FEASIBILITY AND APPLICATIONS OF SULFUR CONCRETE FOR LUNAR BASE DEVELOPMENT: A PRELIMINARY STUDY.

I. Casanova, School of Civil Engineering, Universitat Politècnica de Catalunya, Gran Capità s/n, Mòdul C1, E-08034 Barcelona, Spain, (casanova@etseccpb.upc.es)

A major step in space exploration activities during the 21st century will be the construction of permanent bases on the Moon. Prior to this, suitable lunar structures must be conceived and built in order to provide adequate protection to facilities and personnel from the harsh lunar environment. In this direction, considerable effort has been devoted in recent years to study the feasibility of concrete as a lunar construction material [1] that can be produced largely from components available in the lunar regolith [2,3]. Although additional technological developments are necessary, the mechanical properties and thermo-chemical stability of cement-based materials make them a very promising candidate (among few) for lunar construction activities. On the other hand, it is clear that any progress on the establishment of a permanent lunar base is necessarily constrained by the availability of in-situ resources. Major advances have been made in the design of process methods for the production of oxygen [4], cementitious materials [5] and even water [6] from the lunar regolith.

Proper evaluation of natural resources is therefore a major task in the development of strategies for moonbase site selection. As far as raw materials for concrete are concerned, water is undoubtedly the most scarce resource. Even if the existence of ancient cometary ice deposits in the South Pole-Aitken basin [7] is confirmed by the Lunar Prospector mission in 1997, the location and abundance of such a resource cast serious doubt on the feasibility of using it as a construction material. It is therefore difficult to envision mass production of conventional concrete in such a dry environment, and new options must be considered. In this sense, a need arises to find an alternative material or component to bind the solid ingredients of concrete and subsequently gain strength upon solidification. These criteria constrain the search to relatively abundant volatile substances, capable of undergoing solid-liquid phase transformations at low temperatures. In the lunar geochemical inventory, sulfur is probably the only suitable choice.

Lunar sulfur inventory. The relatively restricted S concentrations in lunar samples suggest that the sulfur content of the lunar regolith is mainly controlled by troilite (FeS) abundance. These contents range from a few tens of ppm in ferroan anorthosites to over 2000 ppm S in high-titanium lavas from the Apollo 11 and 17 sites [8]. Evaporation and condensation have undoubtedly played a significant role in the distribution of sulfur on the lunar surface. However, small veins of troilite are observed in a few lunar breccias suggesting that some kind of sulfide metamorphism, analogous to the formation of terrestrial ore deposits, has operated throughout the geological history of lunar materials. Such features may indicate local enrichments in sulfur during the magmatic history of some lunar igneous rocks; the apparent positive correlation between the S and Ti contents of mare basalt materials is consistent with fractional crystallization of an ancient magma ocean, which would concentrate the chalcophile elements into sulfide beds, as is observed in terrestrial layered intrusions [9]. The sulfide phases would preferentially migrate into the liquid during partial melting, producing a subsequent enrichment in sulfur of late-stage crystallization products such as high-Ti lavas. The global geochemical mapping to be carried out by the Lunar Prospector should provide essential information on the overall sulfur abundance of the lunar surface and identify possible local concentrations of this element.

Is sulfur concrete a viable alternative? Sulfur concrete is not a new concept. In fact, the utilization of sulfur as a molten bonding agent dates back to prehistoric times. Unmodified sulfur and aggregate materials are hot-mixed, cast, and cooled to prepare sulfur concrete products. The sulfur binder first crystallizes as monoclinic sulfur (S_β) at 114 C, with a volume decrease of about 7%. On further cooling to below 96 C, sulfur undergoes a transformation to S_α, the stable orthorhombic polymorph at ambient temperatures. Current applications of modified sulfur concretes are focussed on applications in industrial plants where acid and salt-rich environments result in premature deterioration and failure of conventional Portland cement concrete. In addition to raw material availability, some advantages of sulfur concrete of special relevance to lunar construction are: (1) Tensile, compressive and flexural strengths, as well as fatigue life, are greater than those obtained with conventional Portland cement concrete; (2) Rapid setting, achieving a minimum of 70-80 % of ultimate compressive strength within 24 hours; (3) It can be placed in below-freezing temperatures [10].

In constrast with the complex, ultra-high temperature processing required for the extraction of cementitious components from lunar regolith materials (e.g. anothosites) and in-situ production of water (requiring H_2 imported from Earth), the production of elemental sulfur from troilite is a relatively simple task, demanding only moderate temperatures (on the order of 1000-1200 C), which are easily achieved with standard solar concentrators.

