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Investigating the Possibility of Using Smelted Water-Cooled Copper Slag Regolith as a Terrestrial Based Lunar Regolith Simulant

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Scott Morley is now at the Department of Geological Engineer, MT Technological University.

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ABSTRACT

There is a need for a stable, efficient, and cost-effective option of a terrestrial lunar regolith simulant that can be easily made and at a lower cost to the consumer. A lunar regolith is the layer of unconsolidated rocky material covering bedrock that is on planets. All simulants fabricated for the moon, are based off three types of lunar regolith areas. The first is the lunar highlands which are the high areas of the moon, these areas are anthracitic. The second is lunar mare which is the meteoroid bombarded areas of the moon that look like dark grey areas from earth, these areas are basaltic. The third is lunar dust and miscellaneous lunar regolith. While the amount of lunar regolith material that was brought back to Earth is, considered to be plentiful, with the new "space race," there is not enough material to share with individual companies to evaluate the new equipment that is being built to study the planets in our universe. Today all simulants are created by using the duplicated characteristics of the lunar materials brought back from the moon. There are different regolith simulants that are made for different planets like Mars and Venus. Having a common test site or a site where simulant is already in place and that meets the standards of the lunar regolith that returned to Earth. Thereby allowing companies to bring their new equipment and machinery to evaluate on site, this would be more efficient and cost effective than what is currently offered. In this study a new potential material was examined to be used as lunar regolith simulant. Laboratory tests were conducted to investigate whether using a water-cooled copper slag is a practical alternative for a terrestrial based lunar regolith simulant compared to what is currently being offered in the scientific community and private sector. This study showed that using the water-cooled copper slag is possible according to the data found vs the data standards given by NASA. Using USCS the classification of the water-cooled slag would be GW (gravel well sorted) while classified by AASHTO it is, A-1-a (Granular materials are 35% or less total sample passing No. 200. The relative soil density testing shows that the sample to vary from loose to very dense, the guidelines were medium to dense to very dense. Bulk density showed the data to be right in the middle of the standards given. Specific mass of solids testing determined the specific mass of solids were a little higher than the guidelines, but the number is < 0.1. Deciding unit weight had to be completed using the gravity of earth first then reconfigured to the moon gravity which is 1/6 that of earth the data was within standards. Cohesion testing determined data is .99 kPa and the NASA standards require 0.1 to 1 kPa. Friction angle testing was measured to be 48º the lunar regolith standard measures at 30º to 50º. The ultimate bearing capacity which is the amount of weight the soil can hold before failure the standard is 25 – 55 kPa testing shows the copper slag to be at the following: Continuous (15 kPa) like a small structure, Square (46 kPa) a landing pad, and Circular (45 kPa) the landing gear of shuttles. NASA requires 25–55 kPa, and the intercrater areas to be < 25 kPa the data was found using Terzaghi bearing capacity formulas. Permeability testing data showed that the water flowed freely after soaking the sample.

INTRODUCTION

During the years 1969 – 1972 the National Aeronautics and Space Administration (NASA 2022) conducted six lunar landings. One important goal of these missions was, to observe the properties of the regolith. During the regolith observation, they were asked to assess how these properties affected the crew's ability to move and work on the surface of the moon (Institute, 2019).

The investigation, known as the Soil Mechanics Survey, included employee descriptions and regolith photographs (Institute, 2019); During the manned flights to the lunar surface, the missions returned to earth with approximately 900 pounds of lunar rock, core samples, pebbles, sand, and dust from the surface of the moon (Institute, 2019). From these space mission scientists gained new perspectives on the makeup and materials of lunar soils.

While the regolith of Earth is unique, there is oxygen, wind, water, and activities of life to consider. On the moon the lack of these influences; oxygen, wind, and water create a completely different regolith (David S. McKay, 1991). Having been bombarded for billions of years by meteoroids the fresh bedrock that gets exposed begins to be destroyed immediately (David S. McKay, 1991).

Since beginning the study and exploration of space observers have noted that over the course of the moon’s existence it has been bombarded with countless meteoroids, this has caused any bedrock to be covered by broken, melted, and altered debris. It is recognized that the utmost top layer of soil is referred to as the lunar regolith (David S. McKay, 1991).

The makeup of the soils and minerals of the lunar regolith are Basaltic and Anthracitic materials. As meteorite events occur the impacts have created a constant upheaval of the regolith and therefore mixing the soils and minerals over large areas of the moon. This mixing has also produced a significant amount of fragmentation, melting, and glass formation (L. Sibille, 2006). Therefore, it can be possible to create a terrestrial based simulant matched to the materials of the lunar regolith manufactured by using what is available on Earth and duplicating the characteristics of the target lunar materials.

All simulants fabricated for the moon, are based off three types of lunar regolith areas. The first is the lunar highlands which are the high areas of the moon, these areas are anthracitic. The second is lunar mare which is the meteoroid bombarded areas of the moon that look like dark grey areas from earth, these areas are basaltic. The third is lunar dust and miscellaneous lunar regolith.

While the amount of lunar regolith material that returned to Earth is plentiful, there is not enough material to share with individual companies to assess the new space equipment built on Earth to study the planets in our universe.

There is a need for a stable, efficient, and cost-effective way of a terrestrial lunar regolith simulant that can be easily available and that is not expensive to reproduce. Today all simulants created by using the duplicated characteristics of the lunar materials exclusively for each planet in the universe. Having a common test site with the lunar regolith simulant in one location that meets the standards of the lunar regolith that returned to Earth and studied by NASA allows companies to bring their new equipment and machinery to test would be more efficient and cost effective.

The materials ship to one central location where all the collected materials create one specific formula made to specifications of the client. This finished lunar simulant product is then shipped to the client.

The main rock formation in and around Butte Montana is the largest single pluton in the Late Cretaceous Boulder Batholith. This granite has been hydrothermally altered and mineralized by a complex sequence of porphyry-style pyroxene. Early mineralization included the emplacement of two large domes of low-grade Cu-Mo veins (Kaplan, 2016).

