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Framework for Tetra-functional Control of Viscoelastic Molecular Entropy in Biopolymeric Hydrogel Dynamics for Environmentally Responsive Metabolic Processes in Morphological Architectural Membranes

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ABSTRACT

Efficacious resource harvesting constitutes new modes of conceptualizing the interactions of buildings with surrounding environmental conditions. The internal logic of a biotechnical paradigm in architectural design allows for the potential of fluid exchanges between medium and material to be realized with correlated metabolism. Such concepts avert existing mechanical paradigms based upon linear conservation of energy processes and approach entropic integrated design interactions of nonlinear dynamical processes. Through a physiological analogy that informs architectural anatomy, the genetic code of hydrogels embeds emergent morphological responses to discrete interactions with environmental phenomena. In contrast to the static hard tissue of the skeletal system, viscoelastic soft tissue provides significant environmental impact by means of integrating spatiotemporal adaptation in building systems.

This framework provides an interscalar perspective for integrating biopolymeric membranes within building-envelope systems and informs the microstate design of the polymer chains for optimized mechanical performance. Hydrogels are a translucent three-dimensional water-swollen polymer, which exhibit mechanical work upon interaction with water vapor. In effect, this interaction provides for a variant index of refraction, a variant heat capacitance, and a physical shift in surface morphology. Characteristic changes in material thermal and mechanical properties parallel diurnal climate profiles for circadian biorhythmic membrane designs. The macrostates of temperature, pressure, and volume reciprocally inform the potential microscopic properties, including position and velocity of each molecule within the material system. The viscoelastic molecular entropy (Maxwell model) of hydrogels is established as a fundamental basis for situating a dynamic material logic influencing a high efficacy architectural physiology. The Maxwell model is translated as an algorithmic framework for mechanical control through tetra-functional polymer chain development of biopolymeric hydrogels. In contrast to polyacrylamide hydrogels, the chemistry of biopolymeric polysaccharide hydrogels is well suited for renewable sourcing and down cycling to achieve sustainable material life cycles. However, these biopolymers do not inherently exhibit robust structural properties necessary for influencing morphological shifts of the membranes for intelligent passive design strategies such as self-actuating ventilation apertures or self-shading surface geometries. The research encompassed in this work engages the development of a more acute framework for the trajectory of biopolymeric hydrogel dynamics based upon a necessity for controlled morphological modulations in response to specific environmental conditions.

INTRODUCTION

All buildings exist within climatological and geological contexts that provide vast resources both for thermodynamic functions and for material composition. Traditionally, the building enclosure is conceived as a means of protection from climate for adequate and comfortable functioning of humans within interior environments. Emerging paradigms suggest that climate resources are inherently valuable in consideration of long-term utilization and sustenance, constituting new concepts for building enclosure systems that employ environmental resource harvesting and transformation functions. The seasonal and diurnal climate profiles in combination with building use profiles inform the building-envelope system socio-environmental performance criteria. For the hot-humid climate condition, the annual variations are minimal, with dry-bulb temperatures, solar radiation, and humidity levels remaining fairly consistent. The obvious diurnal variation is the solar radiation and corresponding daylight cycle serving biorhythmic membrane designs. The range of building envelope interactions identified for environmental performance through biopolymeric membrane systems includes adaptable material functions for modulating moisture, light, heat, air, and pollutants (Fig.1). Such systems embody principal behaviors that necessitate innovative material technologies to accommodate multivalent and adaptable design conditions.

