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EFFECTS OF CEMENTS AND ADMIXTURES ON THE PROPERTIES OF VACUUM-EXPOSED CEMENTITIOUS MATERIALS

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Mortar and concrete specimens made with various cements and admixtures were exposed to vacuum conditions. Changes in weight, strain, and strength of these specimens were measured in order to see how they were affected by the vacuum and to find suitable cements and admixtures to be used for lunar concrete. Ultimate shrinkage strains of the vacuum exposed mortar were also estimated using a linear diffusion equation. The results of these experiments and analysis indicated that alumina cement could be the best cement for use on the moon from the viewpoint of shrinkage control. It is also suggested that diffusion analysis is a useful way to predict the long-term effects of vacuum.

Keywords: *Concrete, mortar, cement, admixture, vacuum, shrinkage, compressive strength, flexural strength, diffusion*

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1. INTRODUCTION

One of the targets of future space exploration is to conduct deep-space observations and research studies on the moon and on Mars. Since large amounts of materials are likely to be required for these activities, it will definitely be necessary to use extra-terrestrial materials. In this regard, various lunar-derived construction materials for lunar base structures have been proposed up to this point [1]. Concrete is one of the candidate materials for such structures, and various studies are under way [2] - [5].

The author has been performing studies on the properties of concrete in the lunar environment, especially focusing on the effects of vacuum. In a previous study, a series of vacuum exposure tests was performed to see how mortar behaves under vacuum conditions. According to the results of this test, significant water loss and shrinkage strain were observed, even though the well pre-cured mortar exhibited an increase in strength upon exposure to vacuum [6].

Measures to reduce the shrinkage strain of concrete could include the following: (i) avoiding water evaporation by coating the concrete surface; (ii) reducing evaporable water by controlling the composition; and (iii) mechanically restraining the shrinkage strain. In this study, the focus is on factors relating to the materials, and a new series of vacuum exposure experiments and a theoretical analysis were conducted. In the experiments, mortar and concrete specimens made with various cements and admixtures were exposed to vacuum conditions and their property changes were measured. An analysis was carried out to estimate the long-term shrinkage strain of the mortar, and the ultimate strain of the specimen was calculated using a three-dimensional linear diffusion equation.

2. EXPERIMENTS ON MORTAR

2.1 Outline

The effects of cements and admixtures on changes in weight, strain, compressive strength, and flexural strength when mortar was exposed to vacuum were studied. Three types of cement (ordinary Portland cement, blast furnace slag cement, and high-alumina cement), and three types of admixture (superplasticizer, shrinkage reducer, and expansive admixture) were used, and a total of six mixtures were tested as shown in Table 1.

Table 1 Mortar mix proportions

Mix. No.	Water	Cement			Admixture			Sand
		Ordinary Portland	Blast Furnace Slag	Alumina	Superplasticizer	Shrinkage Reducer	Expansive Admixture	
1	344	529	-	-	C x 0.8%	-	-	1268
2	374	576	-	-	-	C x 2%	-	1152
3	374	518	-	-	-	-	58	1150
4	374	576	-	-	-	-	-	1152
5	372	-	572	-	-	-	-	1145
6	346	-	-	533	-	-	-	1234

(Unit: kg/m^3)

Vacuum exposure for all specimens started at the age of 14 days, and post-exposure measurements were conducted at 21, 42, and 70 days. Companion specimens, which were not exposed to vacuum but instead cured in water, were also tested in the same manner. The temperature of the specimens during water curing and vacuum exposure was kept at 50°C.

2.2 Experimental

a) Materials

Cements: Cement for lunar concrete is expected to be produced from lunar basalt or anorthite. Ordinary Portland cement and blast furnace slag cement will be obtained by sintering and grinding a mixture of calcium oxide (CaO) and anorthite, while alumina cement will be extracted from lunar basalt by melting and separation methods [7].

Since use of these cements on the moon is feasible, ordinary Portland cement (specific gravity = 3.15; Blaine fineness = 3280 cm^2/g), blast furnace slag cement (specific gravity = 3.05; Blaine fineness = 3770 cm^2/g), and high-alumina cement (specific gravity = 2.97; Blaine fineness = 5100 cm^2/g) were selected and used.

Admixtures: Several admixtures thought likely to reduce the shrinkage of vacuum exposed concrete were chosen. A superplasticizer (specific gravity = 1.20; dosage = C x 0.8 wt.%), shrinkage reducer (specific gravity = 1.065; dosage = C x 2.0 wt.%), and expansive admixture (specific gravity = 2.93; Blaine fineness = 2280 cm^2/g, dosage = C x 10 wt.%) were used.

Water: Water can be produced on the moon by reducing lunar oxides with hydrogen [8]. In the experiments, tap water was used.

Aggregates: A past study showed that lunar rock and soil could be used as concrete aggregates [9]. Toyoura Standard Sand (specific gravity (air dried) = 2.60; unit weight = 1538 kg/m^3) was used as the fine aggregate in the mortar specimens.

b) Specimens

Mortar bars (4 x 4 x 16 cm) were used as specimens. The ratio of water to cementitious materials (including expansive admixture) was kept to 0.65, and the unit water content of each mix was experimentally determined so that a flow value of 240 $\pm$10 mm, which was measured for ordinary Portland cement following the JIS method, was obtained. Three specimens were tested for each test condition.

c) Measurements

The following characteristics of the mortar specimens were measured before, after, and during vacuum exposure.

- Weight
- Strain
- Compressive strength
- Flexural strength

d) Testing apparatus

The major tools and testing devices used in the experiments were as follows.