The porphyry-style mineralization was superseded by multiple generations of extraordinarily rich, polymetallic veins and lodes. Mining in Butte Montana started in 1864 with the finding of silver (Ag). Soon the discovery of copper (Cu), gold (Au), manganese (Mn), zinc (Zn), and lead (Pb) created the need for a larger smelter (Karen Lund, 2002).

Local history talks about Marcus Daly receiving credit for creating the largest free standing brick smelter in the world, the brick-and-mortar smelter built during the late 19th and early 20th century was a marvel for its time. Marcus Daly built the smelter at a new location where he created not only the smelter but the town of Anaconda Montana which is approximately twenty-five miles away from the mines in Butte. Because of this distance Marcus Daly founded a railroad company to transport the minerals from his mine the Anaconda, to the smelter.

Once the smelter started production, it used an air blown water-cooled process that created a glassy, granulated slag that resembles a black sand (Kaplan 2016).

As you enter the township of Anaconda Montana from I-90 there is one visible large slag pile on the left. This location is 168 acres covered with approximately 41.3 million tons of granular slag. The makeup of this slag is mostly iron (Fe), calcium (Ca), and silicon (Si) with silicates that are in the olivine and pyroxene groups (Kaplan, 2016). Glass, and magnetite are found to be the most abundant solid phases that are found within the slag (Kaplan, 2016).

Magnetite (Fe_3O_4) is found throughout the slag as the slag itself has magnetic properties. The olivine and pyroxenes that are found in the slag material are rich in metal impurities. These impurities include copper (Cu), zinc (Zn), and manganese (Mn) (Kaplan, 2016). There are sulfides and other metallic compounds found within the slag. The main sulfides are bornite (Cu_5FeS_4) and chalcocite (Cu_2S). There is also chalcopyrite ($CuFeS_2$), sphalerite (Zn, Fe)S, galena (PbS), and pyrrhotite Fe(1-x)S found in the slag (Kaplan, 2016).

The purpose of this study is to decide the feasibility of using water-cooled copper slag to be repurposed as a lunar regolith simulant as per the standards set by NASA. Water-cooled copper slag is found at, and near copper smelters around the world wherever copper is produced. This mineral rich slag is considered a waste product and carries a potential environmental hazard.

MATERIAL

Water-Cooled Copper slag

The process of smelting copper ore separates the ore from waste material. This final waste product slag has separated from the valuable ore. Non-ferrous slag, like the copper and gold ore that originated from Butte and smelted in Anaconda removes iron and silica from the original material. Viscous slag poured from large metal buckets, at which time the slag rapidly cooled with a jet of water that formed the glassy, and granulated product, which resembles the black sand that we see in Anaconda.

The granule sizes are created by the copper slag being water-cooled instantly as it passes through the smelting process. As the material continues to cool it is loaded into the back of a dump truck and dumped off-site of the smelter.

Once dumped the material undergoes the same processes that terrestrial soil does. Through the addition of oxygen, water, and wind the material slowly breaks down. This takes the original granules and breaks them down to a fine powder. Figure 1 shows molten copper being dumped at night.

Figure 1: Molten slag being dumped by railway **Modified from (CBC NEWS, 2015)**

With slag considered human made the metallic elements massively exceed the normal concentrations in the natural environment. The main rock type in the Butte mining district is Butte Granite, which is the largest single pluton in the Late Cretaceous Boulder Batholith. The rock was historically referred to as the Butte Quartz Monzonite, and was reclassified as granite by the U.S. Geological Survey (Kaplan, 2016; Karen Lund, 2002) there will be higher than average levels of metals, such as iron (Fe), manganese (Mn), copper (Cu), zinc (Zn), lead (Pb), cadmium (Cd), and arsenic (As) (Kaplan, 2016). The granite in Butte has been hydrothermally altered and mineralized by a complex sequence of porphyry-style ore bodies, veins, and lodes (Weed, 1912; Meyer et al., 1968). Early mineralization included the emplacement of two large domes of low-grade Cu-Mo veins. The porphyry-style mineralization was superseded by multiple generations of very rich, polymetallic veins and lodes, referred to as the Main Stage (Kaplan, 2016).

METHODS

To determine that the proper testing was conducted properly, the following table 1 shows each test conducted as per the standards listed in ASTM.

Table 1: Shows ASTM next to test conducted for study

TEST	**ASTM**
Grain Size Distribution	D6913-04 (2009)
Sieve Analysis	E11-20
Compaction	D1557-07
Shear Strength	D3080-04
Compaction	D3080 / D3080M
Friction Angle	D3080 / D3080M
Relative Soil Density	D4254-16
Bulk Density	D1556-07
Specific Mass of Solids/ Specific Gravity	D854-14
Unit Weight	D7263-21
Ultimate Bearing Capacity	D1194-94
Permeability	D2434
XRF	E1621-21
XRD analyzer	E1621-21

Anaconda Mt is on an alluvial deposit where the rocks of Precambrian, Cambrian, Mississippian, Pennsylvanian, Cretaceous, Tertiary, and Quaternary age are exposed (Wanek, 1966). There are units of Cambrian, Devonian, Permian, Jurassic, and Cretaceous age present in the subsurface but are missing at the surface because of faulting (Wanek, 1966). Coal beds are found in the volcanic breccia and red bed member, which is the youngest unit of the Lowland Creek Volcanics, and in the overlying conglomerate unit (Wanek, 1966). These coal beds can be seen visually along the walking trail going towards the old smelter. Glacial moraine deposits are found inside Lost Creek State Park. Colluvium and landslide deposits occur along steep slopes above the valleys, and alluvium and terrace gravel are along stream channels (Wanek, 1966).

