

## ADVANCED CERAMIC COMPOSITE ENVELOPE SYSTEMS

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The increasing pressure on finite natural resources from global demand for construction materials combined with rising energy consumption is forcing the construction industry to look for low-impact and less energy intensive alternatives. This presents a need for abundant materials that can meet demanding performance criteria. Oxygen, Silicon, and Aluminum compose the majority of the Earth's crust, and are readily found as silica  $\text{SiO}_2$  and aluminum silicates  $\text{Al}_2\text{SiO}_5$  that can be directly used for the production of ceramics. Ceramic materials can be used in diverse applications and continuously reclaimed as high quality materials saving more precious resources. Composites and coatings augment ceramic materials for high performance architectural applications with particular material response tuned to local climate criteria.

At the turn of the 20th century, the height of building technology utilized hand-crafted terracotta ceramic tiles mounted on structural steel framing. There were more than 15 companies nationwide employing thousands of workers making each tile from custom-built molds interpreted from architects' drawings. Now only three such companies remain and two are primarily involved in the historical preservation of old buildings. Yet the natural process of erosion of the Earth's surface produces clay five times faster than we could ever hope to use it. While terracotta has many desirable properties as a building material--durable vitrified (glazed) finishes, thermal mass characteristics (energy efficiency), humidity controlling properties (environmental control), plasticity of form (structural stability)--modern building techniques require an efficient and resilient construction system with a streamlined design and manufacturing process.

Research into composite ceramic components at Rensselaer Polytechnic Institute continues along similar prototyping protocols with the intended outcome of integrating advanced technologies to modify temperature gradients and minimize diurnal swings into a full-scale demonstration for limited testing. This report describes the continuing development of ceramic prototyping processes and digital simulation studies intended to further second-generation composite wall components towards completion.



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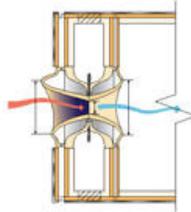
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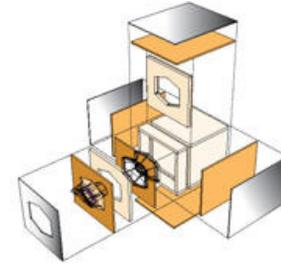
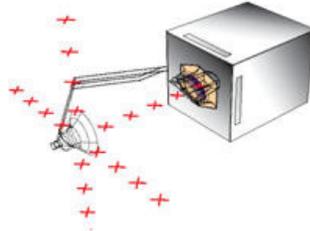
Associate Professor

## Introduction

**A limiting factor in ceramic building assemblies is the lack of intrinsic tensile strength of the ceramic material.** In the traditional brick or concrete masonry unit (CMU) wall assembly, the masonry unit is in compression while the mortar, also in compression, acts as a self-leveling surface. Without any force to resist tension, the wall fails under lateral force and seismic events. To stabilize the traditional masonry wall system, steel reinforcement is added. EcoCeramic blocks incorporate fiberglass and composite materials, replacing steel reinforcing, for localized post-tensioning between each block, so that the entire system is networked into one post-tensioned matrix. The future possibilities of a locally post-tensioned masonry system are being explored for construction in seismic zones.

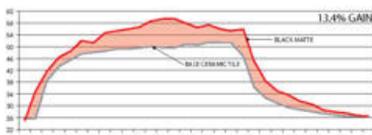


Isolated Testing Condition

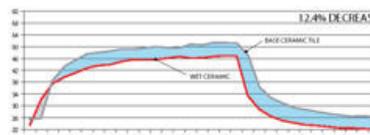


Monitored Testing of Ceramic Components for Solar Absorption Heating and Evaporative Cooling

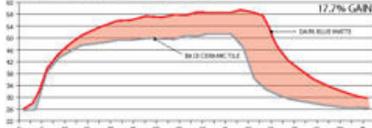
ASTM C1363 - 05 Standard Test Method for Thermal Performance of Building Materials and Envelope Assemblies by Means of a Hot Box Apparatus



