databases and integrating them into the framework constraints of a parametric design approach will enable the new design process workflow, as shown in Figure 13.

Future models should include more parameters so more complex interdependencies could be related to full-scale conditions. Furthermore, future models should be tested under simulated ABL for performance of individual buildings as well as of tall buildings immersed in a built context. Finally, advancing the resolution and type of the models' sensing capabilities will enable the inclusion of other important parameters such as temperature and heat transference, and the prediction of building performance at other scales.

ACKNOWLEDGMENTS

The authors wish to thank Professors Dyson, Letchford, and Amitay at Rensselaer Polytechnic Institute for their knowledge and support.

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CERAMIC PERSPIRATION:
MULTI-SCALAR DEVELOPMENT OF CERAMIC MATERIAL

ABSTRACT

Ceramic building material is a useful passive modulator of heat and humidity in the environment. Components can be designed to respond to specific environmental conditions by controlling material density and porosity as well as surface characteristics. Through investigations into materials engineering, formal design, and prototyping, key physical attributes have been identified. This relates to a number of physical principles: the ability of the material to absorb and release thermal energy, the ability to absorb and then "wick" moisture within the pore structure, and the decrement factor or "time lag" of the effect. The interplay between these effects points to the importance of directionality in the granular structure, as well as at the architectural component scale. Recent work done on monitoring has led to the development of software tools that allow feedback approaching real time—a visual representation of the dynamic thermal and hygrometric properties involved.

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figure 1

1 DEPARTURE POINTS: SCALE AND PROCESS

How can we develop a material intelligence, that is, a set of ceramic material attributes instrumental for achieving a well-tempered environment? The subject area is based on traditional and cultural knowledge of clay properties, such as amphora and rammed earth building, and then ranges forward to present-day uses, from desiccants and space shuttle tile patterns to bioceramics. This study started from three premises. First, the simpler and more robust design the better, especially in considering process transfer from technical ceramics. Second, working with an interdisciplinary team ideally fosters a collaborative and yet experimental methodology. Third, hands-on material engagement is a useful aspect of the design process, essential to developing haptic knowledge as a complement to other forms of data feedback, in regard to understanding material performance.

1.1 Environmental Responsiveness

Environmental responsiveness in building can take many forms, from highly technical systems to more passive, low-tech strategies and solutions. In the realm of silicate materials, both ends of the spectrum are subjects for investigation and both inform and excite further development. Examples range from high-end double-glass facades to the renewed use of rammed earth walls such as in the Chapel of Reconciliation in Berlin, a collaboration between architects Reitermann and Sassenroth and Austrian clay artist Martin Rauch (Figure 1). Considering the use of porosity and vessels at a radically different scale, inexpensive water filters such as the CeraMaji ceramic pots have been developed, using local clay and temper material in Kenya (White 2012) (Figure 1).

By nature of its microstructure, traditional ceramic material can function as a buffer for both heat and moisture. Ceramics have been commonly used in buildings for thermal mass storage. But what about humidity? Reyner Banham states that "Of all the factors involved in environmental management, humidity has, for most of architectural history, been the most pestiferous, subtle, and elusive of control" (Banham 1984).

However, every material now has a Perm rating for vapor transmission, and the position and type of vapor barrier in regard to climate type is critical for the building envelope (Lstiburek 2004). Therefore ***ceramic perspiration*** can be seen as a micro to global consideration of moisture in regard to transfer through ceramic material, building assemblies, and spatial environments.

figure 1

Ceramic Vessels: a) Chapel of Reconciliation, Berlin; b and c) CeraMaji water filter, ceramic pots made with local Kenyan clay and temper material.

figure 2

Microstructural features in ceramics and glasses, showing their length scale and the properties that they determine (after Ashby).

figure 3

Sample of layered porosity with starch filler, toward achieving a cross-sectional gradient. As a point of reference, a human hair has a width of 100 um.

