EPiC Series in Built Environment
Volume 2, 2021, Pages 182–190
ASC 2021. 57th Annual Associated Schools of Construction International Conference

Developing Concrete Mixes using Micro Sized Lunar and Martian Regolith for Space Applications

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NASA announced its anticipated dates to send humans to an asteroid in year 2025 and to Mars in 2030s which requires the preparation of habitats on space for human accommodation. Due to the high cost of shipping construction materials to space, it is required to utilize in-situ materials for the development of concrete mixes. In this research, cement matrix using regular portland cement, and stucco will be tried. In addition, martian and lunar regolith will be utilized as aggregate due to their high availability. Utilized aggregates were sieved and grouped into different sizes to find the optimum aggregate size for concrete properties. Research findings proved that smaller regolith particles tend to produce concrete mixes with higher strength due to the improved packing order. The findings of this research present a step forward into producing economic concrete mixes, using local spatial materials for the development of space habitats.

Key Words: Nanoparticles, Portland Cement, Pozzolanic Admixtures, Lunar Regolith, Martian Regolith

Introduction

Ultra-high performance and high-performance concrete has been produced using terrestrial resources for more than two decades, and was successfully used in special construction projects, high-rise buildings, and highway applications (Akhnoukh, 2008, 2013a, 2013b, 2019, 2020). Successful concrete mixes include a wide range of granular constituents as cement, micro and nano-sized pozzolanic supplementary cementitious materials as micro-silica, fly ash, quartz flour, and blast furnace slag. In addition, well-graded fine sand and different admixtures are used to modify physical and mechanical characteristics of produced concrete.

Due to the successful launching of missions to outside space, the demand has risen in the past few years to build space habitats for the accommodation of humans on the outside space. The main impediment to the widespread of spatial construction includes the high cost of shipping standard construction materials to outside space and the inavailability of manpower to execute the construction projects. Thus, several research programs are currently working on the investigation of using lighter materials with higher strength-to-weight ratio, utilize in-situ spatial construction materials, and use additive manufacturing techniques (3-D printing) for project execution.

The main objective of this research is to develop concrete mixes using lunar and martian regolith as in-situ resources in replacement of fine sand used in terrestrial applications. The produced mixes are adjusted according to the following steps:

1. Supplementary cementitious materials (SCMs) are used in partial replacement of regular portland cement to produce higher strength and better long-term performing mixes using lighter weight materials.
2. In situ aggregates, mainly martian and lunar regolith are used as filling materials in lieu of normal fine and coarse aggregate used in today's construction market. Due to the high cost of regolith, simulants with comparable properties are used. The used simulant was sieved into individual sizes to be used in developing various mixes; and investigate the effect of regolith size on the concrete flowing ability and strength
3. Water-cementitious materials ratio (W/CM) are highly controlled to attain a mix suitable for use in space habitat construction

The afore-mentioned adjustments are made to develop a practical mix with minimal need to terrestrial materials. Sufficient mix flowing ability will be targeted to utilize the developed mix in 3-D printing applications. The effect of different regolith size on the final properties of the concrete produced is investigated. The main properties used for the evaluation of the concrete mix performance are:

1. Mix flowing ability for fresh mixed concrete
2. Compressive strength (fc') at 7 day, and
3. Compressive strength of the concrete mixes at 28 days

Literature Review

Micro and nano-sized particles are increasingly used in producing concrete mixes with superior characteristics in recent decades. The successful use of granular materials in concrete is highly dependent on materials chemical composition, material size, and gradation. Recent research investigations showed that the use of pozzolanic binders results in high early and final strength of concrete (Haber et al., 2018, Abbas et al., 2016). The step wise replacement of cement with micro and nano sized SCMs results in reduction in the global consumption of cement, which reduce the carbon footprint and positively impact the environment (Akhnoukh, 2018, Elia et al., 2018). The use of class c fly ash, micro-silica, and multi-wall carbon nanotubes halts the alkali-silica reactivity within hardened concrete, which reduce the rate of concrete cracking (Akhnoukh et al., 2016). In a recent study, concrete mixes were developed using a small percentage of lightweight aggregate particles as expanded shales and slates to provide internal curing for the hardened concrete mix. Thus, the potential of developing internal micro-sized cracks which negatively affect the performance of concrete is minimized (Akhnoukh, 2018, 2020).

