Lunarcrete – A Review

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Abstract--- *The idea of "Constructions on Moon" is gaining momentum day by given the need for buildings on moon for conducting research in Astronomy and for studying the possibility of survival of mankind on moon. One of the most challenging task to the present day Civil Engineers is laying a structural base on the lunar surface. This is because of lack of awareness on the behavior of building materials on extra terrestrial atmosphere like the lunar atmosphere. As it is not economical to transport materials from the Earth, Lunarcrete is worthy of consideration. The idea of Lunarcrete dates back to 1985. Lunarcrete, which could be prepared using materials on the lunar surface itself, proves to be a highly promising material in the extra-terrestrial construction. This review paper presents all the information and findings regarding Lunarcrete as on date. It starts out with a brief description of experiments conducted on materials used for manufacture of Lunarcrete. All the findings related to Lunarcrete discovered so far are outlined. The uses of Lunarcrete and details on finishing and plastering works over Lunarcrete are also included. The process of manufacture of Lunarcrete and possible difficulties that may intervene with the process is outlined. The paper also discusses the various lunar regolith stimulant materials 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 the present ongoing research all over the world on Lunarcrete. The paper is expected to create awareness in the Structural Engineering community and hence encourage research in the development of more economical and practicable Lunarcrete with less difficulty in the manufacturing process.*

I. Introduction

IT has It has been decades since man first landed on the moon. Now due to the rising requirements and thirst for knowledge human beings feel a need for base on the moon to carry the necessary operations on the lunar surface. Building a lunar base is a very costly affair. Even if we turn up to spend money and resources on this project there are many constraints involved in it. The moon, being a space body with low gravity and no atmosphere conditions, it is highly difficult to build a base on it. So efficient utilization of lunar resources would be a very promising way to construct lunar bases. Keeping the 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 is later named as lunarcrete. This lunarcrete can be prepared using water as well as without using water. Much research has been done on the presence of water on the lunar surface but no positive results are obtained till date. Hence considering water as a very scarce resource and most probably it is an impossible resource on the moon researchers think this property of lunarcrete seems to be of great help.

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II. Raw Materials

The material that is instantly available on the lunar surface is regolith which has formed as a result of meteorite impacts. Some of this material had melted due to the enormous heat and formed as glassy agglutinates. Soil in mare soils is rich in the ilmenite. Lunarcrete is a hypothetical building material. We haven't yet prepared it anywhere. But this hypothetical concept has got a composition for it. Terrestrial concrete is being made by heating limestone and clay at a temperature around 1500C 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 has been thought that lunarcrete can be prepared by mixing water, regolith and cement. Regolith actually would play a role of aggregate thus making it strong enough to work 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 sophisticated techniques which are mentioned below. It may seem to be ridiculous to plan a building material on the Moon with water as a constituent. This is because there are no strong proofs till date to support the presence of water on the Moon except those suspicions related to things at and around the poles. Even if water could be found out in the coming future it will take fairly ample time to find enough water. For this few alternatives have been suggested by researchers. According to these alternatives, sulfur and epoxy can act as binding agents to substitute the water. So the lunarcrete can be prepared with or without water, cement and regolith as the main constituents and now let's go through the proposed techniques for its preparation.

III. Cement

Unlike terrestrial cement manufacturing, various concepts like low gravity and vacuum come into picture in the lunar cement processing. It is expected to obtain cement by heating regolith to a temperature of 2000 C under the solar panels. The various samples of soil on subjected to laboratory tests revealed a mineralogy resembling that of the terrestrial soil. So same composition could be expected in the lunar soil of

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with little variations in numbers. Most lunar materials are found tn 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. [2] Lunar soil is rich in glass and this glass can be utilized in proper way to increase the strength of the lunarcrete.