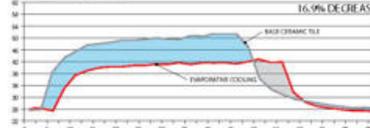
Supplemented Heating with a Black Stain



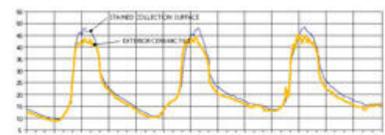
Cooling with Wet Ceramic



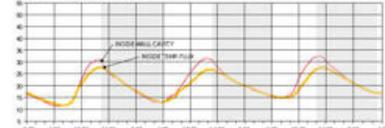
Supplemented Heating with Dark Blue Stain



Wet Ceramic with Allow for Evaporative Cooling



Diurnal Swing Heat Collection

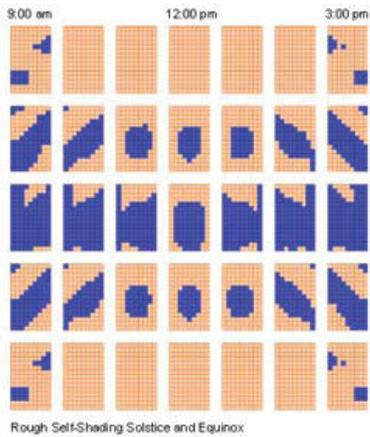


Diurnal Swing Interior and Wall Cavity

Monitored Component Testing

The composite materials are used for the joining of the individual units. Due to the method of fabrication, each structural ceramic unit (SCU) is one half of a complete SCU. Traditional modes of joining ceramics include slip joining, the same method most commonly used to attach a coffee mug to its handle. Slip joints are less than optimal for construction as they shear on impact forces. A second traditional and higher performing joining method uses a high fired glaze as slip. While stronger in resisting tension, high fire cone 11 temperatures are required for sintering, adding time and energy expenditure, and excessive vitrification of the clay body, whereas the SCU clay is fired to cone 6.

By applying composite bonding with woven glassfiber and high strength epoxy, the fired SCU halves can be easily joined in a permanent structural application. The composite creates a joint capable of withstanding shear and tensile forces. In prior research, traditional joints were shown to resist three point bending with approximately 70 lbs/ft<sup>2</sup>, while the typical woven glassfiber reinforced ceramic joint fails at greater than 200 lbs/ft<sup>2</sup>. Further, due to the woven interlayer, the failure is non-catastrophic. To reduce the use of synthetics in the system, the new prototype of phase II will test geo-polymer as the matrix and basalt geo-fiber as the reinforcing interlayer.

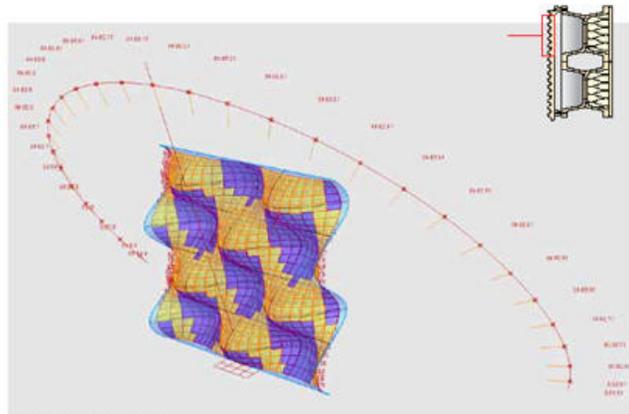


Rough Self-Shading Solstice and Equinox

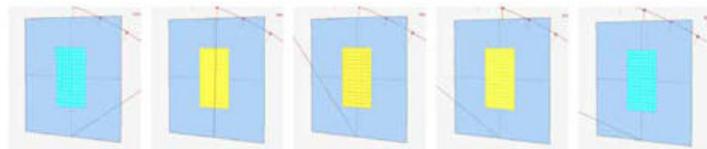
JUN 21: **7.63%** Avg Self-Shading Value

