ADVANCES IN MANUFACTURE OF MOONCRETE – A REVIEW

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Abstract

The idea of "Constructions on Moon" is gaining momentum day by day given the need for Constructions on moon for conducting research in Astronomy and for studying the possibility of survival of mankind on moon. One of the most challenging tasks for the present day Civil Engineer is to lay an economical, safe, stable and durable structural base on the lunar surface. This is because of lack of awareness on behavior of building materials on extra terrestrial atmosphere like lunar atmosphere. As it is uneconomical to transport building materials from Earth, Mooncrete is worthy of consideration. The idea of Mooncrete dates back to 1985. Mooncrete, which could be prepared using materials on lunar surface itself, proves to be a highly promising material in the extra-terrestrial constructions. The aim of this review paper is to present a summary of all the information and findings on Mooncrete as on date. It starts out with a brief description of experiments conducted on materials used for manufacture of Mooncrete. The process of manufacture of Mooncrete and possible difficulties that may intervene with it are outlined. The paper also presents a discussion on various lunar regolith simulants prepared so far and predicts their behavior in lunar environment. Alternatives to water as binding material are also suggested. The paper concludes with a brief reference to the results of current Mooncrete. The paper is expected to create awareness in Structural Engineering community and hence encourage research in development of more economical and practicable Mooncrete with less difficulty in manufacturing.

Index Terms: *Mooncrete/Lunarcrete, Manufacture, Waterless Mooncrete, Regolith, Physical properties, Extraterrestrial constructions, Sulphur concrete.*

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1. INTRODUCTION

Decades after man first landed on moon, mankind finds a rising need and thirst for knowledge associated with moon. Hence, humans feel a need for base on moon to carry the necessary operations on lunar surface. Building a lunar base with raw materials transported from earth is uneconomical. Even if we turn up to spend money and resources on having it, there are many constraints involved in it. The moon, being a space body with low acceleration due to gravity and no atmosphere conditions, is a place where it is highly difficult to build a base. So, efficient utilization of lunar resources would be a very promising way to construct lunar bases. Keeping economy and constraints in mind, most researchers agree that concrete with small changes in its composition would be an ideal construction material for lunar base owing to its strength, durability and excellent shielding properties. It was later named as Lunarcrete. Also known as "Mooncrete", it was an idea first proposed by Larry A. Beyer (Bayer 1985) [1] of the University of Pittsburgh in 1985. As per Kinomere et.al., it is a hypothetical aggregate building material, similar to concrete, formed from lunar regolith, that would cut the construction costs of building on the Moon (Kinomere et al 1990) [2].

The aim of paper is to present a summary of all the information and findings regarding Mooncrete as on date. It starts out with a brief description of experiments conducted on materials used for manufacture of Mooncrete. The process of manufacture of Mooncrete and possible difficulties that may intervene with it are outlined. The paper also discusses the various lunar regolith simulants prepared so far and predicts their behavior in lunar environment. Alternatives to water as a binding material are also suggested. The paper concludes with a brief reference to the results of current Mooncrete. The paper is expected to create awareness in the Structural Engineering community and hence encourage research in the development of more economical and practicable Mooncrete with less difficulty in the manufacturing process.

2. RAW MATERIALS

Lin (Lin 1987) [3] noticed the abundance of calcium oxide in regolith and raised the concept of concrete as a building material in lunar constructional activities. (Hewlett and

Young, 1987) [4] Hewlett and Young discussed the versatility of concrete and studied the chemical composition of it. The material that is instantly available on the lunar surface is Regolith which is formed as a result of meteorite impacts. Some of this material had melted due to the enormous heat and formed as glassy agglutinates. Lunar mare soils are rich in Ilmenite. Though Mooncrete is a hypothetical concept, it has got a composition. Terrestrial concrete is being made cement which is manufactures by heating limestone and clay at a temperature around 1500^0C to form clinker. The limestone breaks into lime and the clay reacts further to form calcium silicates and calcium aluminates. Imitating the terrestrial concrete, it can be assumed that Mooncrete can be prepared by mixing water, regolith and cement. Regolith actually would play the role of aggregates thus making it as strong as a building material. Regolith is a layer of loose, heterogeneous material covering rock on the moon. Cement can be obtained by processing materials on the lunar surface using certain sophisticated techniques. It is almost impossible to imagine a building material on the Moon with water as a constituent. This is because there is no reliable evidence to support presence of water on Moon. Hence, a few alternatives have been suggested by researchers. According to these alternatives, sulfur and epoxy can act as binding agents to substitute the water. So, concrete can be prepared with or without water, cement and regolith as the main constituents. The subsequent sections of this paper propose various techniques for its preparation as proposed by researchers.

