RENEGOTIATING THE INTERFACE BETWEEN THE BUILT AND NATURAL ENVIRONMENTS (pg1, top)

by

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… As modern building technologies have increased our ability to control our environment, we have sought to establish a universal conception of human comfort where the building envelope is often a barrier to nature, a fortress where we have complete control over the parameters of our space, disconnected from the specificity of the varied climates we inhabit… **(pg 2, top)**

…Thus our physical separation from the natural environment not only affects our physical perceptions of climate but also our mental construct of time, further disconnecting us from the realities faced by the natural world.

Gregory Bateson discusses this phenomenon in *Mind and Nature*: "We are parts of living world" but "most of us have lost that sense of unity of biosphere and humanity which would bind and reassure us all with an affirmation of beauty…"[1] **(pg 1, intro)**

…In examining the process of biomimetic research and implementation Arnim von Gleich identifies three "levels of learning from nature," which serve as a framework for discussing methods of implementing these lessons in design: 1)"learning from the success principles of evolution," 2)"learning from the process of evolution," and 3) "learning from the results of evolution." The most abstract of these levels is "learning from the success principles of evolution," which looks at broad, successful evolutionary themes such as solar energy opportunism, multi-functionality, material efficiency, adaptability, and multi-dimensional optimization…[2] **(pg 1, bot)**

…To initiate the material investigation that would become the foundation for the experimental design process of this thesis, I started by examining material properties that I felt had an inherent relationship to the concept of reconnecting to nature-blurring the boundary between inside and outside. The property I decided to pursue is porosity. In nature, most materials "have a cellular structure and thus contain a significant amount of porosity, which plays a key role in optimizing their properties for a specific function."[3] Porosity establishes both a literal and a conceptual connection to the idea of reconnecting the built environment with the natural… **(pg 2, middle)**

…So, by 1) selecting an appropriate starting material, 2) specifying the physical structure of its porosity (through the specific techniques of forming the material), and 3) controlling the density

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[1] Bateson, Gregory. *Mind and Nature: A Necessary Unity*. New York: Dutton, 1979.

[2] Gleich, Arnim von. "Potentials and Trends in Biomimetics," Berlin: Springer, 2010. <http://public.eblib.com/EBLPublic/PublicView.do?ptiID=571317>. 24-27.

[3] Scheffler, Michael, and Paolo Colombo. *Cellular Ceramics Structure, Manufacturing, Properties and Applications.* Weinheim: Wiley-VCH, 2005. <http://dx.doi.org/10.1002/3527606696>. p XIX.

(the ratio of the solid material to void space), a unique material can be developed and its specific properties can be tightly controlled… **(pg 1, top)**

… These techniques can generally be classified into three main categories: 1) replication of polymeric foam by application of a ceramic slurry to a foam template which is burnt out during the firing process (replication), 2) direct foaming of the ceramic slurry through mechanical agitation or in situ formation of gases (direct foaming), and 3) incorporation of additive materials, usually in the form of beads or small particles, which are burnt out during firing, leaving behind their form in the final ceramic product (pore burn out). These processes are described in great detail by Binner[4] and Colombo.[5]

To begin my material investigation, I selected the foam replication technique because it creates the most uniform, easily reproducible results which is an important consideration in trying to understand how to identify and manipulate material properties, having no previous background or experience working with ceramics manufacturing. To create the samples, I simply soaked a soft polyurethane sponge in a ceramic slurry, allowed it to air dry, and then kiln fired it to burn out the polyurethane and sinter the ceramic body… **(pg 2, bot)**

…To explore this behavior further, I sought to establish the relationship between the three critical properties involved: density, water holding capacity (a result of the degree of porosity and interconnectedness of cells), and structural capacity (in this case, compressive strength). To test this, samples were made with different densities by adding more or less ceramic to the foam template to see how the other physical properties of the material would be affected. Despite a difference in weight between the two samples of 35%, the difference in porosity is only 2%, and the difference in the percentage of water volume to void volume is only .02%, suggesting that increasing the amount of ceramic has only a limited negative affect on the water holding potential of the block, within a certain range.

