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Note: While this article was "reprinted" IN MMM in 2010, it first appeared in the L5 News in 1983 and thus is prior conceptually to the articles that follow.

Early lunar settlers will need an inexpensive, easy-to-use concrete for rapid construction of structures.

Introduction

The early pioneers who came to the "New World" brought with them all the tools they could afford. With this small initial supply of tools, they built homes, grew crops, hunted, engaged in trade, and produced new tools from the raw materials of the rich and virtually untouched wilderness. To build their houses, most early settlers used an axe and a great deal of muscle. The remainder of the building material came from the land around them: trees for walls and roofs; a mixture of mud, sand, and sometimes fine plant fibers for mortaring the cracks and joints in the wooden walls and roofs; dried vegetation for thatched roofs; and dirt for floors.

An early pioneer on the lunar frontier should also build his earliest structures using the least amount of imported tools and materials. The Moon lacks many material sources commonly used in terrestrial construction, such as water for concrete and brick mortar; trees for timber; organics and plastics for electrical wire conduit and plumbing; processed metals for load-bearing beams, reinforcing wire or grids, and electrical wiring; and processed concrete materials. The only major source of raw materials is the finely divided lunar regolith, or soil, which is most suitable for making ceramic building materials such as bricks, mortar, and concrete.

Early lunar settlers will need an inexpensive, easy-to-use concrete for rapid construction of structures. For the widest possible use during this early development stage, the concrete must require only minimal initial processing and final placement time and effort. Since the lunar temperatures vary from well above the boiling point of water during the lunar day to well below the freezing point of water during the lunar night, a good concrete should be unaffected by these extremes of temperature during placement, curing and use.

"Concrete" usually refers to a mixture of aggregate, such as gravel; fines, such as sand; and hydraulic setting cement, such as Portland cement. These compounds are mixed together in many different proportions. Most mixtures are moistened with 5% to 25% water and cast into molds or forms.

Conventionally placed concrete mixtures must be kept in the very narrow temperature range of 40 to 80 degrees Fahrenheit for 1- 21 days. Water content of the placed concrete must be held constant for this extended period of time to yield optimum strengths. If the concrete is allowed to freeze during the first day or two it will usually be very weak, and will crumble under very little stress.

During the early days of lunar settlement, water will not be abundant or cheap enough to leave large amounts tied up in housing structures. After a sophisticated and mature industrial base is established, conventional concretes may have limited application in some construction if a sufficiently large, inexpensive water supply is found. But, because of the temperature limitations caused by the water addition, conventional concretes will only have limited use in lunar and space habitats. Therefore, use of the term "concrete" to describe materials placed in a similar manner on the Moon would be misleading. It is proposed the term 'lunarcrete" be used to describe concrete-like materials made from lunar raw materials and used as a building material in the settlement of the Moon.

Previous Proposals

Two feasible methods of constructing lunar dwellings largely from lunar raw materials have been proposed to date. One method 1 involves making precast and prestressed panels of lunar concrete bonded either with epoxy resin imported from Earth, with melted sulfur, or with fused rock. These types of building materials have many potential uses including lunar habitats, inside structures like floors and walls, industrial process equipment, and prestressed concrete for building a large space habitat.

Sheppard? proposes using fused cast rock placed around steel reinforcing cables tensioned between anchorage points. Similar approaches to early lunar settlements would result in significant economy by reducing the use of expensive, highly processed materials such as various steel alloys. However, the first two binders are limited by the amount of resin that can be imported, and by the durability and strength of the sulfur concrete as well as the availability of indigenous sulfur. The third binder requires a great deal of energy, and a material to fill the joints between the panels to prevent loss of atmosphere.

A second method] involves driving heating rods into large piles of lunar soil. Fusion of the soil layer and subsequent removal of the underlying soil results in a "cave-like" structure. This type of structure also requires a great deal of energy to construct. Unless it is sealed, cracking of the internally fused structure could lead to slow leakage of some at mops here.

New Proposal

Table I below lists the major requirements of a lunarcrete intended for widespread structural uses. This paper suggests an approach to development of lunarcretes that may satisfy the requirements in Table I.

TABLE I Requirements for a Lunarcrete

- Must be able to support its own weight plus the additional loads encountered during intended use.
- Must be able to contain air with virtually no loss.
- Must be abundant and therefore cheap.
- Must be easily and quickly prepared and placed.
- Must not require strict control of ambient temperatures during placement and curing.
- Must not contain water in any appreciable quantities.
- Must not fail catastrophically without warning.
- Must be structurally stable, environmentally stable, environmentally inert, impervious to external and internal stresses, such as micrometeriorite impacts.