SEP 21: **3.91%** Avg Self-Shading Value

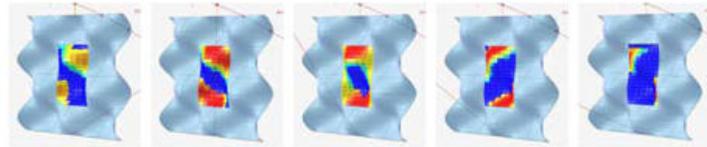
DEC 21: **0.41%** Avg Self-Shading Value



Parametric Self-Shading Tool



Surface Patch Analysis of Flat Surface



Surface Patch Analysis of Redundant Surface

Parametric Solar Insolation and Self-Shading Tool

## Simulation and Experimentation

The High Performance Masonry System (HPMS) has the capacity of locally mitigating arid climates into habitable thermal ranges through passive cooling strategies. The approach required an understanding of the regional climatic conditions and the study of the evolutionary thermodynamic characteristics of natural precedents: barrel cacti and termite mounds. In the upper Sonoran Desert, self-shading and wrinkled surfaces are the first defenses against the intense desert sun and extreme diurnal temperatures ranging as much as 30 F. The HPMS face tile was optimized to receive little solar incidence during the summer while receiving near full exposure during the winter. Similar strategies are being developed for Köppen temperate and cold climate types.

The environmental simulation program, EcoTect, initially provided indexical data for feedback loops establishing zones of re-radiation, shading, and absorption. EcoTect provided a parametric interactive modeling environment that seemed to work acceptably well for complicated surface development. The software verified yearly and hourly solar incidence/exposure on the tile surface and projected sections through the cone to visualize with greater accuracy the depth of solar penetration. While developing the Phase II design, a flaw was discovered in the way EcoTect calculates complex curvatures. The performance of the surface is dependent on accurately calculating solar insolation on the complex surfaces defined by the tool paths. EcoTect uses the normal of a plane to calculate shading rather than the incident angle projection and thus shows less shading as a result. Therefore, we developed a Grasshopper script using the EcoTect algorithm for calculation and Rhino to project the accurate geometry. Our process shows a simulated increase in self-shading of complex surfaces.

Based on solar incidence, physical experimentation, established material properties, and measured radiant thermal gains, an idealized thermal section was compiled as a hypothesis for performance. The winter condition allows solar penetration into the concavity of the tile, warming the blue stained smooth surface and raising the temperature.

Full exposure due to the low solar angle increases the surface temperature, continuing to warm the ceramic modules. In the summer, the high sun increases the shading potential of the face module. The increased surface area reradiates energy back into the environment, decreasing the thermal gain accumulating through the surface geometry. The increase and articulated surface geometry shades most of the tile though summer solar angle conditions. The fundamental strategy for thermal performance between the HPMS and the typical CMU is the management of energy: the CMU is conceived as a unit independent of direct thermal mitigation and requires additional surface insulation or insulated filling while the thermal mitigation in the HPMS is integral and informs the geometry and surface articulation.

Based on thermal experimentation, the following principles may be applied:

01. Smooth surface areas neutralize thermal gain/loss.
02. The surface of the tile is shaped according to solar angles to maximize shading in the summer months and increase solar gain during the winter months.
03. The increased surface area of the CNC tool path allows radiant gain to dissipate back into the environment.
04. The increased surface area facing the wall on the interior surface directs gains back into the wall cavity.
05. Water soaks the tiles during the night for evaporative daytime cooling.
06. Standoff tabs allow air to flow between the face module and the structure.
07. 'Hollow' tiles allow air to flow through the wall, transporting humid cool air inside.
08. Unglazed tile exposed to the summer sun so that the light color can better reflect insolation.
09. The cone, which receives only winter sunlight, is colored dark blue with masonry stain to retain warmth in the wall system.
10. Standoff tabs limit conductive thermal transfer to the structural unit.
11. The hollow section can be filled with insulation further delaying conductive thermal transfer.
12. The tile is thinnest in regions most affected by summer sun and thickest in regions most affected by winter sunlight, similar to principles found in cathedral and dome termite mounds.

