# Production of Gravel from Lunar Soil Simulant by Rapid Microwave Sintering

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**Introduction:** Because the transportation cost from the Earth to the Moon weighs heavily on budgets of lunar mission, utilization of lunar local resource is certainly required in particular for constructing lunar facilities after the initial exploration phase. Various methods for making construction materials from lunar regolith have been proposed and studied up to this point as listed as follows [1].

a. Compacting regolith in-situ or in containers

b. Packing regolith in bags

c. Mixing regolith with binder agent(s), and solidifying in formworks

d. Sintering regolith in-situ or in heat-resistant formworks

An ideal method for making construction material on the moon is that it does not require any additional earth-based consumables, such as binder agents or even formworks. In addition, we do not know yet that the material made by which method can be used for which part of construction.

In this context, more studies on these materials especially to clarify not only the relationships between the productive conditions and the properties of the materials in each method, but also the application of each material are still needed.

In this study, we focused on the pavement as one of the applications of these materials, because the pavement implies essential technologies relating to the important facilities such as roads, launching/ landing pads and foundations of surface structures.

**Functions required to the pavement:** Major technical functions of pavement are summarized as follows;

a. Reducing sinkage of the ground under vehicles, facilities, and so on

b. Reducing bumps for easy transportation and stabilized settlement of facilities

c. Reducing deformation of ground by weathering

d. Reducing generation of dust from ground surface

Various types of paving materials have been developed and applied on Earth to secure these functions. They are stone (gravel), brick, asphalt, concrete, crushed rock (Macadam), interlocking block, and so on. Most of these materials except asphalt are expected to be used on the moon. Considering about simplicity and performance of the pavement however, gravel pavement will be the most promising method in the early phase of lunar construction. In addition, gravel can be used not only for paving but also for various composites and cultivation ground.

**Production of gravel on the Moon:** Gravel can be produced on the moon by 1) collecting pebbles distributed on lunar surface, 2) crushing rocks, or 3) sintering regolith. Collection of pebbles may be the simplest method if proper size and shape of pebbles are sufficiently distributed around. On the other hand, it will be a hard work to collect enough amount of pebbles if they will not be around. Making gravel from lunar rocks will require a relatively large scale mobile crushing machine, which will be difficult to bring from the Earth. In case of regolith sintering, a heating and cooling system will be needed. Because enough amount of solar power and regolith as raw material of the gravel can be easily obtained on the Moon, regolith sintering process seems to be a realistic method.

The gravel can be produced by crushing bricks, which are sintered in ceramic formworks. However, we selected a direct heating of regolith by microwaves, because this method does not need any crushing machines nor formworks. Previously, microwave sintering of lunar soil simulant instead of regolith was conducted using high power multimode microwave reactor [2]. Due to low dielectric loss of the simulant at low temperature, microwave susceptors are required until the simulant exhibit thermal run-away. However, use of susceptor is not desirable due to its high transportation cost. Therefore, in this paper, a single-mode microwave resonator and a semiconductor microwave generator was used for sintering simulant without microwave susceptor by generating highly focused microwave electric field at the simulant.

**Production of gravel by microwave sintering:** Microwave sintering was conducted by a semiconductor microwave generator (2.45 GHz, max: 100 W) equipped with a single-mode ($TM_{010}$ mode) microwave resonator [3]. Simulant (FJS-1) was added to quartz tube in between quartz wool and quartz sand. The quartz tube was inserted at the center of $TM_{010}$ mode microwave resonator (Fig. 1a). Microwaves were irradiated to the simulant by 20 – 100 W and 5 – 25 min in air or under vacuum (0.1-1.0 Pa). The impedance matching was adjusted by inputting resonance frequency to obtain maximum microwave propagation to the irradiated material. The temperature during microwave irradiation was monitored by a pyrometer and a thermography (Fig. 1b).