A concern on the utilization of sulfur concrete may arise from the relatively poor durability of this material in response to repeated thermal cycles. Typical lunar mid-latitude average temperatures are between -53 and -18 C, with maximum monthly ranges of ±140 degrees [11]. This means that suitable locations where T_{max} does not exceed that of sulfur melting may be found on the lunar surface. On the other hand, volume changes due to polymorphic transitions are unavoidable at locations of maximum temperature ranges, with the subsequent detrimental effect on sulfur concrete integrity. Therefore, locations where monthly temperature variations do not exceed 114 C (i.e., T_{max} < 96 C) are required to prevent S_α - S_β transformation. Provided that the T_{max} requirements are met, it is necessary to evaluate the durability of the material against thermal cycles of a substantial temperature range. Freeze-thaw durability experiments (according to ASTM C 666, Method A) on sulfur concrete after one-day cooling yield values of about 60% retention of the original dynamic modulus of elasticity, after 300 cycles [10]. This result, however, cannot be extrapolated to the equivalent 300 lunar month (approximately 23 years) period since the amplitude (temperature range) of the cycles in the lunar thermal environment is substantially larger than in the experimental procedure referred to above. In principle, the larger the amplitude of the cycle, the faster the decay of elastic properties of the material. The question of how much of this amplitude effect may be compensated by the relatively long duration of the lunar thermal cycles (potentially allowing partial restoration of the damage) must be addressed experimentally. In any case, it may be anticipated that using extended cooling periods, the low frequency of thermal cycling on the surface of the Moon (one lunar month) guarantees an extended service life for sulfur concrete-based structures. Repair campaigns may be thus limited to reheating (and/or recoating) surface layers in order to sinter away the cracks. Another possible mechanism of degradation of sulfur cement-based materials is sputtering due to impact of high-energy particles from the solar wind or flares. This effect is, at worst, restricted to the outermost millimeters of the exposed material, and requires long-time scales to produce any significant damage affecting the integrity of the structure. Repair procedures mentioned above are also applicable in this case.

Dust minimization as a potential short-term concrete application in lunar base development. The environment of the Moon imposes severe restrictions on equipment design, and presents major operational difficulties due to several factors, including dust, high-vacuum, temperature fluctuations, radiation hazards, micrometeorite bombardment and low gravity [13]. Among these, the contamination of the lunar environment by dust particles from the regolith is a major concern for both equipment performance and astronomical research activities. Dust is dispersed in the lunar environment as a result of meteorite impacts and (mainly) spacecraft landing/lift-off and surface transportation activities. The construction of thin (a few tens of cm) concrete slabs for their use as landing/lift-off platforms and/or pavements on selected sites of the lunar surface will help minimize this dust remobilization problem. The feasibility of sulfur concrete production with present-day technology, in-situ availability of raw materials and enhanced flexural strength properties, makes it an attractive candidate for short-term development of the first lunar construction activities. While it is premature to conceive the actual application of such material to habitat construction for extended human presence, sulfur concrete is today a viable alternative to conventional cement-based materials for the implementation of the first in-situ-made structures on the surface of the Moon, thus “paving the road” for future lunar exploration developments and, eventually, establishment of a permanent moon-base.

References: [1] Kaden, R.A. (1991) Lunar Concrete. SP-125, American Concrete Institute. 304 pp. [2] Lin, T.D. *Concrete International* **9:** 48-53. [3] Lin, T.D. *et al.* (1987) *Proc. AIAA*, October. [4] McKay, D.S. and Allen, C.C. (1996) *Proc. AIAA* **96-0488**, January. [5] Burt, D.M. (1991) In [1]. [6] Cutler, A.H. (1984) *Symp. Lunar Bases and Space Activities in the 21st Century* (abstract), p.21. [7] Nozette, S. *et al.* (1996) *Science* **274**: 1495-1498. [8] Haskin, L. and Warren, P. (1991) In: Lunar Sourcebook: a user’s guide to the Moon. Cambridge Univ. Press, Chapter 8. [9] Taylor, S.R. (1982) Planetary Science: a Lunar Perspective. Lunar and Planetary Institute, 481 pp. [10] American Concrete Institute (1988) ACI Manual of Concrete Practice, **ACI 548.2R-88**. [11] Vaniman, D. *et al.* (1991) In: Lunar Sourcebook: a user’s guide to the Moon. Cambridge Univ. Press, Chapter 3. [12] Carrier III, W.D. *et al.* (1991) In: Lunar Sourcebook: a user’s guide to the Moon. Cambridge Univ. Press, Chapter 9. [13] Taylor, L.A.and Taylor D-H.S. (1996) *Proc. 5th Int. Conf. Space ’96*, ASCE, **Vol. 2**: 741-755.