2.1 Cement

Unlike terrestrial cement manufacturing, low gravity, vacuum, etc. come into picture in lunar cement processing. It is expected to obtain cement by heating regolith to a temperature of 2000^0 C under the solar panels. The laboratory tests on various samples of soil revealed mineralogy resembling the terrestrial soil. So, same composition could be expected in the lunar soil with little variations. Most lunar materials that are found in some of the soil samples indicate a deficiency of calcium oxide in the lunar soil. Also the other composition of the soil can be seen in the table below. (Monis 1983, Ryder and Norman 1980) [5, 6] Lunar soil is rich in glass and this glass can considerably increase the strength of Mooncrete. It is important to note that samples taken from rim of Shorty Crater have a glass content of about 92%. (Refer Table 1)

Mission	Average glass content
Apollo 11	6.6
Apollo 12	18.0
Apollo 14	12.2
Apollo 15	29.4
Apollo 16	10.6

Table 1: Glass content obtained for various lunar samples (Lin 1987) [3]

Manufacture of cement

A cementetious material can be made with any proportion of CaO : SiO_2 : Al_2O_3 that falls within the Ca-Si-Al phase diagram. On moon, it is possible to heat the regolith at 2000^0C to make a cementetious material. Terrestrial concrete consists of 65% CaO, 23% SiO_2 (silica), 4% Al_2O_3 whereas, the Apollo lunar soils are found to contain relatively lower Calcium oxide (< 20%). (Refer Table 2) There are methods for CaO enrichment involving differential vaporization.

Sample type	Plutonic Rocks		Soils		Breccias		
Sample ID	**60025**	**78235**	**68501**	**70181**	**14305**	**15299**	**72275**
SiO_2	43.90	49.80	45.20	40.90	49.20	46.40	48.30
TiO_2	0.02	0.19	0.58	8.10	1.70	1.50	1.00
Al_2O_3	35.20	17.10	26.60	12.30	16.00	16.30	16.30
FeO	0.67	7.50	5.50	16.40	9.50	12.00	11.00
MnO	0.03	0.12	0.07	0.24	0.18	0.15	0.17
MgO	0.27	15.00	6.30	9.80	12.00	11.10	10.30
CaO	18.90	9.90	15.30	11.00	7.40	11.80	11.00
Na_2O	0.49	0.35	0.47	0.35	0.85	0.49	0.44
K_2O	0.03	0.06	0.11	0.08	1.20	0.20	0.25
Cr_2O_3	0.04	0.35	0.00	0.44	0.17	0.34	0.35
TOTAL	99.55	100.37	100.13	99.61	99.10	100.28	100.01

Table 2: Results of test conducted on lunar samples by NASA (Agosto, 1984) [7]

2.2 Aggregates

Aggregates form the strength rendering part in any type of concrete. Aggregates are classified as per ASTM are classified based on specific gravity. As the lunar soils are found to have a specific gravity greater than 2.6, they will form the best aggregates. Regular methods like crushing and sieving can be done to prepare the aggregates. The lunar environment will have no effect on these two simple and basic processes. Processed Moon rocks can be satisfactory adopted as they are not excessively weak and there is a reasonable thermal match with cementetious matrix. This is necessary to avoid the creation of internal stresses that could cause internal micro cracking and loss of properties (e.g., vacuum tightness, abrasion resistance, etc.). Lack of moisture eliminates most durability problems encountered with aggregates on Earth, such as alkali-aggregate reactions or freeze-thaw distress. However, the success of lunar soil as aggregate will depend primarily on its fineness and particle characteristics. Since weathering does not occur, clay minerals should be absent, helping to reduce the potential water demand. Lunar rocks could be used as aggregates provided they match thermally with other cementetious material. This is to avoid the generation of high internal stresses in concrete at high temperatures.