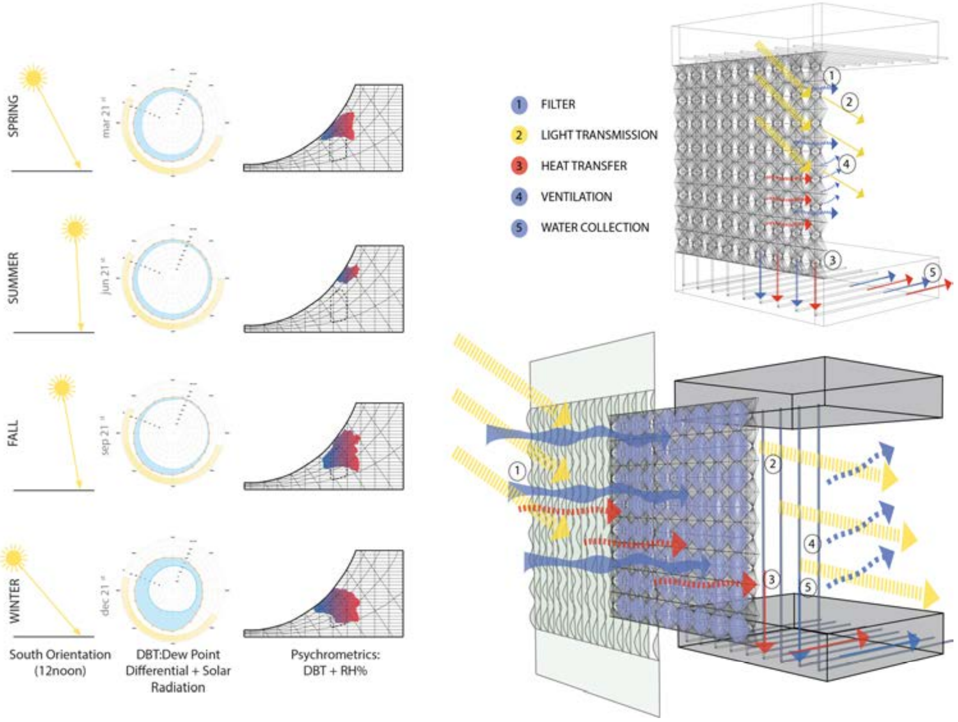

Figure 1. Climate responsive adaptive biopolymeric membrane environmental performance criteria for multivalent temporal design conditions.

The sum of processes occurring in systems that allow for the production of energy, the elimination of waste material, and morphological mutability, are attributes of metabolic processes. Adaptable mutations resulting from catabolic and anabolic processes require water-based environments for functionality. Hydrogel membranes that integrate air-to-water fluid exchanges have an embedded material logic that directly serves physiological analogies and biotechnical design (Fig.2). These membranes exhibit viscoelastic behaviors that provide spatiotemporal adaptation within building-envelope integrated systems due to variations in environmental inputs. The nonlinear dynamical processes that result from integration of soft tissue within the building enclosure directly inform a second law of thermodynamics model for analyzing the energy and work potentials of the system. Macroscopic expressions of disorder are indicative of heat transfer potentials and statistical mechanics of viscoelastic sorption is indicative of the microscopic entropy.

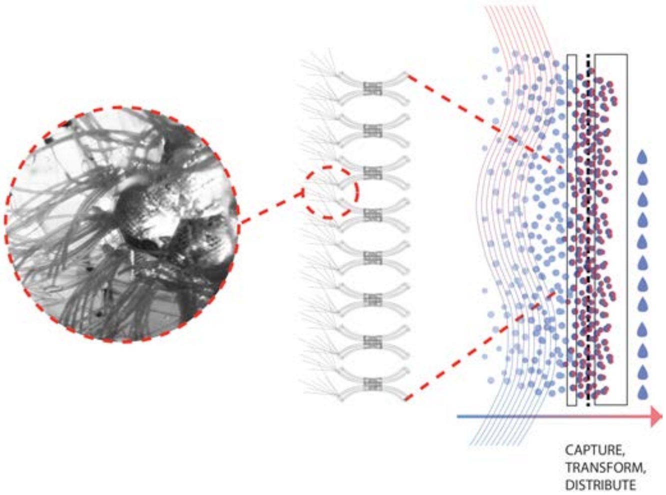

Figure 2. Hydrogel-based building-envelope integrated membrane concept for climate resource metabolism and air-to-water fluid exchanges.

A series of material performance parameters is established to provide a framework for polysaccharide hydrogel design applicable for integration within building-envelope systems. These parameters include sorption characterization, dimensional modulation, mechanical characterization (stress: strain relations), heat capacitance modulation, and light refraction modulation. The desired material behaviors are determined through an interscalar mapping of building context and system design linked to spatiotemporal climate and building program profiles. Reciprocity between theoretical and applied research as well as digital and physical modeling methods are engaged for development of this conceptual framework.