- A dial gauge (mechanical) strain meter with ball-point tags (for measuring the strain of water-cured specimens)
- Paper strain gauges (for measuring the strain of vacuum-exposed specimens)
- Vacuum exposure apparatus-1
- A vacuum desiccator

Vacuum exposure apparatus-1 consists of vacuum chambers, a vacuum controller, a trap, a pump, valves with a complete piping system, and a temperature-controlled water tank system, as shown in Fig. 1. The acrylic vacuum chamber is a cylinder 150 mm in inside diameter and 250 mm in length. The acrylic lid on the upper end of the cylinder is fitted with a pipe and connector for strain measurements. The vacuum controller measures the degree of vacuum in the chambers and keeps it constant by controlling electromagnetic valves. The maximum pumping rate and minimum achievable pressure of the oil-sealed rotary vacuum pump are 200 liter/min and 6.7 x 10^{-2} Pa, respectively.

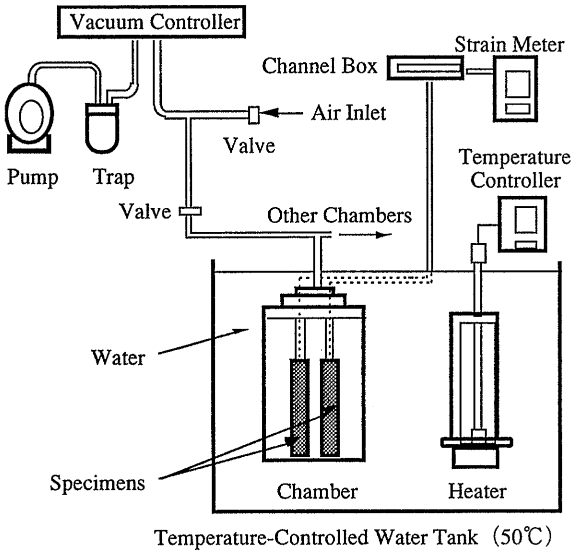

Fig. 1 Vacuum exposure apparatus-1

e) Test Procedure
Mortar specimens were produced in air at 20°C and R.H. 80%. The specimens were demolded at the age of 1 day, and a set of ball-point tags (base distance = 100 mm) was immediately attached to each specimen to provide reference points for measuring length through the use of a mechanical strain meter. After measuring the weight of the specimens, they were placed in water at 50°C.

The specimens selected for vacuum exposure were removed from the water at 14 days. After the weight and tag distance were measured, a pair of paper strain gauges was attached to opposite sides of each specimen. Gauge length measurements began immediately after placing the specimens in the vacuum chamber, and continued until exposure ended. The vacuum and temperature inside the chambers were kept at 10 Pa and 50°C, respectively.

At the age of 21, 42, and 70 days, specimens were taken from the chambers, and their weight were measured again at 20°C. The compressive and flexural strength of each specimen was then measured. During this process, all vacuum-exposed specimens were stored in a vacuum desiccator in order to prevent moisture adsorption.

Measurements of weight, tag distance, and compressive and flexural strength for the water-cured specimens were also carried out in the same manner.

2.3 Results and Discussion

a) Weight change
The changes in weight of the mortar specimens are shown in Fig. 2 and Fig. 3. Weight change is expressed as the ratio of sample weight to the weight of the 1 day old sample.

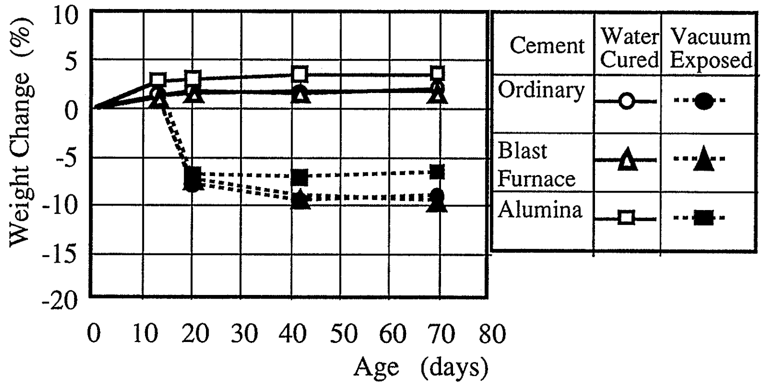

Fig. 2 Weight changes of mortar specimens made with various cements

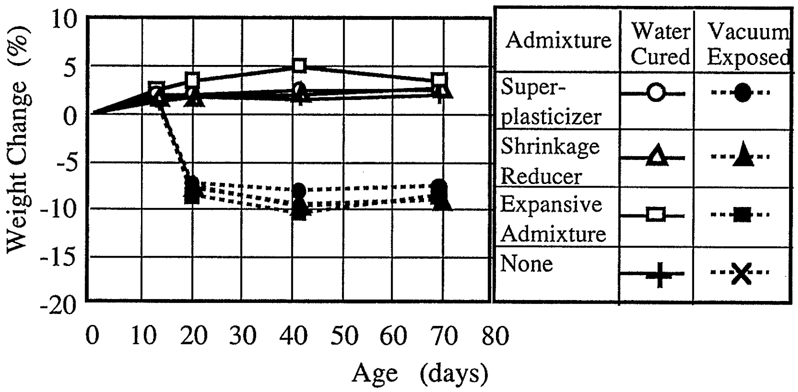

Fig. 3 Weight changes of mortar specimens made with various admixtures

The weight of water-cured specimens increased slightly with age, while the vacuum-exposed specimens showed substantial decrease in weight.

Regarding the effect of cement type, both water-cured and vacuum-exposed specimens made with ordinary Portland cement showed similar weight changes to the specimens made with blast furnace slag cement. On the other hand, vacuum-exposed specimens containing alumina cement had a smaller weight loss than the specimens containing other cements.