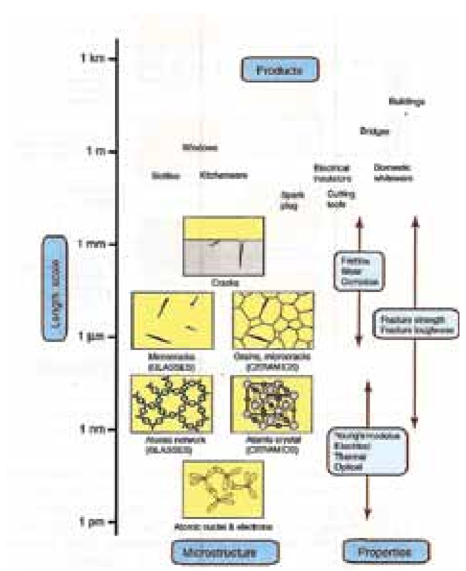

figure 2

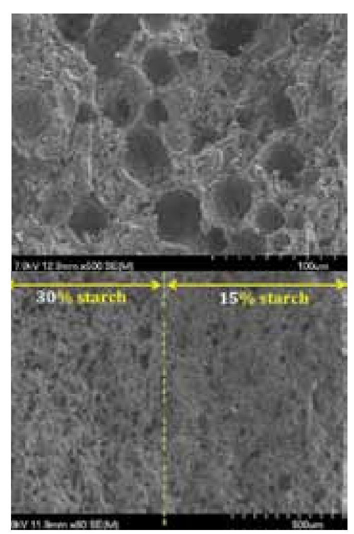

figure 3

1.2 Material Engineering

By investigating different scales of the material, forming processes, and dynamic interactions with the environment, the attributes of ceramic material can be better understood. For silicate-based materials, ceramics are crystalline and glasses are amorphous. Both are near the bottom of the materials microstructure length scale (Figure 2). Most of the properties directly reflect the atomic layout and the intrinsically strong nature of the covalent or ionic bonding— from elastic modulus to electrical insulation (Ashby, Shercliff, and Cebon 2007). The exceptions are strength and toughness. Cracks dominate failure in ceramic and glasses, so these are key features—closely related to grain size and to the surface finish.

Density and porosity have been examined in the laboratory on small disc-like samples using a scanning electronic microscope (SEM). This allows investigation of the microstructure at a number of key scales: 100 um shows material constituents, the 5–10 um range shows porosity and structure (Figure 3).

1.3 Ceramics and Flexible Process

While architectural ceramics are typically mass-produced, another way of working with ceramics is to consider which processes are possible in "post-production," or directly on-site. The collaboration between artists and architects has a long-standing history, and the idea of artistic installation is promising in exploring techniques that allow flexible response on-site. This approach includes patching, direct attachment, and in situ surface finishing (Figure 4). The assemblage nature of this work generated the idea of integrating a range of ceramic material states, from kiln-fired to green nonfired, in the same piece.

2 MATERIAL DEVELOPMENT: INTERPLAY

2.1 Design Synthesis

A ceramic tile has been designed with a number of attributes derived from work done in the laboratory and the ceramic studio (Figure 5). The ceramic tile has discrete functional layers, with a range of material states, which are laminated (or adhere) together. The initial environment considered was a humid maritime condition, where a tile wall could absorb solar energy from the exterior on one side and interior humidity on the other. Therefore two discrete functions lead to an idealized gradient of ceramic material from dense to porous. In the ceramic studio, the gradient translated as a fired dense ceramic frame (vessel) that is then filled with porous green (nonfired) ceramic material. Precedents include the absorbency characteristics of dense kiln brick (heat) and mud bricks (moisture). Permeability research done by Gernot Minke (2006) shows that mud bricks can absorb 50 times more moisture than solid bricks that are baked at high temperatures.

The geometry of the tile interior seeks to maximize the connecting surface area through curvature; this gives the tile a further attribute of directionality. When the tiles are stacked, the curved areas resemble half-engaged columns. The green clay layer forms a matching set of interlocking half-columns, within the fired ceramic frame. Two different prototypes have been developed, varying the amplitude of curvature.

figure 4

figure 5

figure 4

Rory Macdonald's work on in situ installations has been facilitated by the use of a portable kiln

figure 5

Tile design: a) prototype 1; b) column stacking; c) prototype 2.

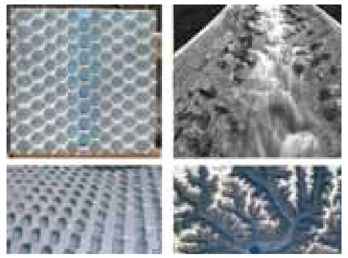

figure 6

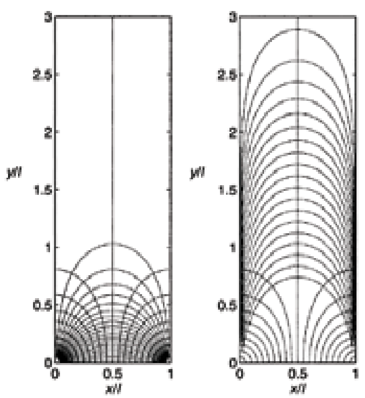

figure 7

How excess surface water flows or pools is a primary concern for the surface pattern of the green clay. Pattern can be stamped into the surface when the clay has partially cured (Figure 6). In this case the wetting angle is important (> 90o), i.e., cos   will be negative and instead of possessing a capillary suction, the ceramic will repel the liquid (Cerdak Bioceramics). Glazes can be used to retard water absorption and surface corrosion by facilitating flow. If a color glaze is applied to the bottom edge of the pattern, the color will be subtly reflected upwards.