2.3 Water

Water can either be transported from earth or prepared on lunar surface. Transporting water is expensive and methods like Ilmenite reduction and alkali-hydroxide based schemes have been developed to produce water (Kanamori and Matsumoto 1998), [8]. This reduction is done with 11 kJ/mol. Equipment is also designed by a team to produce hydrogen through Ilmenite reduction method. (Sachio et.al., 2000) [9]

$FeTiO_3 + H_2 \rightarrow TiO_2 + Fe + H_2O$
Ilmenite Iron Water

Terrestrial hydrogen burnt in oxygen extracted from Moon rocks (Friedlander, 1984) [10] is the most likely source of water, although it may be possible to obtain some hydrogen on the Moon (Carter, 1994) [11]. Hydrogen can also be transported from earth in the form of liquid hydrogen, methane or ammonia. It would be more useful to carry in the form of methane or ammonia instead of liquid hydrogen unless the need of nitrogen and carbon for life support is considered.

3. FACTORS EFFECTING PROPERTIES OF MOONCRETE

Though lunar soil has lesser contents of calcium oxide, the Portland cement when used compensates that deficiency. It is also possible to go for calcium enrichment techniques and improve the calcium oxide content using differential vaporization technique (Agosto, 1984) [7]. Prior to the production process two things should be considered: Low gravity and vacuum on the lunar surface as they are expected to leave a lot of negative effect on properties and characteristics of lunar concrete. Various experiments have been conducted considering these two conditions and results have been produced analogically because it is difficult to produce these conditions naturally. So all the results have been produced based on interpolation concept.

3.1 Low Gravity Effect

Low gravity condition is very difficult to be imitated on earth as hydration time of cement is very high. So experiments were conducted (Noboru et.al., 1988) [12] in high gravity conditions and the results were interpolated for low gravity condition. A specimen of mortar that has Lunar soil to cement ratio s/c = 2 and water to cement ratio w/c = 65% (where c is high-early-strength Portland cement) was slowly fed into a centrifugal separation tank. It was accelerated gradually for some time. The properties like bleeding, compressive strength were measured at the end of the experiment and it was found that as the gravity increases strength also increases. (Table 3) So definitely lunar environment would leave a negative effect on strength of concrete but as it is found to decrease the strength only by 10%, this effect is negligible in view of the significance of lunar base for lunar projects.

Acceleration of gravity (g)	**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

Table 3 Properties of mortar influenced by high acceleration. (Noboru et al 1988) [12]

3.2 Effect of Vacuum

Mooncrete should not be exposed to vacuum after production and before construction with it because it would deteriorate its properties to a considerable extent. The vacuum actually creates pores in the structure of concrete by diffusing the moisture content. This porosity in turn reduces the unit weight and compressive strength of Mooncrete. Experiments were conducted on Portland cement concrete at normal temperature and 1 atm pressure with w/c=54.9%. This concrete was procured for some period at 20.1^0C and it is observed that the properties are better when the procuring period is greater than 4 hrs and worse when it is less than 4 hrs. This implies that the properties of Mooncrete when exposed to vacuum are considerably affected. Hence Mooncrete should not be exposed to vacuum until the hardening process is completed.

4. MOONCRETE MANUFACTURING

4.1 Mooncrete production

Mooncrete manufacture and it's curing are described as follows. Firstly water should be turned into powdered ice and this powder should be mixed with aggregates. As both of these would be in solid state it would result in a uniform mix. This mixed up concrete is then transferred to a place of low

temperature and covered with an air tight material. This air tight material is to prevent its exposure to the vacuum and to prevent the evaporation of water. The Mooncrete is cured for a certain period with a heat insulator. Now after the estimated pre-curing period it is exposed to vacuum.
The tensile strength is generally observed to be one-tenth of the compressive strength. However, Hanna observed that addition of reinforcement material like fiber glass arrests cracks in concrete and doubles the tensile strength when added by 4% of the weight (Hanna 1977) [13]. Fibers could be prepared with the help of iron extracted from the lunar rocks. Otherwise light weight Kevlar (registered trademark for a para-aramid synthetic fiber) could be transported from the earth which acts as a good low weight reinforcement fiber. As weight requirement for increasing the flexural strength is very negligible, Kevlar would be one of the choices for reinforcement.