From Table 1, the initial water contents of the alumina mixture and other cement mixtures were calculated as 16.4% and 17.8%, respectively. The weight changes of the mixes without admixtures (mixes 4 to 6) at the age of 70 days were approximately 7% for alumina cement, and 10% for other cements. From these figures, the W/C ratios of vacuum-exposed specimens at the age of 70 days were estimated as 0.37 for alumina cement and 0.29 for other cements. Since the earlier study showed that the W/C ratio for the complete hydration of cement was approximately 0.23, we can conclude that some amount of water in addition to bound water remained in the mortar specimen after 70-day vacuum exposure[10].

Regarding the effects of the admixtures, no clear trends can be seen. The W/C ratio of a vacuum-exposed specimen at the age of 70 days was estimated to be around 0.30 for a mix containing any admixture.

b) Strain change

Changes in the strain of vacuum-exposed mortar specimens and water-cured specimens are shown in Fig. 4 and Fig. 5. Strains were calculated from the changes in tag distance as compared with the 1-day specimen. Since the strains of water-cured specimens and vacuum-exposed specimens were measured by different methods (dial gauge and paper strain gauge), the strain measured by the paper gauge at the beginning of vacuum exposure was calibrated to the dial gauge value at the end of water curing.

Cement type seems to have no particular effect on the strain change of water-cured mortar specimens. In case of vacuum-exposed specimens, however, every specimen showed considerable shrinkage strain. Specimens containing alumina cement showed minimum shrinkage strain, with ordinary Portland cement specimens next. This tendency is the same as the result generally obtained in drying shrinkage tests [11], [12]. Since the initial strain was taken at the age of 1 day in this experiment, the strain of alumina specimens can be considered unaffected by initial self shrinkage, which usually takes place within 24 hours of first contact between alumina cement and water. Shrinkage caused by carbonation did not, of course, occur because of the vacuum environment.

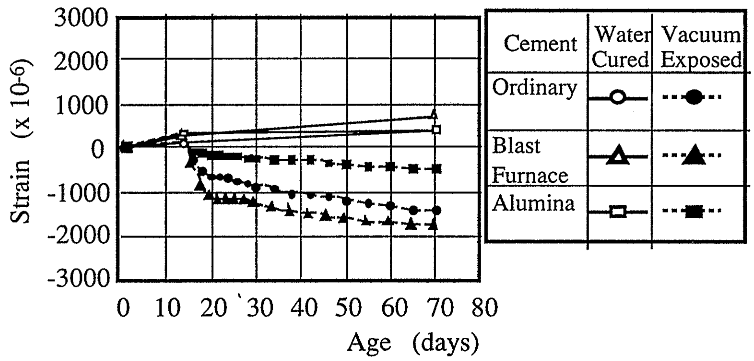

Fig. 4 Strain changes of mortar specimens made with various cements

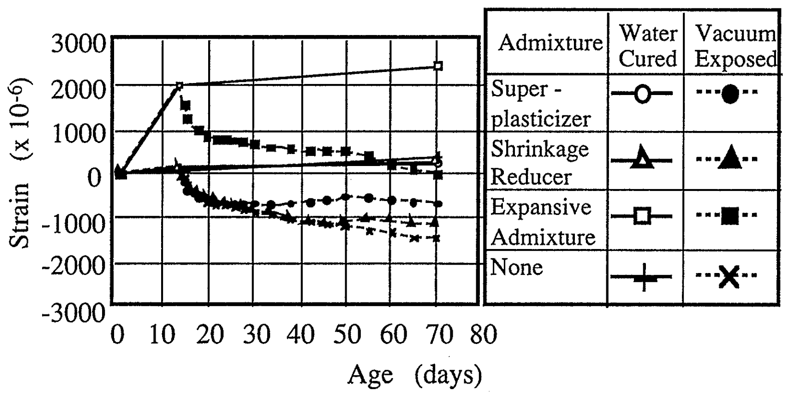

Fig. 5 Strain changes of mortar specimens made with various admixtures

The strain of water-cured specimens containing an expansive admixture was indicative of significant expansion, while other mixes did not show any particular change. In the case of vacuum-exposed specimens, those containing an expansive admixture showed the least shrinkage strain among all specimens tested, followed by superplasticizer, shrinkage reducer, and no admixture cases.

The strain of vacuum-exposed specimens containing the expansive admixture was greatly affected by the drastic expansion before vacuum exposure. If we compare the strain changes from beginning to end of vacuum exposure, the expansive admixture specimens showed the greatest shrinkage.

The superplasticizer seemed to have a small shrinkage strain reducing effect. A shrinkage reducer generally reduces the amount of shrinkage strain by reducing the surface tension of pore water. In this experiment, however, the shrinkage reducer had no effect. The reason for this result is not clear, but the following possibilities can be considered: (1) some of the admixture evaporated during the mixing and forming processes, and (2) the dosage of the admixture was the manufacturer's minimum recommendation, and this was not enough to demonstrate an effect.

c) Strength change

Changes in the compressive strength of vacuum-exposed and water-cured mortar specimens with respect to age are shown in Fig. 6 and Fig. 7.