Due to the active space exploration program launched by the United States National Aeronautics and Space Administration (NASA), multiple research programs started to investigate the possibility of constructing space habitats for the accommodation of astronauts and future space residents (Heemskerk et al., 2020). Current construction materials research focus on the possibility of using spatial resources in the construction process to build economic habitats. The possibility of using lunar in-situ materials including lunar regolith in constructing space-habitats was investigated, and human-habitat structure-size scale was produced using 3-D printing (Benaroya, 2018 and Bodifford et al., 2006). This developed NASA technology, known as Additive Construction using Mobile Emplacement (ACME), allows for the 3-D printing of human habitats, spatial infrastructure, and launching pads using local space resources, thereby tremendously reduce the logistics cost of construction (Mueller et al., 2017, Fiske et al., 2018, Edmunson et al., 2018). The ultimate objective of the NASA ACME project is to develop a shelter from space radiation and space conditions (see figure 1).

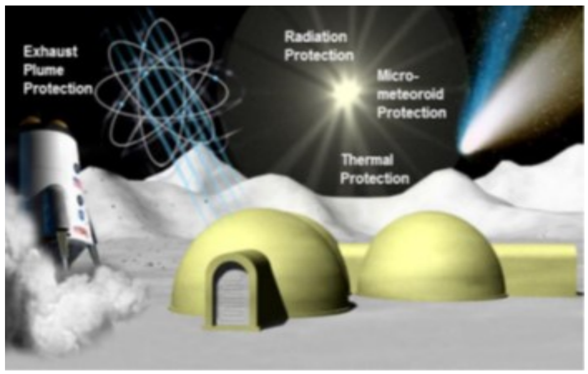

Figure 1. Sheltered habitat to be produced by NASA ACME Project (Mueller et al., 2017)

Additional research showed that any construction project on mars will be exposed to a highly oxidizing environment, thus construction materials used on mars should be capable of resisting oxidation to minimize maintenance requirements (Hecht et al., 2009). The possibility of using sulfur concrete in construction using contour crafting techniques was investigated. Several prototype structures were developed and tested for their structural performance in lab and analyzed using finite element simulations. The results of lab testing, and computer simulations showed that sulfur concrete could be successfully used in terrestrial and space applications using contour crafting techniques. The results of this research project provide a significant potential to the possibility of using 3-D printing technology in construction projects performed with space materials (Khoshnevis et al.,2016, Johnson et al., 1995).

Research Objectives

The main objective of this research proposal is to investigate the possibility of producing flowable concrete mixes using spatial construction materials to minimize the cost and time associated with material shipment to outer space. In specific, different sizes of lunar and martian regolith will be used in replacement of fine sand. Due to material availability and materials cost, regolith simulant is used in conducting this research project. The experimental investigation in this project is divided into two phases. Phase (I) includes the sieve analysis of the simulant to obtain individual sizes to be used in concrete mix development, and Phase (II) where concrete mixes are produced and poured in standard 2-inch cube specimens (see figure 2), to be tested in compressive strength at ages of 7 and 28 days.

Figure2. Mortar cubes poured for 7 and 28-days compressive strength testing

Experimental Investigation

Material Selection

Different materials are identified to be used in this research projects. Additional attention was given to materials with superior characteristics that may potentially increase concrete compressive strength, while reducing the final weight of the produced concrete (high strength to weight ratio is extremely beneficial for economic purposes). Space in-Situ aggregates are also tried as the sole aggregates in concrete manufacturing to minimize freight expenditure (see table 1).

Table 1

Materials used in concrete mix development

Material	Property
Portland Cement – Type I/II	Strength requirements meet Type I and composition meet requirement of type II as specified in ASTM C 150
Multi Wall Carbon Nano Tubes	It comprises particles of diameter up to 30 nm. Exceptionally large specific surface and high-water absorption
Stucco	Containing 25% of its weight cement
Lunar Simulant	With different particle size composition, as shown in the following section
Martian Simulant	With different particle size composition, as shown in the following section

Mix Design

Phase I

During phase I, lunar and martian simulant samples were analyzed using sieve analysis procedure. According to sieve analysis results, martian simulant was classified into 8 different sizes using sieve openings ranging from 4 opening per lineal inch (sieve designation 004) to 120 openings per lineal inch (sieve designation 120), while lunar simulant was classified into 5 different sizes using sieve openings ranging from 18 (sieve designation 018) openings per lineal inch to 230 openings per lineal inch (sieve designation 230) (see table 2).

Table 2

Sieve designations and particle size distribution

Mesh (Sieve Designation)	Nominal Sieve Opening (μm)	
	Martian Regolith (Simulant)	Lunar Regolith (Simulant)
004	5000	
005	4000	
010	2000	
018	1000	1000
035	500	500
060	250	250
120	125	125
230	63	63
000	Un-sieved	Un-sieved

Based on Phase (I) sieve analysis results 9 standard concrete mixes were poured for martian simulant including the 8 different simulant particle sizes and the general non-sieved simulant particle. Example of sieve analysis results for martian Regolith (see figure 3). Similarly, 6 standard concrete mixes were poured for lunar simulant including the 5 different simulant particle sizes, in addition to the general non-sieved lunar simulant.

