LUNAR CONCRETE FOR CONSTRUCTION

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Feasibility of using concrete for lunar base construction has been discussed recently without relevant data for the effects of vacuum on concrete. Our experimental studies performed earlier at Los Alamos have shown that concrete is stable in vacuum with no deterioration of its quality as measured by the compressive strength. Various considerations of using concrete successfully on the Moon are provided in this paper, along with specific conclusions from the existing database.

INTRODUCTION

Concrete is probably the most widely used of all the man-made materials of construction. Its properties are (1) it does not require expensive, high-temperature, shape-forming processes; (2) it develops its strength at ambient temperatures; (3) it has low density and high thermal and electrical insulation properties; and (4) it is noncombustible and generally nontoxic (*Double*, 1981). Based on a historically long successful experience with concrete, it is natural that lunar applications have been suggested by *Lin* (1985) and others.

Concrete is by definition a polyphase material that consists of particles of aggregate connected by a matrix of hardened cement (*Lott and Kesler*, 1967). According to a scenario proposed by *Lin* (1985), cement could be obtained by high-temperature processing of lunar rocks, while aggregates would be obtained by physical processing of lunar rocks and soils.

The purpose of this paper is to discuss the authors' experimental work with concrete as it relates to lunar base construction.

NOVEL TESTING PROGRAM

Very little information exists in the vacuum or concrete literature on the behavior of concrete in vacuum, even though there has been a continued interest over the years in using concrete for vacuum applications. On the other hand, the stability of concrete in vacuum is intuitively questioned without data (*Cullingford and Fox*, 1980). Because there was a need to know the effect of vacuum on concrete's strength for a linear-accelerator line at the Los Alamos National Laboratory (LANL), we designed a test program to investigate both outgassing and compressive strength of concrete in high vacuum (*Cullingford et al.*, 1982a,b).

Outgassing characteristics of vacuum materials are typically reported in the vacuum science literature. Our study of concrete, however, involved a multidisciplinary treatment with an engineering approach to the problem of concrete's behavior in vacuum. To begin with, all concrete used was prepared as a mix, given in Table 1; the local aggregate with the composition shown in Table 2 came from the San Ildefonso Pueblo. Relevant engineering standards were applied for concrete preparation, curing, and

TABLE 1. Concrete design mix.

Material	Mass (lb)	Percentage (%)
Water	2.0	7.05
Portland Cement	4.1	14.47
Fine Aggregate	9.00	31.54
Coarse Aggregate	13.3	46.94
Total	28.3	100.00

TABLE 2. Composition of local aggregate.

	Fine Aggregate	0.25-0.75 in	0.75-1.50 in
Quartzite	2	45	36
Acid Volcanic	16	28	23
Granite	10	13	22
Basic Volcanic	1	8	11
Quartz	57	4	7
Feldspar*	9	—	—
Chert[†]	3	—	—
Residue	2	2	1
Total	100	100	100

where

	Granite	Basic Volcanic	Acid Volcanic	Quartzite
SiO_2	77.0	49.1	75.6	97.05
Al_2O_3	12.0	15.7	12.7	1.39
Fe_2O_3	0.8	5.4	1.2	1.25
FeO	0.9	6.4	0.34	—
MgO	—	6.2	0.12	0.13
CaO	0.8	9.0	0.59	0.18
Na_2O	3.2	3.1	4.0	—
K_2O	4.9	1.5	4.6	—
H_2O	0.3	1.6	0.46	—
Other	0.1	2.0	0.39	—

* Feldspar is assumed to be 50% $KAlSi_3O_8$ and 50% $NaAlSi_3O_8$.
[†] Chert is predominately SiO_2.

testing (*Cullingford et al.,* 1982a,b). Concrete samples thus prepared (cylinders of 6-in diameter by 12-in height) were designated by "test" or "control." The test cylinders were placed in high-vacuum environment for specified periods of time after air curing, while the control cylinders were not.

Figure 1 shows the experimental vacuum apparatus for the outgassing studies. The clean-system base pressure was 3×10^{-6} torr (3.99×10^{-4} Pa) after 160 hr pumping time. The test program involved a progression of air curing, weighing, vacuum treatment, weighing, and then breaking for compressive strength as represented in Fig. 2. All tests involved multiple cylinders for a more representative average behavior. This is an important point because of the inhomogenous nature of concrete.

Mass loss, compressive strength, and outgassing measurements were made during the test program. An increase in compressive strength with time is observed, reaching an equilibrium value of 6500 psi with or without vacuum exposure (*Cullingford et al.,* 1982a,b; Fig. 3). The significance of this result is that structures for vacuum use can be designed without additional safety margins.