THEORY

The hydrogel design framework for building-envelope integrated membranes is intricately informed by the interscalar correlations of building and system performance criteria in conjunction with regional climate and material resources (Fig.3). Based on prior research findings an appropriate application is a commercial building typology in a hot-humid climate context with potential material sourcing from offshore seaweed farming (for agarose-based gels) or crustacean shellfish waste streams (for chitosan-based gels) [1].

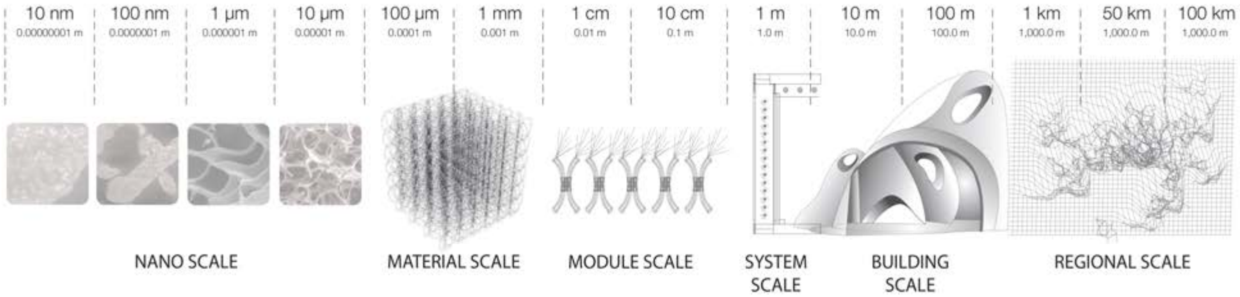

Figure 3. Interscalar correlations of building and system design cross-linked to regional climate and material resources to inform material scale criteria.

Hydrogel characterization

Hydrogels are a three-dimensional insoluble water-swollen hydrophilic polymer. Hydrogels can be classified by their network morphology (physical structure of macroporous, microporous, or crystalline form), by their ionic classification (neutral, anionic, cationic, ampholytic), and by their crosslinks (petroleum-based covalently bonded chemical gels, or weak association physical gels such as van der Waals, hydrogen bonds, electrostatic forces, molecular entanglements) [2].

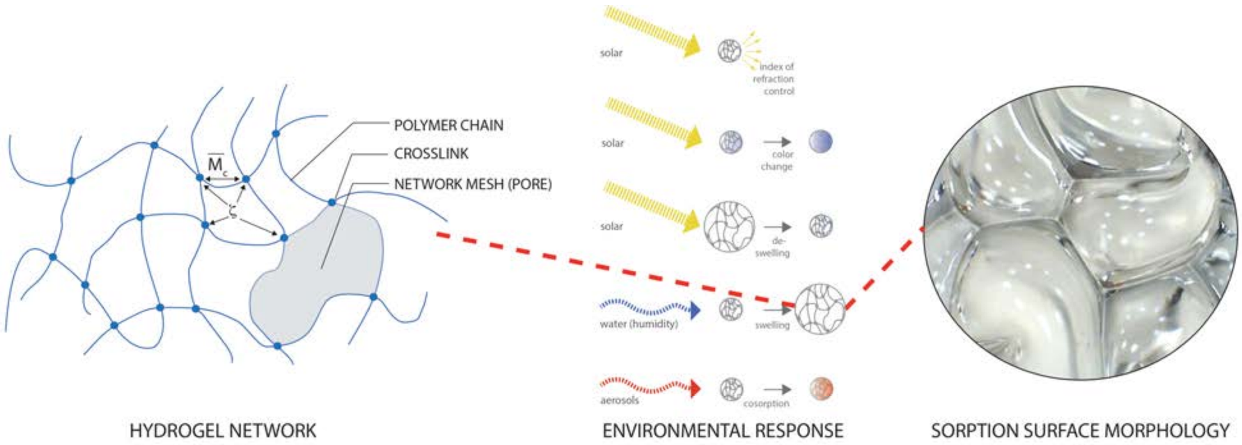

Figure 4. Hydrogel characterization and response to environmental phenomena.

