THE POSSIBILITY OF CONCRETE PRODUCTION ON THE MOON

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When a lunar base that stands on the Moon for a considerable period is constructed, most of the materials for the construction would be natural resources on the Moon, mainly for economical reasons. In terms of economy and exploiting natural resources, concrete would be the most suitable material for construction. This paper describes the possibility of concrete production on the Moon. The possible production methods are derived from the results of a series of experiments that were carried out taking two main environmental features, low gravity acceleration and vacuum, into consideration.

INTRODUCTION

When the base that permanently stands on the Moon is built, most of the materials required for construction should be produced from natural resources on the Moon.

The ingredients of lunar soil and rocks have been investigated in detail in the Apollo program. It is proposed that, as the construction material of the lunar base, concrete can be manufactured from cement that is produced with soil and rocks on the Moon. Concrete has the following advantages for use as the construction material: (1) Raw materials for concrete exist abundantly on the Moon; (2) It has a simple production process compared with other structural material; (3) The production process requires less energy; and (4) Other technologies are not required to form structures.

On the assumption that materials required for concrete production are easily obtained on the Moon, this study examines the influence of low gravity and high vacuum, and evaluates the possibility of concrete production under the natural environment of the Moon.

INFLUENCE OF LOW GRAVITY

The segregation that originates in the difference in specific gravity of materials constituting concrete rarely happens under low gravity. Such a distinctive peculiarity can be disadvantageous to the acquisition of dense concrete. A fundamental test was performed to examine how low gravity affects the quality of concrete.

The influence of low gravity is extrapolated from the results of the influence of high gravity. This is because very few hours of a state of low gravity can generally be gained on Earth, and an experiment of a time-consuming reaction, such as hydration of cement, is extremely difficult to perform.

As a specimen, mortar that has $s/c = 2$ and $w/c = 65\%$ (where c is high-early-strength portland cement) was used. First of all, a fixed amount of well-mixed mortar was placed into a centrifugal separation machine. Second, five hours of a particular degree of acceleration was given to the specimen [five different degrees of acceleration ($1\,g$, $40\,g$, $112\,g$, $300\,g$, and $1062\,g$) were set] and the amount of bleeding water was measured. Finally, the mortar was allowed to cure for seven days and the density and compressive strength of the mortar were measured.

The results of the experiment are shown on Table 1. As the acceleration of gravity increases, the amount of bleeding water, density, and compressive strength increase. Moreover, these values and the logarithm of gravity ($\log g$) have near-linear relationships. Figure 1 shows the changes in compressive strength and an equation representing their relation.

Based on this result, the compressive strength of mortar under low gravity on the Moon ($\frac{1}{6}\,g$) is assumed to be 10% lower than that under Earth's gravity. If concrete is used for this experiment, the reduction in compressive strength would be around 10%. Consequently, low gravity would not seriously affect the quality of concrete.

TABLE 1. The properties of mortar influenced by high acceleration.

Acceleration of Gravity (g)	Amount of Bleeding Water (ml)	Density (g/cm)	Compressive Strength (MPa)
1	1.1	2.15	28.2
40	2.6	2.18	33.0
112	2.8	2.20	29.0
300	3.6	2.24	38.1
1062	3.9	2.24	42.2

INFLUENCE OF VACUUM

When a concrete structure is built on the Moon, concrete is exposed to a vacuum environment at the stage of execution somewhere between the production of concrete and the construction of the structure. If fresh or hardening concrete is exposed to vacuum, the quality of the concrete would be somewhat influenced. Experiments were performed to see how vacuum influences concrete.

