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Establishing Standards for Lunar ISRU Structural Materials

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Lunar structures will be exposed to one of the most extreme environments that has ever been considered for human settlements. In situ, regolith-based materials are being proposed for construction on the Moon, offering the benefit of reducing the cost of transporting large amounts of materials or prefabricated elements, and relying on the ability to transport mainly the equipment needed to construct landing pads, shelters, blast shields, habitats, roadways, etc. However, the properties of materials that are made, all or in part, from indigenous Lunar resources are likely to change based on the make-up of the material, the location where it was taken from, the production processes, and time. No standards or building codes exist for design and construction of infrastructure on the Moon. Engineers will need dependable information about these materials before any design can be completed. Hard-won lessons from centuries of using similar resources on Earth need to be leveraged to develop best procedures that will be critical for testing such materials for structural applications. Here we discuss the technical challenges in establishing such standards. Using the timely example of a landing pad on the Moon, we identify the gaps in both knowledge and testing capabilities that exist today.

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I. Introduction

There is a mounting interest in building infrastructure that will serve human settlements on the Moon. NASA provides a description of plans for such endeavor and highlights specific objectives and an associated process to realize a path for establishing a sustained human presence on the Moon, and subsequently, to reach Mars [1–3]. Plans for establishing an infrastructure on the Moon involve the widespread use of indigenous resources, known as in-situ resource utilization (ISRU), to manufacture the building materials to be used. NASA's Moon to Mars strategy calls for the initial development of reusable launch and landing pads made with ISRU materials [4, 5], to be followed by the construction of pressurized surface habitats that are intended to support robust exploration and reliable operation, and to allow crew to live for extended durations.

While this path offers numerous opportunities to reduce the amount of resources that must be transported to the Moon from Earth, the Lunar surface is a unique and especially challenging environment for human habitation [6–8]. The broad range of environmental conditions anticipated include large temperature fluctuations that result on the Lunar surface due to solar cycles, sustained radiation that is ubiquitous beyond Earth's atmosphere, and hard vacuum. In addition to the expected damage induced by radiation, dust and chemicals brought from Earth will come in contact with infrastructure materials and likely cause deterioration and degradation. Designing structures for this environment will require consideration of service loads due to thermal cycles that have a period of 28 Earth days, and for habitats, pressure differentials necessary to support a breathable interior environment. Along with these service loads, random extreme hazard events that must be considered include micrometeorite impacts, Moonquakes, and short-term spikes in radiation due to e.g. solar flares [9, 10]. The specific characteristics of many of these solicitations will very likely also vary with location on the Lunar surface.

Several types of standards will be critical for building safe and durable structures on the Moon to serve as launch pads, habitats, shelters, foundations, blast shields, and perhaps even roadways. A standard here refers to a guideline to perform a type of test, evaluate the results, and define acceptance criteria. Standards, or specifications, are a necessary tool to perform testing on a uniform and consistent basis. For example, on Earth, ASTM International (founded as the American Society for Testing and Materials) standards are used internationally in dozens of industries to improve product quality, enhance safety, facilitate market access and trade, and build consumer confidence [11]. Such standards may be applicable for a specific product, process, test, or procedure, and they are generated through a consensus process involving a broad set of relevant stakeholders. Adoption of those standards will then enable test results that are repeatable and reproducible. For construction materials, standards provide a reference to characterize a material and verify its suitability for the intended use. Furthermore, tests carried out in accordance with such standards are meant to verify the repeatability and variability of the test results. These results then allow the engineer to make useful comparisons of test data, often needed both before and during construction.

The demands imposed based on the types of loadings expected on the surface of the Moon should inform the performance needs of the structures, and thus should be used to identify the type of test used in the standard. Before one can design infrastructure for the surface of the Moon using materials manufactured from indigenous resources, it is necessary to establish *several* types of standards. The focus of this paper is on standard tests required to evaluate mechanical material properties, which then enable reliable comparisons of test data. Comparisons may be made on the basis of a specific acceptance criterion. Comparisons may also be made to ensure consistency among results from different samples taken from a large volume of a given material. When indigenous resources are used to manufacture structural materials, comparisons are also needed to test materials manufactured at or sourced from different locations. Outside of the scope of this paper, there will also be a need for standards related to those manufacturing processes as well as for the fabrication of the structural elements from these materials. Those standards, while needed, are not what we aim to explore in this particular paper.

The material properties of interest for a particular design will then will then determine the type of standard test needed. For example, the design and construction of a landing and launch pad will require establishing an appropriate standard to test the material at specific phases during construction and ensure that the material properties meet the criteria set forth. In the case of regolith-based materials to be used as structural materials on the Lunar surface, we can learn a great deal from the analogous standards on the Earth, and the successes that have been realized while bringing the design of structures on Earth to a high level of sophistication. Consider as one example, the reinforced concrete skyscraper the Burj Khalifa, at 830m is currently the tallest building in the world.

To design a structure, there must be a reliable basis to *establish safety* in the resulting design. The standard test applies to the material performance assessment typically from the viewpoints of structural, workability or durability properties. Current ISRU construction methods fall into one of two main classes: extrusion and layered in-situ. Extrusion can be achieved through fused deposition modeling, melting, or binding of regolith using other materials such as sulfur or Portland cement [12,13]. Common layered in-situ methods are cold-pressing blocks or sintering, in which the prepped regolith is heated by lasers, concentrated solar energy, microwaves, or other methods. It is imperative that standards for these materials are based on the strength, durability and performance of the end product. Input materials may include sulfur, basalt, metals, glass, biopolymers, etc. [15]. Construction technologies include 3D printing, robotic construction, or other automated additive construction (AAC) techniques, which can influence the properties of the construction material. Standard tests to obtain material properties must be independent of the process, often proprietary, that is used to manufacture the material. This point was also emphasized during a 2023 National Institute of Standards and Technology (NIST) workshop focused on the topic of standards for additive manufacturing for structures on Earth [14]. The designer needs reliable material properties obtained using standard tests.

The purpose of this paper is to highlight the need for and technical challenges in establishing standards suitable for materials to be used for structures, such as landing and launch pads or habitats to be constructed on the Lunar surface. We then make recommendations toward establishing the path for developing those standards. We focus on standards for the testing needed to evaluate the material properties of structural/mechanical materials made from Lunar regolith. We describe the accepted standards and reasons for those standards for a commonly-used, brittle material on Earth, which is likely to be similar in behavior to the structural materials to be manufactured from indigenous resources on the Moon. Then, using a specific example, a launchpad manufactured of in situ materials from the Moon, we walk through the testing needs and the technical gaps that need to be addressed to design and construct such a facility. We aim to highlight the gaps in knowledge that exist, leveraging what has been established on Earth for construction on Earth, and translate that knowledge to explore how to adapt from well-known structural materials (such as concrete) to meet the objectives associated with ISRU-based construction in the extreme environment present on the Moon. We anticipate that this paper will also serve as a framework to establish standards for other material types.