Table 1: Glass Content Obtained for Various Lunar Samples

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Table 2-7. X-Ray Fluorescence Analyses of Different Samples at the Two Viking Landing Sites (Carr et al., 1984)

	Chryse Fines	Chryse Duricrust (1)	Chryse Duricrust (2)	Utopia Fines	Estimated Absolute Error
SiO_2, wt %	44.7	44.5	43.9	42.8	5.3
Al_2O_3, wt %	5.7	N/A	5.5	N/A	1.7
Fe_2O_3, wt %	18.2	18.0	18.7	20.3	2.9
MgO, wt %	8.3	N/A	8.6	N/A	4.1
CaO, wt %	5.6	5.3	5.6	5.0	1.1
K_2O, wt %	<0.3	<0.3	<0.3	<0.3	---
TiO_2, wt %	0.9	0.9	0.9	1.0	0.3
SO_3, wt %	7.7	9.5	9.5	6.5	1.2
Cl, wt %	0.7	0.8	0.9	0.6	0.3
Sum	91.8	N/A	93.6	N/A	---
Rb, ppm	<30			<30	
Sr, ppm	60 ± 30			100 ± 40	
Y, ppm	70 ± 30			50 ± 30	
Zr, ppm	<30			30 ± 20	

Table 2: Average Glass content obtained for lunar samples obtained from different missions

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

IV. Cement Manufacturing

A cementitious material can be made with any proportion of CaO : SiO2 : Al2O3 that falls within the Ca-Si-Al phase diagram. On the moon it is possible to heat the regolith at 2000 C to make cement. Terrestrial concrete consists of 65% CaO, 23% silica, 4% Al2O3 whereas, the Apollo lunar soils are found to contain relatively lower Calcium oxide (<20%). There are methods for CaO enrichment involving differential vaporization.**[1]** The concrete should be placed such that it would not need to absorb carbon dioxide from the atmosphere as it is scarce on the moon. This can be obtained by constructing in lava tubes.

V. Aggregates

Aggregates form the strength rendering part in any type of concrete. Aggregates are not classified basing on mineralogy according to ASTM but they are classified basing on the specific gravity. As the lunar soils are found to having a specific gravity greater than 2.6 undoubtedly they will form the best aggregates. Regular methods like crushing and sieving can be done to prepare the aggregates. Luckily the lunar environment will have no effect on these two simple and basic processes. Processed Moon rocks should be satisfactory provided they are not excessively weak and there is a reasonable thermal match with the cementitious matrix This is necessary to avoid the creation of internal stresses that could cause internal microcracking 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. Whether lunar soil can be successfully used 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.

VI. WATER

Water can either be transported from the earth or prepared there on the lunar surface itself. Transporting water is quite a costly business and methods like Ilmenite reduction and alkali-hydroxide based scheme have been developed to produce the water. [14] This reduction is done with 11 KJ/mol. An equipment is also designed by a team to produce hydrogen through ilmenite reduction method. [4] Terrestrial hydrogen burnt in oxygen extracted from Moon rocks (Friedlander, 1984) is the most likely source of water, although it may be possible to obtain some hydrogen on the Moon (Carter, 1984). Hydrogen can also be transported from the 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 in the form of liquid hydrogen.

VII. LUNARCRETE MANUFACTURING

Prior to the production process two things should be kept in the mind: Low gravity and vacuum on the lunar surface. These two things are expected to leave a lot of negative effect on the properties and characteristics of lunar concrete. Various experiments have been conducted considering these two conditions and the results have been produced analogically because it is difficult to produce these conditions naturally. So all the results have been produced with the help of interpolation concept.

VIII. LOW GRAVITY EFFECT

This low gravity condition is very difficult to be imitated on the earth as the hydration time of cement is very high. So the experiment was conducted (Noboru Ishikawa, Hiroshi Kanamori, Takoji Okada) in high gravity conditions and the results were interpolated for the low gravity condition. What they actually had done is to take a specimen of mortar that has s/c = 2 and w/c = 65% (where c is high-early-strength portland cement). This mortar was slowly fed into a centrifugal separation tank. Simultaneously acceleration was given which was increased gradually for some time. The properties like bleeding, compressive strength were measured at the end of the experiment and to no astonishment they found that as the gravity increases strength also increases. So definitely the lunar environment would leave a negative effect on the strength of the concrete but as it is found to decrease the strength only by 10% this effect is negligible as lunar base is a challenging project.

Table 3: The properties of mortar influenced by high acceleration[5]

Acceleratio n of	Bleeding water(ml)	Density(g/c m)	Compressiv e strength
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

IX. EFFECT OF VACUUM

At a certain stage between production and construction of lunarcrete, it should never be exposed to the vacuum because it would reduce it's properties to a considerable extent. The vacuum actually creates pores in the structure of concrete by a series of diffusion of the moisture content. This porosity in turn reduces the properties of the lunarcrete like unit weight and compressive strength. Experiments were conducted on Portland cement concrete at normal temperature, 1 atm, with w/c=54.9% and s/a=40%. This concrete was procured for some period 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 lunarcrete when exposed to vacuum would be affected thus reducing its properties. Hence the lunarcrete should not be exposed to the vacuum until the hardening process is completed.