Greater density in crosslinks results in smaller mesh pore size and general tougher mechanical qualities. A lower crosslink density implies a less durable polymer material under subjection to physical stresses, constituting a system design requirement for hybridizing and/or compositing hydrogels in conjunction with a mechanism or device. These materials readily stretch in tension (low Young's modulus) and expand during sorption (Fig. 4, right), but there is little strength when swollen with water as the effective density of the polymer network is severely decreased. When the polymers are water-swollen, they behave with non-linear stress-strain behavior [3], comparable to Maxwell model materials. Stronger gels will exhibit dominating elastic behavior, while weaker gels exhibit more viscous behavior. Accommodating fluctuating material properties with respect to dynamic environmental conditions guides the material design determinants for desired mechanical behavior.

Material chemistry ethic

Hydrogels can generally be synthesized from either polysaccharides (physical bonds) or polyacrylamides (chemical bonds). The natural polysaccharides (cellulose, starch, chitosan, agarose) are identified as some of the most abundant organic substances on earth [4], while polyacrylamides can be engineered at a molecular scale for specific functions but are composed of limited petroleum-based resources. The bond length of polymer chains between crosslinks provides the most significant correlation to pore size for polyacrylamide hydrogel synthesis (Fig.5, left), while the pore size in polysaccharides is more difficult to control due to the complex nature of physical crosslinks. The proposition for building envelope-integrated membrane hydrogel design is to emulate chemical crosslinks in polysaccharide synthesis through selective composite chemistry.

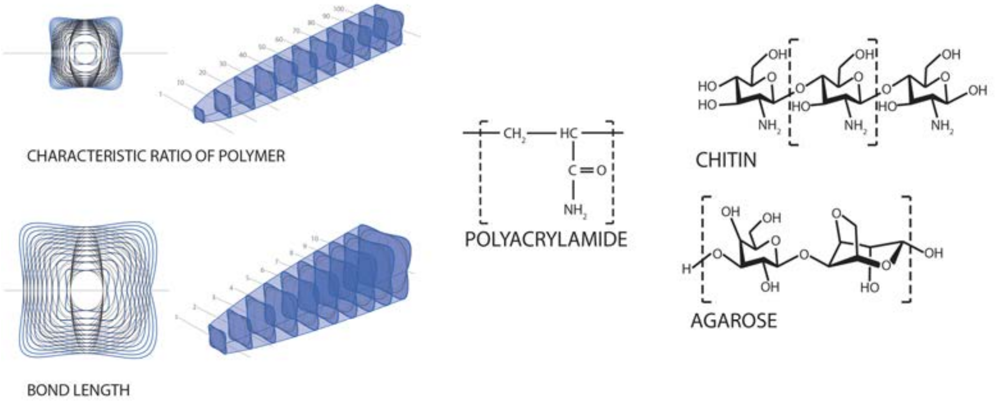

Figure 5. Control of pore size in polyacrylamide synthesis through chemical bonds.

Technical microstate criteria for membrane dynamics

The focus on mechanical functioning of the hydrogel expansion and contraction dynamics is significant for building membrane performance through its effects for self-shading surface conditions and ventilation aperture actuation modes. The range of hydrogel expansion relates directly pore size, which is determined based on the concentration of crosslinks as a result of the characteristic ratios used for chemical synthesis (Flory-Rehner theory, see Fig.5, left) [5].

In addition, ideal network structures are constituted by tetra-functional crosslinks [6] and typical gels are isotropic in their swelling behavior. Interface conditions between hydrogels and other solid phase materials will pose some technical challenges. The tribological interactions, forces of friction and wear, will pose active life limitations for the hydrogel due to its cycling of expansion and retraction in combination with support materials that are static. Developing an anisotropic hydrogel material in order to control swelling direction and orientation would be a technical challenge, but precedents do exist for specific tissue engineering applications [7].

The dynamic hydrogel morphology is informed by the microstate properties of gas and liquid phase molecular velocities within the material system, which are in turn directly influenced by macrostates of temperature, pressure, and volume. The viscoelastic behavior within the hydrogel system informs a fundamental basis for dynamic material logic with an algorithm basis of the Maxwell model for stress and strain relationships to entropy. The translation of this framework is developed in Processing for statistical mechanical generators of the hydrogel membrane dynamic movements in direct response to environmental inputs (Fig. 6). The desired mechanical control from the polysaccharide hydrogel is based on the idealized tetra-functionality emulating crosslinked polymer chain development.

