APPLICATION OF CERAMIC-CERAMIC JOINING TO IN-SITU RESOURCES IN THE CONSTRUCTION OF LARGE LUNAR STRUCTURES

R. S. Crockett and B. D. Fabes

Department of Materials Science and Engineering
University of Arizona, Tucson AZ 85721

Abstract

Structural materials that can potentially be produced *in-situ* from lunar resources include sintered regolith, glass, or glass-ceramic blocks, plates, and beams. The total volume of each of these components will be on the order of 1 m^3, limited by processing constraints. Joining of basic building units will thus be required to produce large lunar structures. In this paper, ceramic-ceramic joining methods are applied to the potential products of lunar soil. Joining options and associated issues are presented. A series of experiments using simulated lunar soil was performed for selected joining techniques. Results indicate that both *material selection* and *heat treatment of components* are areas with significant issues which will require further research.

I. Introduction

The case for using *in-situ* resources as structural materials in a future lunar base has been well established. Building large structures from the products of lunar soil promises to be a key means to reducing dependence on Earth as a lunar base evolves towards self-sufficiency. Designs for large pressurized habitation modules[1], unpressurized storage facilities[2], and ground preparation such as roadways or landing pads[3] have all been presented as potential applications for lunar-produced structural components. Many basic material science issues, however, still need addressing before viable system studies can be performed.

The products of lunar resources, whether formed as large blocks or cast into more complex shapes, will be limited in size. The total volume of each component will be on the order of 1 m^3, limited by processing constraints such as stress induced during cooling, practical limits to form sizes, and the power output of the processing facility. Joining of basic building units will thus be required to produce any type of large lunar structure. In this paper, we discuss techniques for joining individual components, applying ceramic-ceramic joining methods to the potential products of lunar soil.

Six joining options are presented, along with an examination of associated issues and potential applications. A series of experiments using simulated lunar resources was performed to evaluate these options. Results indicate that both *material selection* and *heat treatment of components* are areas with significant issues which will require further research. The joining of sintered regolith through fusion welding seems to be the most promising of all techniques evaluated.

II. Use of In-Situ Resources for Lunar Structures

Several processes have been proposed for producing structural materials from lunar resources. These include[1]:

- Hot-pressing (sintering) of soil to produce blocks of low-to-medium compressive strength.
- Melting the soil and cooling in molds to produce cast basalt blocks, tiles, or pipes with fairly large compressive strength.
- Applying heat-treatment cycles to melted soil under a more controlled process to produce glass and glass-ceramics which may provide a better combination of strength and toughness.
- Direct melting of lunar soil in place to produce continuous glass-like surfaces.
- Lunar soil combined with terrestrial Hydrogen to produce concrete.

The maximum size of a single cast will be on the order of tens of centimeters per side, limited by stresses induced during cooling. The extent to which unusual shapes can be produced will also be restricted by processing limitations. Thus large structures built using lunar resources will require joining of the individual cast

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components. Additionally, the structure must be sealed if it is to hold a pressure atmosphere. Both joining and sealing of components can potentially be accomplished using entirely indigenous materials, by taking advantage of the glass-forming properties of lunar soil.

III. Joining / Sealing Options Using In-Situ Resources

The products of unrefined lunar soil will be ceramic materials; ceramic-ceramic joining techniques used for structural and electronic applications on Earth are thus a logical starting point in developing joining methods for lunar applications. These techniques include *Mechanical Joining, Adhesive Bonding, Fusion Welding, Glazing, Brazing,* and *Diffusion Bonding* [4].

While it may be possible to produce all of these types of joints using in-situ resources, some techniques are more practical for lunar applications than others. The brazing and diffusion bonding processes, for example, are relatively complex, and adhesive bonding will require compounds brought from Earth. The following options for joining structural components produced from lunar soil all make use of available lunar resources. They span a range of complexity from simple stacking of blocks to the formation of a continuous surface by casting lunar materials in place.

The evaluation of options for joining / sealing of individual components must be performed within the context of the final structure. Internal pressure and the effect of lunar gravity on the mass of the structure can either assist or impair a given joining / sealing technique. Since materials cast from lunar soil are generally much stronger in compression than in tension[5], the geometry of the blocks themselves and the orientation of the individual joints within the blocks will be critical. Selection of a joining / sealing technique, then, is a function not only of the individual joints, but of the loading and geometry of the final structure.