X. LUNARCRETE PRODUCTION

Firstly the water should be turned into powdered ice and this powder should be mixed with the 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 the place at 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 lunarcrete is cured for a certain period with a heat insulator. Now after the estimated precuring period it is exposed to the vacuum. This is how lunarcrete can be produced and cured. Since there are no strong evidences of presence of water on the moon lets go through a method of lunarcrete production using sulphur as a binding agent instead of water.

The tensile strength is generally observed to be one-tenth of the compressive strength. Is is observed in a test that the addition of reinforcement material like fibre glass arrests the cracks in concrete and doubles the tensle strength when added by 4% of the weight.(Hanna 1997). Fibres could be prepared with the help of iron extracted from the lunar rocks. Otherwise light weight Kevlar could be transported from the earth which acts as a good low weight reinforcement fiber. As the weight requirement for increasing the flexural strength is very negligible, Kevlar would form a promising material for reinforcement.

XI. WATERLESS LUNARCRETE PRODUCTION

The lunarcrete could also be prepared with sulfur as binding agent. The use of sulfur concrete as a lunar or Martian construction material was first suggested by Leonard and

Johnson, 1988. There is no wonder why sulfur is being used. It has got few advantages with it. Firstly, it eliminates the need for water. Secondly, it helps the lunarcrete 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. **[13]** The sulfur can be extracted from triolite(Vaniman.et.al**)** **[8]** on the lunar surface itself and when mixed with lunar regolith. This waterless concrete can be a viable alternative to the hydraulic concrete. The sulphur content is mainly controlled by triolite (FeS) abundance. 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 a kind of sulfide metamorphism, has operated the geological history of lunar material. Enrichment of sulphur during magmatic history of some lunar igneous rocks; the apparent positive correlation between S & 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, produced 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 130-140C because sulfur melts at about 119C and to stiffen about 148C. Rapid setting acquiring about 70-80% of ultimate compressive strength within 24 hours is possible with this sulfur concrete. Unlike waiting for 7-28 days for conventional concrete, sulfur concrete hardens like a rock in an hour**.[6]**

Sulfur concrete = 12-22% sulfur + 78-68% 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 114C with a volume decrease of about 7% which on further cooling to below 9C undergoes a transformation to monoclinic β-sulfur, the stable orthorhombic polymorph at ambient temperatures. The temperature variations should not exceed 114C to prevent these sulfur transitions. The production of elemental sulfur from triolite requires a temperature of 1000-1200C[11] 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.[7]

Apart from this basic information on sulphurcrete, a test was conducted to determine the relationship between compressive and tensile strengths and sulfur-to-lunar soil simulant ratio by weight**.[12]** Here the lunar simulant was made to mix with the sulphur at varying sulphur contents. The properties of the resultant sulphurcrete were observed to be analogous to those of the hydraulic cement of which few are worth discussing here.

- 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 the concrete with lesser sulfur concrete.
- The density of the concrete was found to be 2200Kg/m3 whereas normal concrete shows a value about 2400Kg/m3.
- No voids were found inside the specimens and they were found to have a very smooth surface.
- Finally, the tensile strengths were found to be 10-15% of the compressive strengths which very well agrees with the values of the normal concrete.

Table 4: Summary of Experimental Results

% Sulphur	25	30	35	40	50	60	70
Number of specimens	3	9	9	10	6	6	6
Avg. comer. Strength	6.07	24.0	33.8	25.4	24.7	25.0	15.7
Avg. Tensile Strength	0.33	2.9	3.7	2.0	2.7	2.6	1.4

The test was also conducted using metal fibres and glass fibres to study the characteristics of reinforced sulfurcrete. Then the mode of failure was observed to be less brittle compared to that of the non reinforced sulfurcrete. The metal fibres are found to increase the durability but decreased the strength by 5%. This was all because of the interference of the fibres with the sulfur bonds creating weak regions. Maximum compressive strength was found to be 33.8 Mpa but addition of fibre increased it to 45.5 Mpa.

