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# Superporous Intelligent Hydrogels for Environmentally Adaptive Building Skins

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## ABSTRACT

This work explores responsive hydrophilic polymers for convergent functions of climate control with architectural material systems. In buildings, the transition across exterior and interior space occurs through the envelope, which is an enclosure system that mediates heat, light, air and moisture transfer functions. Conventional building envelopes are typically constructed to form a barrier that insulates and hermetically separates outdoor and indoor conditions. The dynamic environmental responses of superporous intelligent hydrogels are shown to be beneficial at the interior layer of a double-skin glazing system for building envelope applications. If the hydrogels are integral to the building envelope system, then various environmental functions (such as natural daylighting, heat transfer, airflow and moisture control) can be achieved through integrated actuators to result in improved building energy performance.

The composite embodiments emulate bio-analytical functions when embedded microbore-tube water channels serve as actuators for swelling and deswelling kinetics respectively. Each prototype is conceived in response to hot-arid climate contexts. The prototype presented here is a lightweight ventilation cooling and daylighting system. Initial prototypes are inserted into an environmental test-bed that is consequently divided into two chambers to represent an outdoor and indoor condition. The input chamber includes controllable heat and light elements that affect the dynamics of the hydrogel system. The output chamber on the opposite side of the prototype division includes temperature, humidity and photo sensors that are connected to an Arduino board for data collection. Dependent upon the environmental conditions of chamber two, a control program actuates small hydro-pump to saturate the gels with water.

The initial results provide correlations between mechanical (elasticity) and thermal (conductivity) properties. Current work in progress includes documentation of average rates for sorption-desorption kinetics and correlations between saturation loading and visible transmittance. The physical test data will also be integrated into building-scale energy performance simulations and hygrothermal transfer numerical analysis for building envelope compositions. The embedded material logic of the hydrogel is exploited in an architectural configuration for a convergence of prior building mechanical system and building envelope functions. The current work demonstrates a highly promising application of soft-skin membranes for much needed reductions in energy consumption within the building sector.

## INTRODUCTION

The interscalar framework that informs the characteristics for novel material systems in buildings integrates aspects of regional context (climate, material resource, and infrastructure) in conjunction with the identified building thermal performance needs. A building's thermal performance is dependent upon the material and spatial conditions defined in the architecture, and can be modeled in part through analogy to regional natural systems. Referencing context-specific plant biomes may help to define appropriate thermoregulation functions, such as the succulents in arid environments that retain water at the skin and form folding patterns for self-shading. In addition, the regional material resources are identified for building construction to encourage sustainable regional industry practices. The scale of work in this area of research focuses on the material developments for building enclosure technologies and systems (Figure 1).

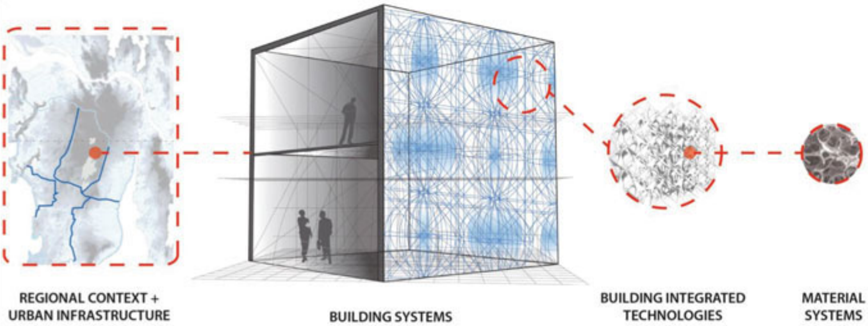


**Figure 1.** Interscalar framework for linking regional context and material systems to building integrated technology design.

The climate context of a building is significant for consideration in the development of any particular material system that will be most appropriate in local application. The greatest amount of heat exchange occurs at the building's envelope. At the same time, the outdoor weather conditions can be quite varied in both diurnal and seasonal timeframes, as shown below in the annual hourly dry-bulb temperature for Tucson, Arizona (Figure 2). In addition to the outdoor climate effects, (which also include daylight, humidity, wind, etc.), a building's programmatic use and occupant use patterns can also influence internal heat gains and varied environmental needs. Thus, a material system that has an ability to both passively and actively respond to these more complex fluctuations through modulations in the material's physical or chemical properties can be most ideal for achieving long-term environmental adaptation and sustainable design for building operations.