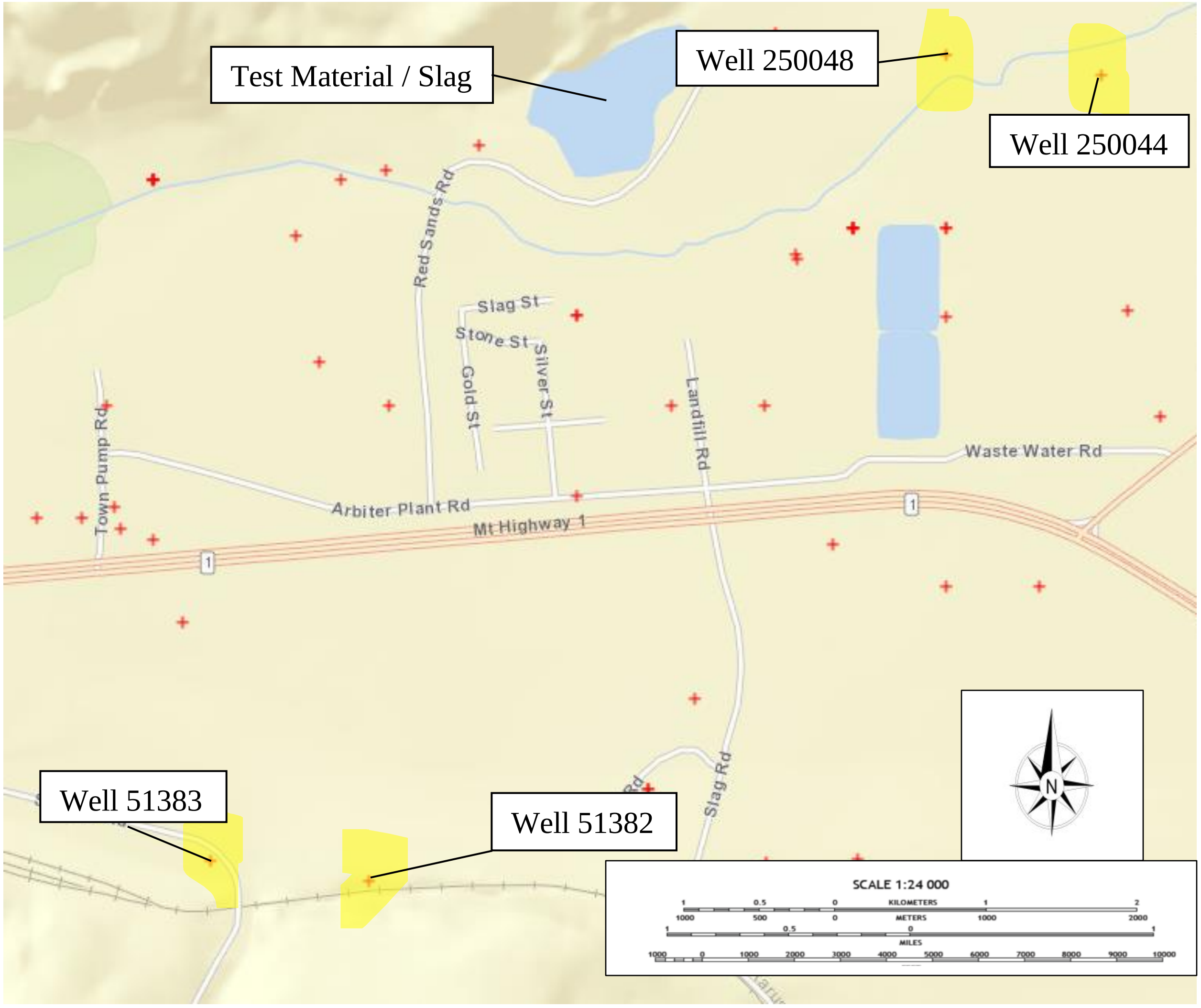
Looking at the data it was noted that tests for the wells are below the toxic to human limit as per the EPA (Agency, 2022). While the metals are high this is to be expected considering the area has been home to a copper smelter for almost 100 years.

Since the closing of the Anaconda Smelter there have been monitoring wells put throughout the valley to ensure the water does not become toxic or harmful to humans or the local wildlife.

Using the four GWIC (Ground Water Information Center) wells listed below in table 2, and the map of figure 2, the wells closer to the smelter identified with an (S) have higher concentrations of minerals harmful to humans and animals. It can also be seen that by the time the water in the aquifer reaches the creek identified with a (C), all four minerals are well beneath the water standards listed. There is a rise in the data for Cadmium, but this can be caused by the slag on the other side of the creek where the original first smelter was located.

Table 2: Well data showing the 4 elements that were above standards by the Smelter and how the minerals came into drinking water standards as the water reached the last well

GWIC ID	**Sulfate (SO_4)**	**Arsenic (As)**	**Cadmium (Cd)**	**Uranium (U)**
Water Std.	250 mg/L [smcl]	10 mg/L [mcl]	5 ug/L [mcl]	30 ug/L
51382 (S)	826.7 mg/L	1,216.5 ug/L	64.3 ug/L	49.6 ug/L
51383 (S)	352.8 mg/L	1,103.6 ug/L	<0.250U ug/L	12.0 ug/L
250048 (C)	42.3 mg/L	0.360 ug/l	3.23 ug/L	NR ug/L
250044 (C)	16.0 mg/L	0.650 ug/L	<0.100U ug/L	NR ug/L



Modified from (DEQ, 2022)

Figure 2: Map showing where monitoring wells are located that may affect the testing area. This figure is showing the location of four wells marked by GWIC Identification number and yellow highlights.

Below in figure 3, (image 1) it shows the water-cooled slag up close, and in (image 2) shows the slag in a cylinder after testing. These pictures are used to give a visual of the scale of the small particulates that make up the sample. Notice the glassy appearance of the sample in image 1 and the sandy appearance of image 2.