In the terrestrial refractories industry, a novel type of material is gaining widespread acceptance. In many applications where monolithic construction is necessary and there is insufficient time for placement moisture to dry prior to use, dry vibratable compositions are gaining favor. These new products can be placed quickly and heated at rapid rates to very high temperatures, while yielding excellent strengths, densities, and low wear rates. Strengths well in excess of conventional, non-pre-stressed concretes are achieved every day, using many compositions of these materials. The terrestrial construction industry would have little or no use for such a product. However, a lunar construction industry would find substitution of energy for water and no strict ambient temperature dependence to be desirable features.

It is proposed that as-mined lunar soils be screened and recombined in the proper grain size configurations to create dry vibratable lunarcrete compositions.

These mixtures should compact much more readily on the Moon due to lunar vacuum, since entrapped air is the main reason why dry vibratables sometimes densify poorly on Earth. Due to the great similarity between the particle configuration of the lunar soils and dry vibratable products, it may be possible to build the early crude structures using lunar soils in the as-mined state. Internal and external metal forms are erected and loose-filled with the lunar soil. Conventional vibrations equipment attached to the metal forms is used to compact the soil to high density. Additional loose soil is added as necessary to maintain structural volume. Because of the lower lunar gravity, we may need further development of vibration technology for optimum distribution of compaction energy. Studies would also be required to determine the effects of pre-stressing cables on the vibration and compaction technique, if prestressed lunarcrete is to be used. Use of variously designed inserts and different arrangements of internal walls should provide considerable diversity.

For a low temperature binder to give structures sufficient strength to support their own weight when forms are removed, silica glass separated from the lunar soil in fine particle sizes could be mixed with a small amount of imported alkali or with indigenous iron to form lower melting phases than the aggregate. Only a very small proportion of binder would be needed in any composition. Because powders form a harder, stronger mass in a vacuum when compared with powders whose particles are surrounded by air, it may be possible that, after compaction, the structures could hold together without need of a low temperature binder.

After the lunarcrete is vibrated in place, heated moderately, and forms removed, a simple focusing mirror could be used to heat the structure. Since the metal form is removed prior to fully sintering the structure, it must be collapsible-which makes it reusable indefinitely. If properly built, the form could hold an atmosphere and be used as temporary housing until completed structures are available. The rigid structure of the form would allow for radiation shielding by lunar soil even before compaction or sintering.

During the lunar night, heat could be supplied by electric heaters fed power from a solar power satellite or by aluminum-oxygen burners using lunar-derived aluminum and oxygen. Obviously, the earliest settlements should be planned so that the critical early heating requirements are supplied by focusing mirrors during the lunar daylight. Knowing the thermal characteristics and thickness of the lunarcrete, the proper size of the mirror and the time for heating can be readily calculated.

It should be possible to heat the structure from the outside so that the exterior surface will become molten and glazed, the interior surface will be moderately well bonded, and the central core portion of the lunarcrete will be fully sintered. The glazed exterior will be impervious to gases so no loss of atmosphere would occur. With increased understanding of the thermal characteristics of the lunarcrete, it may be possible to crystallize a glass ceramic in the glazed exterior and induce a compressive stress to the exterior surfaces of the structure, increasing its overall strength.

A moderately well-bonded interior surface will not crumble, but will be easy to anchor internal fixtures into because of its lower strength and penetration resistance. The well sintered central core portion of the lunarcrete will bear the major portions of the loads on the structure including some of the load-bearing for anchoring floors. This sintered region will also protect the glazed surface from damage from the interior by its high strength and penetration resistance. This structure should be less likely to leak atmosphere because cracks in the exterior could not propagate through to the interior to cause a loss of atmosphere. Similarly, cracks in the interior could not propagate through the sintered region and affect the impervious glazed exterior. Since only a part of the structure is totally melted, this approach should use less energy than the other methods mentioned above. 4.

A foamed or fibrous insulation could be sprayed on the interior or exterior of the structure to even out thermal loads inside the structure. Insulating the exterior will protect the glazed surface from uneven thermal stresses during the lunar day-night cycle, and from meteorite damage.

The finished surface would be concrete-like in appearance and in its physical properties. The structure would likely be very resistant to chemical attack, water damage, fire, and explosion. Small cracks in the structure will act to warn of potential failure. Proper design and construction should prevent catastrophic failure. Repair of the load-bearing portion of the structure could be performed from the exterior in a similar manner to placement or from the interior using conventional concrete repair techniques and materials.