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[4] Binner, Jon. "Ceramic Foams," in *Cellular Ceramics Structure, Manufacturing, Properties and Applications,* ed. Scheffler, Michael, and Paolo Colombo. Weinheim: Wiley-VCH, 2005. <http://dx.doi. org/10.1002/3527606696>. 33-56.

[5] Colombo, Paolo. 2006. "Conventional and Novel Processing Methods for Cellular Ceramics". *Philosophical Transactions: Mathematical, Physical and Engineering Sciences*. 364, no. 1838: 109-124.

Thermal surface temperature testing confirms what was established by the physical property testing: the ceramic density has a limited effect on the porosity and therefore on the evaporative cooling potential. Both samples performed in a very similar way during thermal tests, with the more dense sample lagging behind slightly, but still ultimately reaching the same temperature differential between surface temperature and air temperature as the less dense sample. These tests also suggest that by controlling the amount of wind and water, the surface temperature of the material can be controlled.

The final step was to test the compressive strength of the samples using crush testing on the Instron machine. These tests show that while ceramic density may not have a significant effect on the evaporative cooling ability of the cellular ceramic within the range tested, it does have a significant effect on the structural capacity, in this case specifically, compressive strength. The sample with the greater density (B) had almost double the compressive capacity of the lighter sample (A). These results, combined with the results of the previous tests suggest that the greatly improved mechanical performance of the heavier sample more than makes up for the slight decrease in porosity when considering this material for applications as a building material with evaporative cooling potential. **(pg 3, top)**

After discovering the potential for cellular ceramics to perform as an evaporative cooling building material (an unexplored application for an established class of materials) I decided to move away from the ceramic replication method for creating porosity in favor of a different method that could yield a material of similar characteristic.

The replication process has several restrictive aspects that affect the range of possible properties in the final product. For one, the cellular structure is determined by the foam template used in the process. Unless a unique foam template is first developed and manufactured (an entirely separate process) there is a limited number of foam variations commercially available. Also, the reliance of the process on kiln firing carries its own restrictions-from the toxicity of the foam burn-out to the dimensional limits and the energy consumption involved in firing and transporting the material...**(pg 3, bot)**

…Utilizing the foam generator and foaming agent provided to me by Richway Industries[6] from their CreteFoamer division,[7] I was able to begin exploring the possible material variations. The process involves generating a wet foam (with the specifically designed foaming machine) and mixing it directly with the concrete slurry. The resulting porosity (and related properties) depend on 1) the properties of the concrete mixture (raw materials, ratios, and additives), 2) the quality of the wet foam (effected by water purity and concentration of foaming agent) and 3) the ratio of foam added to the concrete slurry (density).

In exploring this material's potential as an evaporative cooler, one critical issue became how the material interacts with water. The cellular ceramic was effective because it can not only absorb water, it can also hold it within its cellular structure. This is a result of the open nature of the cellular structure and the size of the cells themselves. With the foam concrete, one issue is the nature of the edge condition-if the edge is sealed off and impervious to water, it doesn't matter if the interior structure is open celled, because water cannot pass through the edge to access it. The edge condition of the cured concrete foam can be affected by the type of formwork, stability during the curing cycle, and also finishing techniques after curing. Additionally the degree of permeability (openness) is dependent on the density of the final product (controlled by the amount of foam added to the mix). The less dense the material, the more void (air) space, the greater the connectivity between the void spaces. This is due to the fact that intercellular connectivity is a result of individual cells intersecting each other and creating connected chains throughout the material. When more foam is added to the mix, there is a higher concentration of cells, and therefore they intersect each other at a higher rate, leading to better connected chains of void space.