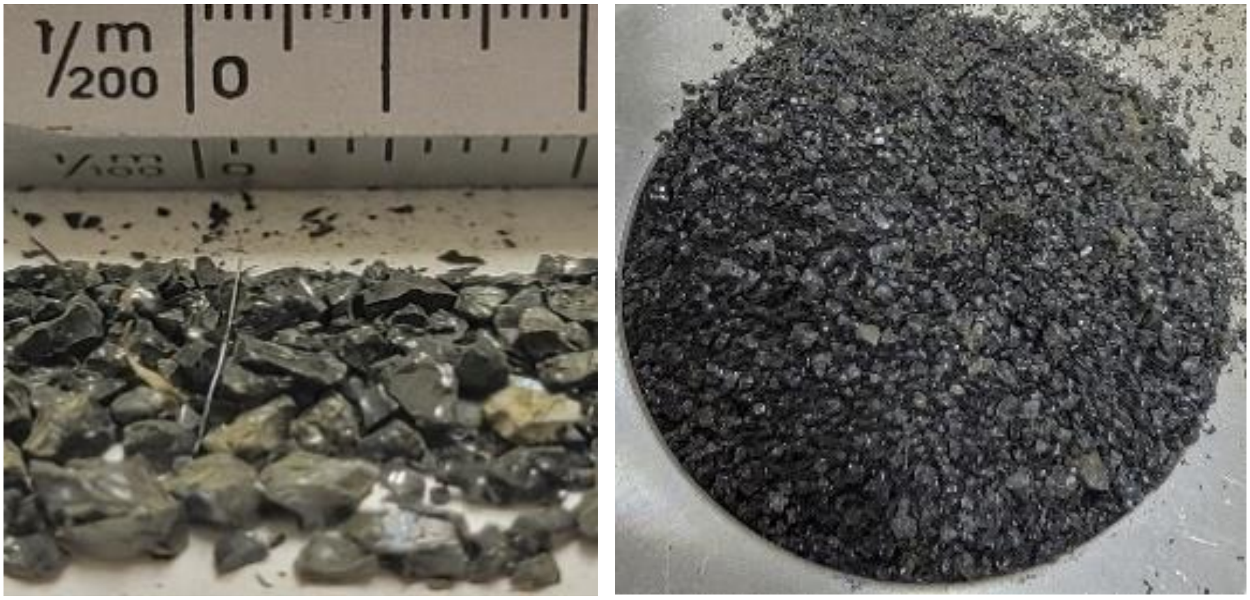


Figure 3: 1, Shows closeup of slag particles next to a 1/200 m (5.00 mm) ruler. Sizes range from below measurement to a larger 1 mm of amorphous material. 2, shows slag particles in a cylinder immediately after shear test.

When reviewing the findings of the Olympus TERRA portable XRD Analyzer in Figure 3 listed below, the findings showed the sample was mostly amorphous with tiny amounts of Fayalite and Hedenbergite showing in the largest spikes. Fayalite (Fe_2SiO_4) is the iron-rich end member of olivine solid. Hedenbergite ($CaFeSi_2O_6$) is the iron-rich end member of the pyroxene solid.

Figure 4: Using the Olympus TERRA Portable XRD analyzer to get a more precise determination of minerals in the sample. The sample used was approximately 15 mg.

While finding the specific gravity the study used a 500 mL bottle with distilled water, the bottle was filled to the line of the concave meniscus. Shown below in figure 5 (image 1) The study used 150 g of sample for each test conducted as seen in (image 2) and used a thermometer to get water temperature. The researcher ran three tests and averaged the data.

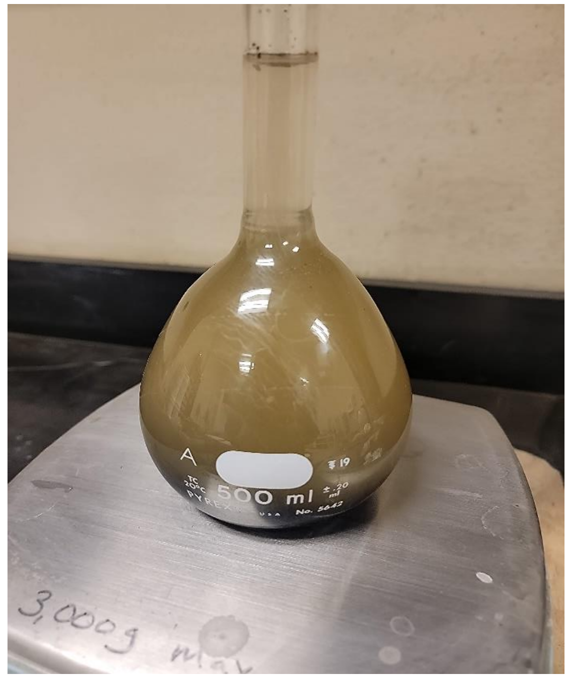


Figure 5: figure 3a shows a 500mL bottle clear, figure 3b shows same 500 mL bottle with 1500 g of sample

Figure 6, images 1 and 2 show the bulk density testing equipment and the equipment for the permeability test. The bulk density cylinders were used to find both the loose and the compacted weight of the sample soil. The permeability equipment is used to find how well the water flows through the material.

Figure 6: 1 shows the cylinders for bulk density testing, 2 shows the permeability testing

Getting the soil prepped for sieve analysis testing shown in figure 7 below, in image 1 the researcher is separating the soil 3 times to ensure a well and proper mix of all sizes of soil. Image 2 shows the samples in tins of 300g each, in image 3 the sieves are set up for vibration and separating the sizes of soils.

Figure 7: Preparing water-cooled slag for sieve testing. Sieves used per ASTM guidelines.

Figure 8shown below, shows the shearSCAN Pro, stress and shear strain testing equipment, it also shows two of the three tests that were conducted. The samples have similar shearing properties both visually and graphically.