Table 5: Reinforced Sulfur Concrete Mixes with 2% Metal Fiber

% 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%

XII. Lunar soil Stimulants

As there is much demand for lunar soil by researchers world wide, it would be ridiculous to use the lunar soil brought from the moon because it is very less in quantity. To help this problem, simulants have been prepared using terrestrial materials. They imitate the lunar soil in every property to the maximum extent possible. Of which JSC-1 is a popular stimulant obtained by using a volcanic ash deposit based in the San Francisco volcano field near flagstaff AZ.[9] JSC 1 is a lunar soil stimulant, developed by NASA Johansson Space centre from a volcanic ash of basaltic composition. Its chemical composition, PSD, specific gravity, mineralogy, cohesion and angle of friction are calculated and they resembled the values that obtained from 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.

XIII. JSC-1 PREPARATION

Ash was mined from Merrian crater. Coarse sieving was done and comminuted in an impact mill. The ash was partially dried and mixed. Average water content of final mix was found as 2.7+-0.31 wt%. Various properties are tested for this stimulant and compared with those found for the original lunar soil.

XIV. 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 the following results were obtained. The lunar soils contain no water and low oxides of Na2O. Besides this lunar stimulant is found to be similar to the terrestrial basalts.

Table 6: Results of X-ray fluorescence analysis on Apollo 14163 soil [10]

Oxide	JSC-1 (wt%)	JSC-1 (wt%)	Lunar soil (wt%)
	Concentration	Standard deviation	
SiO2	47.71	0.10	47.3
TiO2	1.59	0.01	1.6
Al2O3	15.02	0.04	17.8
Fe2O3	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
Na2O	2.7	0.03	0.77
K2O	0.82	0.02	0.6
MnO	0.18	0	0.1
Cr2O3	0.04	0	0.2
P2O5	0.66	0.01	-
Ignition losses	0.71	0.55	-
Total	99.65		99.8

XV. 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 chromite, clay form minor composition.

XVI. PARTICLE SIZE DISTRIBUTION

The sample after sieving was wetted to remove adversing fines and dried. They are resieved on 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. 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 resieved. Finally, the weight per cent smaller than a given sieve opening was computed.

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

XVII. ANGLE OF INTERNAL FRICTION

Values are determined from Mohr coulomb failure criterion. It is found to be 25-50 degrees for lunar soil and 45 degrees for JSC-1. Cohesion is found to be 0.26-1.8KPa for lunar soil and 1KPa for JSC-1.

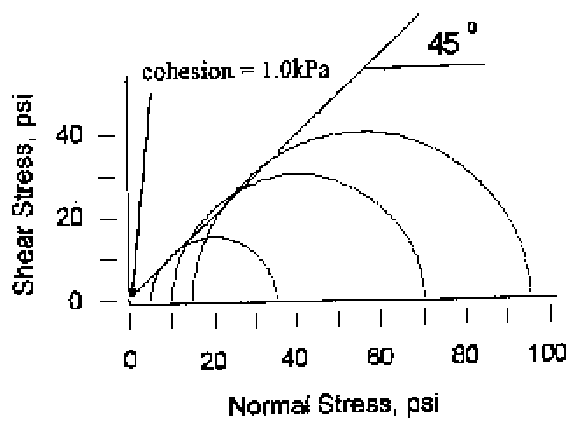

Figure 2: Depiction of Angle of Internal Friction (45°) and Cohesion (1.0 kPa) for JSC-1. [10]

XVIII. SPECIFIC GRAVITY

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

A. *Comparision Of Properties Of Simulant And Lunar Soil*

i. Lunar soils are inferior in terms of alkaline oxides when compared to those of the siLmulant. One more differentiation is that lunar soils were formed long back in reducing environments and that is why they possess iron in the form of Fe2 and FeO.

ii. 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.

iii. The simulant JSC-1 has a narrower particle size distribution than that of the lunar soil.

iv. Specific gravity, Angle of Internal friction values of lunar simulant and lunar soil match with each other.

XIX. Summary and Conclusions

With the increased requirements for constructions on moon, for conducting research in Astronomy and for studying the possibility of survival of mankind on moon, there is huge scope for research on viable construction materials that can be used. Lunarcrete, which could be prepared using materials on the lunar surface itself, proves to be a highly promising material in the extra-terrestrial construction. This review paper presents all the information and findings regarding Lunarcrete since 1985 till date. The authors expect that the paper will create awareness in the Structural Engineering community and hence encourage research in the development of more economical and practicable Lunarcrete with less difficulty in the manufacturing process.

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