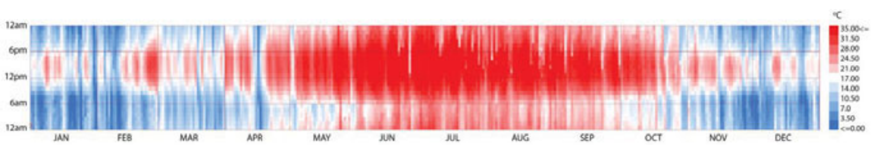


**Figure 2.** Annual hourly Typical Meteorological Year (TMYIII) Dry Bulb Temperature (DBT) data for Tucson, Arizona, USA visualized with Ladybug analysis tools.

On a conceptual level, the building enclosure is functioning as a material system that has the ability to potentially harvest climate resources (heat, light, air, water) and store, transform, and re-distribute to the interior spaces (Figure 3a). Because of the unique behaviors of hydrogels under various environmental conditions (thermotropic, reflectance band-gap shift, water absorbing, vapor diffusion, etc.) there is a potential to consider the gels for integration in building skins to calibrate the environmental adaptation (Figure 3b).

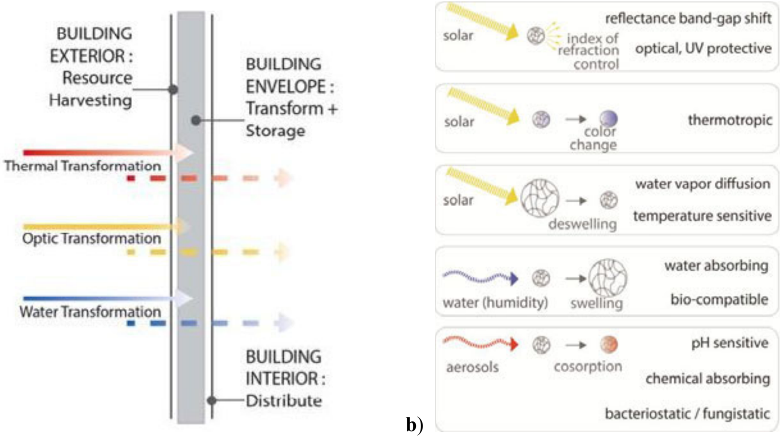


**Figure 3.** a) Building envelope as transfer function for thermal, optic, and water phenomena (left); and b) Hydrogel multifunctional properties and environmental response (center and right) [1].

There is limited application of hydrogels in building systems to date, but there is one existing technology known as CloudGel by Saint Gobain [2]. The CloudGel is a building glazing technology that incorporates hydrogel in sheet form between two layers of glass. The gel responds to thermal changes, collapsing under higher temperatures causing densification of the polymer chains and reducing the amount of solar transmission. The system serves for both natural daylighting and thermal control at the building envelope. Other examples include the integration of superabsorbent hydrogels in concrete as an add-mixture to serve as self-sealing of cracks during the curing process or to slow the rate of curing in general to prevent cracks from forming [3].

## EXPERIMENTS

### Prototype Design and Fabrication

An initial prototype developed for experimental investigation assumes a hot-arid climate context that requires cooling systems in buildings for reaching human thermal comfort. Part of the literature review analysis included comparisons of existing mechanical air conditioning systems, resulting in identification of direct outdoor air systems (DOAS) as the most effective contemporary modes for energy efficiency and decent air quality control [4]. The prototype concept developed here is a lightweight ventilation evaporative cooling and daylighting system. The membrane is constructed with polyacrylamide gels encased in a porous mesh suspended from an enclosure of flexible fabric on the outer laser-cut for distributed aperture control, as well as a heavier hydrophobic material on the inner face that was perforated for ventilation flow (Figures 4 and 5). When the gel is hydrated, the swelling kinetics actuate the ventilation flap to allow for passive airflow cooling through the membrane, concurrently pulling humidity off the gels to induce a sensible temperature drop in the surrounding atmosphere.