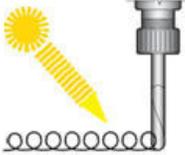


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**Advanced Ceramic Composite Envelope Systems**



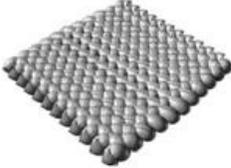
  



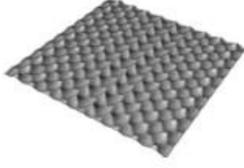
- Climatic data informs surface articulation through the 3D toolpath.



- Mapping of the cutting tool along the toolpath following manipulated 3D Spiral.

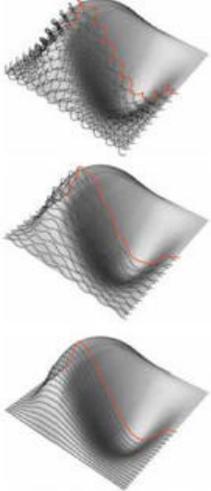


- toolpaths projected over a square tile surface in field condition.

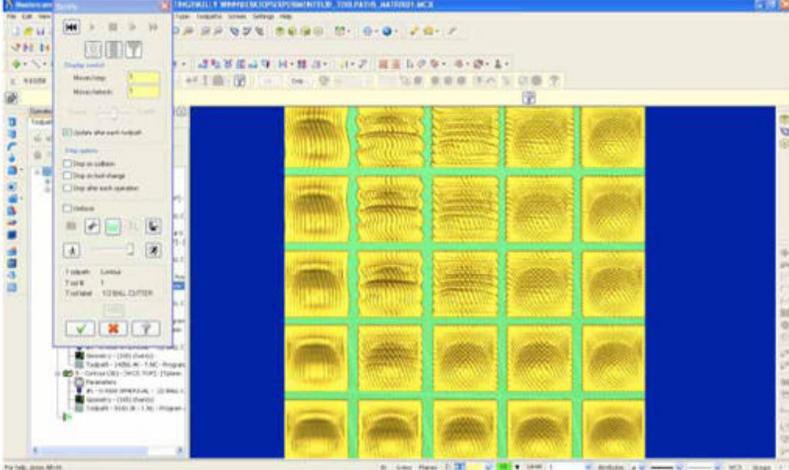


- Resulting approximation surface in a mesh model.