II. Problem Definition

Engineers, when designing or building a component, structure or facility, in addition to fulfilling the user needs of the project, an acceptable design must include two key aspects: what are the hazards and load (both also referred to as solicitations) and serviceability demands, and what is the appropriate level/factor of safety or acceptable probability of failure. Civil engineers are no exception. The two key aspects described are well constrained when it comes to activities on Earth. Such knowledge has been accumulated and perfected over decades and even centuries of civil engineering practice and observed performance of the built environment. Through this accumulated experience, and by incorporating the risk accepted by society in the design procedure, an acceptable level of performance has been established. All these factors are engrained in codes, standards and regulations that stipulate how hazards, load and serviceability demands are quantified and what should be the strength and performance of materials and components to withstand, within prescribed margins of safety, such load and serviceability demands. It is the combination of codes and standards, and accepted practices that guides engineers to make the decisions that result in safe structures with an acceptable performance throughout their service life. It is important to realize that neither experience, standards, guidelines or building codes exist for design and construction of infrastructure on the Moon, Mars or on any extraterrestrial body. Clearly, as Lunar construction becomes more common with expanded human activities, regulatory agencies will also need to become more involved to ensure that safe practices are followed [15].

The Moon has an extremely hostile environment. There is no air or atmosphere (no pressure), temperature can fluctuate over a range of 250°C between Lunar day (with temperatures of the order of 120-130°C) to Lunar night (of about -130°C), with a period of 28 Earth days [10]. Lunar seismicity, from Moonquakes, is not negligible. Even though most quakes have magnitudes in the range of 1 to 2 on the Richter scale, occasionally they may reach a magnitude of 5 [9]. However, their signature is very different than those on Earth [8]. On the Moon, quakes may last for one hour, in contrast to the few tens of seconds they last on Earth, and may have a frequency content of tens of Hz, about one order of magnitude larger than their counterparts on Earth. Induced seismicity may be caused by nearby meteoroid impacts and may generate, depending on the mass of the impactor and the distance from impact, accelerations that may be tens or even hundreds of the Earth's gravity. Their effects on the surface of the Moon, in the form or craters, are ubiquitous. In contrast to the millennia of observations and nearly one century of quantitative measurements of seismic activity on Earth, relatively little is known about the localized seismicity of the Moon. A great deal more data is needed to understand and quantify this hazard.

The low gravity on the Moon, about one sixth of the Earth, may not have the positive effects that one may expect with the reduced structural loads. On the one hand, any structure intended to support human life must be designed to withstand an internal pressure of ~100 kPa (one atmosphere). This requirement means that the structure will most likely work in tension, as opposed to earthen structures that, because of the pervasive Earth's atmosphere, tend to work in compression given that an important part of the loading demand comes from the self-weight. On the other hand, low gravity/low weight may pose more of a challenge to perform routine construction operations such as excavation and bulk transport because of the limited traction that can be achieved with the Lunar surface. In addition, solar events and cosmic radiation continuously impact the surface of the Moon, which is unprotected because of the absence of a magnetic field. Radiation is not only harmful to humans, and thus any construction must be designed against radiation, but can also damage building materials depending on the material and exposure time. And chemicals or biological compounds transported to the Moon by humans are likely to have an unpredictable effect on structural components manufactured from indigenous materials [15].

There is no benchmark on what is the risk that should be assumed when designing and building infrastructure on the Moon, Mars, or anywhere. Years of experience on Earth have informed engineers and society at large what the accepted risks are for different human endeavors. In civil engineering, the result of this experience is encapsulated in design codes and specifications that define the minimum acceptable standard of safety. Each structure is classified based on its intended function and occupancy (e.g., residential, essential), and the target annual probability of failure ranges from ~10^{-4} through 10^{-7} [17]. Load factors and resistance factors are applied during the design process to manage the risk in non-extreme situations, typically accepting damage during extreme events aiming to preserve the lives of the occupants. Uncertainties in material properties, workmanship, modeling and loading necessitate this approach. Would society accept the loss of lives on the Moon equally as on Earth? Probably not. The accidents of the Space Shuttle Challenger and later Columbia, with their toll on human lives, seem to point to a lower risk tolerance. To reach a level of risk in Lunar construction that is tolerable, more knowledge is needed.

One of the first projects on the Moon that NASA has identified for construction with ISRU technologies is a landing and launch pad [4, 5]. This structure can be taken as an example to bring into focus the previous discussion. NASA's Moon to Mars plans anticipate that such launch and landing pads will be made using in-situ resources, i.e., the Moon's regolith, mixed with some sort of bonding agent or fused into a sort of artificial rock using high temperatures [15].

It is likely that the landing pad will be placed near the South pole of the Moon because water, in the form of ice, is expected to be found there. Should a civil engineer design such a structure, per the previous comments, all the expected hazards would be identified and quantified (the goal here is to recognize knowledge gaps rather than provide magnitudes of load and service demands). From a structural point of view, the mass of the lander and its payload, and the amount of thrust produced during launch would be needed. Determining these values should be rather straightforward since the design and mass would be known. However, the performance of the launch/landing pad to other loads becomes more complex and, to some extent, is not fully known. For example, the behavior of the material used to construct the pad when exposed to cycles of extremely cold sustained temperatures (-130°C during Lunar night) to the extremely high temperatures of the lander thrusters during takeoff and landing, is not fully known. It is also not known whether long-term exposure to radiation will induce any mechanical damage to the material. Further, the location where the pad is placed is of great importance due to the local conditions of the ground. What the engineer should know is the stratigraphy of the site: depth of regolith, type of rock underneath; the mechanical properties of the material(s): stiffness, strength and how those properties change with the magnitude of loading, with temperature, with the size of the structure, with cycles of loading (taking off and landing), with cycles of temperature, with time (creep may be a major factor) and with extreme events such as Moonquakes or meteoroid impacts, which may cause volumetric deformations of the regolith. In addition to all those "known" hazards/solicitations, the engineer must consider possible "unknowns". For example, the interaction of materials with humans. Regolith and other soils and rock on the Moon have never been exposed to liquid water or to other fluids that are part of human activity. It is extremely likely that water, fuel, oxygen and other gases, organic compounds and other chemicals will come in contact with the landing pad and with the ground underneath and around the structure. It is unknown how these in-situ materials will react, not only at the time of contact, but also long-term exposure [18] to in-service conditions.