A. *Mechanical Joining:* *Simple Stacking / Interlocking Blocks*

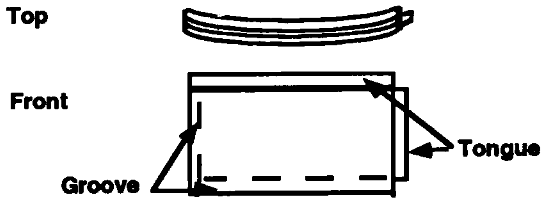

Figure 1. Simple Stacking / Interlocking Blocks.

This is the least complex of all joining options. Individual components are stacked in a tongue-in-groove type arrangement. Gravity, external loading, the geometry of the blocks, and forces from internal pressure are balanced to produce a stable structure. If the structure is to be pressurized, it will require an internal bladder or additional sealing. This technique is also applicable to flat structures, such as a surface covered by interlocking tiles.

Key Issues -
- o Requires more complex shapes of cast components to provide interlocking.
- o Structural integrity depends on shear and tensile strength of tongue.
- o Low gravity of moon does not provide a large stabilizing force, possibly limiting this option to low pressure or unpressurized structures.

Likely Applications -
Low pressure / unpressurized enclosures, ground preparation.

B. *Mechanical Joining:* *Interlocking Blocks + Gaskets*

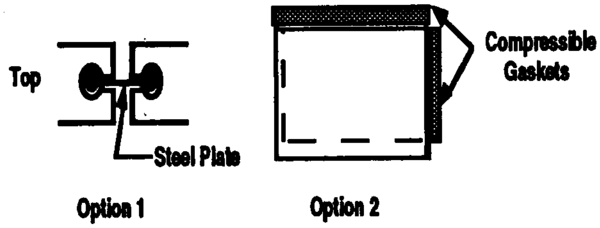

Figure 2. Interlocking Blocks + Gaskets.

This technique is similar to simple stacking, but provides for the ability to seal the structure by compression from internal pressure. An internal bladder or additional sealing may not be required, but gasket material must be manufactured locally or brought from Earth.

Key Issues -

- o Same as for simple stacking, but with increased complexity.
- o Compression sealing requires interlocking of blocks to support higher loads (places more burden on the strength of cast lunar components / interlocking joint).
- o Expansion of the gasket material must be compatible with that of the blocks through the thermal cycling of lunar day/night.

Likely Applications -
Pressurized enclosures.

C. *Fusion Welding*

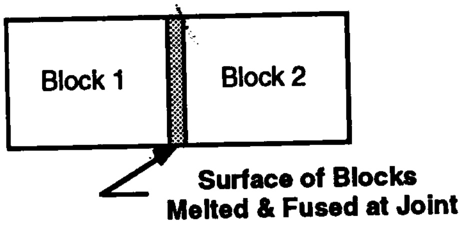

Figure 3. Fused Blocks.

This method uses heat (potentially in the form of a concentrated solar flux) to melt the surface of adjoining blocks so they fuse together. Fusion welding can be used for interlocking or simple flush-surfaced blocks, but the surfaces must be closely butted together. A likely application is to use this method with interlocking blocks to ensure stability of the structure. If structure is pressurized, an internal bladder or additional sealing will most likely be required. This method also lends itself to the joining of flat tiles.

Key Issues -

- o Resulting joint will be relatively brittle.
- o If the coefficient of thermal expansion of the material formed at the interface is different from that of the blocks, the fused zone will be subject to high stress and may crack as it shrinks during cooling.
- o Ability to melt surface of blocks will vary dramatically with the material being fused. Heat transfer through the material must be low enough to maintain sufficient surface temperatures, but high enough to avoid thermal shock -- this may limit the practicality of this method to the joining of sintered blocks.
- o Preheating of blocks may be required to minimize thermal shock.

Likely Applications -
Low pressure / unpressurized enclosures, ground preparation.

D. *Glazing: Heat Melt*

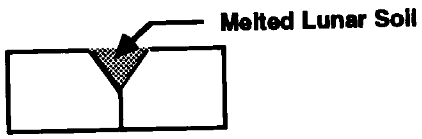

Figure 4. Heat Melt.