Now that some basic relationships between the processes for making the material and the potential for the material to function as an evaporative cooler are established, it is necessary to figure out the relationship between the material's capacity to hold water and its structural qualities. Testing of samples showed that water holding potential was dramatically reduced near a threshold of 0.8 g/cm3 (50 lbs/ft3) which corresponds to a compressive strength of less than 900 psi (based on established density and compressive strength data found on the cretefoamer

[6] Richway Industries. <http://www.richway.com>.

[7] CreteFoamer. <http://www.cretefoamer.com>.

website).[8] In effect this demonstrates that in its most effective water holding range, the foam concrete cannot be used as a structural material. It does demonstrate high potential for use as an evaporative cooling material but must depend on a stronger material system for structural stability in building application… **(pg 4, top and middle)**

…In response to these conditions, native species to desert regions offer a framework of possible strategies that can be applied to the design process. For example, to deal with the lack of water, desert plants and animals store water when it's available and then conserve it by minimizing water loss during transpiration and respiration. And ultimately, when the water runs out, they have a certain tolerance for dehydration. To mediate the extreme heat and radiation, desert species strive to reduce heat input on a formal level (through shading, posture, and orientation) as well as a material level (insulative and reflective properties). Then, what heat they are exposed to, they seek to dissipate either through evaporation or through long appendages that radiate heat away from the central body. And once again, to a certain level, the species have learned to tolerate the extreme heat by adapting activity patterns to correspond to the hot and cooler parts of the day.[9]

One native species that demonstrates many of these strategies is the barrel cactus. To conserve water, it has minimal stomata openings and its outer membrane is made of a waxy material that keeps water inside. In response to solar radiation, the proximity of ribs is maximized to the southwest, where the most extreme sunlight hits, creating a denser system of shadows and also causing the entire barrel to tilt in that direction, providing further shade.[10] In essence, the barrel cactus accepts the reality of the environment and modifies its growth patterns to mitigate the extreme conditions.

African Termites (*Macrotermes bellicosus*) regulate the interior conditions of their mounds through a series of porous membranes that allow a continuous exchange of air between the interior and exterior environments. As air moves through the porous membrane, it is cooled by

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[8] Cretefoamer. "Cellular Concrete Technical Information," < http://www.cretefoamer.com/index.html?page=TechInfo1>.

[9] Goodall, David W. *Evolution of Desert Biota*. Austin: University of Texas Press, 1976.

[10] Brown, G. W. *Desert Biology; Special Topics on the Physical and Biological Aspects of Arid Regions*. New York: Academic Press, 1968.

the high water content of the lower chambers. As the air heats up again, sometimes due to the cultivation of fungus underneath the mound, it rises through the layers of the chamber and is exhausted at the top of the mound. The balance of water and fungal cultivation allows the termites to maintain optimal conditions for survival of the colony.[11] This ability is based on the relationship between material properties and system thermodynamics where air is filtered through a porous membrane which regulates the extremes down to an optimal level.

The Mining Bee (*Halictus quadricinctus*) has a similar strategy: air vents (intake and exhaust) allow air to flow through underground chambers surrounding their excavated nesting pods. These ventilation chambers are lined with clay that has a high water content. This cools the nesting chambers which have thick walls and a high thermal mass. This combination of evaporative cooling and high thermal inertia allows for the precise control required for the raising of the larvae. The mass of the nesting chamber wall causes temperature change to be gradual and muted. And if the nesting pods still get too hot, the bee simply adds water to the clay lining the ventilation chambers to bring the temperature back down through evaporative cooling…[12]

…The passive design strategies that have been identified for their positive response in regulating comfort in hot, arid climate zones are evaporative cooling (due to low humidity), high thermal mass (due to extreme heat and solar energy), night ventilation of (due to large diurnal temperature shift), comfort ventilation, shading, and in the winter time, direct solar gain…**(page 5, mid)**

…The purpose of conducting extensive performance testing of the materials is so that data can be incorporated directly into the computational design process, just as environmental forces are, because it is the combination of the two sets of information that will help generate the formal solution**…(pg 4, bot)**

[11] Collias, Nicholas E., and Elsie C. Collias. *External Construction by Animals*. Stroudsburg, Pa: Dowden, Hutchinson & Ross, 1976.