Toolpaths Mapped Over Base Geometry



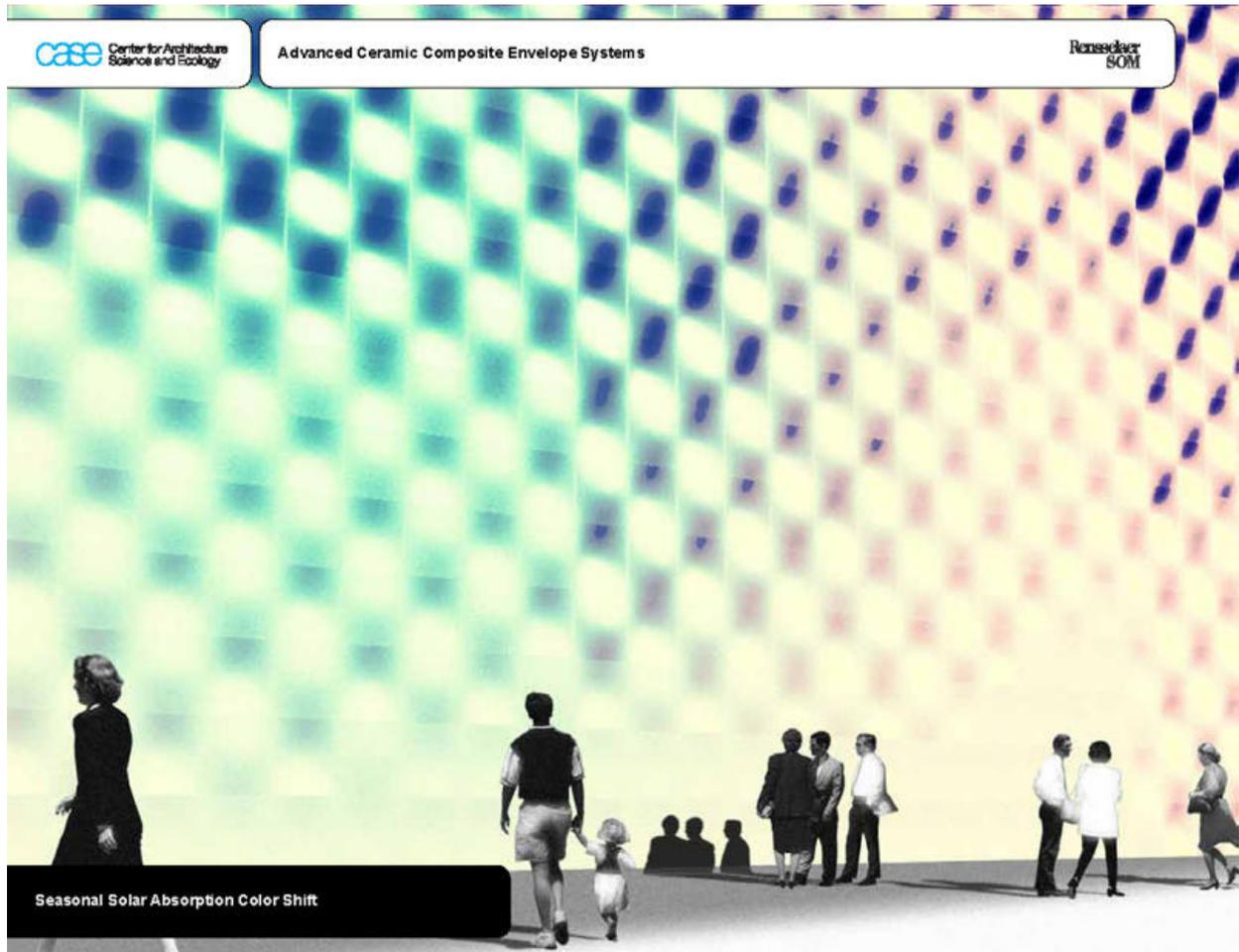
CNC Simulation of 3D Toolpath Cutting

**Toolpath Modeling and CNC Manufacturing Simulation**

The thermal testing was conducted during the winter solar cycle, at which time the entire system receives greater solar exposure than summer months, maximizing potential winter radiant thermal gains. The researchers expected the interior cone of the face tile to absorb solar radiation during the day and retain heat into the night, delaying the cooling of the wall. In order to limit horizontal air movement and conduction, expandable insulating foam was added to the interior half of the SCU. Continuous vertical ventilation between the face tile and the SCU would act as a convective thermal barrier.

Instrumented data is essential to corroborate performance simulations in prototype development and necessary for the feedback loop of iterative development. The American Society for Testing and Materials International (ASTM) does not have a standard radiation thermal gain test procedure. Therefore, the researchers adapted ASTM C1363 (Guarded Hot Box) by exposing the test surface to solar radiation. Unlike other standard tests, which wait for thermal equilibrium, this experiment requires a three-day cycle, similar to field experimentation. In order to reduce weather-related errors, the researchers will alternate the test series between wall surface assemblies.