This method is similar to the fusion welding technique, but with melted lunar soil acting as the interface material. Soil is packed between components and heated, melting to form a glass bond.

Key Issues -

- o Lunar soil is an extremely effective thermal insulator at high temperatures, where heat transfer occurs by radiation. If direct solar heating is used, only the top few mm of soil will melt to form a useful bond unless additional heat transport mechanisms are introduced.
- o Vaporization will occur in high vacuum environment during heating, changing the composition of the melt.
- o Joint will become highly stressed due to change in volume during cooling unless the joint is annealed.
- o Resulting joint will be relatively brittle.
- o Preheating of blocks may be required to minimize thermal shock.

Likely Applications -
Low pressure / unpressurized enclosures, ground preparation.

E. *Glazing: Cast Joining*[6]

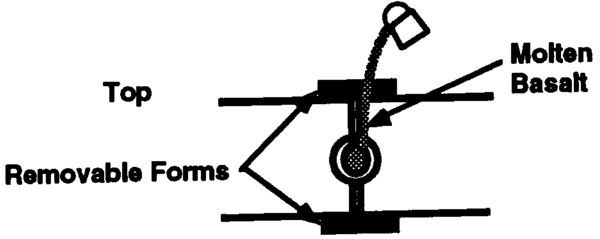

Figure 5. Cast Joining.

A high temperature (~1600 C) melt of the same material is poured between components. This re-melts the outer layer of the blocks, forming a continuous interface gradient. Ideally, the joint formed will be as strong as the components themselves.

Key Issues -
- o Requires more complex shapes of cast to provide surface for melt containment.
- o Forms are required during pouring, which must withstand the high temperatures involved.
- o Vaporization will occur in high vacuum environment during heating, changing the composition of the melt.
- o Heat content must be sufficient to melt the block surfaces.
- o Method may be limited to small joints, as melt will tend to cool rapidly, becoming extremely viscous before filling entire void.
- o Cooling cycle must be controlled to allow for an acceptable interface gradient and matching of mechanical properties.
- o Preheating of blocks may be required to minimize thermal shock.

Likely Applications -
Pressurized enclosures.

F. *Continuous Cast*

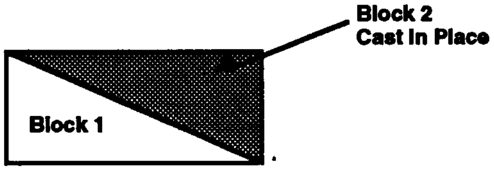

Figure 6. Continuous Cast.

This is an extension of the Cast Joining method, where each block is cast in place during structure construction to form a single unbroken surface. The melt for a new block is cast in direct contact with adjacent blocks. As new cast is cooling, surfaces of existing blocks will re-melt, forming a continuous interface gradient between components. May not require internal bladder or additional sealing.

Key Issues -
- o Forms are required during pouring, which must withstand the high temperature of the melt.
- o Cooling cycle must be controlled to allow for an acceptable interface gradient and matching of mechanical properties.
- o Vaporization will occur in high vacuum environment during heating, changing the composition of the melt.
- o Preheating of existing blocks will most likely be required to minimize thermal shock.

Likely Applications -
Pressurized enclosures.

IV. Experimental Evaluation

To evaluate these methods, potential joints were experimentally tested. These experiments were limited to techniques involving direct manipulation of lunar soil and performed on small block sample sizes. Simulated lunar soil was processed into *sintered soil*, *glass*, and *glass-ceramic* blocks. These samples were cut and then rejoined using four methods: *fusing*, *heat melt*, *cast joining*, and *continual cast*, with the effect of preheating and cooling profiles evaluated to identify potential pitfalls and key issues.

A. Sample Preparation

Both the block samples and the joining material were prepared from the same batch of simulated lunar soil The composition of Apollo 15 lunar soil was chemically reproduced (except for trace elements) from 99.5+% pure oxides in the following weight percentages:

Table 1. Simulated Lunar Soil Composition (Modeled After Apollo 15).