A specimen was tempered under normal temperature and 1 atm and cured under a normal state (20.1°C) for a fixed period (precuring period). Then, concrete had $w/c = 54.9\%$, $s/a = 40\%$,

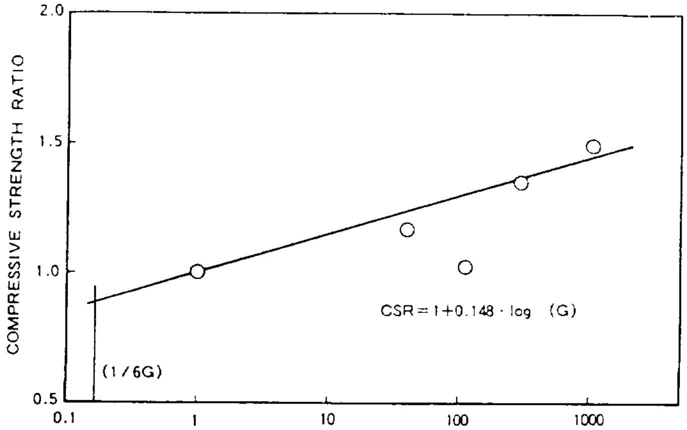

Fig. 1. Influence of acceleration of gravity on CSR, which is the ratio of compressive strength of mortar under high gravity vs. that under 1 *g*.

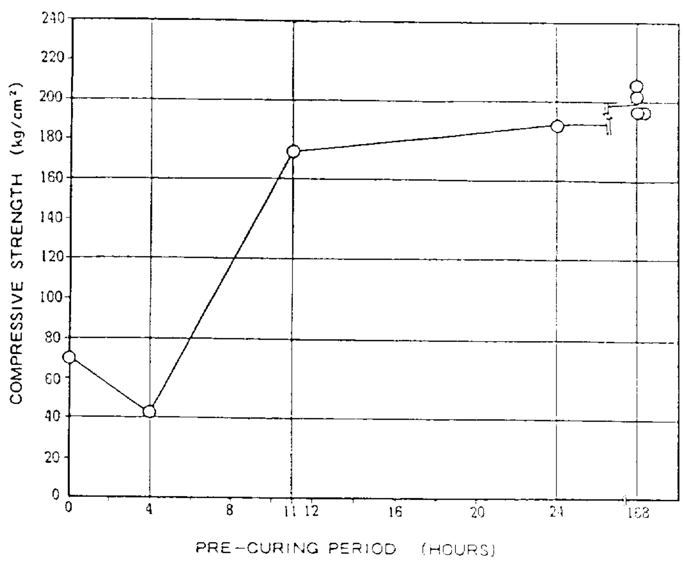

Fig. 2. Influence of precuring period on compressive strength of concrete.

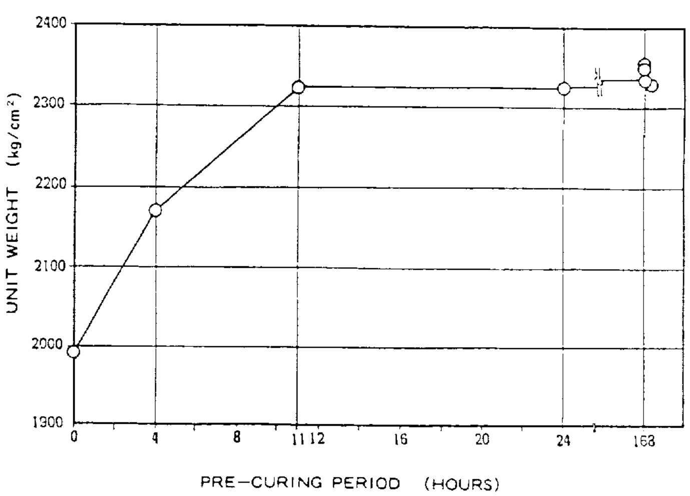

Fig. 3. Influence of precuring period on unit weight of concrete.

and 10 cm of slump. Normal portland cement was used for this experiment.