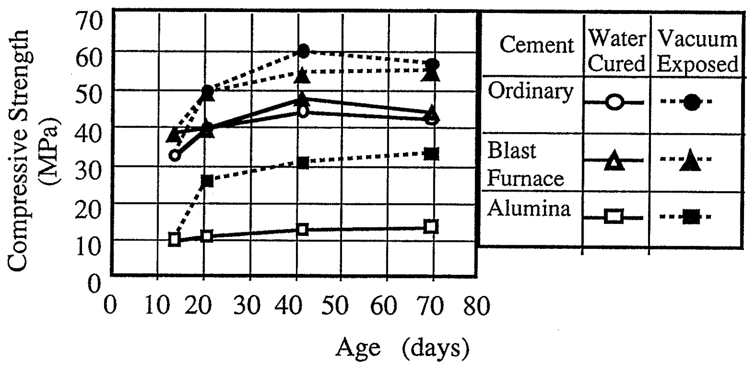

Fig. 6 Compressive strength changes of mortar specimens made with various cements

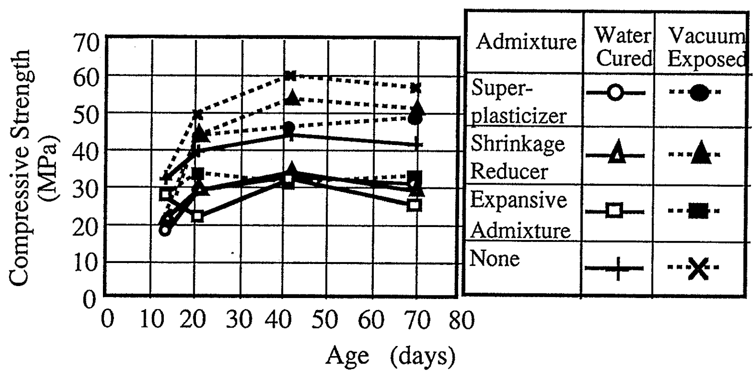

Fig. 7 Compressive strength changes of mortar specimens made with various admixtures

The compressive strengths of vacuum-exposed specimens at the age 70 days were 15 to 20 MPa higher than those of water cured specimens, except in the case of specimens containing the expansive admixture.

The increase in strength during the first several days of exposure is considered to have two principal causes. One is hydration of the cement. Because water in the mortar is contained in small pores, such as gel pores and capillary pores, it takes several hours for all the evaporable water to leave the specimen. Therefore, cement hydration continues even after vacuum exposure. The other cause is the drying effect. As a rule, mortar and concrete which have been oven dried just before a strength test exhibit higher compressive strength than wet specimens. The interfacial strain energy between hydrated cement particles and water molecules increases with falling moisture content in the specimen. This increase in interfacial strain energy causes the increase in strength.

The alumina specimen was apparently lower in compressive strength, while the other specimens did not show any clear differences. The low strength of the alumina specimen is considered to be caused by a transformation of CAH_{10} or C_2AH_8 to C_3AH_6 at the 50°C temperature of the experiments. The specimen with these transformed alumina cement hydrates also showed a gradual increase in its strength, as reported in past studies[13]. All of the specimens showed significant gain in compressive strength as they were exposed to vacuum, and specimens with alumina cement demonstrated the largest gain.

The effect of admixtures on compressive strength could not be clearly identified except in the case of the expansive admixture specimens. In this latter case, the compressive strength of both water-cured and vacuum-exposed specimens did not show a clear increase with time. The reason for this result is considered to be over-dosing of the admixture. The unit content of the expansive admixture used in this experiment was about a twice the usual amount, and it is speculated that this generated many defects in the cement matrix.

Changes in flexural strength of the mortar specimens are shown in Fig. 8 and Fig. 9 in the same manner. The flexural strength of mortar and concrete generally decreases after drying in a oven, because the effect of small cracks induced in the cement matrix by the rapid shrinkage exceeds the effect of the increased interfacial strain energy [14]. In the case of vacuum exposure, however, the flexural strength did not decrease. This means that the rate of shrinkage in vacuum is not as high as that experienced in a drying oven. It is also concluded that long-term vacuum exposure distributes the partially induced shrinkage strain over the whole specimen.

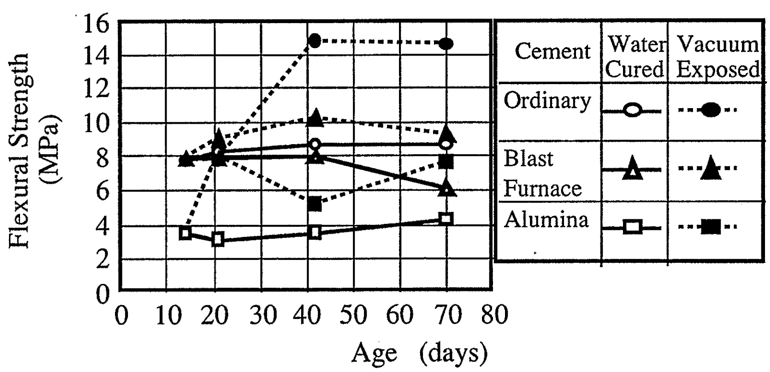

Fig. 8 Flexural strength changes of mortar specimens made with various cements

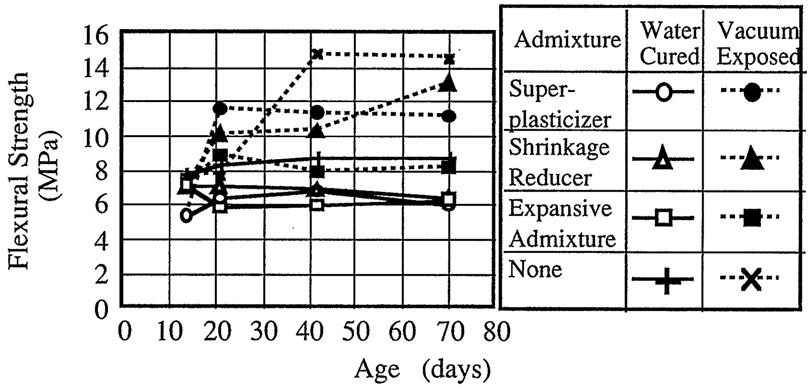

Fig. 9 Flexural strength changes of mortar specimens made with various admixtures

3. EXPERIMENTS ON CONCRETE

3.1 Outline

The effects of cements and admixtures on changes in weight, strain, and compressive strength of vacuum-exposed concrete were studied in this experiment. Concrete, which contains larger aggregates than mortar, may be a more realistic material than mortar for use in actual structures. Since the larger aggregates were expected to have their own particular effects on shrinkage behavior in a vacuum, a series of vacuum-exposure experiment was conducted using concrete.