Component	Formula	wt. %
Silica	SiO_2	47.0
Alumina	Al_2O_3	14.7
Ferrous Oxide	Fe_2O_3*	14.4
Magnesia	MgO	11.6
Calcium Oxide	CaO**	10.9
Titania	TiO_2	1.4

The simulant was prepared by mixing the oxide powders in a ball mill, melting the mixture in a platinum crucible at 1600° C, and casting into glass blocks by pouring the melt onto a copper plate. The resulting glass was then ground into a fine powder, remixed, and remelted to ensure homogeneity. From this second, homogeneous melt, the samples were prepared as follows:

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* Actual lunar soil contains the reduced state, FeO

** Produced from reaction: $CaCO_3 \rightarrow CaO + CO_2$

Glass -
The melt was poured at 1600° C and cast into 95 X 45 X 15 mm blocks using copper forms on a copper plate. These blocks were then annealed for 1 hour at 600° C and allowed to cool overnight in the furnace. Resulting blocks were opaque black without any visible flaws.

Glass-Ceramic -
Glass blocks were cast and annealed as described above. These blocks were then subjected to the following temperature profile to allow crystallization: ramp to 800° C, soak 4 hrs (crystal nucleation), ramp to 1000° C, soak 2 hrs (crystal growth), allow to cool overnight in annealing oven[†].

Sintered Soil -
To produce blocks made from sintered lunar soil, a glass-ceramic was prepared as described above, then ground to a powder and sieved to a maximum size of roughly 1 mm. The powder was then hand-pressed (~25 psi) into 95 X 45 mm alumina molds, sintered at 1140° C for one hour, and allowed to cool slowly in an annealing oven. Resulting blocks were red, fairly weak and crumbly where they were in contact with the mold, darker gray and nearly glassy at the exposed surface. The total porosity of the final sintered samples was ~ 60%, as determined by micrographs taken of a polished cross section.

Each block was cut into four 23 mm wide pieces using a low speed diamond saw to produce two sets of samples (see photo of prepared and cut samples, Figure 7). The remaining crystallized powder was used as the joining soil for the heat melt method, and scrap lunar glass was used for the cast join and continual cast methods.

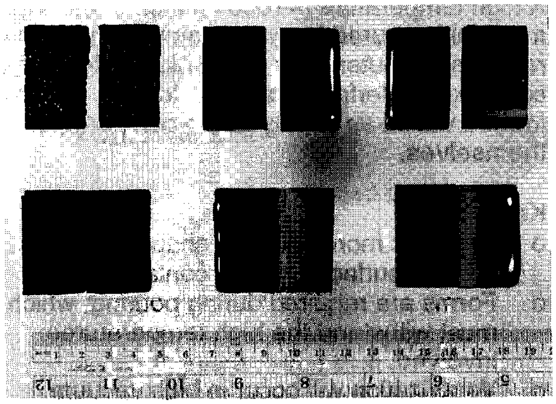

Figure 7. Prepared Samples: Sintered Soil, Glass, Glass-Ceramic Blocks.

B. Joining Techniques

The University of Arizona 1.5m solar furnace[8,9] was used to provide a solar flux for the fusing and heat melt methods, and an electric furnace was used to melt the soil for the cast join and continuous cast methods. Joining of samples was performed in the following manner:

1. *Fusing -*
Blocks were butted up against each other on a motorized positioning platform. The joint was then placed under the focus (approximately 1 cm beam) and moved through the length of the joint at a rate determined by visually monitoring the sample for signs of surface melting.

2. *Heat Melt -*
A 45° notch was cut on each sample side, the pieces were butted up against each other, and crystallized powder (simulating unprocessed lunar soil) was placed in the notch. The sample was then placed under the focus of the beam and moved as described before through the length of the joint.

3. *Cast Join -*
A 45° notch was cut on each sample side, the pieces were butted up against each other, and melted soil (1650° C) was poured into the notch for three cases of pre-and-post heat treatment:

a. Sample blocks at room temperature, joint allowed to cool in air.

[†] This temperature profile was selected based on previous work[7] on a composition with less iron. When applied to the Apollo 15 composition, however, one of the blocks fractured during crystallization and most had small but visible flaws. This indicates that the selected profile is not *universally* optimum.

b. Sample blocks preheated to 600° C, joint allowed to cool in air.
c. Sample blocks preheated to 600° C, joint annealed at 600° C and allowed to cool slowly in oven.