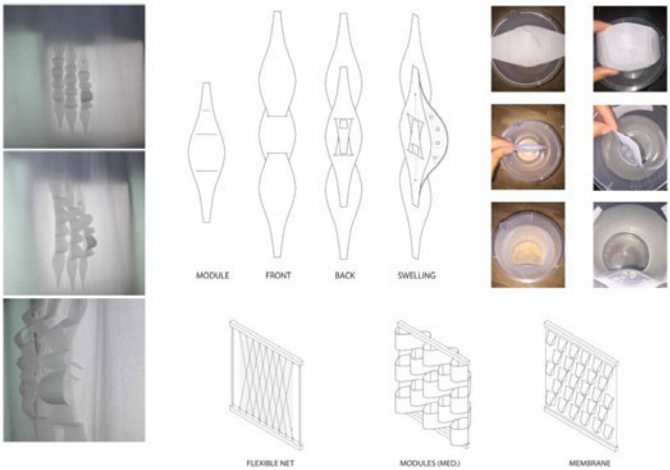


**Figure 4.** Hydrogel embodiment module concepts and process development for swelling-deswelling kinetic membrane actuation.

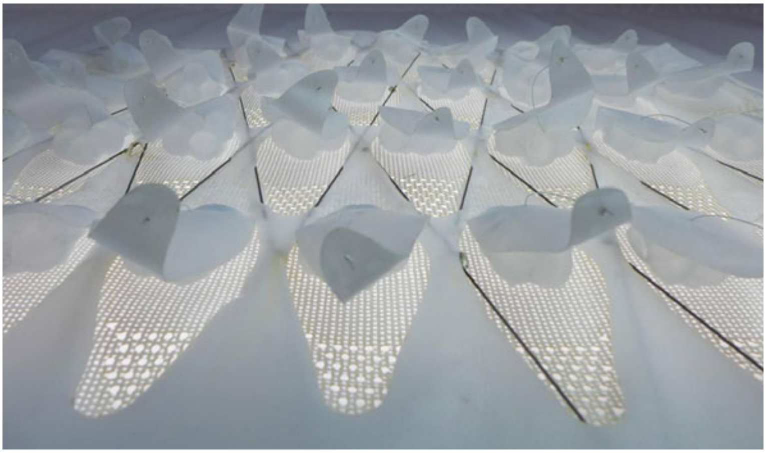

**Figure 5.** Gel-actuated Evaporative-cooling Membrane System (GEMS) prototype in swelling and ventilation-flap actuation mode.

**<u>Prototype Testing and Simulation</u>**

A physical environmental test chamber was constructed with two volumes that emulate an outdoor and indoor condition (Figure 6). The chamber allows for the insertion of various building envelope prototype systems in the middle and includes a number of apertures for sensors and device connections. At the end panel of the chamber on the outdoor condition side, there is a removable panel attachment that accommodates any variety of environmental input representations. The initial GEMS prototype is shown here with a dimmable halogen light array with photosensors, temperature sensors, and humidity sensors in each chamber to monitor the environmental conditions.

**Figure 6.** Environmental test chamber set up with GEMS prototype 01 inserted in between the outdoor and indoor chamber conditions, with integrated light-array input, sensing, and actuators.

Current experiments include the measure of visible light, infrared, and UV transmittance through the hydrogel in various states of saturation. Another is the measure of hydration rate of the gels with the microbore tube connection to the water pump and time required to reach maximum loading. The hydrogel membrane will be tested under a range of temperature and airflow conditions to determine desorption kinetics for ventilated evaporative cooling applications. Another is the test-chamber sensing of temperature and humidity conditions under manual water pump actuation. Ultimately, the pump will be linked to an actuator control from an Arduino microcontroller that receives instruction from a machine-learning algorithm corresponding to real-time chamber sensor data.