Three types of cement (ordinary Portland cement, blast furnace slag cement, and high alumina cement) and three types of admixture (superplasticizer, silica fume, and expansive admixture) were used, and a total of 12 mixtures were tested as shown in Table 2.

The vacuum exposure of all specimens started at the age of 28 days, and post-exposure measurements were conducted at 91 and 182 days. The water-cured companion specimens were also tested in the same manner. The temperature of the specimens during water curing and vacuum exposure was kept at 20°C in this experiment.

3.2 Experimental

a) Materials

Cements: Ordinary Portland cement (specific gravity = 3.15; Blaine fineness = 3280 cm^2/g), blast furnace slag cement (specific gravity = 3.08; Blaine fineness = 3770 cm^2/g), and alumina cement (specific gravity = 2.96; Blaine fineness = 4800 cm^2/g) were selected and used.

Admixtures: Superplasticizer (specific gravity = 1.05; dosage = C x 1.1 wt %), silica fume (specific gravity = 2.20; specific surface = 200000 cm^2/g; silica fume/(cement + silica fume) = 10 wt %), and expansive admixture (specific gravity = 3.00; Blaine fineness = 3200 cm^2/g; dosage = 30 kg/m^3) were used.

Water: Tap water was used.

Aggregates: Fine aggregate (specific gravity = 2.60; Fineness Modulus (F.M.) = 2.88; water absorption = 1.13%), and coarse aggregate (maximum size = 20 mm; specific gravity = 2.64; F.M. = 6.85; water absorption = 0.71%) were used.

Table 2 Concrete mix proportions

Mix. No.	Water	Cement			Admixture			Sand	Gravel
		Ordinary Portland	Blast Furnace Slag	Alumina	Superplasticizer	Silica Fume	Expansive Admixture		
1	208	520						645	982
2	210		525					638	972
3	180			450				686	1045
4	160	400			4.40			702	1069
5	163		408		4.48			702	1070
6	160			400	4.40			723	1101
7	191	430			5.26	47.8		661	1007
8	193		434		5.30	48.3		657	1001
9	178			401	4.90	44.5		689	1049
10	209	493					30	637	970
11	212		500				30	632	964
12	197			463			30	652	993

(Unit: kg/m^3)

b) Specimens

Concrete specimens were cylindrical (ϕ10 x 20 cm), and tailored using the standard methods specified in JIS A 1132. Specimens were made for 12 mixes as shown in Table 1, with various combinations of cements and admixtures. The water/cement (including silica fume and expansive admixture) ratio was kept at 0.4 for all mixes, and the water content of each mix was determined by preliminary tests to obtain a slump of 12 cm. Three specimens were tested for each test condition.

c) Measurements

The following properties of the concrete specimens were measured before and after vacuum exposure.

- Weight
- Strain
- Compressive strength

d) Testing apparatus

The major tools and testing devices used in the experiments were as follows.

- A vertical-shaft mixer (100 liter)
- A dial gauge (mechanical) strain meter with ball-point tags
- Vacuum exposure apparatus-2
- A vacuum desiccator

Vacuum exposure apparatus-2 consists of five vacuum chambers, a vacuum controller, a trap, a pump, and valves with a complete piping system as shown in Fig. 10. The steel vacuum chamber is a cylinder, 400 mm in inside diameter and 700 mm in length. Both ends of the cylinder are sealed with circular steel plates. One end plate is equipped with a gas outlet and a valve, while a probe for the vacuum meter is attached to the other plate. Maximum pumping rate and minimum achievable pressure of the oil-sealed rotary vacuum pump are 200 liter/min and 6.7 x 10^{-2} Pa, respectively.

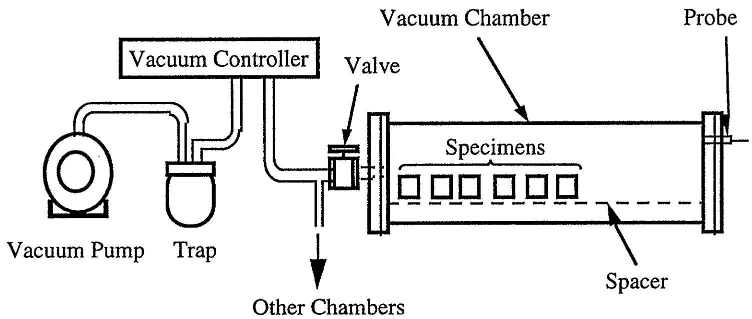

Fig. 10 Vacuum exposure apparatus-2

e) Test Procedure
Concrete specimens were produced in air at 20°C and R.H. 80%. The specimens were demolded at the age of 1 day, and a set of ball-point tags (base distance = 100 mm) was immediately attached to each specimen to provide reference points for measuring length through the use of a mechanical strain meter. After measuring the weight of the specimens, they were placed in water at 20°C.

The specimens for vacuum exposure were picked out from the water at 28 days. After the weight and the tag distance were measured, they were placed in the vacuum chamber. The vacuum and chamber temperature were kept at 10 Pa and 20°C, respectively.

At the age of 91 days and 182 days, specimens were taken from the chamber, and their weight and tag spacings were measured again. After that, the compressive strength of each specimen was tested. During this procedure, all vacuum-exposed specimens were stored in a vacuum desiccator.
Measurements of weight, tag distance, and compressive strength for the water-cured specimens were also conducted in the same manner.

3.3 Results and Discussion

a) Weight change
Changes in the weight of the concrete specimens with respect to age are shown in Fig. 11. The weight change is expressed as a ratio of the changes in sample weight from the 1-day sample to the weight of paste (cement + water + admixtures) of the 1-day sample. This ratio was adopted to remove the influence of initial water content, which was different among the mixes.