4. *Continuous Cast -*
Samples were cut lengthwise at a 45° angle. They were then preheated to 600° C, and a melt of ~same volume was poured on the slanted top surface at 1650° C. Resulting block was annealed at 600° C and allowed to cool slowly in an annealing oven.

Successful joints were then cross-sectioned, with one half broken through four-point bending on a mechanical testing machine.

C. <u>Results</u>

1. *Fusing -*
During heating in the solar furnace, the glass and glass-ceramic samples fractured (Figure 8). The glass sample fractured into small fragments where the solar flux was greatest. The glass-ceramic sample failed much more dramatically -- it fractured forcefully into ~2 cm blunt pieces, with the fragments being propelled off the test stand.

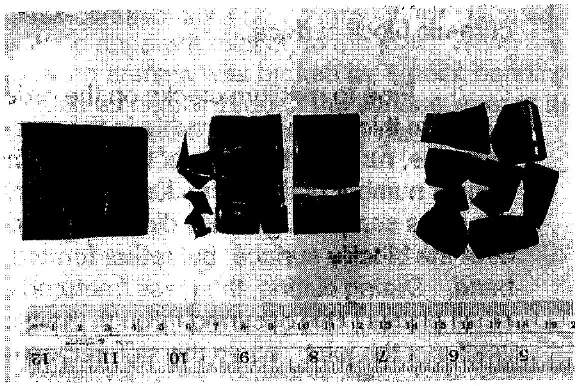

Figure 8. Fused Joints: Sintered Soil, Glass, Glass-Ceramic Blocks.

Although the glass and glass-ceramic blocks fractured after the same amount of time (approximately 5-10 seconds under the solar flux), the amount of surface melting which occurred in this period was quite different between the two samples. The surface of the glass sample had melted to a depth of almost 2 mm, whereas the glass-ceramic sample showed almost no surface melting. The amount of melted glass on the surface of the glass blocks appears to be equal to the amount on the sintered sample, yet it did not flow together to form a joint before the sample fractured.

The sintered sample survived the thermal shock without any signs of damage. A bond was formed between the surface and the glassy melt to a depth of 2 mm. As the time in the solar flux was increased, the melted surface area increased, but the depth did not (the glass puddle got wider, but not any deeper). When the sintered sample was broken by 4-point bending, it failed through the surface layer of the sample around the thinnest edge of the glassy joint.

2. *Heat Melt -*
As seen in Figure 9, the sintered sample was again the only one to survive the thermal shock of the solar flux. The glass and the glass-ceramic blocks fractured, but less dramatically than in the fusing experiment. This is possibly due to the fact that the blocks were partially insulated by the powder in the joints. Additionally, some preheating of the blocks was achieved by moving the focus rapidly over the entire sample before attempting the joint.

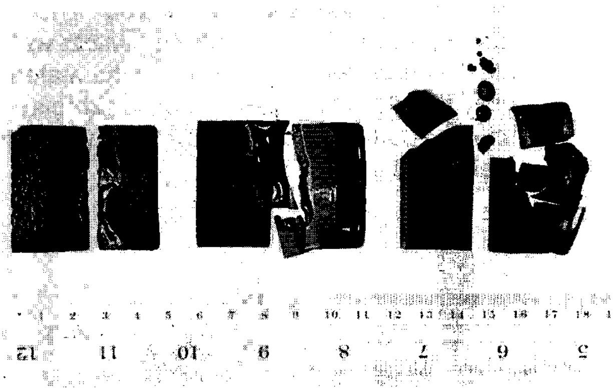

Figure 9. Heat Melt Joints: Sintered Soil, Glass, Glass-Ceramic Blocks.

The effect of soil melting under the solar flux was the same for all samples:

- Small glass spheres formed almost immediately.
- These spheres eventually consolidated into a large "ball" held together by surface tension and not bonded to the surface of the blocks.
- As the ball increased in size, it actually drew additional powder up out of the notch.

- Only when the *blocks themselves* got hot did the large ball of glass flow out to form a bond with the surface (the glass actually appeared to be vaporizing at this point).