2.2 Mass, Time, and Building Physics

Porous ceramic materials have the capacity to absorb humidity from the ambient air and to desorb humidity into the air, thereby helping achieve humidity balance in indoor climates. Two key factors are the *equilibrium moisture content*, which depends on the temperature and humidity of the ambient air, and the water *absorption coefficient* over time. It should be noted that for the humidity-balancing effect of building materials, the speed of absorption and desorption processes is probably more important (Straub 2006).

Bentonite has an equilibrium moisture content of 13 percent under 50 percent standard humidity conditions, whereas the equilibrium moisture content of kaolinite under the same conditions is only 0.7 percent. Desiccants in the packaging industry use a type of bentonite clay as it is easily recharged (dried out) at temperatures of 40° C. Bentonite has therefore been used as the green nonfired porous material in the tile.

Water always travels from regions of higher humidity to regions of lower humidity. The capacity of water to respond to suction in this way is termed *capillarity*, and the process of water transportation is capillary action.

Moisture movement in a larger body such as a wall can be understood by borrowing from soil mechanics, in particular flownet modeling based on Darcy's Law (Chanson 2009). However, both saturated and unsaturated states need equal consideration when modeled. Hall and Hoff (2009) show that fully saturated materials will not transmit moisture as readily (Figure 7).

Introducing porosity into any material will improve the thermal insulating characteristics (decreasing the conductivity) of the material. Porous materials consist of solid matrix and gas inside the pores. Their good insulation properties are achieved due to the very small thermal conductivity in gases compared to solids or liquids (Ashby, Ferreira, and Schodek 2009). Consider the three means of heat transfer in the environment: *conduction*, *convection*, and *radiation* for a porous material. Conduction of heat energy in a porous material increases with the increase of pressure around it and inside the pores; convective heat transfer increases with the increase of the motion of air inside the pores; and radiation increases significantly with an increase in temperature and an increase in pore size.

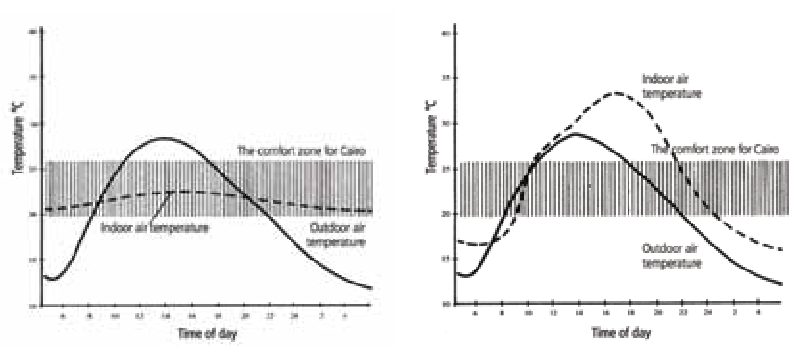

figure 8

figure 6

Surface pattern prototypes modeled on a turbulence precedent by Kathryn Gustavson (upper right) and a branching precedent (lower right

figure 7

Humidity: Flownet modeling, steady flow in a rectangle, comparison of saturated and unsaturated flow (after Hall, Hoff).

figure 8

Comparison of indoor and outdoor air temperature of a building with adobe vaults (above), with one using prefabricated concrete slabs (below) (after Fathy, 1986).

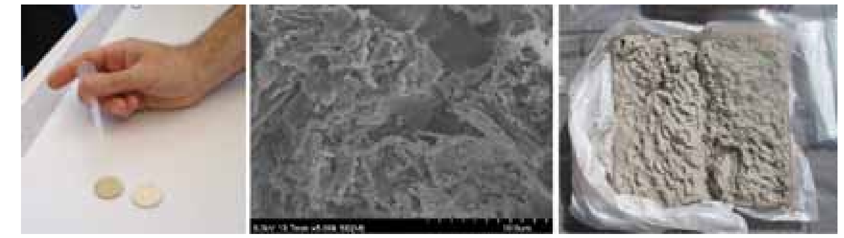

figure 9

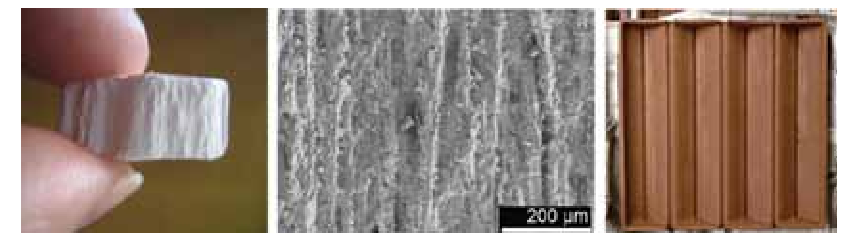

figure 10

figure 11

figure 9

Nonlinear (open-cell sponge) porosity for a humidity flywheel effect.