4.2 Waterless Mooncrete Production

Since there is no strong evidence of presence of water on moon, a method of Mooncrete production using sulphur as a binding agent without water is suggested. The use of sulfur concrete as a lunar or Martian construction material was first suggested by Leonard and Johnson, 1988 [14]. Sulfur eliminates the need for water. Secondly, it helps the Mooncrete to gain maximum strength in comparatively lesser time and requires low heat. Sulfur concrete sets very rapidly and achieves a minimum of 70 to 80 percent of ultimate compressive strength within 24 hr. (Anon, 1988) [15] Sulfur can be extracted from triolite (Vaniman.et.al) [16] on lunar surface itself and when mixed with lunar regolith. Thus waterless concrete can be a viable alternative to the hydraulic concrete. The sulphur content is mainly controlled by triolite (FeS) availability. These contents range from a few tens of ppm in ferrous anthrosites to over 2000 ppm in high titanium lavas from Apollo 11 and 17 sites. Evaporation and condensation are expected to play major role in sulphur distribution. Small veins of triolite are observed in few lunar breccias, suggesting that a kind of sulfide metamorphism has operated in the geological history of lunar material. Enrichment of sulphur during magmatic history of some lunar igneous rocks; the apparent positive correlation between S and Ti contents of mare basalt materials is consistent with fractional crystallization of an ancient magma ocean, which would concentrate the chalcophile elements into sulfide beds. The sulfide phases would preferentially migrate into the liquid during partial melting, production and subsequent enrichment in sulfur of late stage crystallization products such as high-Ti-lavas. For the sulfur to work as a binding agent it should be in liquid or semi liquid form. This requires heating it to a temperature between 130^0C-140^0C because sulfur melts at about 119^0C and to stiffen about 148^0C. Rapid setting (acquiring about 70-80% of ultimate compressive strength within 24 hours) is possible with this sulfur concrete. Unlike conventional concrete which requires 7 to 28 days for hardening, sulfur concrete hardens like a rock in an hour (Toutanji and Grugel 2008) [17].

Sulfur concrete = 12% to 22% sulfur + 78% to 68% aggregate.

Unmodified sulfur and aggregate materials are hot-mixed, cast and cooled to prepare sulfur concrete products. The sulfur binder initially crystallizes to α-sulfur at 114^0C with a volume decrease of about 7% which on further cooling to 9^0C and below undergoes a transformation to monoclinic β-sulfur, the stable orthorhombic polymorph at ambient temperatures. The temperature variations should not exceed 114^0C to prevent these sulfur transitions. The production of elemental sulfur from triolite requires a temperature of 1000^0C to 1200^0C (Casanova, 1997) [18] which can be produced using standard solar concentrators. Current applications of modified sulfur concretes are focused on applications in industrial plants where acid and salt rich environments result in premature deterioration and failure of conventional Portland cement concrete. Freeze-thaw durability experiments conducted for 1-day cooling gave values of about 60% retention of original Dynamic Modulus of Elasticity after 300 exposure cycles (ASTM Standard C 2008) [19] . Apart from this basic information on sulphurcrete, a test was conducted by Husam and Mohsen to determine the relationship between compressive and tensile strengths and sulfur-to-lunar soil stimulant ratio by weight (Husam and Mohsen, 1994) [20]. Here the lunar stimulant was made to mix with the sulphur at varying sulphur contents. The properties of resultant sulphurcrete were observed to be analogous to those of the hydraulic cement (Table 4, 5, Figure 1).

% Sulfur	25	30	35	40	50	60	70
Number of specimens	3	9	9	10	6	6	6
Avg. comp. Strength	6.07	24.00	33.80	25.40	24.70	25.00	15.70
Avg. Tensile Strength	0.33	2.90	3.70	2.00	2.70	2.60	1.40

Table 4: Strength with varying percentages of sulfur mix (Husam and Mohsen, 1994) [20]

The workability was quite low and unacceptable when the sulfur content was less than 30%. It was found to be acceptable in the sulfur range of 30-40 % and it needed light compaction to fill in the moulds. But when it is more than 40%, it behaved very similar to that of the Portland cement with w/c greater than 0.55.