It is of paramount importance to remark that engineers, without experience working in an extreme environment such as the Moon or guidelines and codes developed for the same, are even more dependent on testing materials to develop the data needed to design and build safe structures that will perform as needed during their service life. Core fundamentals such as how materials fail in hard vacuum, how chemical reactions take place under low gravity, or even how soils are classified come into question [19]. For example, on Earth, soils are divided into fine- and coarse-grained based on size [20]. However, such classification may come to question because the low gravity of the Moon may change the accepted boundary where the effects of gravity on interparticle forces become more prevalent than those of electrostatic and other forces. Characterization of the particle size distribution of lunar regolith simulant JSC-1A – similar in chemical composition to samples from the Apollo 14, 16 and 17 missions – results in a finer material than the limit specified by ASTM C33 using sieve analysis [19]. This finding suggests that additional processing based on standard tests is needed for classification of lunar materials based on particle size.

There is a large number of tests, each geared at a very specific material and for specific types of load and/or environment. Most of the tests are standardized by professional societies or standard agencies such as ASTM

International, ACI (American Concrete Institute), ASME (American Society of Mechanical Engineers), ISRM (International Society for Rock Mechanics and Rock Engineering), to name a few. One of the most used and fundamental tests in civil engineering is the uniaxial compression test as applied to unconfined concrete for use in structural applications. The test can be used, as an example, to illustrate the knowledge gaps that exist in using this, and other tests, in the Lunar environment.

In essence, the test consists of axially loading a cylinder (other shapes are possible, but the cylinder is the most common) of the material until failure. However, for it to become a standard test significant requirements should be met. In the US, the standard acceptance test for structural concrete requires a static compression test (carried out at a moderate rate to reach failure between 1.5 and 3 minutes) typically using concrete cylinders 6 in. (15.24 cm) in diameter and 12 in. (30.48 cm) in height. The specifications for making the specimens, curing and testing are laid out in ASTM standards C31 and C39. Testing of concrete cylinders 4 in. (10.16 cm) diameter and 8 in. (20.32) height is also permitted for the assessment of structural concrete as per ACI 318-19. The concrete cylinders are formed by pouring concrete in molds of required size with a standard compaction process and allowing the concrete to harden in the molds for 24 hours on site while protecting them from moisture loss and excessive cold or heat. The cylinders are then cured by immersing them in lime-saturated water or by placing them in a moist room at 73°F (22.8 ºC). As the concrete ages, it gains strength through the hydration of the cement. The standard test is performed on concrete cylinders at an age of 28 days. For a given batch of concrete, the standard test result is considered as the compressive strength value obtained by averaging the results of two 6 in. x 12 in. cylinders or three 4 in. x 8 in. cylinders [21].

The test is of great importance in construction because it is also used to establish modulus of elasticity, maximum strain at failure, flexural tensile strength and derivative structural properties used in design such as diagonal tensile strength, direct shear strength and bond strength of reinforcement in concrete. The standard test is also used to develop the data necessary to check that the strength is consistent throughout a given project. Lunar applications such as the one described in this section, in the absence of experience and codes or guidelines, is but one example where the availability of materials standards for testing, to generate data used to compare the properties from different batches of the same material and to ensure safety in design, are of paramount importance and the subject of this paper.

Although there are several different technologies being considered for construction, the basic behavior associated with brittle materials dictates that these standards are necessary to enable Lunar design and construction. Irrespective of the process used to manufacture the material, it must be tested for strength and performance at scale. In subsequent sections relevant background on how such standards came about is discussed and key gaps are identified for indigenous Lunar materials. Understanding the origins of accepted standards for terrestrial construction is critical so that stakeholders can use this knowledge as a starting point for a discussion about appropriate standards for construction materials on the Moon.

III. Perceived Gaps in Standards

To determine the most appropriate way to test Lunar regolith-based structural materials, one must first ask how we expect the material to behave in structural applications. Both the size and shape of the test specimens and the methods for characterization of any material depend primarily on the assumed material behavior. Thus, one needs to first determine whether the material is ductile or brittle, whether it yields or fractures, whether it is uniform and homogeneous or not, and so on.

A. Basis for Standards in Common Brittle In-Situ Structural Materials

Several similarities between regolith-based materials and concrete on Earth are evident and thus a reasonable assumption would be to consider the overall behavior of a structural material made of Lunar regolith to have similarities to that of concrete on Earth. Thus, both the wealth of knowledge about the behavior and variability of these structural materials and the standards that have been established should be leveraged to establish suitable guidelines and specifications for regolith-based materials. Here we start with the premise that structural materials made from indigenous Lunar regolith are brittle, and that they are likely to be significantly weaker in tension than in compression. The questions raised here, and many more, suggest that we take a close look at test procedures that have been established on Earth. Let's consider the behavior of standard concrete on Earth, and how that leads to the specific standards that exist for its use in structural applications.

Standardized tests inform the engineer performing the structural design. One of the most important properties of the material needed for structural design is strength. The coarse aggregate in concrete provides bulk and strength, the fine aggregates primarily provide workability, and hydrated cement serves as the bonding agent to bind the material together and provide strength. Concrete is tested for its compressive strength, or its tensile strength, using several kinds of specimens and test procedures. Well-established test procedures that are in place make use of the fact that concrete is significantly weaker in tension than in compression. It can be argued that concrete cannot fail in volumetric compression and therefore the compressive strength of concrete is a misnomer. This belief eventually translates to the fact that even when we compress a concrete specimen in a test machine, its failure depends on how the internal tensile stresses develop inside the test specimen when subjected to a compressive load.

Depending on the national standards that apply, different testing methods are used worldwide to define the uniaxial compressive strength of concrete. However, these methods can largely be divided into the two most common: (i) through compressive strength tests on a cylinder with a certain height to diameter ratio (usually 2), and (ii) through compressive strength tests on a cube-shaped specimen. The most widely used sizes for such specimens are the 6 in. (15.24 cm) diameter concrete cylinder and the 150 mm-side concrete cube. Sometimes, especially in production control or for research purposes, smaller size specimen (e.g. 4 in. (10.16 cm) diameter cylinders or cubes with 100 mm) are used.