figure 10

Pore directionality for transport of heat and moisture in a specified orientation.

figure 11

Closed cell pore structure for lightweight strength and insulation, thermal mass.

And vice versa, overall thermal conductivity decreases with a decrease of the pressure inside the pores, a decrease in temperature, and a decrease of pore diameter. Therefore, control over pore size and interlinkage (from closed cell to continuous) has a major effect on both thermal conductivity and capillary action. In the interplay between temperature and moisture, a material with greater moisture content will be more heat conductive.

Decrement factor and *time lag* refer to the way the exterior wall of a building reacts to damp and to the period of delay before outside temperatures reach the interior. A wall with a high thermal storage capacity creates a large time lag and heat decrement, while a wall with high thermal insulation reduces only temperature amplitude.

Hassan Fathy studied the way in which timelag was attenuated by building material and form to climate type, to provide a leveling effect (the so-called flywheel effect) on temperature for the human comfort zone in Cairo (Fathy 1986). He demonstrated how adobe vaults would moderate interior diurnal heat gain in comparison to prefabricated concrete slabs, which exacerbated heat gain. Likewise for humidity, Bill Carty has estimated that the amount of green clay surface (1 cm deep) in a room with standard conditions (50 percent relative humidity) necessary to achieve a viable humidity flywheel effect is 16 percent of the wall surface area (Carty and Sinton 2006).

2.3 Porosity and Directionality, Thermal Mass

As we have seen, the characteristics of the pore structure can be of benefit to material performance. We have identified three characteristics of ceramic microstructure that, by varying in amount and combination, could respond to a particular climate type (Figures 9–11):

The three microstructure types vary in the complexity of production. This ranges from the simple with fugitive filler additives or partial sintering (Figure 9), to the novel with ice templating (Figure 10), to the more complex ceramic-glass composites that can be formed as closed-cell foams (Figure 11). Translating to the macro scale, our tile component utilizes green bentonite clay for sponge porosity, inner tile geometry with voids for directionality, and a thick ceramic depth for thermal mass (with a lightweight steel rod substructure).

But what is the main problem with brittle materials? They are susceptible to fracture, which may be traced back in many cases to the inherent defects built in during processing. Ceramic and glass making is therefore largely about the control of defects. The microcracks in ceramics mostly reflect the size of powders or grain used initially (Ashby, Ferreira, and Schodek 2009).

One approach to rectify this is based on "partial sintering," so that porosity is retained because the material is not processed to full density; in this instance the porosity is fine scale (i.e., nm to μm range) and does not degrade the strength too significantly. Sintering is the same heat-based process as kiln firing, but refers to a much smaller scale process in the laboratory.

Using bentonite as green clay poses problems due to large shrinkage rates and the crushing effect possible on porous materials. The solution is generally to add cellulose material as a binder and compress the material together. Adhesion of the green clay to the fired clay frame was actually facilitated by the rough inner surface of the fired clay frame, due to delamination during the firing process (Figure 12).

3 EXPERIMENT AND TESTING

Ceramic porosity was examined at material scales of microstructure, individual tiles, and wall assembly.

figure 12

figure 12

Tile section showing bentonite with cellulose binder at its greatest depth, with the fired clay frame below.

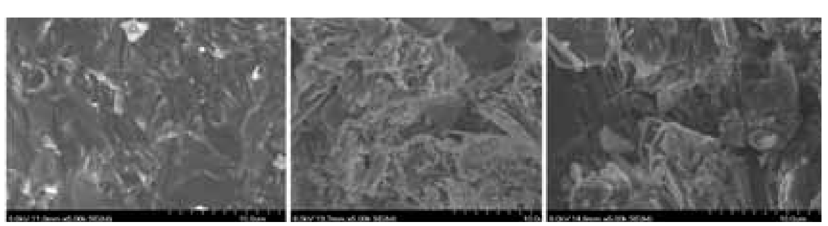

figure 13

figure 13

Partial sintering: a) Clay body sintered at 1,200° F, nonporous; b) same clay body sintered at 1100° F, porous; c) green clay, porous (all images 10 um).