The predominant pumped species in concrete outgassing was not a diatomic gas, but water vapor as studied by mass spectrogram of the residual gas in the test chamber (*Cullingford et al.,* 1982a,b). During the first several days of pumping, the outgassing rate was approximately 10^{-6} torr · l/cm^2 · sec. The empty chamber throughput at this time was about 3 orders of magnitude lower than the gross throughput with concrete samples in the chamber.

The mass-loss information was reduced to water content as percent of concrete dry mass and is also plotted in Fig. 3. Concrete became stronger as it aged. As expected, a faster drying rate was observed under vacuum exposure. A final water content of 6.6% and 4.93% was calculated on a dry-mass basis for the control and test samples, respectively. The total amount of water lost from the concrete cylinders was 0.13 and 0.35 lb_m/ft^2 for control and test cylinders, respectively. Thus, about 2.7 times the mass of water was released overall under vacuum treatment, without a reduction in compressive strength. The next section discusses further the effect of vacuum on concrete's water.

VACUUM EFFECT ON CONCRETE'S WATER

Water is present in concrete in three states: chemically bonded water in the hydration product, adsorbed water on the surface of gel particles, and condensed water in the capillary pores. When water is added to a mixture of Portland cement and aggregate to prepare concrete, hydration reactions occur between calcium silicates and the water. This hydration process continues for several days, and the concrete becomes stronger and harder. The drying phase during the air cure involves release of the free (not chemically bound) water from the concrete (*Lott and Kesler,* 1967).

Our data show that vacuum exposure produced faster release of this free water from the concrete samples. However, the fact that compressive strength does not worsen under vacuum treatment suggests that cement dehydration reactions do not occur. In addition, a constant rate of moisture loss (0.04% per day) was experienced during the early part of vacuum exposure, regardless of the length of the preceeding air-curing period (see Fig. 3).

The water evaporation rate corresponding to this constant rate of evaporation under vacuum is 3.97×10^{-8} g/sec·cm^2. On the other hand, the control samples underwent an evaporation rate of 0.92×10^{-8} g/sec·cm^2. These rates were compared with the calculated rate of free evaporation of water at the test conditions, using the following equation derived from the kinetic theory of gases (*Roth,* 1976; *Kaldis,* 1980)

$$W = 5.83 \times 10^{-2} \, \alpha \, P_v \, (M/T)^{-\frac{1}{2}}$$

where W is the rate of evaporation (g/sec·cm^2), α is the evaporation coefficient (1.0 for free evaporation), P_v is the saturation vapor pressure (torr), M is the molecular weight, and T is the surface temperature (K). This comparison showed that an evaporation coefficient of 1.59×10^{-7} is attributable to the vacuum's effect on concrete.
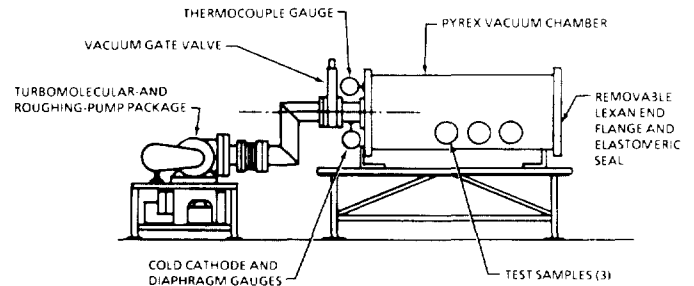

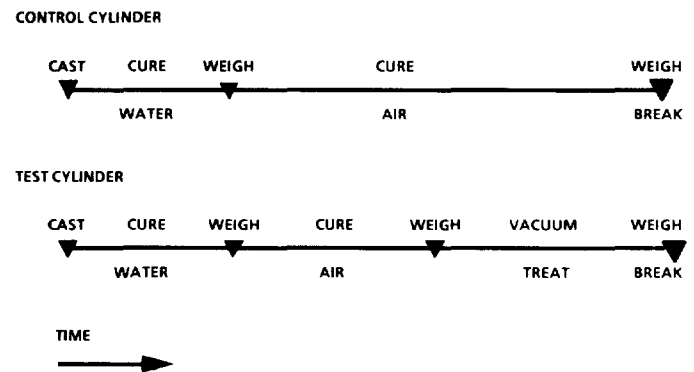**Fig. 1.** Layout of vacuum pumping chamber for concrete samples.

