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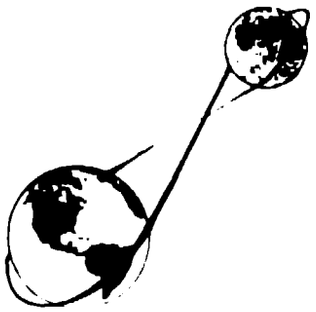

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LUNAR CONCRETE FOR CONSTRUCTION

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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 data base.

INTRODUCTION

Concrete is probably the most widely used of all the man-made materials of construction. It does not require expensive, high-temperature shape-forming processes; develops its strength at ambient temperatures; has low density and high thermal and electrical insulation properties; and 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 (1984) 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, cement could be obtained by high-temperature processing of lunar rocks while aggregates would be obtained by physical processing of lunar rocks and soils (Lin, 1984).

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 vacuum's effect on concrete's strength for a linear-accelerator line at the Los Alamos National Laboratory (LANL), we designed earlier a test program to investigate both outgassing and compressive strength of concrete in high vacuum (Cullingford et al., 1982).

Outgassing characteristics of vacuum materials are typically reported in the vacuum science literature (for example, Perkins, 1973). 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 I; the local aggregate with the composition shown in Table II came from the San Ildefenso Pueblo. Relevant engineering standards were applied for concrete preparation, curing, and testing. (See Cullingford et al., 1982). Concrete samples thus prepared (cylinders of 6-inch diameter by 12-inches high) 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-h pumping time. The test program involved a progression of air curing, weighing, vacuum treatment, weighing, and then breaking for compressive strength as represented in Figure 2. All tests involved multiple cylinders for a more representative average behavior. This is an important point because of the nonhomogenous 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., 1982). (See Figure 3.) Significance of this

TABLE 1. CONCRETE DESIGN MIX

Material	Mass (lb)	Percentage (%)
Water	2.0	7.05
Portland Cement	4.1	14.47
Fine Aggregate	9.0	31.54
Coarse Aggregate	13.3	46.94
Total	28.3	100.00

TABLE II. 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.

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., 1982). During the first several days of pumping, the outgassing rate is approximately 10^{-6} torr.L/cm^2.s. The empty chamber throughput, at this time, is about three 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 Figure 3. Concrete became stronger as it aged. A faster drying rate was observed, as expected, under vacuum exposure. A final water content of 6.6 and 4.93% was calculated on 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).

The Los Alamos 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 air curing period preceeding. (See Figure 3.)

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

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

where W = rate of evaporation (g/s.cm^2),

α = evaporation coefficient (1.0 for free evaporation),

P_V = saturation vapor pressure (torr),

M = molecular weight, and

T = surface temperature (K)

This comparison showed that an evaporation coefficient of 1.59×10^{-7} is attributable to the vacuum's effect on concrete.

Finally, the evaporation rates calculated for concrete in air or vacuum (in the order of 10^{-8} g/s.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 at Los Alamos on concrete are significant in planning for lunar construction with concrete. The following specific conclusions are derivable from our study.

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

- 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.

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

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

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

Various considerations of using concrete on the moon are listed below.

1. 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 that we are accustomed to.

2. 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.

3. Reinforcing would then require the manufacture of steel on, 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.

4. 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 gravity as it is, this would be a high backfill over the dome. The anchoring problem around the perimeter would have to be solved.

5. Excavated underground with lined walls would be another possibility. This would also offer protection from meteroids which 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.

6. At entrances and shafts, preplaced aggregate could be formed and a grout be pumped next into the voids to construct various concrete shapes. Consideration will have to be given to shapes to assure that the low lunar gravity and the internal pressure are acting to place the concrete in compression.

7. Form enclosures would have to be air-tight 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.

8. Concrete can be formed by using an air filled dome. If two domes are constructed one within the other so that they are concentric, for example, by about two feet; the interior air bag could be inflated to

about 10 psia with the differential between the inner and the outer bag to be about 2 psia. Straps could be used so that the bags will always remain separated by about 2 feet. 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 mixed 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 at the perimeter. The bags could be fabricated on earth complete with a floor and a number of airlock already formed in the walls of the bag.

9. The air bags mentioned in item 8 would supply the tensile strength. The concrete cast within the annulus would provide resistance to penetration and radiation protection.

