martian simulant against potential energy absorbed from dropped metal weight
Co, Coffee Grounds; Ce, Cellulose Powder; Pa, Paper Towels; SD, Sawdust; N.D, Not Determined

Martian Mycelium Brick Potential Energy Resistance (J) per Unit of Mass (g).

The durability per unit of weight due to the addition of Mars Simulant was greatly reduced in bricks containing paper. Among the bricks made using *G. resinaceum* or *Penicillium sp.*, the durability of bricks containing coffee grounds and cellulose increased significantly with the addition of Mars Simulant, and among bricks made using *P. ostreatus*, the durability of bricks containing coffee grounds and sawdust was also greatly increased (Fig. 2).

DISCUSSION.

It is important to restate that the goal of this experiment was to see if the usage of mycelium bricks in in situ Martian bases was viable for increasing the efficiency of spaceship transport for construction materials. With that in mind, this experiment has opened many avenues in achieving the presented goal via the exploration of a diverse range of materials for mycelium brick growth. For instance, the way the paper-based mediums did not "break" is quite interesting and can be attributed to its fibrous nature. The bricks developed using paper mediums do not crumble, instead deforming under plastic deformation,

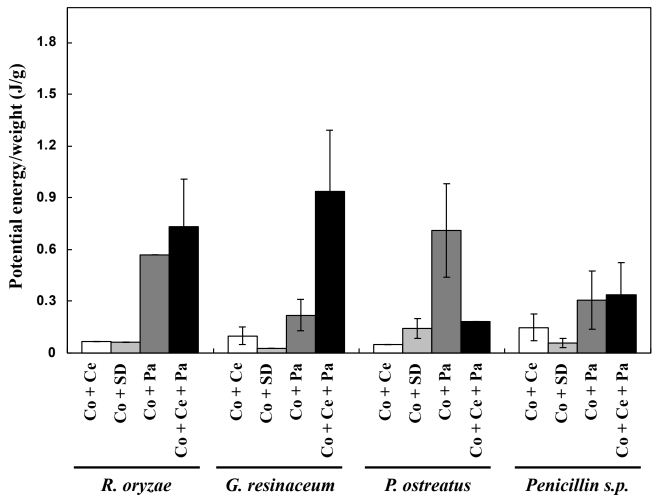

Figure 2. Point of structural failure in J/g of bricks containing Martian simulant against potential energy absorbed from dropped metal weight
Co, Coffee Grounds; Ce, Cellulose Powder; Pa, Paper Towels; SD, Sawdust; N.D, Not Determined

permanently deforming into a more compressed form, leading to higher-than-normal tolerances than any of the other substrate brick materials. Considering Mars has a thin atmosphere with a surface pressure less than 1% of the Earth's [15] that does not offer much in terms of destructive force through winds and other natural conditions, this paper-based medium may offer a means of creating bases that do not have microfractures formed after prolonged use that other earth-based rigid structures are notorious for, prolonging their stability and integrity. Another topic of further research is the shape in which the bricks are made in. The shape in which the *P. ostreatus* samples came in was that of a cylinder with a hole bored in the middle. Presumably, this was done to give the fungi in the middle of the sample more oxygen and thus allow for faster growth. In future experiments, this may be implemented to reduce the growth time of the sample to be tested. Unlike other organisms, the cultivation of fungi does not require large amounts of water or nutrient pre-processing to break down macromolecules into smaller molecules to be used as energy sources. As a result, crew may be able to use food leftovers to provide moisture and nutrients for fungal culture. In addition, since the migration to Mars, a travel period taking about six to ten months [16], provides ample time to cultivate the fungus, the bricks required for construction could be prepared during migration and used for building as soon as the crew arrive on Mars. Making bricks that can be used immediately upon arrival to Mars using a small amount of cargo weight during travel can significantly increase the efficiency of the long transit periods for Mars colonization. Such advances would lessen resource use by reducing the number of required trips, making space colonization a more viable possibility in the near future.

CONCLUSION.

For any bricks to be made from substrate and mycelium, a cellulose powder-paper mixture with *G. resinaceum* is advised for its high potential energy to weight ratio. For bricks mixed with a martian simulant, a cellulose powder-coffee ground-paper substrate with *G. resinaceum* is recommended for the same reasons as above. Through the strength of these bricks in withstanding high forces with such little mass, the idea that mycelium bricks with low masses can support structural loads is maintained and makes mycelium bricks a viable material for future Martian bases.

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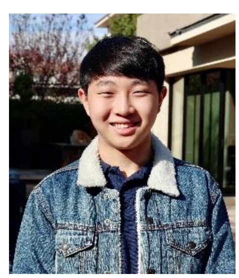

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