Fig. 2. Sequence of testing for typical control (air cured) and test (vacuum treated) cylinders.
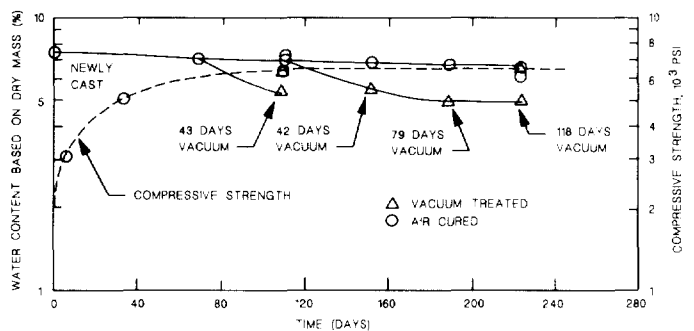

Fig. 3. Water content of concrete based on dry mass and compressive strength for air-cured and vacuum-treated cylinders.

Finally, the evaporation rates calculated for concrete in air or vacuum (in the order of 10^{-8} g/sec·cm^2) suggest a small surface cooling, and thus little uncertainty in the surface temperature of concrete (*Kaldis*, 1980). This assures a higher confidence in the constant-temperature analysis of the concrete data.

DISCUSSION

The experimental data obtained on concrete at Los Alamos are significant in planning for lunar construction with concrete. Several specific conclusions can be derived from our study.

1. Concrete is stable in vacuum with no deterioration of concrete quality as measured by compressive strength (ours was about 6500 psi).

2. Water loss from the concrete cylinders was 0.13 and 0.35 lb$_m$/ft^2 for control (without vacuum exposure) and for test (with vacuum exposure) samples, respectively.

3. An evaporation coefficient of $1.59 \cdot 10^{-7}$ is attributable to the vacuum's effect on concrete during constant rate of drying.

4. An outgassing rate of 10^{-6} torr · l/cm^2 · sec was observed after 73 hr of vacuum pumping. The predominant gas species was water vapor.

5. A high vacuum of 2×10^{-4} torr was maintained with the mechanical pumping system used in the experimental apparatus.

Using concrete on the Moon requires, however, various considerations like those discussed below.

The Moon gravitation is less than that of the Earth; therefore, concrete would be better able to handle stresses of large structures. However, the forces would not always be acting in the ways to which we are accustomed.

Any dome structure on the Moon would probably have pressure on the inside and vacuum on the outside. The dome would therefore have to act in tension. However, concrete is weak in tension. Reinforcing would then require the manufacture of steel on the Moon or shipment of steel to the Moon. Fiber reinforcing, especially of a type that could be manufactured locally, would aid in providing tensile strength for concrete.

Assume the pressure inside a dome is about 10 psia. This would require 1440 psf of pressure exterior to the dome to resist by "dead weight." With the Moon's gravity as it is, this would be a high backfill over the dome. The anchoring problem around the perimeter would have to be solved. Another possibility would be an excavated underground volume with lined walls. This would offer protection from meteoroids that do not burn up due to lack of atmosphere. A combination of cement, lunar rocks and soils, and fiber reinforcing could provide a coating on walls for protection against rock slides.

To construct various concrete shapes at entrances and shafts, preplaced aggregate could be formed and a grout pumped into the voids. Consideration would have to be given to concrete shapes to assure that the low lunar gravity and the internal pressure are acting to place the concrete in compression. Form enclosures would have to be airtight to assure that water is not lost before the hydration process is complete. Vacuum would then be directed so that moisture could be captured when it is withdrawn from the hardened concrete.

Concrete can be formed by using an air-filled dome. For example, if two domes are constructed with one bag placed within another so that they are concentric and separated by about 2 ft, the interior air bag could be inflated to about 10 psia with the differential between the inner and the outer bag being about 2 psia. Straps could be used so that the bags will always remain separated by about 2 ft. Concrete can then be placed in the annulus between the two bags. Concrete operations can be carried out within the inner bag, while the lunar aggregate is also mined inside the bag. The water needed could be also manufactured inside. Problems to solve include the breaking of the bag material by penetration of flying objects and the anchoring necessary at the perimeter. The bags could be fabricated on Earth complete with a floor and a number of airlocks already formed in the walls of the bag. The air bags would then supply the tensile strength. The concrete cast within the annulus would provide resistance to penetration and radiation protection.

We don't know how firm the rock structure is on the Moon, or how deep the loose top material is. Unless an enclosed tube is constructed with pressure in all directions (thereby eliminating any vector forces in the vertical direction), we could look forward to being forced to remain deep below ground. Air bags, in concert with concrete, could provide us with a viable alternative for a stable above-ground structure. Alternative geometric shapes and sizes of the air bags would have to be carefully studied.

CONCLUSION

The experimental data discussed in this paper are significant for lunar base construction with concrete. Having studied the effect of vacuum on concrete, we find that additional safety margins are not needed for vacuum use. Our recommendation is to focus future inquiry on developing structural options with concrete for lunar habitation.

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