10. We don't know how firm the rock structure is on the moon, or how deep is the loose top material. 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.

11. Air bags, in concert with concrete, could provide a viable alternative giving us an above ground structure which would be stable. Geometric shapes and sizes 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. Additonal future inquiry should be focused on developing structural options with concrete for lunar habitation.

ACKNOWLEDGEMENTS

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FIGURES

Figure 1 Layout of vacuum pumping chamber for concrete samples.

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

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

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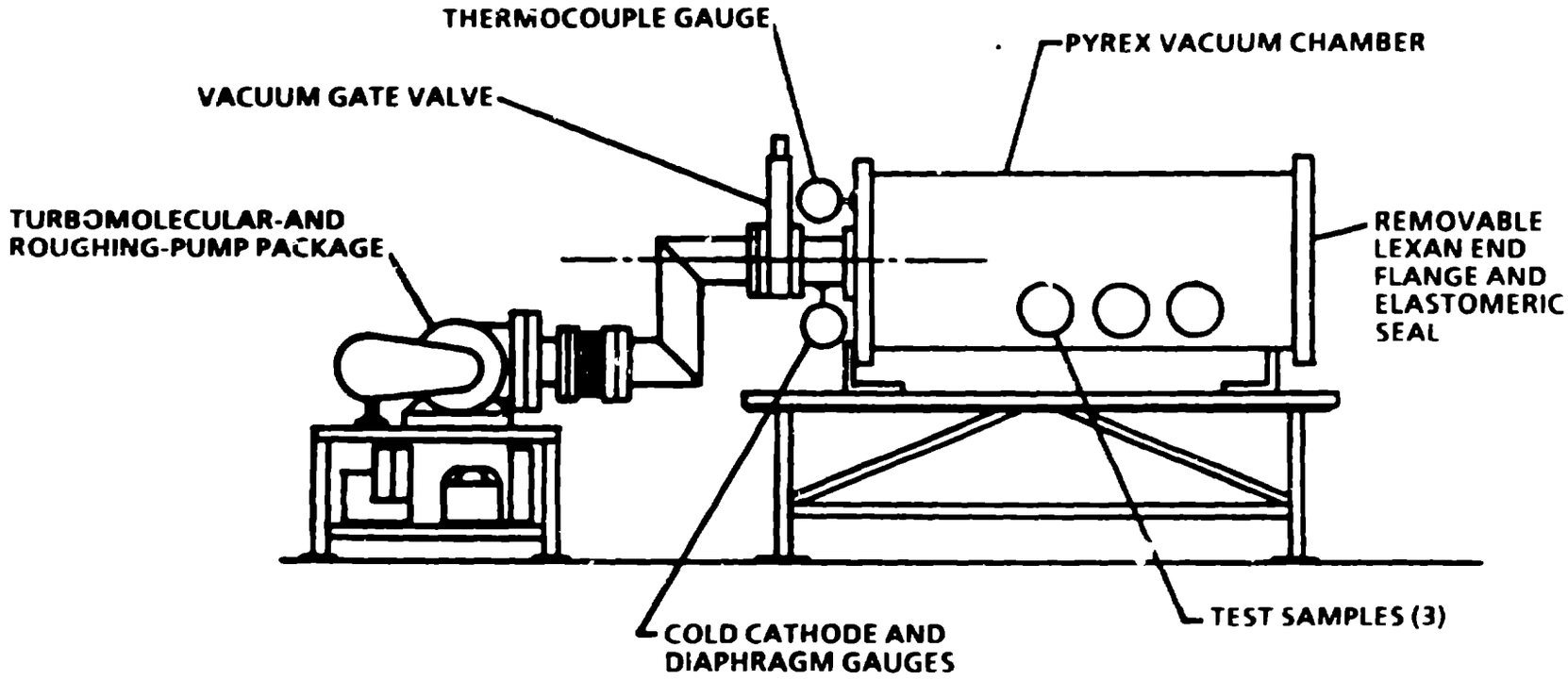