figure 14

figure 14

Cracking control, bentonite with cellulose added. Measurements taken include temperature on both sides, humidity, and electrical resistance. The thermal imaging camera gives a good visual indication of how the tile is drying, indicating that the tile dries fastest where the green clay is thinnest.

figure 15

figure 15

Measuring relative moisture at the interlayer region between fired and green clay. An array of eight points measures resistance in specific regions, indicating the amount of moisture in each (dry = darker, moist = lighter).

figure 16

figure 16

Measuring: a) the context, an east-facing room with a large volume; b) the sensor array measures humidity and temperature at the front of the tile and temperature at the back; c) handheld tools give spot readings during the building phases.

3.1 SEM and Porosity Testing

Initial testing of the clay materials was done in the ceramics lab. SEM visualization was done for a range of samples, at various scales (Figure 13). Of particular interest is the sample that has been partially sintered and maintains porosity (Figure 13b), where the same sample sintered at 100° F more has an even texture without porosity (Figure 13a). Green clay has an even larger pore structure, but is more difficult to work with due to instability and shrinkage factors. If the porosity value is sufficient, partial sintering will allow for a more durable product that is easier to manufacture. To establish values, further testing at this scale is possible using porosimetry: the technique involves the intrusion of a nonwetting liquid (mercury) at high pressure into a material.

3.2 Individual Tile Tests

To see material characteristics at a larger scale, the different tile types were initially tested (frames only) for density, thermal conductivity by using theater lights, and sorptivity using a permeability test. During the measurement process, major cracking patterns occurred as the green bentonite clay dried.

figure 17

Temperature: fired clay tile frames as thermal mass. Wall in direct sun 5,000 seconds

figure 18

Staggered measurement: a) temperature (top): fired clay tile frames filled with green clay in direct sun 6,000 seconds; b) humidity (bottom): fired clay tile frames filled with green clay in direct sun 1,500 seconds.

figure 19

Combined temperature (center) and humidity (right) for the integrated fired/ green clay tiles, on an overcast day, for 1,000 seconds.

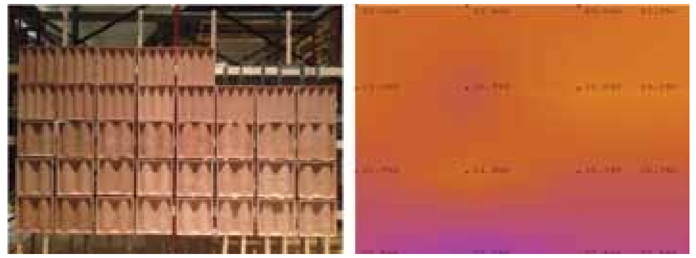

figure 17

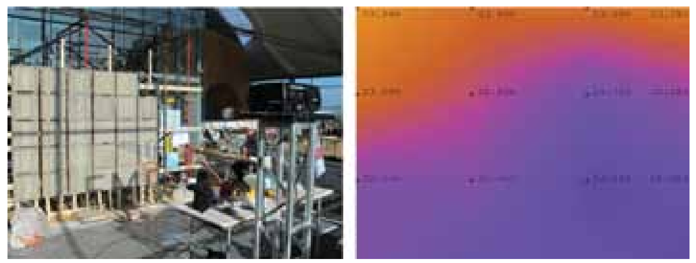

figure 18

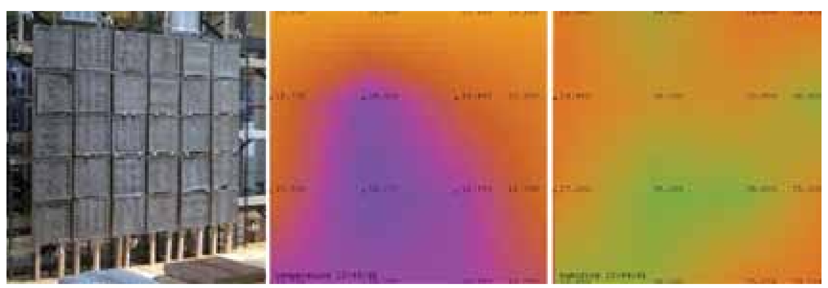

figure 19

To understand factors affecting this cracking a further test was devised, using a mix of bentonite and cellulose as the fill material (Figure 14). This test was based on the electrical resistance of the material being greater given less moisture content (and vice versa), as measured between two poles, directly within the green clay. The sensor output was imported into a processing script and matched to a series of date-stamped photographs as an animation. Cracking was significantly less, even under extreme testing conditions; however, some cracking behavior and delamination was still evident.

