論文内容の要旨

論文題目　Investigation on practical production methods of lunar concrete
（ルナコンクリートの実用的製造手法に関する研究）

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On 4th December 2006, NASA (National Aeronautics and Space Administration, U.S.A) unveiled their Global Exploration Strategy; “To return astronauts to the Moon no later than 2020”. 13 other countries including Japan agreed on cooperative lunar exploration with USA, and have discussed the mission objectives for the exploration. The term “In-Situ Resource Utilization” means the production of materials from local resources on the target site, instead of delivering the materials. Employment of ISRU reduces launch mass/cost and mission risk, and increases usable material, power, margin of safety, and whole mission capabilities. Therefore, ISRU is considered to be essential technology for future space exploration, and identified as one of the mission objectives of the international lunar exploration.

Lunar concrete is one of possible materials obtained by ISRU, and expected to start demonstration on the Moon around at 2020. It is considered to be an essential material for future lunar base development due to;

- Relatively cheap production cost compared to metals.
- High performance under the severe lunar environment, such as extreme temperature, heavy space radiation, and meteorite impact
- Versatile applications, such as precast panel production and assembly, onsite casting, grouting, shotcrete, etc

Assumed composition of lunar concrete is approximately 17% of cement, 78% of aggregate and 5% of water. All components of lunar concrete except 0.5 wt% of hydrogen can be produced by ISRU on the Moon. However, even though necessary elements for cement exist on the Moon, typical minerals of cement materials on the Earth, such as lime stone, iron ore, bauxite created by sedimentation or weathering, cannot be found on the Moon. In short, all minerals on the Moon are rather uniform and unnecessarily rich in SiO_2 and poor in CaO to apply typical cement production method. Therefore, special technique called vacuum pyrolysis is proposed by T. D. Lin in 1981, as a promising method to produce cement from lunar materials. This cement production method utilizes difference in volatility of elements ($FeO > MgO > SiO_2 > CaO > Al_2O_3$), and evaporates highly-volatile elements, FeO, MgO, and SiO_2, and condenses low volatility elements, CaO and Al_2O_3. Theoretically, as impurities evaporate, High Alumina Cement (HAC) can be manufactured as evaporation residues.

However, feasibility of this cement production method had never been experimentally proved. Actual chemical composition of evaporation residues should be investigated if evaporation of CaO initiates much before complete evaporation of SiO_2 to deviate from the compositions of HAC. In addition to cement chemical composition, conversion efficiency from lunar soil to cement, evaporation rate of

elements (cement production speed), and associated oxygen production by evaporation reaction had never been investigated by previous research. Lack of knowledge about associated oxygen generation in previous research resulted in wrong design of lunar concrete plant facilities and overestimation of mass and power budgets. Therefore, this research aimed to reveal production processes, facilities, and its mass and power budgets based on mechanism of cement and oxygen production processes and its experimental data.

Moreover, along with evaporation pass of SiO_2, various HAC with different SiO_2 content can be manufactured. From the energy and cost saving point of view, material processing rate should be minimized by employing either high SiO_2 content cement (low SiO_2 evaporation from lunar soil) or glassy highland soil as pozzolanic material. However, neither properties of high SiO_2 content cement in the lunar cement chemical compositions nor pozzolanic reactivity of the glassy lunar soil has never been studied. Hence, hydration products, hydration reactivity and strength property of various cements were investigated, applying different hardening accelerators and curing temperature.

Thus, this research examined following three topics

(1) Feasibility of cement and oxygen production by vacuum pyrolysis
(2) Properties of cement with different SiO_2 content and cooling conditions
(3) All processes, facilities, mass and power budgets of a prototype lunar concrete plant based on vacuum pyrolysis and proper curing method of concrete

Firstly, to reveal the feasibility of cement and oxygen production by vacuum pyrolysis, lunar highland soil simulant was manufactured and processed in a vacuum furnace at 1937K, 1994K and 2045K. Following results were obtained by the experiment.