Figure 1

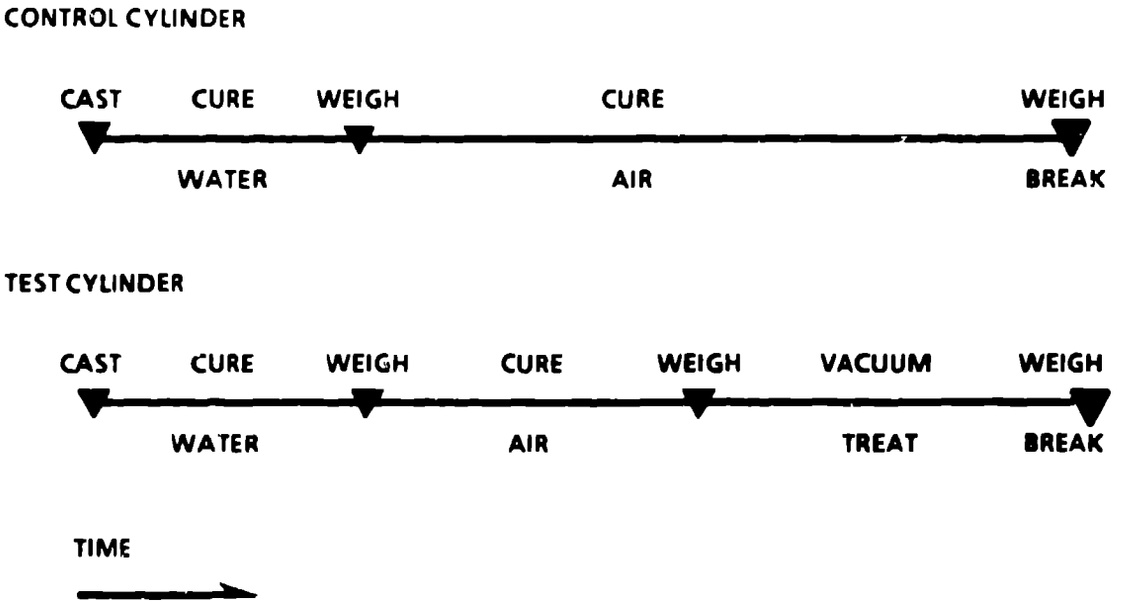

Figure 2

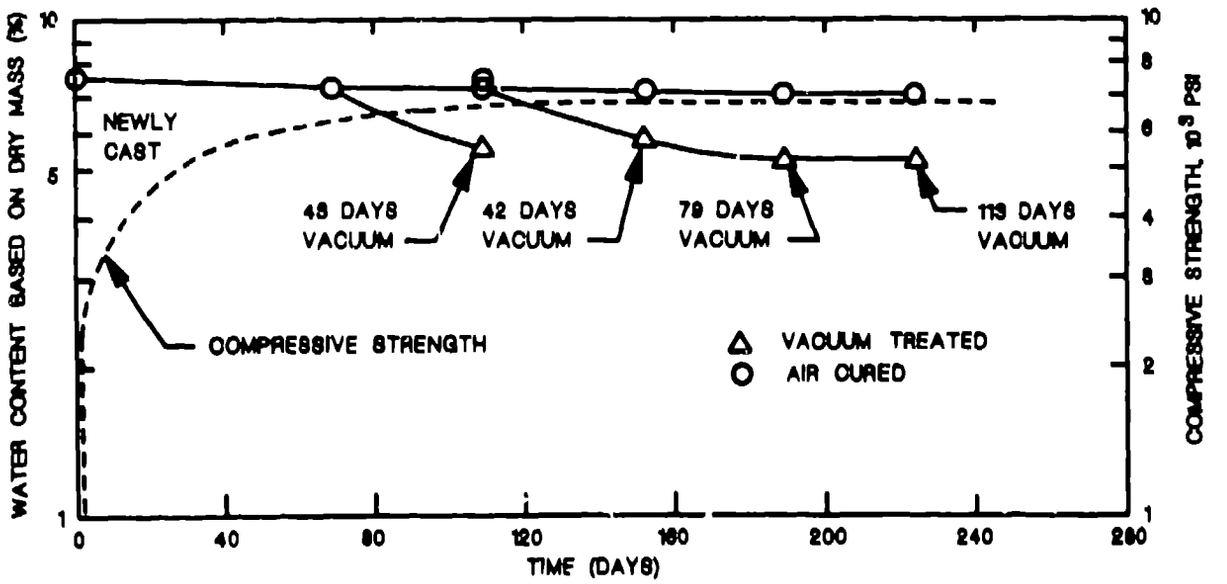

FIGURE 8

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