[12] Frisch, Karl von, and Otto von Frisch. *Animal Architecture*. New York: Harcourt Brace Jovanovich, 1974. 67-69.

…The material samples are initially saturated with water and then allowed to dry in the wind tunnel as data is collected on both sides of the sample to determine cooling efficiency… **(pg 4, bot)**

…To summarize the findings of the material research and testing: foam concrete is an effective insulator, has a high evaporative cooling efficiency, a low permeability, and a low compressive strength; pervious concrete is an effective thermal mass, has a lower evaporative cooling efficiency, a high permeability, and a high compressive strength…**(pg 5, top)**

…The first step in the evolutionary design process (Table 5.2.1) was to mold the form of the starting dome shape in an specific way related to the basic material functions outlined in the schematic design. The digital model was given a wide range of potential formal deformations. Then the parameters to determine successful form were made. In this step, the focus is on solar radiation. Based on the schematic design, the goal is to minimize solar radiation on the north side in the summer (to further cool that zone) and maximize solar radiation on the southwest side in the winter to allow for a solar gain opening that lets in the most heat in the winter to charge the thermal mass of the floor and the north wall. Formal iterations were generated by galapagos using the parameters I defined. Each iteration was then sent to ecotect for summer and winter solar radiation analysis and that data was brought back in to galapagos to determine relative success or failure (based on balancing the two concurrent fitness parameters) to generate the next iteration…. **(pg 5-6)**

…The next step in this process (Table 5.2.2) deals more directly with the material properties themselves. The goal of this step is to determine the optimal material thicknesses throughout the form and also the optimal sizes for the direct solar gain openings. This was achieved by inputting specific material performance data into the parametric model and again using Galapagos to generate formal iterations which were fed into Ecotect to get solar gain data, which was then incorporated into mathematical equations within the model that relate material properties and thicknesses with environmental data. These equations calculated Thermal Time Constant (TTC)[13] which should be maximized year round, and Diurnal Heat Capacity (DHC)[14] which

[13] Givoni, Baruch. Climate Considerations in Building and Urban Design. New York: Van Nostrand Reinhold, 1998. 133-135.

should be maximized in the winter for heating. These fitness parameters were balanced and the results helped generate the next iteration in Galapagos.

Due to time constraints, this was the last step in the design process. Ideally, having addressed the issues of the optimization of solar radiation and thermal storage, the next step would be to optimize the evaporative cooling function and maximize its affect on the space. Additionally, if all these optimizations ran together at the same time, in conjunction with structural and all other forces, the final result would no doubt be different. By breaking the process down into smaller operations, the designer is also exerting greater control over what the final form will take and reducing the direct effect of environmental and material forces on the final form. That is the struggle in this design process: not to design the form, but to design the system that will generate the 'best' form based on the design criteria and the specific environment where it exists. This is the power and problem inherent in the process. Complexity begets greater complexity and the fluidity of the tools to interact with and inform each other is still in the early stages of functional development… **(pg 6, bottom)**

... Generally speaking, the foam concrete is used for insulation and evaporative cooling (where it is insulation, it is intended only to function as insulation, not both) while the pervious concrete is used as a thermal mass and a structural shell, though it can also function as evaporative cooler if needed **(pg 5, top).** A mechanical fan is placed at the top to draw air through the small holes in the evaporative cooling region and pull that cooled air through the space...**(pg 7, bottom)**

…Looking specifically at the materials researched, tested, and implemented in this process-foam concrete and pervious concrete- there is significant potential for these materials to be developed further for arid and semi arid regions, but also in other climate zones…**(pg 7, bottom)**

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[14] Jones, G. F., and William O. Wray. "Simplified Methods," in *Passive Solar Buildings*. ed. Balcomb, J. Douglas. Cambridge, Mass: MIT Press, 1992. 194-195.