Regarding the effect of different cements, both water-cured and vacuum-exposed specimens made with ordinary Portland cement showed similar weight changes to the specimens made with blast-furnace slag cement. On the other hand, vacuum-exposed specimens containing alumina cement (mixes 3, 6, 9, and 12) exhibited smaller weight losses than those containing other cements.

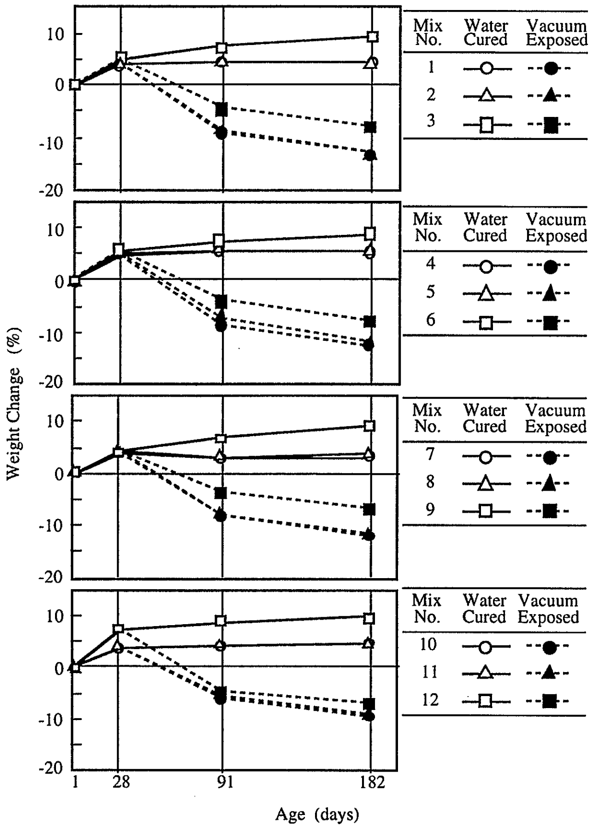

Fig. 11 Weight changes of concrete specimens

Since the initial W/C ratio for every mix was 0.4, the water content in the initial paste was calculated as 0.29 (0.4/(1+0.4)). The weight changes of the non-admixture mixes (mixes 1 to 3) at the age of 182 days were approximately 7% for alumina cement and 14% for the other cements. From these figures, the W/C ratios of vacuum-exposed specimens at the age of 182 days were estimated to be 0.28 for alumina cement and 0.17 for the other cements. We can conclude that most of the water, other than bound water, evaporated from the concrete during long-term vacuum exposure.

Regarding the effects of the admixtures, specimens made with silica fume (mixes 7 to 9) and expansive admixture (mixes 10 to 12) showed slightly smaller weight loss than other specimens. These admixtures seem to reduce the water evaporation to some extent.

b) Strain change

Changes in the strain of concrete specimens are shown in Fig. 12. Strains were calculated from the changes in tag distance from the 1-day sample.

The strain of water-cured specimens containing an expansive admixture or alumina cement indicated a slight expansion, while other mixes did not show any particular change. Expansion of water-cured concrete specimens containing an expansive admixture was smaller than that of mortar specimens because of the restraining effect of the coarse aggregates.

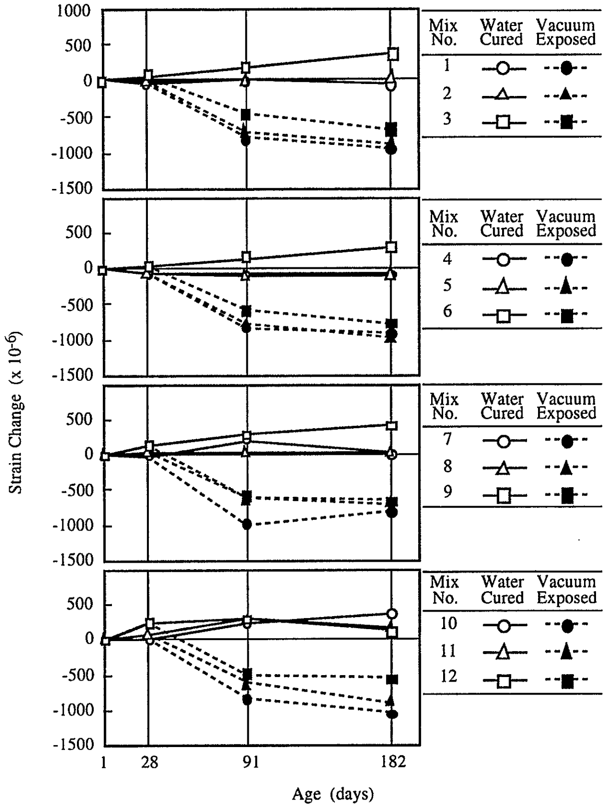

Fig. 12 Strain changes of concrete specimens

In the case of vacuum exposure, specimens containing alumina cement showed the least shrinkage strain among all specimens tested. However, the effects of admixtures on the shrinkage strain could not be clearly identified.

c) Compressive strength change
Changes in compressive strength of vacuum-exposed and water-cured concrete specimens with respect to age are shown in Fig. 13.

Only the mixes containing alumina cement (mixes 3, 6, 9, and 12) showed notable increases in strength caused by vacuum exposure. This suggests that shrinkage stress caused by the presence of coarse aggregates might generate some defects in the cement matrix of vacuum-exposed concrete.

The effects of admixtures on compressive strength could not be clearly identified in this experiment. This means that the admixtures tested are not effective for reducing the shrinkage of vacuum-exposed concrete.