But it was observed that the mixes with higher sulfur content solidified in a very less time when compared to that of concrete with lesser sulfur concrete.
The density of Mooncrete was found to be 2200 kg/m3 whereas that of normal concrete is about 2400 kg/m3.
No voids were found inside the specimens and they were found to have a very smooth surface.
Finally, the tensile strength was found to be 10-15% of the compressive strengths which very well agrees with the values of normal concrete.

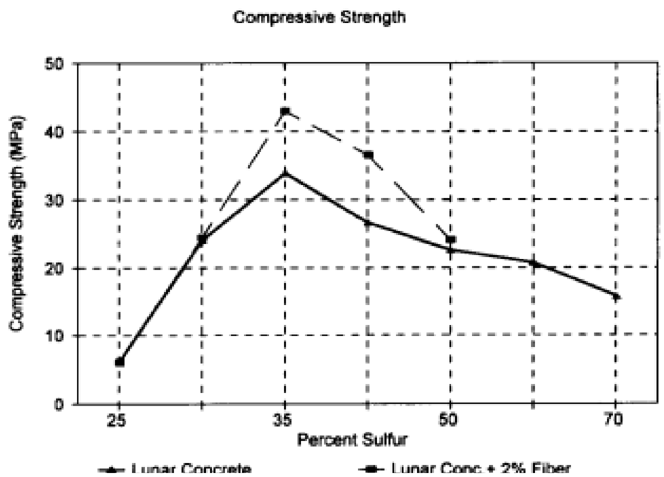

Figure 1: Lunar sulfur concrete compressive strength (Husam and Mohsen, 1994) [20]

% Sulphur	30	35	40	50
Number of Specimens Tested	9	9	9	9
Compressive strength (MPa)	24.4	43.0	36.5	24.1
Percent Increase in Strength	1.7%	27%	37%	6.4%

Table 5: Reinforced Sulfur Concrete with 2% Metal Fiber (Husam and Mohsen, 1994) [20]

Note: Tests were conducted using glass fibers too but they resulted in 27% reduction of compressive strength and 20% reduction of tensile strength.
The flexural strength of Mooncrete would be as low as about one-tenth of its compressive strength. The Mooncrete thus can be reinforced like terrestrial concrete. For this, either steel or glass fibers can be used as a reinforcement material. The test was also conducted using metal (Aluminum) fibers and glass fibers to study the characteristics of reinforced sulfurcrete. The metal fibers were 0.05 mm in cross section and each fiber was 1.25 mm in length. 2% by weight of these fibers along with some percentages of sulfur was added to the concrete and strength increase was observed to be maximum at 40% of sulfur. Further, the mode of failure was observed to be less brittle compared to that of non reinforced sulfurcrete. The metal fibers are found to increase the durability but decrease the strength by 5%. This is because; the interference of the fibers with sulfur bonds creates weak regions. The maximum compressive strength was 33.8 MPa and it was found that addition of fiber increases it to 45.5 MPa.
Experimental results revealed that the reinforcement increases the flexural strength, strain energy capacity and ductility of the Mooncrete. Fibers' function is to resist the micro cracks acting as crack arresters. (Toutanji.et.al, 2006) [21]The ultimate strength can be considerably increased by adding 1% glass fiber derived from the lunar regolith simulant. It is also found that usage of 4% of steel fibers almost doubles the flexural strength. Continuous fibers could be drawn using a fiber pulling apparatus and the addition of boric oxide improves the viscosity of these fibers.
Samples were made with JSC-I and Mooncrete is poured into them followed by arranging these fibers longitudinally at about two-thirds thickness of the sample. Finally the results showed an increase both in the strength and ductility.

5. PHYSICAL PROPERTIES OF MOONCRETE (by Lin et.al., 1987) [22]

40 gm of soil sample with glassy rhyolite as fine aggregate, calcium aluminate as cement and distilled water was used to prepare Lunarcrete of slump ½ to 1 inch. Cube and beam specimens made and steam cured. The water for such steam could be produced by mixing hydrogen with lunar Ilmenite at 800°C, to produce titanium oxide, iron, and water. The specimens were studied to know their compressive strength, modulus of rupture, modulus of elasticity and thermal coefficient of expansion.