The strength of a concrete specimen decreases with size, e.g., the concrete compressive strength obtained with a cube having 100 mm side will typically be higher than that obtained using a cube with a 150 mm side. This reduction in the measured strength with an increase in the specimen size is termed the "size effect," and is described in standard texts on the subject, e.g. [22]. Generally, the strength obtained from a non-standard size specimen can be used to obtain the strength of a corresponding standard specimen using empirical conversion factors. Similarly, conversion factors can be used to obtain the strength of different specimen shapes, i.e., the cylindrical strength can be related to the corresponding cube strength using appropriate conversion factors. The differences in strength obtained from specimens of different shape is termed the "shape effect" [23].

A true uniaxial state of stress in concrete compression testing is not possible due to the presence of friction between the loading plate and the specimen. Due to this friction, a multiaxial state of stress occurs, and the apparent strength exhibited by the specimen is higher than its true uniaxial compressive strength. In the case of a cubic specimen, the lateral stresses developed due to friction between the plate and the specimen affect the specimen throughout its height (see Fig. 1). However, in the case of a cylindrical specimen with a height to depth ratio of 2, a certain portion in the mid-height of the cylinder remains unaffected by end effects [23]. Therefore, the concrete cube specimen displays a higher strength than the corresponding cylindrical specimen for the same concrete mix.

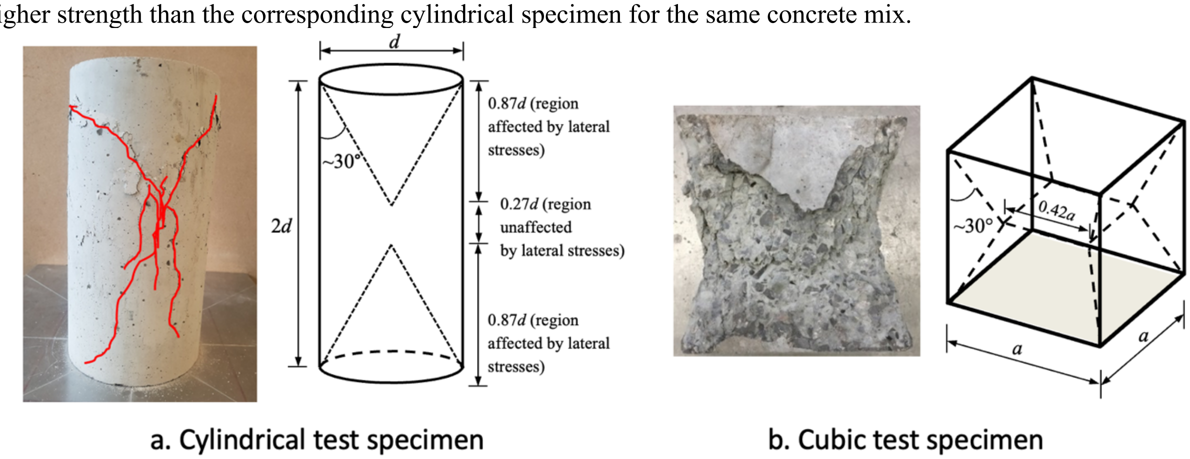


Fig. 1 Influence of the loading plates on the stresses on concrete cylinder and cube specimens.

For normal strength concrete, a factor of '0.8' gives a reasonable ratio of the cylindrical strength to the cubic strength, for a cube with 150 mm side and cylinder with 150 mm diameter [24]. For high-strength concrete, this ratio is typically slightly larger. The strength measured with specimens having an even higher aspect ratio (height to diameter ratio), may be even lower than the strength measured on a standard cylinder with an aspect ratio of 2. For normal concrete, its compressive strength reaches and stagnates at a value of approximately 0.85 times the strength measured on a standard for cylinders with an aspect ratio of 4 or larger.

Clearly the shape and size of the specimen have a significant influence on the values obtained in a given test, and how those values should be treated for their use in design.

Concrete gains its strength with age as the cement hydrates to form the calcium silicate hydrate (C-S-H) gel, and hardens. As cement hydrates, it releases heat (known as heat of hydration). If the rate of this hardening process and the release of heat of hydration is too high, the rapid drying of the concrete surface can lead to shrinkage and cracking. To avoid this, the temperature and moisture content of concrete must be maintained such that the hydration process takes place at a slow rate, which is achieved by a process referred to as curing. ACI defines the term curing as "action taken to maintain moisture and temperature conditions in a freshly placed cementitious mixture to allow hydraulic cement hydration and (if applicable) pozzolanic reactions to occur so that the potential properties of the mixture may develop" [25]. Good curing is essential to realize desired structural properties, aesthetics, and durability. When a large amount of concrete is poured at once, the heat of hydration is higher, and the susceptibility to shrinkage and cracking increases. Therefore, when the dimensions of the member being cast are relatively large (i.e., mass concrete), special measures must be taken to control the temperature difference between the inside and the surface of the concrete to reduce the potential for cracking due to the thermal gradients [26]. Special care must be taken with concrete that is cast in very cold or very hot weather.

The rate at which concrete reaches its full strength depends on the material composition and the chemical reactions that take place. Ordinary Portland cement-based concrete typically reaches approximately half of its final strength in three days, around two-thirds of its final strength in seven days, about ninety percent of its final strength in 14 days. Concrete reaches almost 100% of the final strength (~98-99%) in 28 days. Therefore, for quality control purposes, concrete is tested to assess strength at 7-, 14-, 21- and 28-days after casting. The standard acceptance test for concrete consists of compressive strength determination at 28 days of age. However, this process varies considerably for other materials.

While one can claim that the specifics described here may not apply to other manufacturing processes that do not require a bonding agent or cement, e.g., sintering, we argue that the basic structural behavior remains similar, as applicable to brittle and non-homogeneous materials with low tensile strength to compressive strength ratio. On the contrary, the manufacturing process can significantly influence the development and retention of strength with age. While concrete strength is considered to continuously increase with age, though with ever reducing rate of strength gain, the evolution of strength of sintered materials with age might be rather different.

Because concrete is essentially an artificial rock formed by mixing natural and man-made materials, transporting and placing in molds and compacting by vibration, a significant variation in strength is inevitably obtained from one specimen to another. For compressive strength, a coefficient of variation of 15% in the field is considered to be normal. However, this value can be much lower in a controlled laboratory setting; the level of quality control does affect the coefficient of variation. Using the average strength for design purposes is obviously too risky – statistically, half the concrete strength will be below the average value. Therefore, design standards require using a value of concrete strength chosen such that the probability of the actual concrete strength falling below this value would be rather low. For example, according to ACI, the specified compressive strength (used for design) of concrete refers to a strength such that not more than 1 in 11 sample tests fall below it, and the average of any three consecutive strength tests (uniaxial compression tests of a cylinder) shall be equal to, or greater than, the specified strength [27, 28]. In Europe, the strength used in design is referred to as the characteristic strength of concrete, which refers to the value at which not more than 5% of the test values would fall below it. Considering a normal distribution for the variation of concrete strength and assuming a 15% coefficient of variation, the specified strength of concrete is approximately 80% of the average strength, while the characteristic strength is approximately 75% of the average concrete strength.