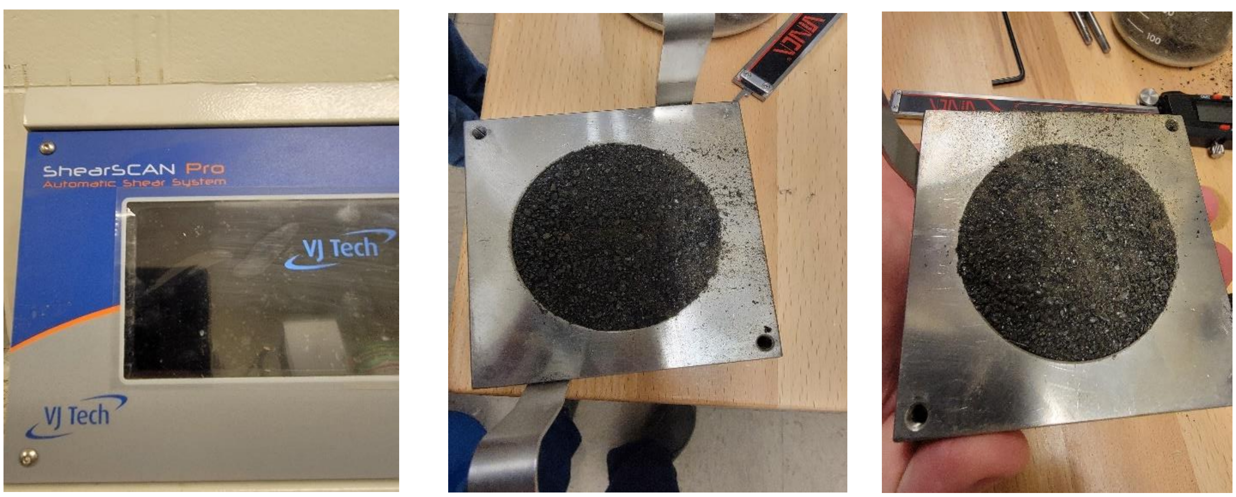


Figure 8: Shows shearSCAN Pro, and two samples that a shear test was conducted on

RESULTS AND DISCUSSION

Listed below in table 3 are the list of tests required for the standards given by NASA (Lunar Regolith) and the results of the testing (Water-Cooled Slag).

- Relative soil density: testing shows at 15 cm to be (loose) soil, 45 cm is (dense) while at 140 cm is (very dense). NASA standards are 15-cm depth (medium to dense), below 30-cm depth (very dense)
- Bulk density: is 1.79 g/cm^3 – 2.00 g/cm^3. NASA standards 1.4 g/cm^3 – 2.2 g/cm^3 which for our testing shows a granulated sand looking at figure 6 the cylinders used are shown
- Specific mass of solids / *Specific Gravity*: testing determined found the specific mass of solids measures 3.40 g/cm^3. NASA guidelines have concluded that a max of 3.32 g/cm^3 is standard. This test can be seen in the earlier figure 5
- Unit weight: is 2.9 kN/m^3 – 3.2 kN/m^3 at (1/6 g) and the NASA standard is 2.9 kN/m^3 – 3.6 kN/m^3 at (1/6 g). At (1/6 gravity) or the gravity of the moon, testing showed that the data matches the findings of NASA
- Cohesion: testing determined data is .99 kPa and the NASA standards require 0.1 to 1 kPa see the graph on figure 9 below
- Friction angle: testing was measured to be 48º the lunar regolith measures at 30º to 50º
- Ultimate bearing capacity: the standard is 25 – 55 kPa testing shows the copper slag to be at the following: Continuous (15 kPa), Square (46 kPa), and Circular (45 kPa). Standards NASA requires is 25–55 kPa, and the intercrater areas to be < 25 kPa (Terzaghi Formula)
- Allowable bearing capacity: test was not completed as it is not pertinent to this study
- Permeability: testing data showed the copper slag at (1.57 x 10^{-2} cm/s) while the standard (1.65 x 10^{-3} cm/s) as seen in figure 6 above

Table 3 lists the mechanical properties of the lunar regolith according to the "Lunar Regolith Simulant Materials: Recommendations for Standardization, Production, and Usage" workshop (L. Sibille, 2006). As well as the test results for the Water-Cooled Slag.

Table 3: Lists the values of the recommendations for standardization, production, and usage of a lunar regolith simulant paper during a conference for NASA and the findings of the properties of the water-cooled copper slag used in this study.

Geotechnical Index Property	**Lunar Regolith**	**Water-Cooled Slag**
Relative soil density	15-cm depth (medium to dense), below 30-cm depth (very dense)	15 cm = (21 g/cm^2), 45 cm = (93 g/cm^2), 140 cm = (401 g/cm^2)
Bulk density, ρ	1.4–2.2 g/cm^3	(1.79 g/cm^3 - 2.00 g/cm^3)
Specific mass of solids, ρs	> 3.32 g/cm^3, Basalt particles 1 to > 3.32 g/cm^3, Agglutinate/glass 2.9 to 3.1 g/cm^3, Breccia	(3.4 g/cm^3)
Unit weight, γ	2.9–3.6 kN/m3^ (at 1/6g)	17.6 kN/m^3 – 19.6 kn/m^3 (at 1g) 2.9 kN/m^3 – 3.2 kN/m^3 (at 1/6g)
Cohesion, c	0.1 to 1 kPa	(0.99 kPa)
Friction angle, φ	30° to 50°	(48º)
Ultimate bearing capacity, q*ul*	25–55 kPa, intercrater areas < 25 kPa	Con (15 kPa), Sq (46 kPa), Cir (45 kPa)
Allowable bearing capacity, q*all*	8 kPa (1-cm acceptable settlement depth) 0.2 psi recommended	N/A for this study
Permeability, K	1-7 x 10^{-12} m^2 (1.65x10^{-3} cm/s)	(1.57 x 10^{-2} cm/s)

Modified from (L. Sibille 2006)

The moon is home to a large variety of mineral elements, this can be attributed to the formation of the moon and the fact that it has been bombarded for millions of years with meteorites. Showing in table 4 below is a list of mineral elements that are found to be on the moon from the Apollo missions next to the copper slag mineral elements that were identified by the XRF during research. To the left on table 4 is where in Montana each of the mineral elements can be found in Montana for the lunar regolith simulant.