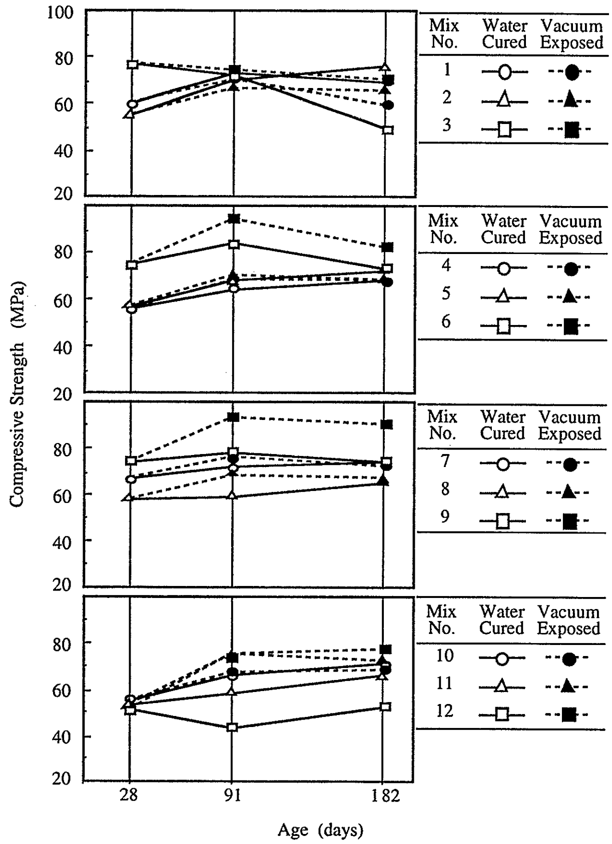

Fig. 13 Compressive strength changes of concrete specimens

4. ESTIMATION OF ULTIMATE STRAIN

The strain behavior induced by vacuum exposure was analytically studied and the results are discussed in this section. The ultimate shrinkage strain was considered to be particularly important, because lunar structures would be exposed to vacuum for extended periods.

The drying shrinkage behavior of concrete can be generally expressed by a diffusion equation, and is thus determined by diffusion coefficient (k), surface coefficient (f), and ultimate shrinkage strain (S_∞)[15]. In the early stages of drying shrinkage, the shrinkage strain needs to be expressed by a non-linear equation because of the large change in diffusion coefficient. In the case of the long term behavior, however, the diffusion coefficient becomes nearly constant, and a linear equation can be used[16].

A linear diffusion equation for a rectangular parallelepiped can be expressed as follows.

$$\frac{S_{av}}{S_\infty} = 1 - \sum_{n=1}^{\infty} e^{-T_a \alpha_n^2} \cdot \frac{G\alpha_n}{\alpha_n} \cdot \sin \alpha_n \cdot \sum_{n=1}^{\infty} e^{-T_b \beta_n^2} \cdot \frac{G\beta_n}{\beta_n} \cdot \sin \beta_n \cdot \sum_{n=1}^{\infty} e^{-T_c \gamma_n^2} \cdot \frac{G\gamma_n}{\gamma_n} \cdot \sin \gamma_n \qquad (1)$$

$$T_a = \frac{kt}{a^2}, \quad T_b = \frac{kt}{b^2}, \quad T_c = \frac{kt}{c^2}$$

$$G\alpha_n = \frac{\sin \alpha_n}{\sin \alpha_n \cos \alpha_n + \alpha_n}, \quad G\beta_n = \frac{\sin \beta_n}{\sin \beta_n \cos \beta_n + \beta_n}, \quad G\gamma_n = \frac{\sin \gamma_n}{\sin \gamma_n \cos \gamma_n + \gamma_n}$$

Where,

S_{av}: mean strain of a whole specimen
S_∞: ultimate shrinkage strain
k: diffusion coefficient (cm^2/day)
f: surface coefficient (cm/day)
t: elapsed time (day)
α_n: n th solution of $\alpha \tan \alpha = f \bullet a/k$
β_n: n th solution of $\beta \tan \beta = f \bullet b/k$
γ_n: n th solution of $\gamma \tan \gamma = f \bullet c/k$
a, b, c: distance from the center to each surface of a specimen (cm)

Values of k and f were calculated using equation (1) such that the estimated shrinkage strain agreed with the measured strain. Figure 14 and Figure 15 show the changes in k and f with respect to the strain ratio, which is the ratio of ultimate strain S_∞ to measured strain at 50-day exposure, S_{50}. Agreement between estimated strain and measured strain is not evaluated within the first 20 days of vacuum exposure, because the diffusion equation is apparently not linear in this period.

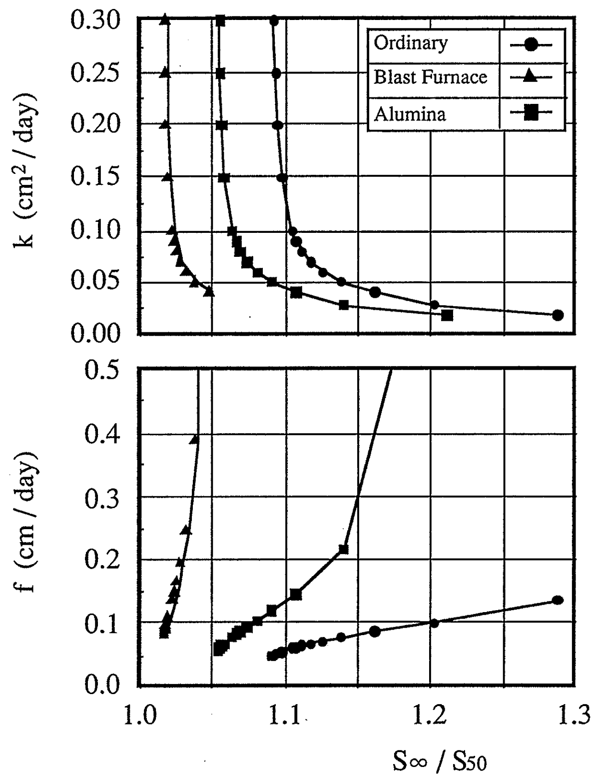

Fig. 14 Variations in k and f with type of cement

Since S_∞ was not measured in this study, specific values of k and f could not be determined; they varied depending on S_∞. For all mixtures, however, larger S_∞ caused k to become asymptotical to zero and f to be divergent, while a smaller S_∞ made k divergent and f asymptotical to some value. Table 3 shows the ranges of strain ratio and ultimate strain with no divergence in k and f.