The testing chamber is one cubic meter in volume, or 35.3 cubic feet. Floor dimensions are 1.3 meters wide by 1 meter deep (approximately 4 feet by 3 feet). Five of the six sides are sheathed in 7.62 cm (3 inches) of homogenous polystyrene insulation with an R-value of 12. The combined material R-value is 13.4 on five sides of the cube, with a wall thickness of 12 cm (4.75 inches). Nine thermocouple data loggers record environmental, wall, and interior temperatures.

Work from this project is expected to be presented and published in the following year, following appropriate intellectual property disclosures at the Institute level.

We are currently seeking new funding for the next prototype and have engaged in conversations with possible manufacturers. Several large architecture and engineering firms have expressed interest in using the product in upcoming projects.

## Research Pedagogy

The current energy situation demands that faculty and students rethink traditional studio pedagogies. In this sense we begin with the statement, “architecture must perform in a physical and environmental context.” This premise, in and of itself, is not novel. The focus on developing architectures based on building components derived from energetic material principles provides a visceral learning environment to address a serious global concern. Accordingly, a research-based pedagogy provides architectural solutions to the current energy situation through performance-based design, constrained simultaneously by regional criteria and material characteristics.

Design parameters of form, space, material, color, texture and assemblies are engaged in the context of performance. Looking through the lens of our current global environmental situation, students translate their prototypes into the context of the larger building culture.

Environmental simulation programs addressing solar insulation, shading patterns and ventilation strategies are integral components for developing the iterative process of performance-based design. While architectural studios often utilize evaluation programs, few have made the leap from academic speculations to the rigor of testing design components in the building assembly.

The initial research occurred at the Emerging Materials Technology graduate program, initiated in 2004 by Director and Professor Álvaro Malo. This research originally was developed through a multi-year curricula stream by several faculty and students with interdisciplinary participation from the Department of Material Science and Engineering and the Department of Physics. Financial support was provided through several granting agencies and local industries. Over the course of two years, sequential fall studios, ARC 451 and ARC 601, supported by ARC 481/581a/a and Arc 561i/j, provided ample time to develop the materials-based research project. Studio courses were based on a laboratory model of systems, material logic, formal logic and prototyping. The support courses ARC 481/581/a/c provided material-specific research with an emphasis on digital design, simulation, and fabrication. ARC 561/i/j offered material-specific exploration into fundamental properties and tests that were exploited.

## The Value of Funded Research in the Curriculum

Typically, schools of architecture claim that architectural research is misunderstood by the larger university research community; rather, research is misunderstood by the larger architectural community. Funded research invites architectural researchers to enter a larger conversation with experienced research culture. More immediately, however, architectural research is only feasible with adequate funding, technical support, administrative understanding, and curriculum flexibility.

As an enabler of architectural inquiry, funded research in architecture curricula actively involves and engages students in critical problem solving with the added mandate of a very real responsibility, economic as well as ecological, to external funders. Most importantly, while external funding encourages publication and necessitates creative and innovated solutions, it lends external review and legitimacy to architectural research.

## Architectural Research

Research-driven design balances an understanding of material properties and manufacturing techniques. The EcoCeramic approach combines regional manufacturing techniques with emergent material practices in material science to advance architectural technology. Product-driven research could not be successful if the designers were not cognizant of building assemblies, technologies, and product production methodologies. Clay bodies are generally formed by extruding, casting, pressing, and jiggling (Figure 8). While the EMT laboratories are capable of all these methods, ram pressing and slip casting provide an effective mode of production to design and fabricate complex asymmetrical surface textures.

The HPMS approach itself is a prototype of a design methodology. The choice of material depends on the design criteria or systems that a material is required to address. The production influences the analogue prototype. Materials are chosen for their characteristics, and clay bodies can be formulated to meet specific performance criteria. Thus, unique clay bodies can be formulated in response to a specific latitude or climatic region. Applied architectural research, as differentiated from scholarship and creative activity, begins with a set of properties defined by material testing and ends with a refined working prototype.