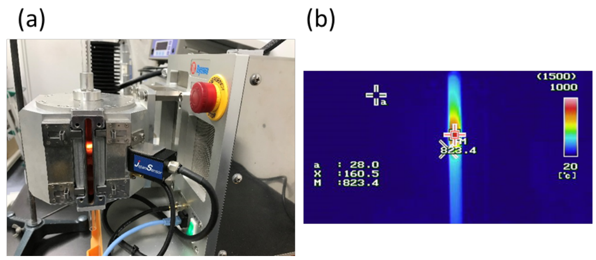


Fig. 1 Microwave apparatus equipped with (a) single-mode ($TM_{010}$ mode) microwave resonator and semiconductor microwave generator and (b) thermal distribution during microwave irradiation.

Fig. 2 shows temperature profile during microwave sintering in air and under vacuum condition. The temperature increase attained 500 °C/min and reached around 900 °C within 2 min in air. As a result, sintering of the simulant was completed within 5 min. In case of vacuum condition, the heating rate was relatively lower than air condition due to higher microwave reflection by generation of plasma inside the quartz reactor. After 18 min, the simulant exhibited thermal runaway and reached around 900 °C.

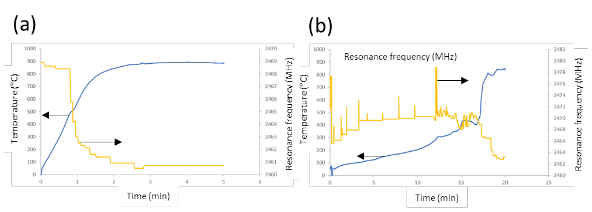


Fig. 2. Temperature profile of lunar soil simulant during microwave irradiation (a) in air and (b) under vacuum

Fig. 3 and 4 shows the gravels produced by microwave sintering in air and under vacuum. In air condition, the size of gravel was relatively smaller due to higher amount of unsintered simulants. Microwave power above 40 W was required to obtain gravel-like shape. Under vacuum condition, the size of sintered simulant became larger due to better thermal insulation during microwave irradiation. The gravel could be obtained even at 20 W microwave power.

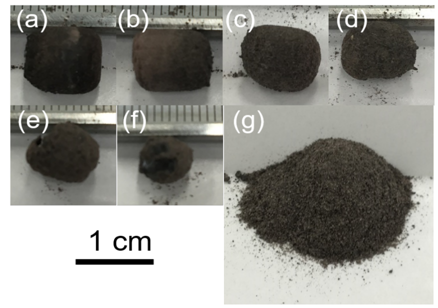


Fig. 3. The gravels produced by microwave sintering in air. (a) 100 W 10 min (b) 80 W 5 min (c) 60 W 5 min (d) 50 W 5 min (e) 40 W 10 min (f) 30 W 10 min (g) 20 W 20 min.

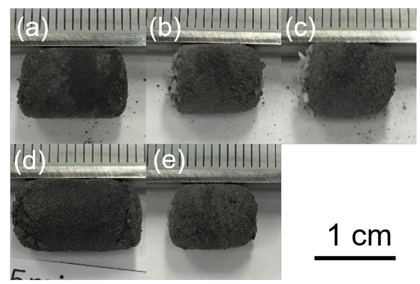


Fig. 4. The gravels produced by microwave sintering under vacuum. (a) 100W 25min, (b) 60W 20min (Frequency range: 2,400 - 2,500 MHz), (c) 60W 20min (Frequency range: 2,460 - 2,470 MHz), (d) 40W 25min, (e) 20W 20min.

**Conclusion:** The gravel produced from lunar regolith could be a useful material for pavement, composites, cultivation, and so on. We have proposed a production method of gravel, in which a lump of regolith is heated by microwaves using a single-mode microwave resonator and semiconductor microwave generator. The gravels could be obtained within 5 min (in air) and 25 min (under vacuum) at low microwave power output (20 – 100 W). Because this method is simple and does not need any additional microwave susceptor, we are expecting that this could be one of the realistic processes in future lunar construction.

**References:**

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