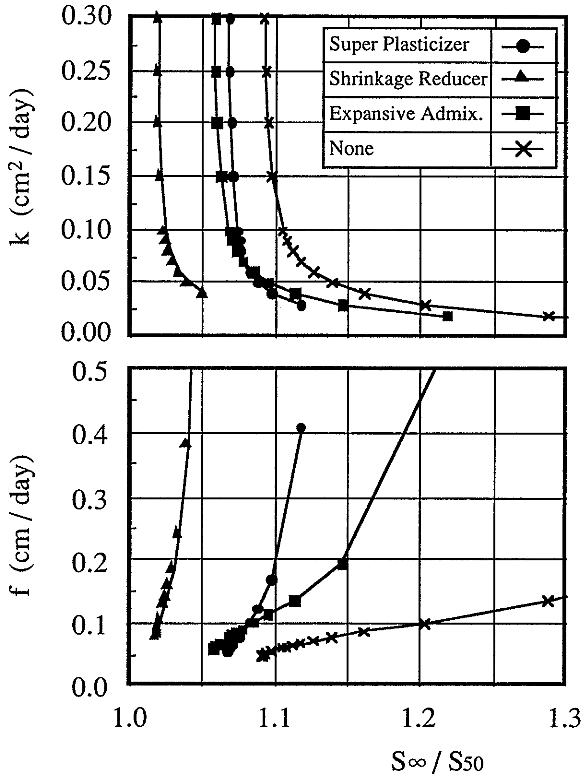

Fig. 15 Variations in k and f with admixture type

The value of S_∞ for mix 4 with ordinary Portland cement was larger than that of mixes containing other cements, and was estimated to be 2992 x 10^{-6} at maximum. Although mix 5 containing blast furnace slag cement indicated the largest strain after 50 days of exposure, the ultimate strain was estimated to be 2144 x 10^{-6}, which was smaller than that of the mix with ordinary Portland cement. The ultimate strain of the mix containing alumina cement was 983 x 10^{-6}, which was far smaller than that of mixes containing the other cements.

Table 3 Possible ranges of ultimate shrinkage strain

Mix No.	Cement	Admixture	S_∞ / S_{50}	S_∞ (x 10^{-6})
1	Ordinary	Super Plasticizer	1.07 ~ 1.15	820 ~ 881
2	Ordinary	Shrinkage Reducer	1.02 ~ 1.05	1257 ~ 1294
3	Ordinary	Expansive Admix.	1.06 ~ 1.30	2073 ~ 2543
4	Ordinary	None	1.09 ~ 2.00	1631 ~ 2992
5	Blast Furnace	None	1.02 ~ 1.05	2083 ~ 2144
6	Alumina	None	1.05 ~ 1.20	860 ~ 983

Regarding the effect of admixtures, the value of S_∞ for the mix with no admixture (mix 4) was the highest, followed by the mixes with expansive admixture (mix 3), shrinkage reducer (mix 2), and superplasticizer (mix 1) in order.

Since estimates of S_∞ for each mix include some error allowance, no clear pattern in the effects of certain cements and admixtures on ultimate shrinkage strain was seen. Mixes containing alumina cement and superplasticizer, however, apparently had smaller ultimate shrinkage strain.

4. CONCLUSIONS

The effect of cements and admixtures on the properties of vacuum-exposed mortar and concrete was studied in order to determine suitable materials for lunar concrete. The results of the study are summarized below.

(1) Vacuum-exposed mortar and concrete specimens made with alumina cement showed less weight loss than those made with other cements.

(2) Vacuum-exposed concrete specimens containing silica fume or expansive admixture showed slightly less weight loss than those not containing these admixtures. On the other hand, no clear effect of these admixtures was seen in the case of mortar specimens.

(3) Vacuum-exposed mortar and concrete specimens made with alumina cement showed the least shrinkage strain among all specimens tested.

(4) Superplasticizer and shrinkage reducer resulted in some reduction in the shrinkage strain of mortar specimens, while no clear effect of these admixtures was obtained in the case of concrete specimens.

(5) Vacuum-exposed mortar specimens made with any cement and admixture demonstrated higher compressive and flexural strengths than water-cured specimens. The increased strength was particularly large for alumina cement mixes, while it was small in the case of expansive admixture mixes.

(6) Vacuum-exposed concrete specimens made with alumina cement showed an apparent increase in compressive strength, while the effects of admixtures could not be identified in this experiment.

(7) The ultimate shrinkage strain of vacuum-exposed mortar specimens was estimated using measured strains and a linear diffusion equation. The estimated ultimate strain showed that alumina cement and superplasticizer were effective for reducing shrinkage strain caused by vacuum exposure.

It is concluded from this study that alumina cement is one of the most realistic possibilities for use in lunar concrete. In addition to the advantage arising from the availability of suitable mineral resources on the moon, alumina cement has another advantage in that it does not require much time and energy for curing. Regarding the effects of admixtures, however, further studies seem to be needed.

These studies will continue in order that the production of lunar concrete becomes a reality. It is hoped also that technologies derived from these lunar concrete studies will contribute to existing terrestrial concrete work.

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