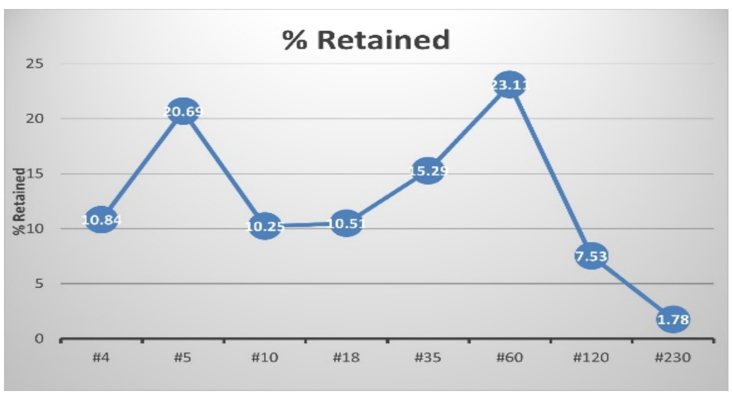

Figure 3. Percentage of martian regolith retained (by weight) on different sieve sizes

Phase II

The different simulant sizes obtained from Phase I were used in mixing 15 different standard concrete mixes to investigate the effect of simulant size on the compressive strength properties of the concrete. Concrete batches using martian and lunar simulant were produced by preblended dry granular materials including Type I/II portland cement, stucco, martian, or lunar simulant for 2 minutes. Once a homogeneous dry blended powder is attained, mixing water and chemicals are added to the mix for wet mixing. Average wet mixing procedure duration ranged from 3 to 5 minutes (until sufficient mix is attained). Flowing ability testing of developed mortar concrete mix is conducted to ensure that developed mix has developed enough flowing ability; and could potentially be used in future research for 3-D printing of concrete. An average diameter of 8 inch or more is acceptable for a flowable concrete mix (see figure 4). Each concrete mix was used to produce 6 2-inch cubes for testing in compression at 7 and 28 days of age. 3 cubes were tested in compression at each age.

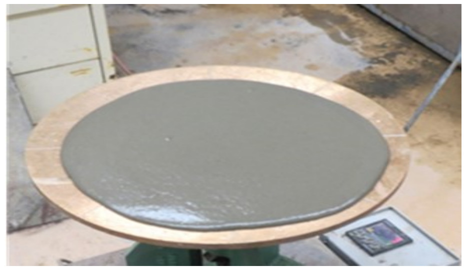

Figure 4. Flowing ability test of concrete using flow table

Experimental Results

Compressive Strength Test Results

The afore-mentioned lunar and martian Regolith sizes were used to produce concrete mixes for strength testing to investigate the effect of regolith particle size on the early and final strength of concrete. The research results showed that the incorporation of an individual size of regolith results in a higher compressive strength as compared to un-sieved regolith with different available particle sizes. Detailed results are shown in the following sub-sections.

Martian Regolith Samples Test Results

The martian regolith was used to produce 9 different concrete mixes. 8 mixes were produced using individual (sieved) regolith sizes. Two-inch cubes were poured and cured according to standard specifications. Specimens are tested in compression at age of 7 days and 28 days. A minimum of 3 specimens were tested at each age and average compressive at each age is recorded, As written (see table 3).

Table 3

Compressive strength test results of martian regolith mortar cubes

Size	Day 7	Day 28	% Increase
General	3311	3536	6.80
PTM004	2950	4673	58.41
PTM005	3067	5161	68.28
PTM010	3207	4739	47.77
PTM018	3094	4861	57.11
PTM035	3183	5168	62.36
PTM060	3717	4627	24.48
PTM120	4032	4979	23.49
PTM230	3472	4346	25.17

Concrete poured using individual martian regolith sizes displayed higher compressive strength at day 7 and 28. Regolith passing from sieves with opening dimensions of 4000 µm and 500 µm resulted in mortar mixes with optimum compressive strength. Regolith particles with extreme (large and small) sizes results in lower compressive strength. These results are comparable to using terrestrial aggregates. Usually, large particle sizes result in higher voids ratio and lowered strength, while smaller particles tend to absorb the water content and reduce the cement hydration process, which negatively impacts the final compressive strength of any concrete or mortar specimens. (see figure 5)