Table 4: Elements that are found in the lunar soil, XRF reading conducted from water-cooled copper slag pile in Anaconda and where in Montana the elements can be found by location

Lunar Mineral Elements found on Moon	Slag Mineral Elements identified by XRF	Mineral Elements found by Location
Strontium (Sr)	Strontium (Sr)	Anaconda MT / Butte MT
Silicon (Si)	Silicon (Si)	Anaconda MT / Butte MT
Aluminum (Al)	Aluminum (Al)	Anaconda MT / Butte MT
Calcium (Ca)	Calcium (Ca)	Anaconda MT / Butte MT
Iron (Fe)	Iron (Fe)	Anaconda MT / Butte MT
Magnesium (Mg)	Magnesium (Mg)	Anaconda MT / Butte MT
Titanium (Ti)	Titanium (Ti)	Anaconda MT / Butte MT
Potassium (K)	Potassium (K)	Anaconda MT / Butte MT
Chromium (Cr)	Chromium (Cr)	Anaconda MT / Butte MT
Zirconium (Zr)	Zirconium (Zr)	Anaconda MT / Butte MT
Nickel (Ni)	Nickel (Ni)	Anaconda MT / Butte MT
Oxygen (O)	Oxygen (O)	Anaconda MT / Butte MT
Cobalt (Co)	*	Stillwater MT
Manganese (Mn)	*	Butte MT
Sodium (Na)	*	Common Element
Phosphorus (P)	*	Philipsburg MT

Modified from (Korotev, 2022)

To determine the grain size distribution of the slag, five sieve tests were conducted. Table 5 shows the results of one of the tests as an example.

In table 5 listed below it was found that this soil should be classified using USCS as GW (gravel well sorted) classified by AASHTO it is, A-1-a (Granular materials are 35% or less total sample passing No. 200.

Table 5: Sieve analysis of sample material, this sample is the 1st of 5 sample sieves. All 5 tests are similar in sizes of fines percent passing.

Sieve No	Sieve Size (mm)	Sieve Weight (grams)	Cumulative Weight Retained (grams)	Soil Retained (grams)	Cumulative Wt. Retained (gm)	Mass Retained	Fines % Passing
3/8”	9.5	545.5	545.5	0	0.0	0.0	100.0
4	4.75	500.5	504	3.5	3.5	1.2	98.8
10	2	399	579	180	183.5	61.1	38.9
20	0.85	390	460	70	253.5	84.4	15.6
40	0.425	293	318	25	278.5	92.7	7.3
60	0.25	266	278	12	290.5	96.7	3.3
100	0.15	330.5	337.5	7	297.5	99.0	1.0
140	0.106	329	330.5	1.5	299.0	99.5	0.5
200	0.0075	329	329.5	0.5	299.5	99.7	0.3
Pan	0.0001	361.5	362.5	1	300.5	100.0	0.0
TOTAL				**300.5**	601.0		
% Gravel	1.2		**D60 (mm)**	3.0		**Cu= D60/D10**	5.3
% Sand	98.5		**D30 (mm)**	1.6		**Cc= D30^2/D10*D60**	1.5
% Fine	0.3		**D10 (mm)**	0.6			

Below in figure 9, is a visual representation of the sieve tests fine percent passing the tests were all similar in the amount and the size of the gravely sand and fines that were recovered from the sieves after testing concluded.

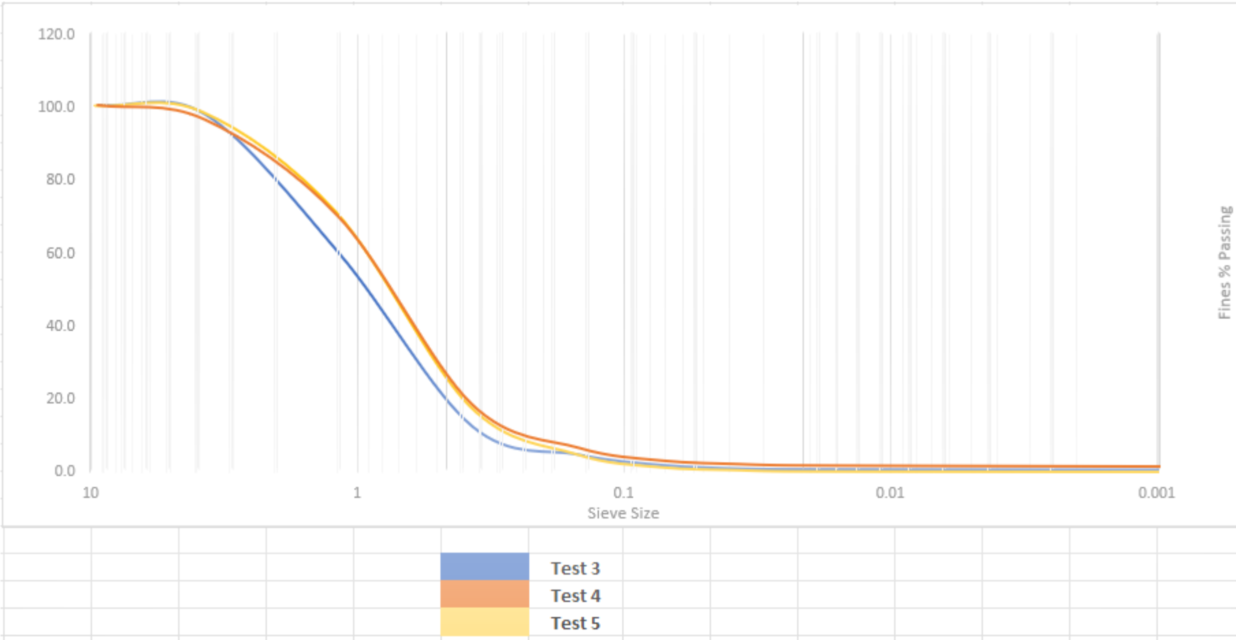


Figure 9: Sieve analysis fines percent passing, three tests are overlapped to show the similarities in passing sizes.