5.1 Compressive strength

In compression test, rate of loading was varied such that the cube contraction values were in and around 10uin/sec and for duration of 45 min. Cubes of normal concrete were also subjected to test. The results were 7960 psi for Rhyolite mixed lunar sample concrete and 10970 psi for lunar soil sample cubes. No deformation was observed till the stresses reached 6600 psi in lunar soil sample cubes and the value is 4800 psi for Rhyolite mix. Poisson's ratio was observed as 0.39 and 0.27 for lunar mix and Rhyolite mix respectively. (Figure 2)

5.2 Tensile strength

In tensile test, 1 lunar mix beam and 3 Rhyolite mix beams were subjected to test. Section modulus was calculated from their geometric properties. The modulus of rupture for beams made with lunar mix was found to be 1244 psi and that with Rhyolite mix was found to be 1206 psi. Hence, difference between them is observed to be negligible.

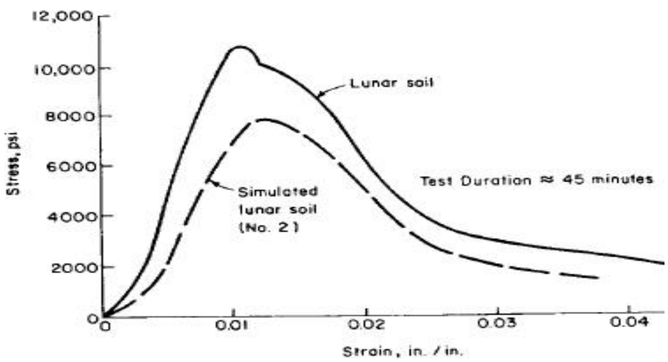

Figure 2. Stress-Strain curves for Rhyolite mix and lunar mix (by Lin et.al., 1987) [22]

5.3 Dynamic modulus of elasticity

A Sonometer was used to find the Dynamic modulus of elasticity. Vibrations were produced in beams with the help of crystal phonograph cartridge and the results were observed to be 3.12 million psi for lunar mix beam and 2.81 million psi for Rhyolite mix sample.

5.4 Thermal expansion coefficients

A dilatometer and a cooling unit were the test equipment. Thermally induced deformations were transferred to the equipment through a fused silica rod. Specimens were subjected to 2 cycles of cooling and heating at temperatures ranging from 100^0C to 350^0C. Corrections were also applied owing to the expansion of silica tube. Finally the coefficients were observed to be 2.9 millionth in/in/F and 3.5 millionth in/in/F for lunar and Rhyolite beams respectively.

6. LUNAR SOIL SIMULANT

It is not practical to meet the demand of Lunar soil by researchers world wide as the lunar soil brought from moon is very less in quantity. To solve this problem, simulants have been prepared using terrestrial materials. Researchers who cannot acquire high amounts of lunar soil use high moisture content coal ash as they tend to simulate lunar soil. These simulants are prepared using sulfur instead of 'water + cement' as binding material. They imitate the lunar soil in every property to the maximum possible extent. Of all known Lunar soil simulants, JSC-1 is a popular stimulant obtained by using a volcanic ash deposit based in San Francisco volcano field near flagstaff AZ. [23] (David et.al, 1994) It is developed by NASA Johansson Space centre from a volcanic ash of basaltic composition. (Hayder et.al 2010) [24] Geotechnical properties of the simulants like grain size distribution, cohesion, friction angle, dilatency angle, tensile strength and many such properties are found out experimentally. Its chemical composition, grain size distribution, specific gravity, mineralogy, cohesion and angle of friction are calculated and they resembled the values obtained for lunar mare soil samples. JSC-1 is a glass rich basaltic ash. It is being used for various researches like dust control, spacesuit durability and agriculture (JayaLakshmi et.al 2012) [25].

6.1 JSC-1 Preparation and properties (David et.al, 1994) [23]

6.1.1 JSC-1 Preparation

Ash was mined from Merriam crater. It was comminuted in an impact mill along with Coarse sieving. The ash was partially dried and mixed. Average water content of final mix was found as 2.7 ± 0.31 % by weight. Various properties are tested for this simulant and compared with those found for the original lunar soil.

6.1.2 Chemical composition

The samples were dried for 2 months and the crushed sample was ground to pass 177 micron sieve. Then the tests were conducted and results as shown in Table 6 were obtained. The lunar soils contain no water and low oxides of Na_2O. Besides this, lunar stimulant is found to be similar to terrestrial basalts.