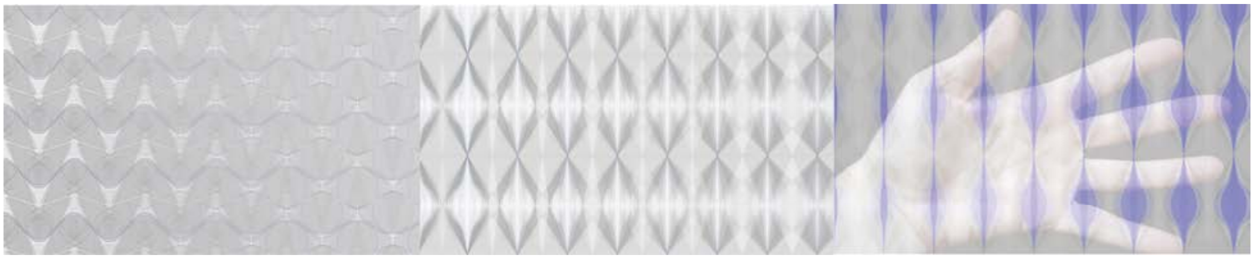

Figure 6. Dynmiac hydrogel membrane animation stills from Processing algorithmic framework based on Maxwell model stress-strain behaviors and tetrafunctionality.

DISCUSSION

Material thermodynamic and statistical mechanic generators for dynamic membranes are useful micro-scale phenomena to establish robust material logic for response to varying environmental phenomena. This unique basis for dynamic material behavior determinants enables more robust capacity for hydrogel integration in building systems. While there are a number of uncertainties in terms of cycling fatigue and creep, the primary material design framework is established through a wide range of environmental phenomena response.

CONCLUSIONS

Investigations across interscalar aspects for environmentally responsive building envelope-integrated biopolymeric membrane designs provide an innovative concept for a polysaccharide hydrogel design framework. As an emerging material for application in dynamic building systems, it was shown that the hydrogel exhibits unique behaviors such as viscoelastic properties that are advantageous for building integration to achieve multivalent performance. The present study indicates that tailoring aspects of enhanced polysaccharide synthesis with statistical dynamic mechanical performance limits informs the framework for material design improvements.

REFERENCES

1. Smith, Shane I. M*edium, Matter, Form, and Process: Dynamic Hygrothermal Polymeric Membranes.* Dissertation, Rensselaer Polytechnic Institute, August 2015.
2. A. Borzacchiello and L. Ambrosio, "Structure-Property Relationships in Hydrogels," in *Hydrogels,* ed. Rolando Barbucci (Milan, Italy: Springer, 2009), 9-20.
3. A. Borzacchiello and L. Ambrosio, "Structure-Property Relationships in Hydrogels," in *Hydrogels,* ed. Rolando Barbucci (Milan, Italy: Springer, 2009), 15.
4. Hinori Izawa et al., "Unique gel of xanthum gum with ionic liquid and its conversion into high performance hydrogel," *Journal of Materials Chemistry* 19 (2009): 6969.
5. P.J. Flory and J. Rehner, "Statistical Mechanics of Cross-Linked Polymer Networks: II. Swelling," *Journal of Chemical Physics* 11 (1943): 521-526.

6. A. Borzacchiello and L. Ambrosio, “Structure-Property Relationships in Hydrogels,” in *Hydrogels,* ed. Rolando Barbucci (Milan, Italy: Springer, 2009), 10.
7. M.C. Swan et al., “Synthesis and properties of a novel anisotropic self-inflating hydrogel tissue expander,” *Acta Biomaterialia* 7 (2011): 1126-1132; and A.L. Buyanov et al., “Anisotropic swelling and mechanical behavior of composite bacterial cellulose-poly(acrylamide or acrylamide-sodium acrylate) hydrogels,” *Journal of the Mechanical Behavior of Biomedical Materials* 3 (2010): 102-111.