Figure 10 which is listed below shows the friction angle and the cohesion of the copper slag. These numbers were used to find the strength properties of the lunar regolith simulant. These numbers show the soil to be a GW (gravel-well graded).

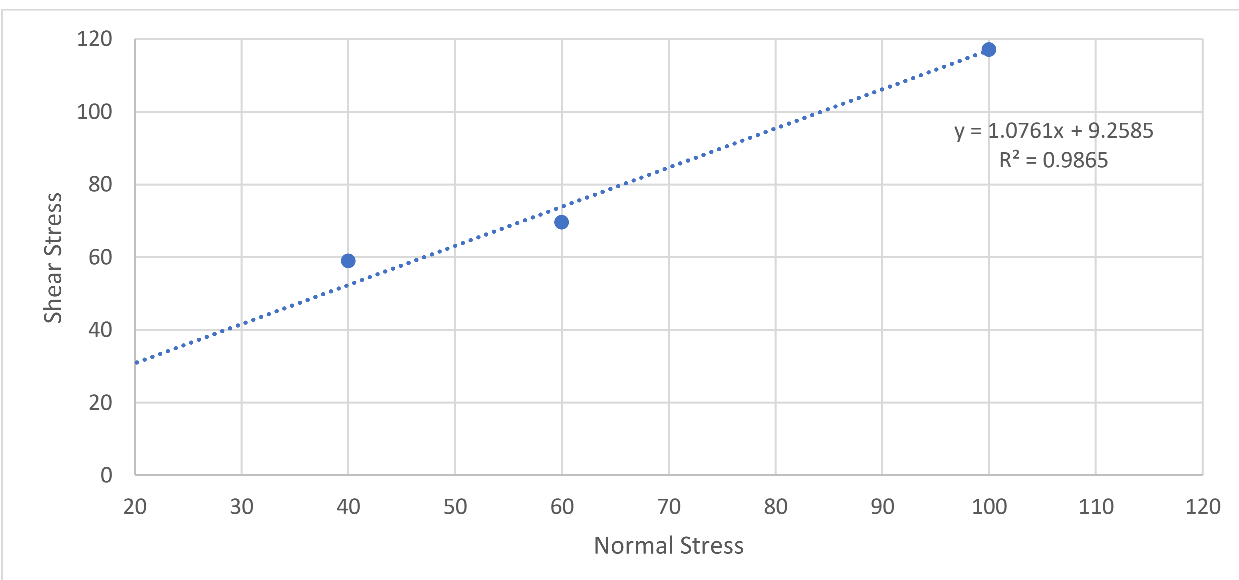


Figure 10: Max shear graph trendline showing the friction angle at 47.8º and the cohesion is 9.25 kPa

Looking at figure 11 below, it can be noted that all three tests started consolidation at approximately the nineteen second mark. As for the vertical displacement all three tests show displacement beginning at approximately the 0.0029 mark, the 0.0037 mark, and the 0.0046 mark.

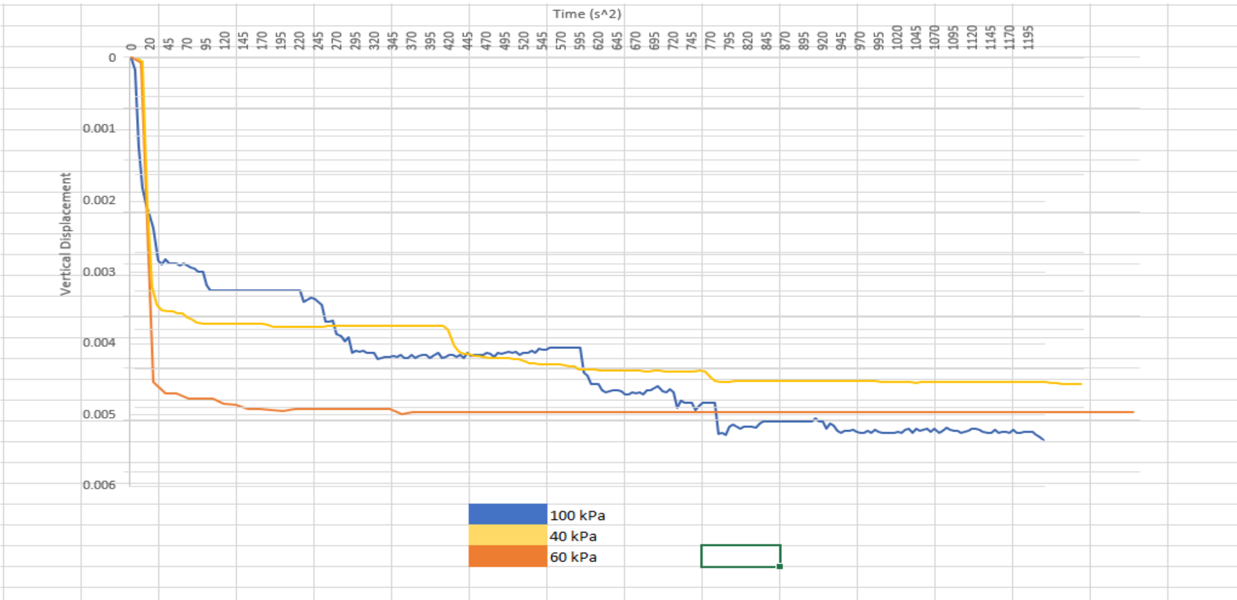


Figure 11: Consolidation phase before the shear test, this figure is at 100 kPa, tests were done using 40 kPa, 60 kPa, and 100 kPa. This figure was chosen as all tests were relatively similar in consolidation when overlapping the data onto one graph.