Oxide	JSC-1 (wt%)	JSC-1 (wt%)	Lunar soil (wt%)
	Concen-tration	Standard deviation	
SiO_2	47.71	0.10	47.3
TiO_2	1.59	0.01	1.6
Al_2O_3	15.02	0.04	17.8
Fe_2O_3	3.44	0.03	0
FeO	7.35	0.05	10.5
MgO	9.01	0.09	9.6
CaO	10.42	0.03	11.4
Na_2O	2.7	0.03	0.77
K_2O	0.82	0.02	0.6
MnO	0.18	0	0.1
Cr_2O_3	0.04	0	0.2
P_2O_5	0.66	0.01	-
Ignition losses	0.71	0.55	-
Total	99.65		99.8

Table 6: Results of X-ray fluorescence analysis on Apollo 14163 soil (David et.al, 1994) [23]

6.1.3 Mineralogy

Mineral species were identified by X-ray diffraction, optical microscopy and scanning electron microscopy. The major minerals are plagioclase, pyroxene and olivine whereas Ilmenite and Chromites form minor composition.

6.1.4 Particle size distribution (PSD)

The sample after sieving was wetted to remove adhering fines and dried. They are re-sieved and the weight percentage corresponding to sieve size is plotted on a graph. This PSD experiment was done by University of Texas and NASA and the two curves resulted in almost concurrent results. Two particle size distribution curves for JSC-1 are presented in Figure 3. In work done at the University of Texas, Dallas (UTD curve), fifteen 250 g splits were analyzed. The samples were initially sieved dry, wetted to remove adhering fines, dried, and re-sieved. Finally, the weight per cent smaller than a given sieve opening was computed.

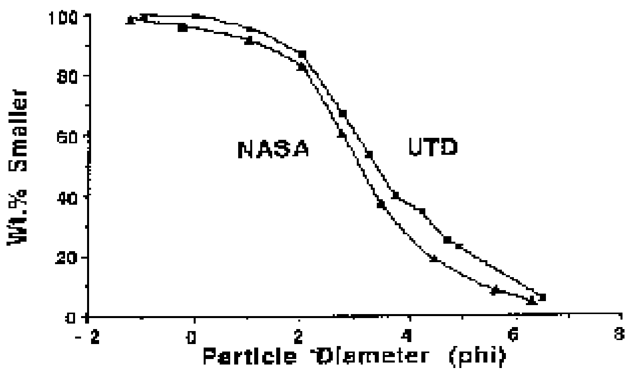

Figure 3. Particle size distribution curves for JSC-1. (David et.al, 1994) [23]

Another analysis at the Johnson Space Center (NASA curve) followed procedures developed for lunar soil samples (McKay et.al., 1974) [26]. Four 25 g splits were mixed, and a 15 g subsample was separated. This material was sieved while being wetted with Freon.

6.1.5 Specific gravity

The average specific gravity of JSC-1 particles is 2.9 g/cm3. This was measured at 4^0C, by method of Lambe and Whitman. Specific gravity of lunar soil is found to be between 2.9 and 3.5 whereas that of JSC-1 is found to be about 2.9.

6.1.6 Angle of Internal friction

Values are determined from Mohr coulomb failure criterion. It is found to be between 250 and 500 for lunar soil and 450 for JSC-1. Cohesion is found to be between 0.26 and 1.8 kPa for lunar soil and 1kPa for JSC-1(Refer Figure 4).

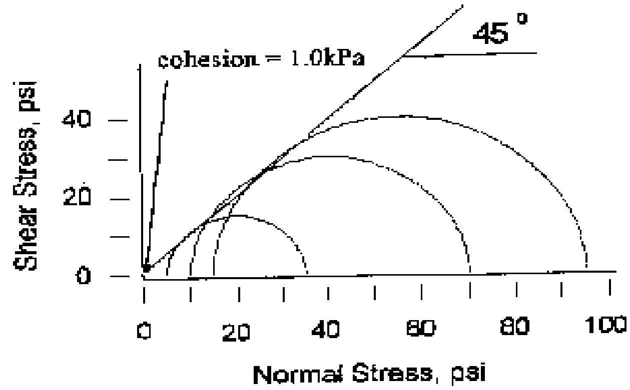

Figure 4. Angle of internal friction (45°) and cohesion (1.0 kPa) for JSC-1 (David et.al., 1994) [23]

6.1.7 Results from direct tensile test

With increase in density, strength of the samples also increased. Maximum stress is found out and entered into the Mohr circle. At varying confining pressures, values of stress are found out and a tangent is fitted to this circle. For a density of 1.7 g/cm3, cohesion was found to be 1.4 kPa and the friction angle is found to be 42.90. For a density of 1.9 g/cm3, the cohesion and internal friction values are found to be 2.4 kPa and 48.80. Reasonable values of cohesion and internal friction were obtained with lunar soil samples.