Reuse of the same forms would greatly simplify construction, but would give a company-town appearance to the settlement. However, use of variously designed inserts could alter the external appearance significantly and, combined with different arrangements of the internal walls and furnishings, should provide considerable diversity within the community.

Future Research

The Pittsburgh L-5 Society has initiated research into this novel concept for rapid construction of lunar dwellings using the vibration formed lunarcrete described above. This research will involve further literature reviews; computer design and modeling of the particle configuration, chemical or mineralogical structure, mirror size, heating profiles, and building structure; and limited laboratory testing to confirm technical details.

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Larry Beyer, a member of Pittsburgh L5 Society

From MMM #3, March 1987

Making Concrete on the Moon & Building a Concrete Outpost

Peter Kokh reports on a visit by Dr. T. D. Lin

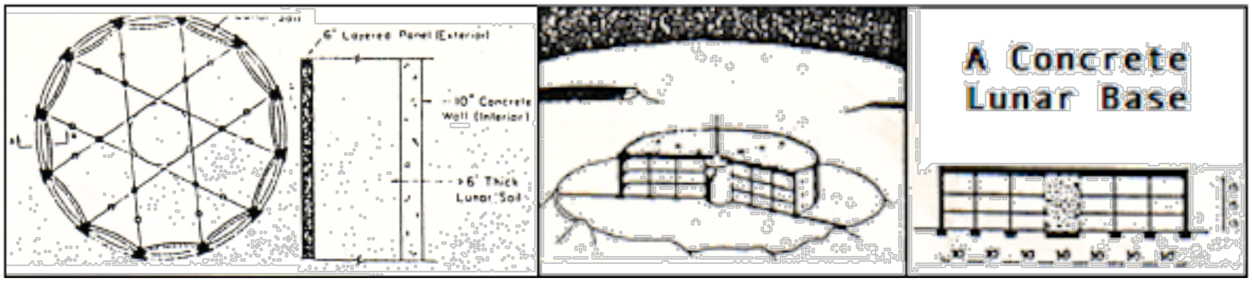
Dr. T. D. Lin, a native of Taiwan, is now living and working in this country for Construction Technology Laboratories in Skokie, Illinois wants to build a lunar base out of concrete. He appears to have done his homework. In connection with the Portland Cement Association, Lin approached NASA and received a small amount of Apollo sample return moon dust for an experiment in making concrete using lunar materials.

Since the sample was too small for more than one test, Lin experimented with lunar highlands soil
simulant, rich in aluminum and calcium, to prepare his "cement" and using raw simulated regolith in place of sand and aggregate to mix in to make his batch of concrete. It worked fine.

Once he had the experiment down pat, he tried it using the real thing. Combining water, cement, and 1.4 ounces of moon dust he produced a one inch cube of concrete that proved to be considerably stronger than our garden variety terrestrial concrete.

"We measured its compressed strength at 10,971 psi, compared to 7,900 psi for a comparative sample of conventional concrete. Since the minimum standard for a reinforced concrete slab is 4000 psi, the results were very encouraging." Lin believes the angular shape of most particles that make up the lunar regolith -- they have never been exposed to weathering by wind or water -- help create the stronger bond.

Now on the steering committee of the Lunar Development Council (LDC), whose logo is a crescent moon with a steam shovel poised on the bottom cusp, Lin has designed a large concrete lunar base. At 210 feet in diameter the three floor round concrete structure would provide 90,000 square feet with all of the materials coming from the Moon, except for 55 tons of hydrogen which would come from Earth. In addition to the cement to be processed from highland regolith, raw local regolith would be used for shielding as well as for aggregate.



The walls of each floor would consist of 12 convex sections tied together by a crisscross maze of cables under tension. As concrete is stronger under compression than it is under tension, the 10" thick convex panels work, in combination with the cable stays. An outer wall of 6" thick concrete, not under pressure would provide a surrounding bay to be filled with a minimum of 6' of regolith shielding, more piled on the roof. iron extracted from the soil would be processed not only into the tension cables but into H-shaped connectors joining the convex panels forming the inner pressure wall and the concave outer panels holding in the regolith shielding.

So instead of taking to the Moon a collection of Earth-made modules to assemble into a prefab ready-to-do-nothing outpost, with good intentions of someday working towards some early industrial projects, Lin's group would start with lunar industry, enough of it to process cement, his steel cables and panel connectors, his concrete wall, floor and roof panels, etc. The outpost itself would be the first project

This is a radically opposite approach from all others we have come across. The LDC base, once finished would be just the beginning as everything would be in place to make additional pressurized structures. You have to wonder if Lin's approach isn't the better one, that everyone else has the cart and the horse mixed up. This approach seems tailor made for a turn-key approach. LDC would build the Moonbase and then turn it over to NASA or a comparable operator who could then concentrate on operations: prospecting, exploring, and science experiments..