Design specifications or guidelines such as ACI 318-19 and ASCE 7, respectively, use this knowledge of the variability in the material properties and actions as well as simplifications in modeling assumptions to provide structural designs that result in a high reliability index and low probability of failure. Without knowledge of the material variability, it is not possible to achieve an acceptable level of safety in structural designs.

Specimen shape and size are not the only factors that must be standardized for the concrete uniaxial compression test. The rate at which the loads are applied to the specimen are specified to remain within a certain range. The reason for this requirement is the well-known influence of loading rate on concrete's material behavior (as well as other types of brittle materials such as rock). The response of concrete to time-dependent loading is generally classified as being attributed to one of three different effects: (1) rate dependency of the growing microcracks (influence of inertia at the micro-crack level), (2) the viscous behavior of the bulk material between the cracks (creep of concrete or viscosity due to the water content), and (3) through the influence of structural inertia forces. This means that at higher loading rates the resistance of concrete (strength) increases. The classical tests by Dilger et al. [29] show the influence of loading rate on the stress-strain behavior of concrete in compression (see Fig. 2). At low to moderate loading rates, the resistance of concrete is governed by the first two effects mentioned above and the strength appears to increase linearly with loading rate when plotted on a semi-log scale. At high to very high loading rates, a progressive increase in resistance of concrete is observed. However, this is mainly attributed to structural inertia and is not considered to be a part of the material behavior [30, 31]. Generally, for material characterization, quasi-static loading rates are specified such that the influence of loading rate on the material response is negligible. Currently, there are no standard test methods to evaluate the behavior of concrete at high loading rates and the results obtained from different researchers are followed to establish the material models. In this case, the lack of standard test methods results in a large scatter of test results, with larger variability observed for compressive strength than for tensile strength of concrete (Fig. 3). Going beyond strength, observations show that the fracture behavior of concrete is also significantly affected by the rate of loading. For example, a mode-I fracture of concrete under static loading typically changes to a mixed-mode fracture, characterized by multiple cracks and crack branching, under high loading rates [32, 33].

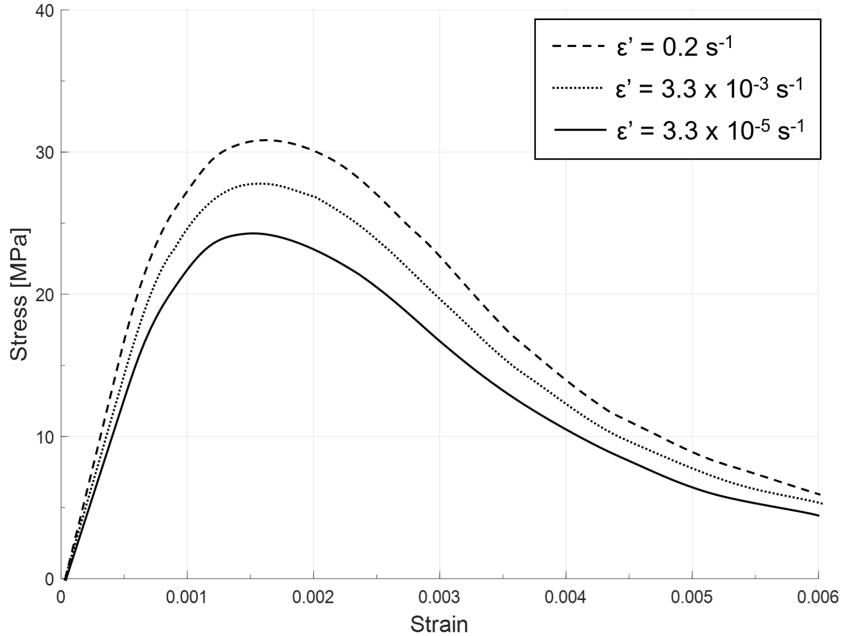
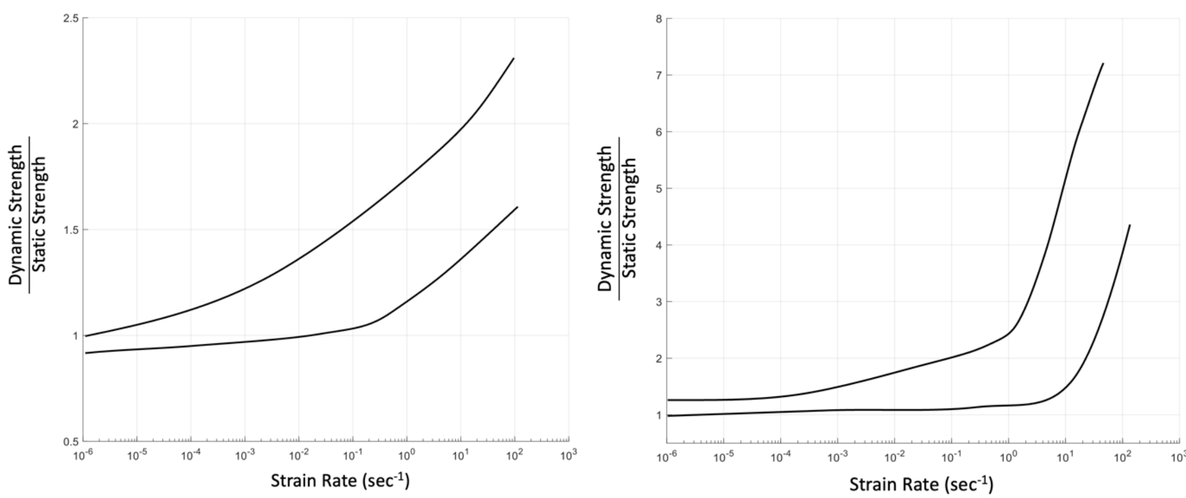


Fig. 2 Typical variation and variability in concrete stress-strain curves under different strain rates [32].



a) Compression **b) Tension**

Fig. 3 Typical variation and variability in the ratio of dynamic to static strength with strain rate: a) compression [35], b) tension [36].