6.1.8 Comparison of properties of Simulant and Lunar soil

Lunar soils are inferior in terms of alkaline oxides when compared to those of simulants. One more differentiation is that lunar soils were formed centuries ago in reducing environments and hence they possess iron in the form of Fe_2 and FeO.
The simulant contains such glass in which more micrometer-scale plagioclase and metal oxide crystals are present whereas the lunar soil contains micrometer scale iron metal.
The stimulant JSC-1 has a narrower particle size distribution than that of the lunar soil.
Specific gravity, Angle of Internal friction values of lunar stimulant and lunar soil match with each other.

7. PREPARATION OF CEMENTITIOUS MATERIAL WITH LUNAR SOIL SIMULANT (Yu Qiao et.al., 1990) [27]

The preparation of lunar soil simulant is already discussed. Now, the preparation of cementetious material using one of the known lunar soil simulants and the subsequent results would be presented. Strips of cementetious material of considerable thickness have been prepared using a nano interphase and a lunar soil stimulant. The nano interphase is mainly of exfoliated silicate monolayer, continuous polyamide 6phase, and dispersed silicate tactoids. JSC -1 stimulant of known properties is initially taken in a container. At room temperatures, the nano interphase was prepared. The nano interphase in this experiment is a result of mixture obtained when monomers, silicate, acids and de-ionized water were mixed in proportion. The whole mixture is made thermal in an environment of nitrogen at 260^{0}C for 6 hours. This environment helps in expansion of silicate followed by exfoliation of the nano layers. Now the whole mixture is cooled and broken into pellets of size 0.5 mm. This completes the preparation of the nano interphase. At this stage 15% of the prepared nano phase material and lunar soil stimulant are thoroughly mixed at 120 rpm. The obtained lunar cement was made strips of 3.5 mm thickness with the help of a compressor. These strips were later tested for the flexural properties of the lunar cement using the formula for strength as

$$Y = \frac{3}{2}\left(\frac{P \times L}{b \times t^2}\right)$$

where
P = maximum center-point loading,
L = support distance,
b = sample width and
t = sample thickness.

As the content of interphase is increased the flow ability of the cement also increases and thus the handling would be easier. But, as we want to limit the amount of materials to be transported from the earth, it is advisable to use a lesser content of nano phase. The nanophase helps in wetting the particles and thus any particles left unwetted due to the low amount of nanophase would thereby decrease the flexural strength. Gap gradation is found to be useful in these kinds of situations where the nano phase amount is limited. This nanophase is a polyamide 6 phase matrix nano composite with intercalated silicate tactoids and exfoliated silicate layers as reinforcement.

8. DISCUSSION AND CONCLUSIONS

Construction of lunar bases and colonization of the moon is the most intriguing challenge to the engineers all over the world. Before advancing to scientific activities on the moon suitably shielded structures to house facilities and personnel must be built on the Moon. Mooncrete is proved to be the most promising construction material till date. The Insitu resource utilization is the concept behind this Mooncrete preparation and thus the transportation costs could almost be considered nil. It can withstand high temperature differences, meteorite impacts, and can act as a very good radiation shielding material according to the present studies made. Tests conducted so far are not sufficient and complete. Further tests to characterize its engineering and thermal properties, gas evolution, density variations, and the bearing capacity of soil using lunar soil simulants are required. Sulfur concrete tests could be conducted for stress strain behavior, durability and effects of different types of reinforcement. Feasibility of epoxy as a binding agent has not been studied in detail and this could be done as well. The aim of this paper is to present a summary of the research related to Lunarcrete. Although hundreds of papers have been published in this area, the authors believe that the few works that have been presented have realized the aim to a satisfactory level.

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