Changes in compressive strength and unit weight of concrete in various precuring periods are shown in Figs. 2 and 3. When the precuring period was less than four hours, compressive strength and unit weight of hardened concrete were far less than those of the specimen with standard curing; nevertheless, it would hold the moisture required by hydration, even if it is exposed to vacuum. Therefore, a porous structure created inside the concrete by expansion and departure of air bubbles in the concrete and evaporation and diffusion of moisture, causes reduction of those properties. This porosity inside concrete was confirmed with the use of a scanning electron microscope.

Based on this result, concrete should not be exposed to vacuum until a certain setting point is reached because vacuum affects concrete during the hardening process and lowers its quality.

PROPOSAL FOR THE NEW PRODUCTION METHOD OF CONCRETE ON THE MOON

It is necessary to make use of the Moon's natural environment in order to utilize concrete for the construction of various structures. However, with the results from the prior section, concrete containing moisture and air should not be exposed to vacuum unless hydration of concrete proceeds up to a certain point. The lunar concrete method proposes a possible process under the natural environment of the Moon.

Outline of the Lunar Concrete Method

The production process would be as follows:

1. Water or cement paste is frozen to be powdered ice within an airtight chamber. If the lunar environment is utilized, special equipment would not be needed. Powdered ice is produced by spraying water or cement paste inside a cold chamber or onto the surface of a cold metallic board.

2. The concrete's structural materials, such as cement, aggregate, and powdered ice, are mixed under low temperature and vacuum. Since all materials are solid particles, a uniform concrete mixture is easily produced. Besides, mixture of concrete is easily handled under vacuum because the water vapor pressure of ice at low temperature is very low.

3. The concrete mixture at low temperature is transported and placed in a prescribed location. The temperature of the concrete should not be excessively raised when the concrete mixture is transported and placed.

4. The placed concrete is covered with airtight material and is thawed with energy applied from the outside. At the same time, the concrete is compacted with applied vibration and pressure. Microwave is considered as an external energy. The concrete is covered with airtight material for thawing and prevention of water evaporation.

5. The concrete is used as a structural material after having been cured for a predetermined period. A heat insulator is used for curing in order to control the maximum and minimum temperature of the concrete. After the concrete is hardened to a certain extent, the airtight material is removed from the concrete and the concrete is exposed to vacuum.

An Examination of the Lunar Concrete Method

As the first stage of examining the possibility of the lunar concrete method, an experiment with the use of mortar was performed as follows: (1) The mortar mixture is produced from powdered ice, cement, and fine aggregates; (2) The mortar mixture is packed in an acrylic mold ($4 \times 4 \times 16$ cm); (3) Microwave is applied to the mold around a circumference to thaw the mortar mixture in the mold, during which the mortar is compressed several times to compact it; and (4) After it is cured in water at 20°C for 28 days, the mortar specimen's unit weight, flexural strength, compressive strength, and dynamic modulus of elasticity are measured.

The mortar's water/cement ratios were 35%, 50%, and 65%, with $s/c = 2$ and the use of high-early-strength portland cement. A domestic microwave oven was used to irradiate the specimens.

The results of the experiment are the following:

1. Powdered ice, cement, and fine aggregates had high dispersion since those materials did not have any adhesion. Therefore, the mortar was well mixed. Also, powdered ice in mortar was uniformly thawed by microwave. However, it became clear that final compacting is needed during or after thawing the powdered ice because the specimen's volume was reduced by thawing.

2. The ratios of the properties of the standard specimen to the mortar specimen (MW specimen) produced with the use of powdered ice and microwave are shown in Fig. 4. When the water/cement ratio is 65%, the MW specimen has quality for practical use since significant reduction in physical property figures, except for compressive strength, could not be found.

However, as the water/cement ratio got lower, those ratios became smaller. Void ratios of each MW specimen were calculated by mixing measured unit weight and mortar. They were 11% with a 35% water/cement ratio, 7.1% with a 50% water/cement ratio, and 5.0% with a 65% water/cement ratio. From these results, reduction in physical properties is considered to be caused by lack of setting.