The next experiment installed nodes directly within the tile, in the region where green clay meets fired clay. Eight nodes act as both transmitter and receiver, in order to measure the resistance between nodes, and form various routes of cross-measurement (Figure 15). Each node transmits only to the nearest three to five other nodes. The ceramic material is an integral part of the sensor system, and measurement gives a map of the internal resistance, directly related to the moisture content in the clay. If the clay is drier between two nodes, the conductivity becomes lower than the average and the connection will be shown as a dark line in the processing script, with other connections exhibiting progressive grayscale jumps toward the norm. A snapshot of the final test setup reveals where (and when) green clay was applied, by showing moisture content (Figure 15c)

figure 20

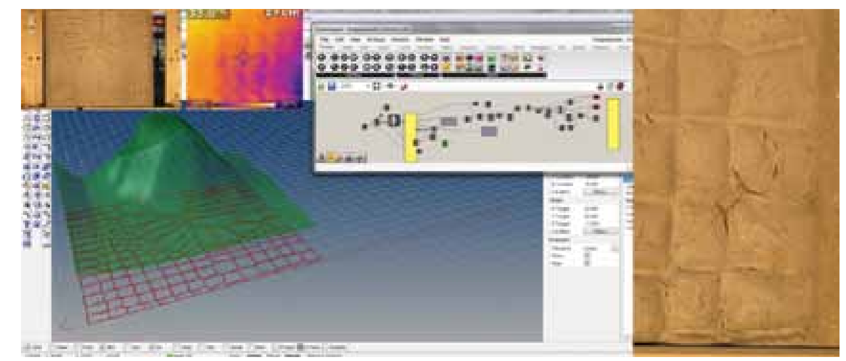

figure 21

figure 20

Surface pattern development to maximize surface area, mitigate cracking, and engage surface moisture flow.

figure 21

Parametric modeling of surface pattern to test/predict cracking control.

figure 22

Development of data feedback using processing scripts, color scales, and vector visualization.

relative between nodes. Note that the sensors tell nothing about the actual moisture content in the tile, but show moisture in relation to the average measured throughout the tile. A hygrometer indicates moisture values. This test gives an indication of how the internal geometry and material porosity of a tile affect vapor movement, in relation to specific environmental inputs.

3.3 Wall Assembly Tests

A number of wall configurations were tested, with a wall composed of an average of 40 tiles and a sensor array of 16 measuring points, each typically located where four tiles meet, then directly above and below the tile boundaries (Figure 16).

Sensor data is ported from an Arduino microprocessor into a Processing script, which generates visual output at a specified time interval. The color field is based on a bilinear interpolation (bilerp) of sensor data that populates values between four points (so more properly quadratic), for each unique grid area, as defined by the sensor positions. The color range was initially based on that of the thermal imaging camera. Numeric data is then overlaid for each sensor. Initial data visualizations (Figures 17–19) show the utility of the sensor array for revealing environmental performance of ceramics at an architectural scale.

The first measurement was made with just the steel rod substructure in place, as a baseline reading. The space was mechanically conditioned, but when sunny it experienced a noticeable rise in temperature. Measuring the fired clay tile frames as thermal mass in the morning sun, the data

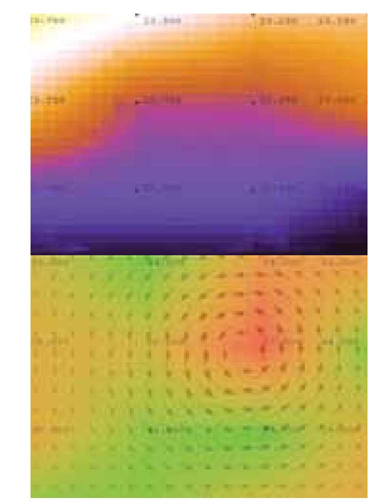

figure 22

visualization recorded a quick temperature climb up to 30° C, with a color range changing from darker blue to warmer orange/yellow (Figure 17).

Measuring the combined fired/green clay tiles, the temperature and color range is noticeably cooler as the green clay cures (Figure 18a). This is related to wall performance because as the percentage of water vapor increases (with time), the thermal conductivity of the material increases as well. Humidity values were measured for the same wall condition at a different time (Figure 18b). The data visualization recorded more patchy conditions that continued to vary as the tiles cured. When a heat source was applied to the back wall, the humidity values were stronger toward the top of the wall, indicative of a thermal stack effect, with a bright red color range. The last measurement was a combined temperature and humidity reading on an overcast day (Figure 19). The data visualization recorded a cooler area in the center of the wall with a blue color range, generally corresponding to an area of lower humidity with a green/yellow color range. Tracking heat and humidity on a surface over time facilitates greater understanding of the assembly's performance.