The stress-strain curve of concrete under direct tension is relatively difficult to determine compared to that under compression. This is because concrete is rather weak in tension, and the failure may occur not at the critical section but elsewhere (e.g., the region of stress-concentration near the loading points). Due to the difficulties associated with holding the specimen in a way that it does not induce undesirable stress concentrations at the holding points, direct tensile tests are rarely used in practice. The most common method is a split cylinder test, where a cylindrical specimen is tested by applying a compressive load along its diametric line segment. The compressive load applied results in practically uniform lateral tensile stresses along the diameter. However, these tensile stresses are accompanied by very high local compressive stresses near the loading points, as depicted in Fig. 4 [36]. The tensile strength of concrete measured by this test is referred to as the split concrete strength, and the direct tensile strength of concrete is often considered to be 90-95% of the split concrete tensile strength.

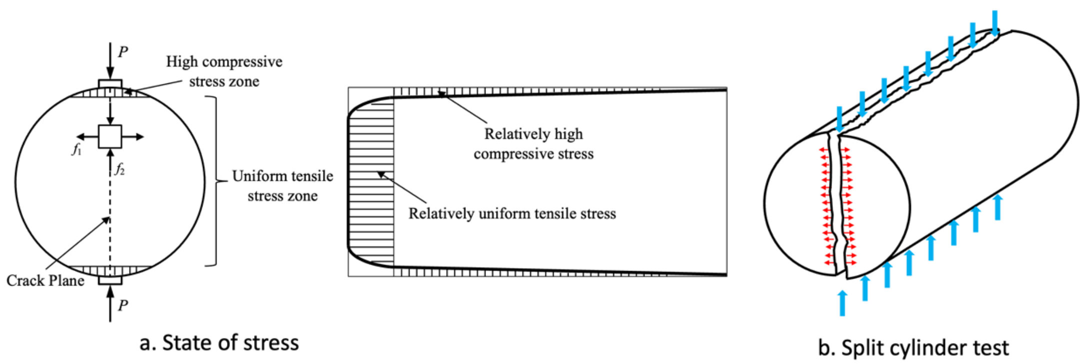


Fig. 4 State of stress in an element at the crack plane in the case of a split cylinder test for tensile strength of concrete.

Many of concrete's material properties, e.g., tensile strength and modulus of elasticity, are considered to be related to its compressive strength (typically taken as directly proportional to the square root of the concrete compressive strength) measured in a standard unconfined compression test. This relationship is understandable because the tensile strength of concrete is essentially what controls the compressive strength measured in a standard unconfined compression test, as discussed earlier. Therefore, the relatively simple unconfined compression test is the single most used and most accepted test for assessing the quality and characterizing the material behavior of concrete.

For concrete on Earth, temperature is also a factor that must be considered. Although concrete is an excellent insulating material and has good thermal resistance, it undergoes significant degradation in its properties when subjected to elevated temperatures because of many chemo-physical phenomena activated in the cement paste and in the aggregates at different temperatures [37]. These phenomena typically include initial swelling of the free water followed by the expulsion of free and bound water, degradation followed by breakdown of the aggregates, decomposition of the C-S-H gel, etc. Differences in the thermal dilatancies of its components result in an incompatibility between the cement paste and the coarse aggregates, which in turn results in a degradation of concrete at the meso-scale. At temperatures in the range of 400 to 600°C, creep in concrete markedly increases and may even become unstable. Furthermore, the behavior of concrete under elevated temperatures (e.g., during fire) can be significantly different than the behavior of concrete in a cooled state after exposure to elevated temperatures (e.g., post-fire scenario). Upon sudden heating, as in the case of fire, the exterior surface of the concrete is heated rapidly while the inside remains cool due to concrete's low thermal conductivity. This differential results in the development of thermal gradients inside the concrete. Upon cooling (e.g., after extinguishing the fire), the situation reverses and the outside tends to cool rapidly while the inside temperature is still high and even rises for a few minutes (e.g., after extinguishing the fire). The resulting thermal gradients then lead to the development of high tensile stresses, which may result in significant cracking and associated reduction in strength [38]. Thus, temperature extremes, and cycles, have a significant effect on the strength of concrete over time.

B. Perceived Gaps for In-Situ Lunar Materials

To establish the standards needed to design structures using an entirely new material, the vast amount of experience that has led to meaningful standards on Earth should be leveraged, and adapted. It is logical to assume that some of the fundamental ideas are transferrable to other materials, and especially to those with similar behavior such as our assumption that structural materials made from indigenous Lunar regolith will be brittle, with a low tensile to compressive strength ratio. However, there are also significant gaps associated with the use of these materials due to the extreme Lunar environment that do not need to be considered for structural materials on Earth. Most of those questions are due to the harsh environment the materials will be exposed to during their service life, including factors that are related to human activities, and the associated loadings that are anticipated.

Some of the questions that need to be answered are:

If the material requires curing, what are the conditions under which curing can and should take place?
How does the strength of the material evolve with age and how frequently should strength be assessed?
What is the appropriate specimen size and shape for assessing structural strength?

Does the behavior of the specimen change with loading rate?
Is temperature a factor and how does it influence the behavior of the material both near term and over time?
Will the material's strength degrade under thermal cycles?
Is the lack of pressure going to influence the behavior of the material both while curing and in service?
Will the material creep under loading?
What factors affect the durability of the material?
What human activities may cause the materials to be exposed to new environmental factors?
What shape and size specimen are appropriate for a standard test to assess the material?
How will structural material properties (at scale) be different from material properties?
What testing techniques should be used to evaluate the relevant material properties, destructive or non-destructive?

To put our discussion about the technical gaps into context, let us consider how to approach these questions if a large-scale facility was available with the capabilities to prepare and test appropriately-sized material specimens under the range of conditions expected on the Moon. Imagine that we have a large universal testing machine in a temperature-controlled vacuum chamber. In this facility we would need to prepare, manufacture and cure specimens made from Lunar regolith in a vacuum in quantities that would be necessary for testing their strength under the variety of conditions that must be considered, to sufficiently understand how these conditions influence their behavior and durability.

Specifically, consider how one might approach the question of establishing standards for the structural materials needed to design and construct a landing pad, a question introduced earlier in this paper as a topic of great interest currently. It is necessary to identify and examine the many factors that will influence the strength, behavior, and durability of the material specimens, and thus lead to information needed to establish the standards to safely design structures with these materials. For instance, the Moon has a much wider temperature range than Earth. The lack of an atmosphere also introduces questions about any curing needed for the materials [12]. And environmental factors, including the presence of ambient radiation more than 100 times greater than on Earth, bring up concerns about durability and degradation. To answer these questions, and many more, let us look at how might we adapt the test procedures that have been established for indigenous materials on Earth.