At 90,000 square feet, equivalent to a square one floor structure 300" on a side, this one structure would provide plenty of space for early expansion, far more room than any other proposal for a starter outpost.

Lin has also expressed a desire to repeat his experiments with simulated Mars soil. And he thinks he can cut down the amount of water (i.e. of imported hydrogen) needed if planned experiments to create concrete by steaming the ingredients instead of soaking them work as he expects. **MMM**

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CONCRETE: A Versatile Lunar Material of Choice

By Peter Kokh

In case you haven't noticed, concrete "isn't just for sidewalks and driveways anymore." Concrete is being reinvented, brought "into the 21st Century" and reformulated for a whole host of new applications old concrete people had never thought of before.

We've all been aware of "shotcrete" for some time now. Shotcrete is a refined homogenized mixture strengthened by fiber additives so it can be pumped through a hose and sprayed on interior and exterior surfaces over attached steel mesh. Common applications are on the ceilings of lofts and industrial buildings and the inside of dome structures. But now manufactures are using it for high end flooring, tile, shingles, textured wall panels, and more.

Concrete has these things going for it:

- it is poured at room temperatures (and below) and does not need high heat to fabricate as do glass, ceramic, and metal alloys
- it can be pigmented
- it can be stained and painted with many faux finishes to mimic other materials or with a unique character all its own
- it is an ideal for one of a kind and low quantity items and for outside the factory on site production.

Relevance for the Space Frontier:

Lunar Concrete Enterprises

These "selling points" make it an attractive material for frontier pioneer entrepreneurs catering to the Lunar and Martian homestead market, as well as to do-it-yourself inclined individual homestead owners. Future Lunans will have to show considerable resourcefulness in substituting for exotic (to them) materials commonplace on Earth: wood, plastics, other petroleum-based synthetic materials.

That making items for the homestead out of concrete does not require special factory furnaces or even small houseworthy kilns, as would on site manufacture of glass, ceramic or metal alloy items, makes concrete an option that is sure to become a mainstay. Cured and used indoors, the water in the poured wet mix is recovered to the biosphere. It can be pigmented with metal oxide powders.

With all the new recently field-tested ways to play with concrete's surface appearance, one doesn't have to "settle for" concrete. Concrete can be made to mimic ceramic tile, terra cotta, even wood (in surface texture and color at least). However, not all the new tricks being applied here on Earth promise to be applicable on the Moon!

Here are just some of what would seem to be "Moon-appropriate" applications:

- tables, table tops and countertops
- contour-shaped seating surfaces & benches
- lamp bases
- planters - big, small, inside, streetside
- sink basins
- shotcrete interior finishes
- textured wall panels
- floors and floor & wall tiles
- trimwork (analogous to "woodwork")

• mantles & fireplace surrounds
• fountains & pools
• inside sculptures
• garden hardscapes
• "architectural" elements
• streetside entry trim
• streetscape sculptures
• embrasures (hold back shielding surrounding an airlock access)
• air lock entry trim
• shielding mound decorative cladding
• out-vac sculptures

Some of these items are likely to be mass produced, others custom ordered or even custom made by entrepreneurs in a shop or on site, and by do-it-yourselfers, for themselves, or as part of a "cottage industry" enterprise startup. This wide range of applications and appropriate fabrication situations makes concrete so versatile.

The Devil is in the Details

Many of the new applications for concrete involve products made by extrusion. This requires a very smooth and homogeneous mixture with considerable strength. That strength is achieved by a high fiber content. Now on the Moon, it should be no problem to manufacture both glass and steel fibers. Relying on them alone will not produce the higher qualities of the cement formulations now being widely used. For in almost all cases, here the glass fibers are jacketed with polypropylene, a petroleum-derived material that will surely fall in the exotic category on the Moon. Further, these glass-composite fibers are complemented by PVA polyvinyl alcohol fibers, another Moon-exotic material.

[New tests show that glass fibers produced in vacuum have some elasticity. This may solve the perceived problem.] In addition to this fiber content, most extrudable concrete mixes substitute "Illinois Fly Ash" for up to 70% of the cement. Cement is a calcium based material that will be fairly easy to produce in large quantities on the Moon. As for the ash, a substitute that comes to mind is the fine powdery component of regolith, likely to be sifted out (and thus available as a homogenized byproduct) of most lunar regolith processing operations.