The glass-ceramic sample fractured before the powder melted and began to consolidate. On the glass sample, only the surface of the powder was melted, to the same 2 mm depth found in the fusing experiment. The powder below this layer of glass remained unchanged.

In the case of the sintered sample, there was a distinct bond between the glassy melt and the surfaces, but actual joining between blocks occurred over only a small area. This was typical of the observed tendency in all samples for the new melt to cling to the individual block surfaces without flowing across the joint.

3. *Cast Join -*

3a. No Block Preheat or Anneal

Figure 10 shows the results of pouring melted simulant directly on the three unheated samples. As in the other cases of unheated block material, only the sintered blocks survived the thermal shock without breaking. The melt formed a glass immediately on contact with the block surface without bonding to the material. Only the glass and glass-ceramic samples showed partial bonding, in the area where the melt made it's first contact.

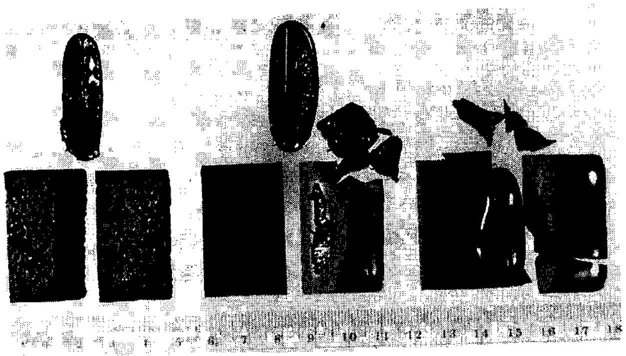

Figure 10. Cast Joints - No Preheat or Anneal: Sintered Soil, Glass, Glass-Ceramic Blocks.

3b. Preheated Blocks

Figure 11 shows that all three of the preheated blocks survived the initial thermal shock of the melted simulant. There was no visible damage to the sintered block, and only a small amount of surface damage visible on the glass and glass-ceramic samples (cracks in the glass block, surface flakes on the glass-ceramic block). The glass and glass-ceramic samples were highly stressed as a result of the thermal shock, however, for they fractured during later cutting.

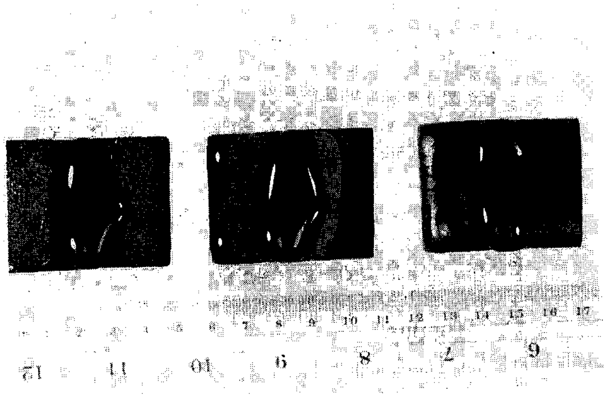

Figure 11. Cast Joints - Preheated Blocks: Sintered Soil, Glass, Glass-Ceramic Blocks.

A uniform bond was formed between the melt and the surface of the sintered and glass blocks. The glass-ceramic sample also bonded, but the joint broke cleanly away during later cutting, taking with it a small layer of the glass-ceramic block surface.

Fine to medium cracks on the order of 0.05 mm thick were observable in the glassy interface, running the width of the joint. The largest number of these cracks was observed in the glass sample. The melt did not spread out over the block's surface, but rather formed a bead. During cutting, the glass fractured into small pieces; this occurred through the block itself, not the joint. When the sintered sample was broken by 4-point bending, it failed through the surface layer of the sample around the edge of the glassy joint.

3c. Preheated Blocks / Annealed Joint

Figure 12 shows that again all three of the preheated blocks survived the thermal shock of the poured melt. There was no visible damage to the sintered block, and the observable surface damage to the glass and glass-ceramic samples was similar to that found in the preheat alone experiment, but with fewer cracks present. Again, however, the glass and glass-ceramic samples fractured during later cutting.