## DISCUSSION

Initial hydrogel samples were tested for thermal conductivity and correlated to literature review data for the estimated elasticity (Figure 7). The samples tested included various polyacrylamide gels in saturated or gellated states [5]. The characteristics of the hydrogel samples tested here align within the elastomers grouping at the weaker end of the modulus spectrum (<0.005 GPa) [6, 7] and lower end of thermal conductivity (0.393 to 0.573W/mK). The gellated polyacrylamide sample with the highest conductivity value (0.573 W/mK) is due to higher water content.

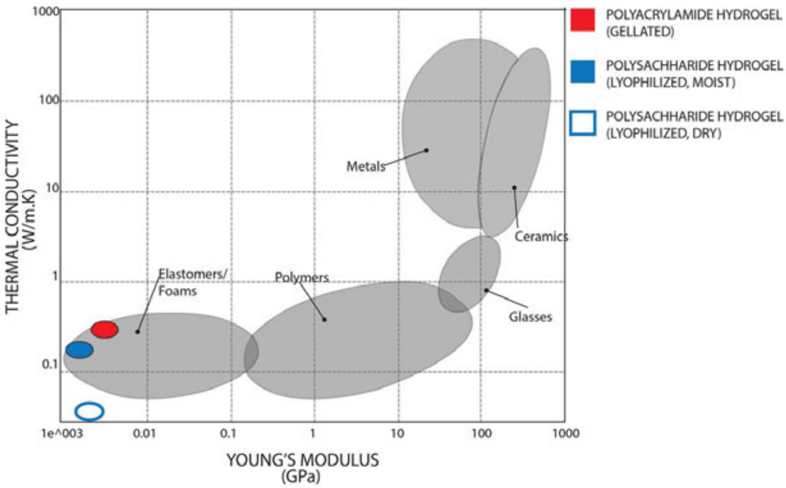


**Figure 7.** Thermal conductivity vs. elasticity: Polyacrylamide and polysaccharide hydrogels in relation to other material groups [8].

In general, it can be inferred that the more porous the dry gel, the lower thermal conductivity but weaker Young's Modulus. While the heat capacitance will increase during hydrated state of the gel, providing greater storage of thermal energy, the conductivity will also increase due to high water content at the same time the strength will decrease due to expanded pores. Considerations are necessary for the embodiment of the hydrogel within the proposed material system (whether membrane or module) to separate the gel from direct contact with primary structure building materials to avoid heat transfer in this mode. The range of the thermal conductivity for the saturated and unsaturated gel are relatively small, and compositing the membrane with alternate high heat resistance, or insulative, materials (such as lyophilized gel) should be considered. In addition, because of the low Young's modulus values of saturated gels, further development on the kinetic strength improvement as well as study of fatigue cycling are necessitated [9].

## CONCLUSIONS

The study to date establishes a framework and methodology for proceeding to address the potential integration of hydrogels for multivalent environmental response into building enclosure systems. Because the identification of a number of potential needs in building performance situates the work, the development of specific hydrogels may be approached from a standpoint of optimal adaptivity, rather than optimization for a single design parameter. Currently, the work is also combining both passive functions in the material logic with active functions in the sensing and controls, and identifies a need for superporous gel for maximum loading and humidity diffusion properties. The intent for such combination in the building's environmental control systems serves as a removal of current redundancies between building envelope materials and ducted networks and mechanical equipment.

In addition to the current experiment in progress mentioned in the prototype testing section above, the future work on this research project will require a number of ongoing and new collaborations with other disciplinary expertise. One major consideration in the development for exterior envelope applications that are exposed to sun and hold moisture is the development of biofilms, necessitating further research in collaboration with microbiologists. Specific performance functions of building-integrated hydrogels that are identified for particular applications will be linked into a simulation framework for building scale analysis. The simulation platform requires custom development of dynamic algorithms reflecting the multivalent properties of the identified hydrogels, but initial pilot simulations show improvements on building environmental performance compared to baseline systems. The application for soft membranes in buildings is also promising for the thermally active surfaces that can be spatially integrated to benefit human physiology through thermal comfort.

## ACKNOWLEDGMENTS

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