To design for the mechanical loads and other solicitations that a landing and launch pad will be subjected to, a reliable assessment of the strength of the structural material when it reaches full strength, is needed. Reproducing the environmental conditions in which the materials for the landing pad would be manufactured on the Lunar surface would be ideal. Consider the facility imagined previously, and assume that a pressurized container designed for mixing and curing the material is not available. This assumption thus translates into the need for the mixing, preparing and processing of the material in a vacuum and in low-gravity.

Inside the large vacuum chamber, the curing timeline and associated conditions for the chosen material will first need to be established to ensure that the material will reliably reach a proper strength in this environment. For example, for polymeric materials, the curing time may be as small as a few seconds to as high as a few days and it also depends on the environmental temperature. Environmental conditions can have a significant effect on the rate at which strength develops. Studying these under normal conditions on Earth is relatively easy. However, the rate at which the strength matures and the influence of environmental conditions on this process must be studied across the range of extreme environmental conditions expected in service. The lack of an atmosphere introduces numerous questions about the curing process and timeline. Throughout curing, testing will need to be conducted periodically to assess the strength of the material with time. Even if the material is formed by sintering, the evolution of strength over time must be verified. This procedure would necessitate that compression tests be performed in the vacuum chamber according to a pre-determined schedule to establish the curve that describes how the material strength matures over time. This requirement applies to not only the initial stages of strength gain, but also for the strength retention over a longer period of time, especially if the materials do not cure and gain strength with age. A sufficient number of samples should be tested at each age to also assess the variability in the strength of the material.

Temperature is another factor that may affect the structural properties. Temperature fluctuations on the Lunar surface are expected to be much wider than those on the Earth. Furthermore, the material used for a landing pad is expected to be subjected to cycles of extremely cold temperatures (-130°C during Lunar night) to the extremely high temperatures when exposed to the lander thrusters during takeoff and landing. At the low end, temperatures of -130°C do not exist naturally on Earth (thus there has not been a need to test structural materials on Earth at these temperatures). Under high temperatures, the duration of exposure is potentially a key factor. Although fire sustained over a long period will degrade concrete, exposure of concrete to high temperatures for a short time period is not likely to do so. An understanding of the behavior of regolith-based materials under both temperature extremes and thermal cycles will need to be determined.

To examine these factors, compression tests should first be performed in this testing facility at a constant temperature level, and then with the application of appropriately high and low temperatures. Eventually, as more is known, temperature cycles and thermal gradients should be applied to the material. If the material is to be used for a landing pad, the temperature extremes and temperature gradients expected in service should be the target for such tests. Exposure to high amounts of radiation adds another level of complexity to the problem, which must be addressed at a later stage.

Similarities between Lunar regolith-based structural materials and concrete on Earth indicate that there is a likelihood that ISRU materials will exhibit a very similar tension/compression relationship, and that loading rate dependence should be expected. To make these decisions, the relationship between compressive strength and tensile strength will need to be understood. If lunar-regolith based structural materials also exhibit a brittle fracture behavior and a low tensile-strength to compressive-strength ratio, a similar approach of relating other material properties to the compressive strength could very likely provide a good basis on which to assess the performance of the structural material. However, this possibility also comes at the price of all the aspects that are relevant for concrete, e.g., shape effect, size effect, scale effect, etc. to being applicable for the lunar concrete as well. However, if this assumption (low tensile to compressive strength ratio and a brittle material) is not true, it might be necessary to develop an entirely different type of test. Attention should also be paid to the well-known “size effect” and “shape effect” for these studies to ensure there is no overestimation of the strength of the material for design purposes. Testing very small size specimens is likely to provide misleading and unconservative results.

Each of these factors need to be considered in isolation first, and then their coupling will need to be studied along with the influence of temperature gradients that will occur during curing and during the service life of the structure. Including a study on how low gravity affects the strength of the material would also be desirable, although that would be the most difficult condition to replicate on Earth.

The composition of the material will influence the structural properties. The specimen shape and size should consider whether or not the material uses an aggregate (to achieve strength and bulk), and what specific bonding agent is used. It may be appropriate to begin with the standard size and shape used for concrete, and then look at consistency of the results (at several points in time), consider the state of stress throughout the specimen including the bonding material. The testing setup, including the boundary conditions, will affect the ability to induce a uniform state of stress in the chosen material for assessing structural strength. Depending on the design of the structure and state of stresses that would develop under the applied loads, further material properties such as tensile strength, shear strength, elasticity modulus, etc. may be needed. For concrete, these properties are generally related to its unconfined compressive strength. Similar relationships between compressive strength and other properties of the material would be needed for design purposes.

Once the influence of these factors is understood and appropriate test(s) are identified to assess the material properties, one must determine the variability in the results of standardized tests. Ensuring safety and reliability requires multiple tests, multiple results from batches of the material. The desired reliability of the test will need to be identified (on Earth this is codified through defining the number of samples tested), and then the acceptance criteria for a standardized test that will define the number of samples and the acceptable variability in the results to achieve the acceptable level of risk. Because the resources available will vary from region to region, its variability must also be assessed when used to manufacture a structural material. Knowledge of the expected variability is necessary to establish standards for comparisons from region-to-region and acceptance of the material in the field, thus meeting an acceptable level of safety in structural designs. Such knowledge is not currently available for structural materials made from Lunar regolith.

For the design of structures that may need to withstand impact loads, it will be important to understand the behavior of the material at various loading rates, including both its strength and fracture toughness over repeated cycles of exposure, use and loading. Knowledge of the durability of the material is critical for estimating the lifetime of the structure and ensuring that it will be able to withstand the anticipated loads as the structure ages and degrades. In particular, the thermal conductivity of the material will need to be determined and an assessment will need to be conducted to determine if temperature fluctuations affect the material’s behavior over time. Such a study should be done with a sizable specimen as the thermal stresses that build up and degrade the structural material over time may not be evident in small specimens. A material that is thermally stable over such a vast range of temperature variation is essential for the structural integrity of the lunar launching pad. Creep and other long-term durability aspects will also need to be considered.

Loading rate is relevant to design a launch and landing pad as such a structure will be subjected to blast loads due to the thrusters, impacts during landings and high velocity meteoroid impacts. Further, the interaction of these materials with humans is unknown. The presence of oxygen and other substances used for fuel and food production may influence the structural properties over time. Each of these factors must be assessed before a predictable lifetime can be estimated.