However, particle grain-size isn't the only thing that matters. Particle shape comes into play as well. While the irregular jagged shape of lunar "fines" gave the lunar simulated concrete prepared by Dr. T.D. Lin in the 1980s great strength, "twice that of everyday terrestrial concrete," that very same asset becomes a liability when it comes to extrusion of the liquid concrete mix. Illinois Fly Ash (IFA) has a spherical particle shape that makes it slippery, much like graphite powder. It should be possible, however, to further separate the lunar regolith fines for their high glassy spherule component. These spherules have been produced by the high extremely concentrated heat of impact in eons of constant micrometeorite bombardment.

But what about the fly ash chemical character - the regolith fines and glassy spherule inclusions should both be rather inert. According to the Fly Ash Resource Center fly ash is "the finely-divided CCB [coal combustion byproduct] collected by electrostatic precipitators from the flue gases." It has a high 20% carbon content.

[www.geocities.com/CapeCanaveral/Launchpad/2095/flyash.html]

Using coal fly ash conserves energy by reducing the demand for typical pavement materials such as lime,cement and crushed stone, which take energy to produce. Each ton of fly ash used to replace a ton of cement, for example, saves the equivalent of nearly one barrel of imported oil."

The most important fact of life for would be pioneers of lunar industries to keep in mind at the very forefront of consciousness can be summed up in this one phrase: "The Path Not Taken." Here on Earth, when R&D discovers something that works very well, further experimentation on all other lines that has not yet produced equivalent promise, is halted. It's simply a matter of conserving research and development dollars. Let's translate that into a "Space Frontier Pioneering Guiding Light Principle."

That R&D has been halted on a line of experimentation, doesn't indicate that there is nothing promising to be gained from pursuing it further.

We need to find people in cement industry R&D laboratories who are willing to find a way to sneak in some off-line experiments using strictly those ingredients we can produce or simulate on the Moon at acceptable energy and source material costs. Make no mistake, without that research, concrete will still be a mainstay building material on the Moon. But barring success in formulating lunar-appropriate extrudable formulations, some of the new wonder applications we are seeing here on Earth in the 90s and the current "double oughts" [as the first decade of the 20th C was called] will not be practical on the Moon. And that would be a shame.

Environmental Friendly Concrete

For the sake of argument, let's say that the suggested research is done and turns up nothing promising. Concrete would still be a space frontier workhorse even with out extruded products, without shotcrete. It can still be poured and molded and pigmented and textured.

But especially interesting from the environmental point of view is that concrete accepts aggregate inclusions: pebbles, stones, gravel – we all know about that. But if that is as far as your familiarity goes, you're no longer up to date. A California firm, Syndesis, [www.syndesisinc.com] has pioneered using the detritus of civilization in lieu of 'normal' aggregate:

> **Syndecrete®** is a restorative product, reconstituting materials extracted from society's waste stream to create a new, highly valued product. The advanced cement based composite contains natural minerals and recycled materials from industry and post consumer goods which contain up to 41% recycled content. Such materials include metal shavings, plastic regrinds, recycled glass chips and scrap wood chips to name a few. These materials are used as decorative aggregates, creating a contemporary reinterpretation of ... terrazzo. ... Syndecrete® uses no polymers or resins. ... a solid surfacing material which provides consistency of color, texture, and aggregate throughout ... less than half the weight with twice the compressive strength of normal concrete. Surfaces can be ground, polished, or textured to expose the natural porosity and aggregates. Form or mold surface finishes allow exacting detail, from wood grain to glass.

What is exciting to me about this is it will help minimize the need of lunar civilization to follow the sorry steps of their terrestrial ancestors "from mine to landfill" by creating an avenue, particularly attractive to entrepreneurs, to use the kind of manufacturing and domestic usage waste like that cited above (less the plastic and wood!) to make valued consumer goods for total less expenditure given to source materials. These inclusions have character of texture and color and visual interest, for which the energy has already been spent. Reusing that spent energy in this way will be one way to make lunar settlements more efficient and minimize what I call "throughput" – the percentage of, and rate at which, raw lunar materials pass through the lunar consumption system to end in some lunar crater landfill.

Concrete is a material with much promise for Lunan contractors and entrepreneurs and consumers. In the newborn space frontier tradition of spin-up (not off) entrepreneurs here can help pioneer the road, for profits here and now. <MMM>

Note: In other articles in other issues of MMM, there is occasional mention of concrete.

If you want to check out these references, download the

Lunar Architecture and Construction Theme issue.

http://www.moonsociety.org/publications/mmm_themes/mmmt_construction.pdf

This file is some 300 pages long. But you can simply **search for the word "concrete"** as it will appear hear and there throughout, and some of these references may shed more light on the topic.

Editor, MMM