4 DEVELOPING KNOWLEDGE AND TOOLSETS

4.1 Performance Criteria—Surface Pattern and Cracking

Relief patterns were molded to maximize the absorbing surface area of the green clay in contact with air. These studies considered the control of cracking through control lines mimicking actual cracking patterns (Figure 20, upper row), or with deeper patterns that when pressed tended to densify the clay (Figure 20, lower row). An interesting variation mimicked whisker microstructure as a surface pattern. The deeper patterns would channel the movement of excess surface moisture. With further development, the inner surface of the underlying fired ceramic frame could project to create small ridge shelves; this would facilitate a better mechanical connection with the green clay and mitigate crack propagation.

Further studies led to the use of parametric tools. Using an image sampler in Grasshopper, a surface was created from a thermal image of a tile that had been packed with green clay and heated for several hours (Figure 21). From this surface a cracking pattern was generated using a Voronoi diagram. The pattern was pressed into bentonite clay and tested successfully with a heat source. The goal of the study was to be able to predict and then influence where cracks, of multiple scales, would likely emerge over time.

4.2 Adapting Tools—Dynamic Feedback Loops

Taking into account the representation of data and information to even a small interdisciplinary group, legibility is paramount to effective communication. In considering the two color fields representing temperature and humidity (Figure 22), a further differentiation in the color fields helped with pattern

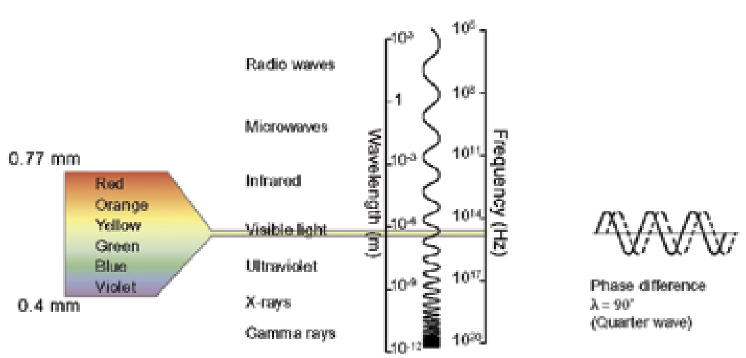

figure 23

figure 23

Phase shift allows a color field overlay that better differentiates colors in the midrange (after Ashby 2009).

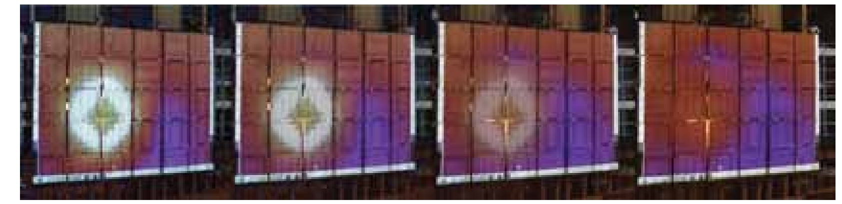

figure 24

figure 25

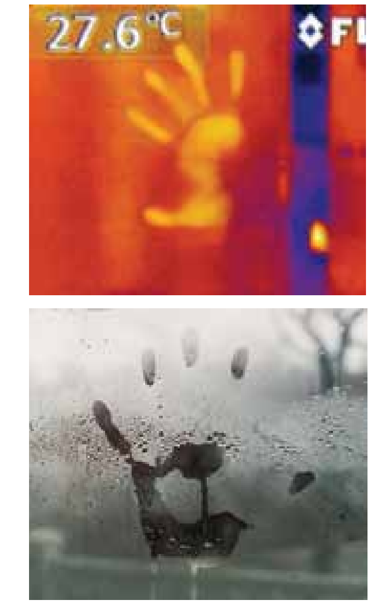

figure 26

recognition and cross-comparison. A richer palette was achieved in the intermediate areas, where most values lie, by the use of a positive phase difference in which a color range slightly overlaps with itself (Figure 23). A vector representation of movement indicating amplitude and direction usefully complements the shifting color field.

In terms of visualization, Steinfeld/Case states that known approaches (to environmental modeling) succeed with how well they support the design of existing bioclimatically responsive building strategies, but do not adequately address the needs of designers seeking to invent new strategies. Central to this failure is the lack of recognition of the dual role that such visualizations must play in the design process, as they must depict quantifiable data in support of a consciously authored design position (Steinfeld et al. 2010).