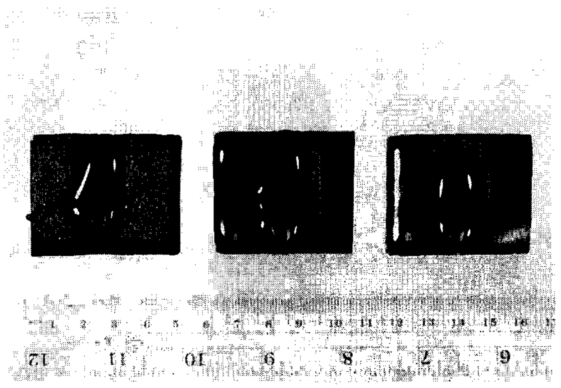

Figure 12. Cast Joints - Preheated Blocks / Annealed Joint: Sintered Soil, Glass, Glass-Ceramic Blocks.

Bonding occurred on all blocks, with the annealing appearing to have reduced the stress in the glass-ceramic block and eliminate the problem of joint separation which occurred in the preheat alone experiment. Cracks observable in the joints were minimal, with each crack approximately 0.03 mm wide. Figure 13 shows the cross-section of all three samples. The glass block fractured during cutting almost identically to the glass sample without annealing. The glass-ceramic block broke through the material with no apparent relation to the joint. When the sintered sample was broken by 4-point bending, it failed as before through the surface layer of the sample around the edge of the glassy joint.

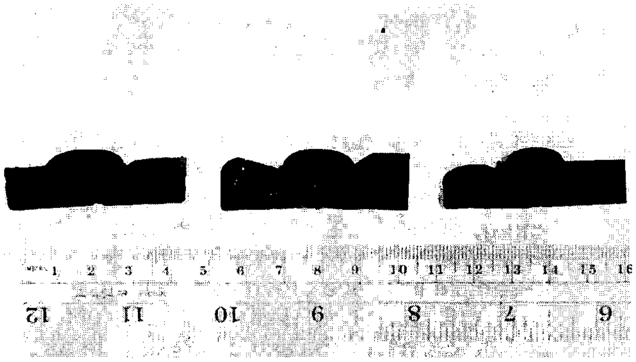

Figure 13. Cast Joints - Preheated Blocks / Annealed Joint: Cross section of Blocks.

4. *Continuous Cast -*

Figure 14 shows the cross section of the glass and glass-ceramic blocks prepared using the continuous cast method. Both samples held together during the thermal shock, but the glass-ceramic showed numerous fine cracks approximately 0.03 mm wide. A uniform bond was formed, which showed no preference when the samples were broken. The interface of the glass-ceramic block is visible by a distinct color difference between the original crystalline material and the poured melt, which formed a glass. The interface of the glass block is visible due to a ~3mm band where the block surface crystallized during cooling.

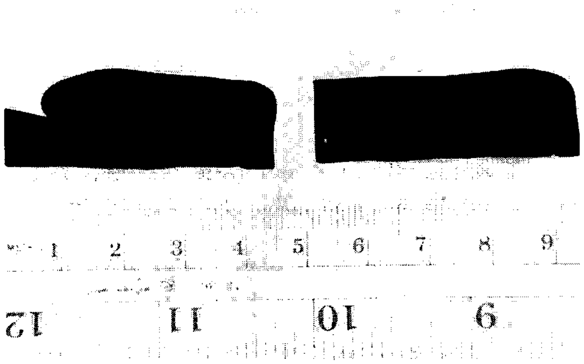

Figure 14. Continuous Cast Joints: Cross section of Blocks.

D. Discussion

As is evident by the number of samples which fractured, there are significant issues associated with joining by the methods evaluated. These can be grouped into two general categories -- *material selection*, and *heat treatment of components*:

1. Material Selection

Success of these techniques depends on the material properties of the components being joined. Thermal shock and residual stress in the blocks were the limiting factors in this set of experiments. A material's ability to survive thermal shock is a matter of both avoiding fracture upon a high temperature gradient, and suppressing propagation of any cracks that do form. Equations 1 and 2 , below, show that the allowable temperature drop without causing fracture is a function of R_i, a material's resistance to thermal stress, and S, a geometric shape factor[10].

$$\Delta T_f = R\,S \qquad (1)$$

$$R_i = \frac{\sigma_f\,(1-\mu)}{E\,a} \qquad (2)$$

High fracture stress (σ_f), low modulus of elasticity (E), and low coefficient of thermal expansion (a) all tend to increase the value of R_i, and thus are the factors which limit crack initiation.