IV. Discussion

Establishing a robust infrastructure to support a long-term human presence on the Lunar surface, or that on any extraterrestrial body, requires that engineers have the information needed to design structures. Most of the prior research and trade studies to date have focused on demonstrating advances in the technology readiness level (TRL) for manufacturing ISRU materials and for implementing construction techniques [18, 39]. Although these studies expose gaps, they still lack a realistic perspective of what is needed to design and construct structures. If the assumption that Lunar ISRU materials will have similar structural behavior as those of concrete on Earth is plausible, the shape and size of the specimens tested, and the behavior of the material for structural uses will matter a great deal in the design process.

Designing structures requires a good understanding of both the structural materials and the solicitations that the structure will be exposed to. This understanding must include behavior, strength, durability and degradation. Strength is the basic information needed to determine the size of structural components. The relationship between tensile strength and compressive strength will influence what sort of structural shapes may be designed and constructed. Brittle materials are generally not suited for dynamic loads such as seismic inputs and micrometeoroid strikes. And, no matter how one manufactures the material, engineers need to know the properties of the material product to design structures using this material.

Materials currently being manufactured from regolith simulants with this application in mind include those made by bonding particles together through a chemical reaction (e.g., cement, polymers) and those where the binding is achieved through heat (e.g., sintering, etc.) [15]. These manufacturing processes are conducted using several different techniques including material extrusion through automated additive construction (AAC) or layered in-situ construction [12]. These studies have reported material properties (i.e., compressive strength) at the coupon scale. However, small scale tests of materials are not sufficient to inform structural design. Scale effects and shape effects are quite likely to be present in Lunar ISRU materials as with other brittle materials. Note that the concepts that are being planned for the Lunar surface include the construction of some very large structures [4]. Although one of the many regolith simulants initially may need to be used [40], simulants are not the real material, and can only give us a portion of the evidence that is needed. Eventually Lunar materials will need to be tested.

Materials durability also needs to be examined, especially for this extreme environment. To know whether a landing pad can endure one landing or dozens of landings, the following will need to be considered: mechanical durability due to thermal and loading cycles; chemical durability due to spills, fuel, chemicals and even oxygen from human activities; and radiation durability which is really unknown for most materials when dealing with this type of extreme radiation.

Studies to date on materials manufactured from regolith simulants also lack consistency in testing methods. Specimen size and shape, as well as testing conditions are not considered in these studies and thus their relevance for structural materials is quite limited [41, 42]. One must ask whether the information obtained from testing small specimens made of a given material is translatable to large specimens made from the same material with the same processing techniques. And before a material can be used for construction, strength, performance, and durability, need to be verified at scale.

As-built verification of design and construction is important due to unanticipated site conditions. With a better understanding of the materials, there is the opportunity to establish standard tests. Several types of testing standards are necessary to enable test results to be generated that are repeatable and reproducible, and therefore lead to the ability to design and build safe and durable structures able to withstand the loading in the Lunar environment.

One concern is the effectiveness of the technology and material behavior in the space environment of vacuum and low gravity [12]. For example, studies on the hydration process of cementitious materials in the microgravity environment of the International Space Station showed that microgravity samples had different microstructures than those hydrated in a terrestrial environment [43]. The harsh conditions not only affect the constructability of the material but are likely to produce different mechanical and structural material properties which have yet to be explored [15].

Quality control will also be an essential tool for verification of the construction. Inspection through visual or measurement methods is being proposed [44]. However, inspection will only address questions about flaws that may be present due to the construction process – inspection will not address or measure the strength of the material. Standards to specify the testing are needed to do that.

Several standards will be necessary. For example, to use concrete on Earth a large number of standards are needed regarding strength, durability and workability. For strength there are standards governing the size and shape of the cylinders, as well as for how to obtain the structural properties such as compressive strength, modulus of Elasticity, and tensile strength. These provide a good set to consider as a starting point. To similarly design structures with an ISRU-based material for the Lunar environment, it is likely that analogous standards as well as many more will be necessary. However, the standard to be adopted should be independent of the process used to manufacture the material.

A structure meant to serve as a launch and landing pad is discussed herein as a timely example of some of the questions that need to be addressed. We propose a possible path to establish some of the necessary standards. These questions are posed to start a discussion with a very specific scope – how to establish test standards to establish the strength of ISRU-based materials. This discussion does not address many other factors that will need to be considered along this path, including the variety of construction methods, the quality control associated with the processing of the materials, and the many other factors that will play a role in such construction.

Clearly, this discussion will need to be continued through activities that include all of the stakeholders that are involved. Standards for construction on Earth are developed with a broad representation of stakeholders that follow a specific process with the goal of reaching a consensus on what the standard should be. There are also logistical questions that will need to be addressed. Methods and equipment for implementing the necessary standard tests for in-situ regolith-based materials will eventually be needed on the Moon. The specifics of those are not known at this time, but these reusable items would need to either be transported to the Moon or built, all or in part, from in situ materials. If the concrete compressive test is the path deemed most appropriate by the stakeholders involved in the development of the standard, a machine like the UTM (universal testing machine) would be the logical choice. However, there may be various ways to obtain the necessary results.

V. Summary and Conclusions

The design and sustainability of the infrastructure required to establish a booming scientific and economic settlement on the Moon represents a multidisciplinary engineering and scientific grand challenge for humanity. In a context of extreme environments, it is especially important to design buildings whether for habitation, laboratories or manufacturing, that are capable of responding to prevailing conditions—not only as a protective measure, but also to enable future generations to thrive under such conditions. Clearly, having the ability to design structures that serve as landing and launch pads is a critical step in meeting the objectives NASA and its partners have set forth to establish a human presence on the surface of the Moon. However, gaps in knowledge and associated testing standards are now restricting our ability to design these structures in the near term. These gaps span many factors, ranging from their structural strength and behavior to mechanical and thermal loads – the most basic knowledge needed – to their durability and behavior under sustained loads and for life cycle engineering.

It is critical to realize that neither experience, standards, guidelines or building codes exist for design and construction of infrastructure on the Moon, Mars or on any extraterrestrial body. Without the experience working in an extreme environment, engineers are going to be especially dependent on testing the materials to develop the data needed to design and build safe structures that will perform as needed during their service life. Many other types of standards will also be necessary to ensure safe and reliable operation in this new and challenging environment, e.g., for construction practices and tools, for structural design choices such as reinforcement and prestressing, for radiation protection and exposure monitoring (for both structural materials and humans), and for safe environmental impacts.

To the extent possible, controlled testing should be performed on Earth to understand the influence of these factors on the material and to establish standardized test behavior. It is imperative that we make use of the hard-won lessons from developing testing standards on Earth for indigenous materials and leverage this knowledge as we move toward realization of this new frontier.

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