The shear strain showing in figure 12 below show all three of the shear strain tests at 40 kPa, 60 kPa, and 100 kPa all begin straightening out at the 4.3 mark. For the shear stress the 40kPa begins earlier at 30 while the 60 kPa, and 100 kPa begin stress at about the 60 mark.

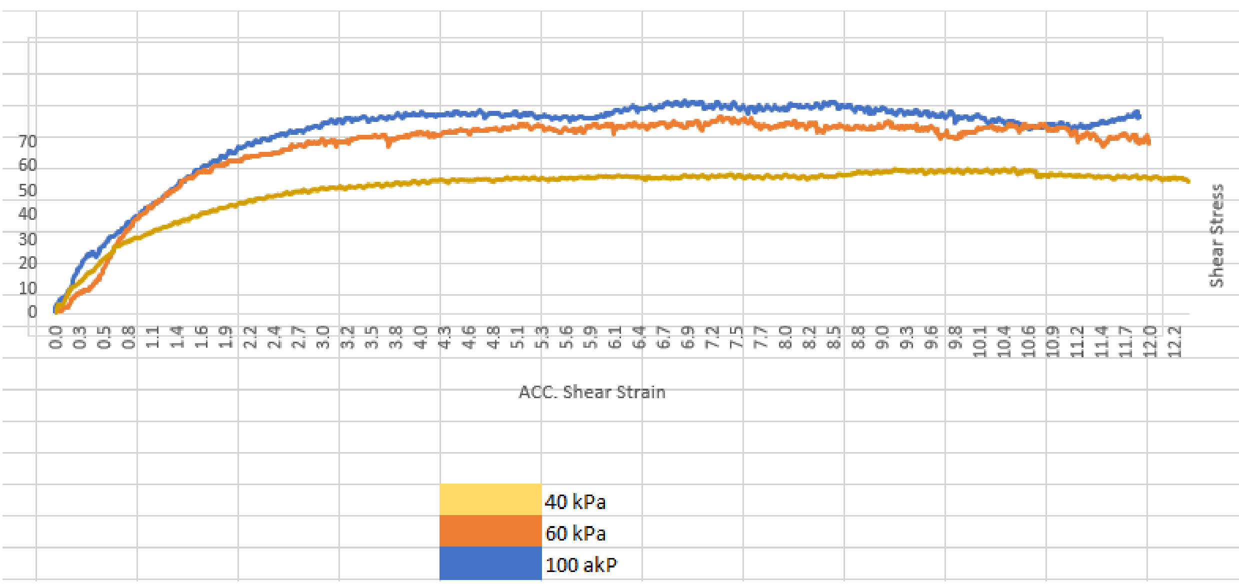


Figure 12: Shear stress vs shear strain testing, all tests were relatively similar in where the stress and strain occurred at the 40 kPa, 60 kPa, and 100 kPa marks.

CONCLUSION

Investigation into the possibility of using a water-cooled copper slag to create a lunar regolith simulant has yielded promising results. This study shows that using the water-cooled copper slag is not only possible but probable according to the data found vs the data standards given by NASA. As shown above, the standards have all been met to be within the guidelines suggested and approved by NASA.

Concerning the possible environmental impact of the copper slag, what the evidence from the well data shows to be the largest concern is the four main heavy mineral elements, Sulfate (SO_4), Arsenic (As), Cadmium (Cd), and Uranium (U) in the slag that can leach through the soil into the aquifer. Looking at the well logs it appears that this is not a problem as the samples get lower numbers as the water travels further east. A possible issue is the Arsenic (As) content through the dust. It is considered harmful to humans and animals, though this can be mitigated by the proper PPE and other protections for dust control; the water ways would not be affected per the DNRC records of well testing so neither issue should be an environment concern. Having an environmental engineering company verify these findings would be best before a project continued.

Using USCS the classification of the water-cooled slag would be GW (gravel well sorted) while classified by AASHTO it is, A-1-a (Granular materials are 35% or less total sample passing No. 200. The relative soil density testing shows that the sample to vary from loose to very dense, the guidelines were medium to dense to very dense. Bulk density showed the data to be right in the middle of the standards given. Specific mass of solids testing determined the specific mass of solids were a little higher than the guidelines, but the number is < 0.1. Finding unit weight had to be completed using the gravity of earth first then reconfigured to the moon gravity which is 1/6 that of earth the data was within standards. Cohesion testing determined data is .99 kPa and the NASA standards require 0.1 to 1 kPa. Friction angle testing was measured to be 48º the lunar regolith standard measures at 30º to 50º. The ultimate bearing capacity which is the amount of weight the soil can hold before failure the standard is 25 – 55 kPa testing shows the copper slag to be at the following: Continuous (15 kPa) like a small structure, Square (46 kPa) a landing pad, and Circular (45 kPa) the landing gear of shuttles. NASA requires 25–55 kPa, and the intercrater areas to be < 25 kPa the data was found using Terzaghi bearing capacity formulas. Permeability testing data showed that the water flowed freely after soaking the sample.

The economics of selling the slag to lunar regolith simulant users has a plethora of benefits. This action would clean up the waste copper slag from the areas and create jobs and a monetary income for the residents of the affected locations. If instead of selling the slag and shipping is not practical, then building a testing facility on and around the water-cooled copper slag pile could be another option. This kind of facility would bring in the companies that are creating items to survive and work in space. Space mining is currently in its infancy yet there are already remote-controlled mining vehicles. These could be evaluated in a real-world simulation. Smaller rovers and personal equipment could also be evaluated in this environment. Again, this would create a monetary income for the residences of the areas affected by slag.

While researching the cost of copper slag there was a large discrepancy in price depending on usage and how well the company cleaned the material. Economic value of slag is $330 per ton - $3500 per ton depending on usage and how “clean” the material is. Having a sand and gravel set up would make the most sense in running and selling the slag. Keeping the price on the high end of $3500 there are approximately 41.3 million tons of material this equals $144,550,000,000.00 if the project chose to ship the material. The possible money to be earned and the ease of making the simulant make this study possible as hypothesized.

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