I. It was proved that vacuum pyrolysis technique enables to produce High Alumina Cement, containing $CaO \cdot Al_2O_3$, a high hydration reactivity component, as a major component.
II. Practical chemical compositions of lunar cements were clarified and drawn by extrapolation lines
III. Evaporation rates of lunar soil simulant were measured in three different temperatures. Then, a versatile formula representing relationship between processing temperature, evaporation rate and evaporation surface area were acquired

In response to the proof of the feasibility of lunar cement production, lunar cement simulants were manufactured based on obtained chemical compositions in vacuum pyrolysis experiment. The lunar cements were $CaO/Al_2O_3=0.66$ and varied in SiO_2 concentration (5%, 10%, and 15%) and crystal conditions (glass or crystal). Then, hydration products, hydration reactivity and strength property of the cements were investigated with various mixture compositions and curing temperature. For cost effective lunar concrete production, this study assumed to apply cement/concrete composition which requires low cement processing mass, by means of

- Production of high SiO_2 content cement
- Replacement of cement with glassy highland soil

At the same time, the lunar concrete should have sufficient property to be applied in severe lunar environment

- Marginal strength property to support load and avoid penetration by meteorite impact
- Stability of structure by generating stable hydrates C_3AH_6 to prevent dehydration and structure failure of lunar concrete

From the experimental results, following conclusions were obtained.

I. Mixing with water at 20ºC was found not effective for all the lunar cements to produce stable hydration products C_3AH_6 within short time period before vacuum exposure. Some activation is necessary.

II. For low SiO_2 content cement, activation by mixing 0.1-1.0% of Li_2CO_3 or curing more than 40 ºC is sufficient to generate C_3AH_6 within 3days. Moreover, those mortar specimens developed 30MPa of compressive strength after conversion reaction.

III. In the case of high SiO_2 content cements, hydration reaction was not observed with water at 20 ºC. Mixing $Ca(OH)_2$ and Li_2CO_3 found to be effective to initiate hydration reaction. However, obtained hydration products were mainly unstable C_2ASH_8, and it was converted into C_3AH_6 at 100 ºC. Therefore, more than 100 ºC of high curing temperature was found to be necessary for low cost lunar concrete production which employs high SiO_2 content compositions.

IV. As a conclusion, high temperature and high pressure curing method called Dry-Mix Steam Injection method (DMSI method) is considered to be rational for low cost concrete production. Since greater hydration reaction and more rapid conversion of low SiO_2 cement were observed at 40 ºC of higher temperature, employment of high temperature curing is considered to be effective for all the lunar cements.

Then, necessary processes and facilities for lunar concrete production which employs vacuum pyrolysis technique and DSMI method were clarified. Then, mass and power budgets of the lunar concrete plant were estimated by sizing terrestrial facilities. Experimental results, lunar soil physical properties and lunar environmental factors were also taken into account. Estimated budgets declared that

I. The mass of concrete plant which has less than 300 tons of annual concrete production capacity is less than 20tons, and might be possible to be delivered to the Moon by one launch.

II. Employment of lunar In-Situ production reduces launch mass down to 9.5% to 5.5% in a case 100 tons to 500 tons of annual concrete production. Then, mass production of concrete is demonstrated to be more cost effective.

Consequently, suitable application of lunar concrete is discussed. To understand advantages and disadvantages of concrete, concrete was compared with three other In-Situ construction materials; regolith-bag, brick/cast regolith, and sulfur concrete. The comparison of launch mass saving effect showed that more cost effective materials in following order.

Rogolith-bag (1.5%)> Lunar brick (3.3%)> Hydraulic concrete (9.1%)>> Sulfur concrete (50.0%)

However, mass and power budgets of hydraulic concrete is considered to be competitive level, if versatile application of lunar concrete is taken into consideration. Through the comparison of launch mass and power budgets, application of each material, it was concluded that lunar base development needs to employ various different materials depending on the application. Hence, extensive effort to research and develop various materials should be exerted at the same time, considering advantages, disadvantages and application plan of each material for effective lunar base development.