Equation 3 shows a material's resistance to crack propagation (R_p). Cracks are less likely to propagate in materials with *low* strengths and *high* elastic moduli, or in porous / non-homogeneous materials where the energy of cracks initiated at the surface can be dissipated by pores or grain boundaries:

$$R_p = \frac{E}{\sigma_f^2 (1-\mu)} \qquad (3)$$

There is often a direct trade-off, then, between strength and thermal shock resistance.

Of the samples used in the experiment, the sintered blocks consistently survived thermal shock because of their high porosity (~60%), which prevented crack propagation. The glass and glass-ceramic blocks, however, had reactions more typical of brittle ceramic materials, fracturing dramatically upon sudden temperature changes or during later cutting as a result of residual stress. It is important to note that these blocks were not optimized -- a heat treatment schedule could be developed to create a stronger glass-ceramic block, and the sintering used in the experiments produced samples which were highly porous but significantly weaker than the glass or glass-ceramics. Nonetheless, components *will* be thermally stressed without preheating, with glass and glass-ceramic materials the most susceptible to failure by thermal shock.

A key limitation to any method employing a solar flux is the opaqueness of melted lunar soil. As soon as a melt forms under a solar flux, the opaque surface layer blocks any further radiative heat transfer. In agreement with previous experiments[5], it was found that only the top few mm could be melted by direct solar radiation. This can also explain the difficulty of melting the surface of the glass and glass-ceramic samples using the fusion welding method. The surface of the sintered samples melted much more rapidly under a direct solar flux, possibly due to a combination of a higher initial absorbance coefficient, and because of the high porosity of the sintered sample's surface.

There is a trade-off in material selection when receptiveness to joining by these methods is considered. Glass and glass-ceramics are potentially strong materials, but have low thermal shock resistance and are harder to work with under a solar flux. Although the sintered material was weaker, it was by far the most receptive to the types of joining methods studied due to its combination of resistance to thermal shock and ease of use in direct solar melting.

2. Heat Treatment of Components

As discussed above, thermal shock and residual stresses were the critical factors in all materials except the sintered blocks. This shock was reduced, but not eliminated, by preheating the blocks to 600° C. To eliminate structural damage to brittle materials, preheating temperatures will have to be closer to the actual temperature of the melt used in joining. Post-joining treatment, or annealing, did not appear significant to the survival of joints on this scale, but will have to be evaluated on a larger scale.

Additionally, the temperature of the surfaces being joined plays an important role in ability to bond. In the glazing process, heat transferred from the melt acts to raise the surface of the material to a temperature sufficient for bonding. Because the same composition is used for both the components and the joining medium in these methods, the final temperature must be fairly close to the composition's melting temperature to ensure a good bond. Without preheat, the melt may not have enough heat content to melt the block surface. Preheating the blocks to 600° C appears sufficient at this scale of joint.

Another consideration in elevating the temperature of surfaces prior to bonding is the observed effect of temperature on the surface energy of the samples. As seen in the heat melt experiments, the high energy of the glass melt-to-sample interface prevented wetting, and thus any significant bond, until the surface of the blocks was nearly the same temperature as that of the melt.

A final, though critical, effect of block temperature is that of maintaining low viscosity of the glass melt. In extending these methods to a larger scale where the joining material must flow over longer distances, cooling rate and resulting viscosity increase will be critical.

V. Conclusions

Methods of joining lunar-produced structural components using indigenous resources cannot be developed or evaluated independent of the materials to be joined. Surviving thermal shock and avoiding residual stresses are the limiting factors to the success of a joint; susceptibility to these are determined by material properties. The set of properties considered optimum for use as a structural material may not be the same as that for successful joining. While procedures such as pre-and-post heat treatment can reduce the impacts of the joining method, they also tend to increase the complexity of the process. What is needed, then, is to find the balance between practicality as a structural material and ease of joining. At this point, fusion welding of sintered regolith appears to be a promising combination, and it should be further investigated.

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