This project demonstrates the power of creating real-time visual feedback to represent processes not normally visible. In particular, images of temperature decay within the wall (Figure 24) document a shifting reciprocal relationship with the environment. This illustrates how thoughtfully engineered ceramic components can produce Fathy's leveling effect and bring about human comfort with simple means.

Working with a multidisciplinary group allowed for advanced querying of the goals and methods utilized, as well as for timely expert knowledge useful in moving the project forward. This was sometimes countermanded by too much wealth regarding possible avenues of development. Gaining haptic knowledge has been important for the production of the ceramic tiles, toward establishing dependable performance and therefore reliable sensor data. In that light, the exercises involving cracking were a necessary adjunct to this investigation. Establishing a performance datum using common, "everyday" materials will allow future iterations involving technical ceramic processes to be evaluated for both robustness and effectiveness.

5 FUTURE WORK

5.1 Process Investigation

Transfer of technical ceramic processes from the micro to the macro scale is a long-range investigation. However, both partial sintering and freeze-casting offer viable, relatively inexpensive processes to achieve porosity and/or directionality, with minimal shrinkage.

figure 24

Informing the feedback loop, temperature decay from a single energy source over time.

figure 25

Real-time feedback projections for the tile and for the wall.

figure 26

Wall monitoring captures traces of human interactions.

Considering the next tile prototype, the introduction of phase-change materials as micropellets into the ceramic material will significantly increase the thermal storage capacity and hence the leveling factor of the thermal mass. Vollen and Clifford's ecoceramic facades (2012) provide an example of how ceramic vessels filled with phase-change material can be sculpted to work with specific sun angles for passive environmental benefit.

5.2 Future Toolsets

A feedback loop is cyclic by nature: between a simulation model based on material characteristics, the actual material composition of the piece, and the material behavior in a specific context (Figure 25), measured with a sensory array which then inputs behavior data into the model.

In this project, the use of handheld instrumentation (spot thermometer, hygrometer) informed the haptic aspects of making, and to some extent helped quantify material characteristics comparative to a priori knowledge. The sensory array delivered data that was useful toward verifying this knowledge and is a basis for further modeling assembly behavior. Performance modeling such as the flownet is a useful starting point toward a simulation of a dynamically balancing system, based on leveling effects of temperature and moisture (Figure 26), which can effectively accommodate human comfort.

ACKNOWLEDGMENTS

The authors wish to thank Smartgeometry 2012, the Rensselaer Polytechnic Institute, and the Experimental Media and Performing Arts Center in Troy, NY. The generous support for the Transgranular Workshop cluster is greatly appreciated.

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WORK IN PROGRESS

MATERIAL INTENSITIES

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ABSTRACT

For many years now, two distinct strains of inquiry have preoccupied both theoreticians and critical practitioners in the field of architecture: first, the adoption of computation as both an analytical and a generative tool, and second, concern with performance of the actual—how real materials and systems perform in the environment. The dialogue between the two has tended toward a result wherein one process subjugates the other as a means of qualification and verification, and rarely have we seen instances of designers allowing a level of parity in inquiry between these two strains. However, in the format and staging of the 2012 Smartgeometry Conference (sg2012), this question of parity in the inquiry between computation and the world of performance and material was explicitly staged. The challenge was designed with the aim of using as a productive resistance the notion of material intensity—described below—as both a foil to and a measure of current concepts of simulation and intensive modeling in architectural computation. The holding of sg2012 aimed to stage this resistance in the form of workshops, roundtable discussions, lectures, and symposia, with the outcome attempting to define a new synthetic notion of material intensities in modes of architectural production. This paper aims to form the basis of a continued exploration and development of this work. In summary, we focused on:

> *Intensive thinking as derived from the material sciences as an actual and philosophical framework that emphasizes qualitative attributes, which is likened to behavior, simulation, and dynamic modeling. Extensive attributes lead to analytical, representational, and static modeling.*
>
> *Material practices can also be formed as a result of this method of thinking. As demonstrated by the glasswork of Evan Douglis and "paintings" by Perry Hall, the managed complexity possible by working with materials during intensive states of change allows for scalar, morphological, and performative shifts according to a designer's criteria.*

Although both are necessary and actually complement each other, architects need to "catch up" to intensive thinking in process and modeling strategies. Our methods rely on static modeling that yield often complicated frameworks and results, wherein accepting methods of dynamic modeling suggests the capacity to propose complex and nuanced relationships and frameworks.