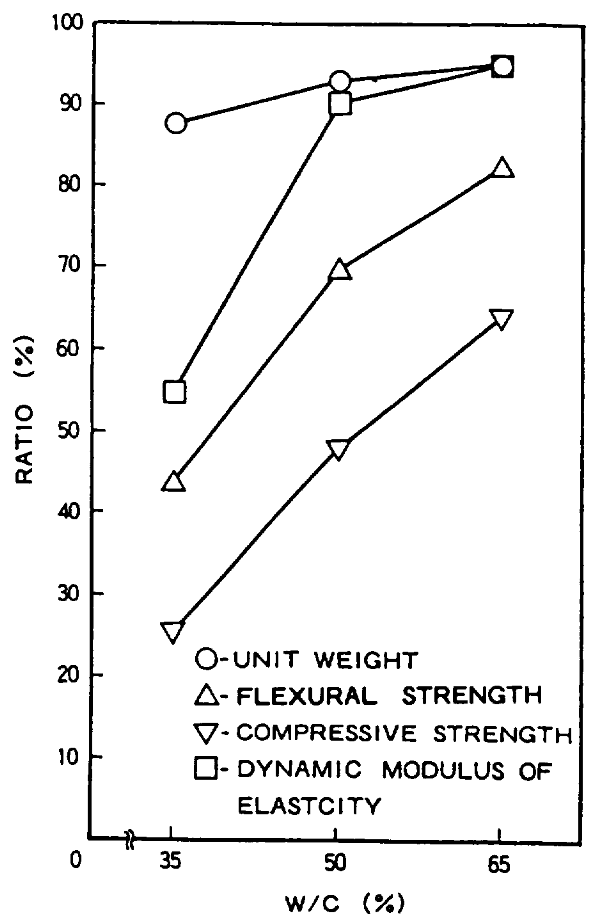

Fig. 4 The ratios of the properties of a standard specimen to the mortar specimen (MW specimen) produced with the use of powdered ice and microwave.

Features of the Lunar Concrete Method

The advantages of this method are (1) most of the manufacturing processes can be performed under the natural environment of the Moon; (2) an unnecessary amount of water is not used since ice can be equally dispersed into concrete, so the water/cement ratio can be relatively low, and especially when the cement paste in the state of powdered ice is used, the quality of cement is easily maintained because all cement particles hydrate within the concrete; (3) only the vapor, which is generated by heating ice, exists within the concrete mixture, so compacting concrete under vacuum is easier than in atmosphere; (4) given energy in the form of microwaves, the whole concrete mass is uniformly heated so partial strain accompanying thawing is hardly generated; and (5) concrete mixture in the solid-phase state influences the facilities for mixing, transporting, and placing concrete, which enables a reduction of labor in security and cleaning of those facilities.

Possibilities of basic technology for this method are confirmed to some extent. Nevertheless, immediate problems to be solved are (1) examination of the method of compacting and (2) verification of concrete production under vacuum. In the future, technological problems of the energy production process will have to be examined in detail.

CONCLUSION

The construction of a lunar city has to be planned by taking careful account of the natural environment, precious material, and human energy. Several possible methods of concrete production on the Moon are shown below.

1. When concrete is used for important structural members, a precast concrete panel is produced in the pressure chamber. At the time of production, pressure in the chamber should not be less than saturated water vapor pressure at curing temperature. Therefore 1-atm pressure need not be maintained within the chamber.

2. When concrete is used for less important structural members, precast concrete should be produced under the natural environment of the Moon by curing lunar concrete in a closed pressure vessel.

3. When concrete is used as a nonbearing member, it may be produced under the natural environment of the Moon. However, the concrete's surface should be covered with airtight material in which the concrete will be cured.

An experimental verification of concrete production under vacuum with these methods is a major subject in the near future. Besides, appropriate technology has be to improved to provide sufficient performance or efficiency for structural materials.