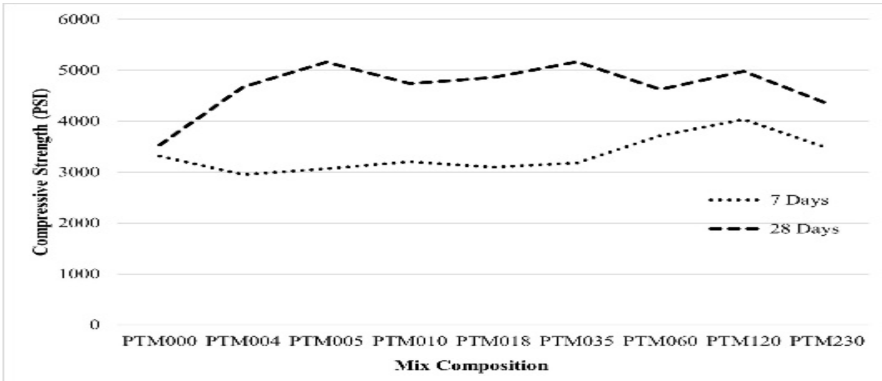

Figure 5. Martian regolith compressive strength test results

Lunar Regolith Samples Test Results

The Lunar Regolith was used to produce 6 different concrete mixes. Five mixes were produced using individual (sieved) Regolith sizes, and one mix used the as-is Regolith with no size separation. Results of cube compression testing at age of 7 days and 28 days As written (see table 4).

Table 4

Compressive strength test results of Lunar regolith mortar cubes

Size	Day 7	Day 28	% Increase
General	4031	5235	29.8
PTM018	2981	4097	37.4
PTM035	3587	4954	38.1
PTM060	3059	3796	24.1
PTM120	4035	5381	33.35
PTM230	4259	5387	26.48

The compressive strength test results for concrete mixes developed using lunar regolith has comparable results to mixes developed using martian regolith. Compressive strength test results of samples tested at age of 7 days (see figure 6). Similarly, compressive strength test results for samples tested at age of 28 days (see figure 7).

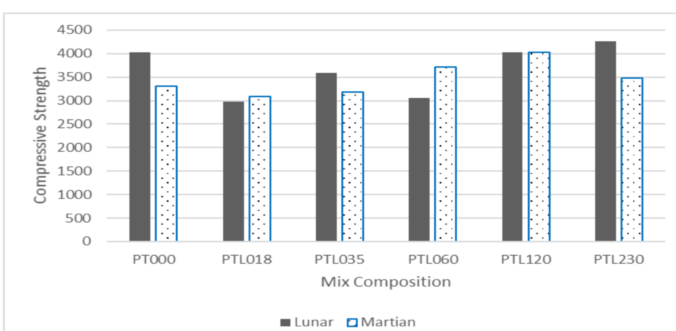

Figure 6. Compressive strength test results for martian and lunar regolith mixes at 7 days

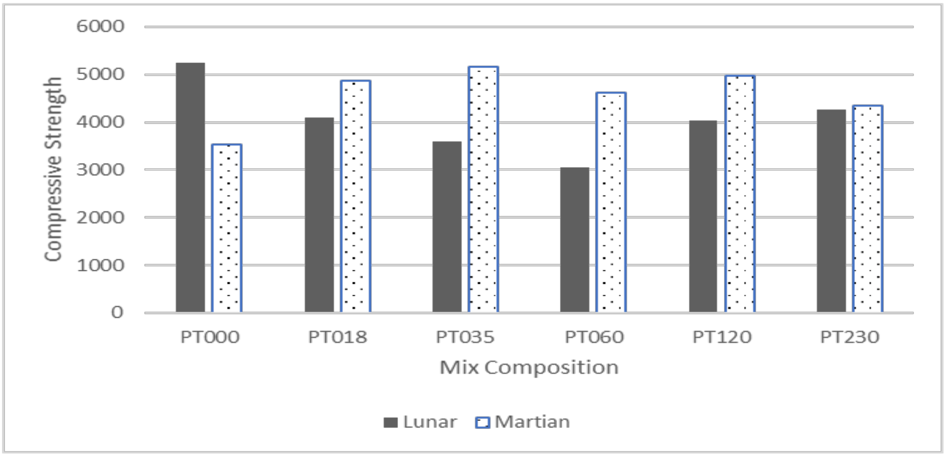

Figure 7. Compressive strength test results for martian and lunar regolith mixes at 28 days

Conclusion

This research investigated the possibility of using lunar and martian regolith in developing concrete mixes to be used in the construction of space habitats. Lunar and martian regolith were used in total replacement of concrete aggregates (sand and gravel) to minimize the need to ship terrestrial construction materials to outer space. Several mixes were developed using different sizes of regolith, and concrete mixes characteristics including mix flowing ability and compressive strength were tested. The outcomes of this research showed that both lunar and martian regolith could be used in producing flowable concrete with relatively high strength. Produced mixes could be potentially used in construction of economic space habitats using 3-D printing techniques.

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