Natural and Living Building Materials as Carbon Reduction Strategies in the Built Environment

Jay H. Arehart & Wil V. Srubar III, PhD

Department of Civil, Environmental, and Architectural Engineering, University of Colorado Boulder

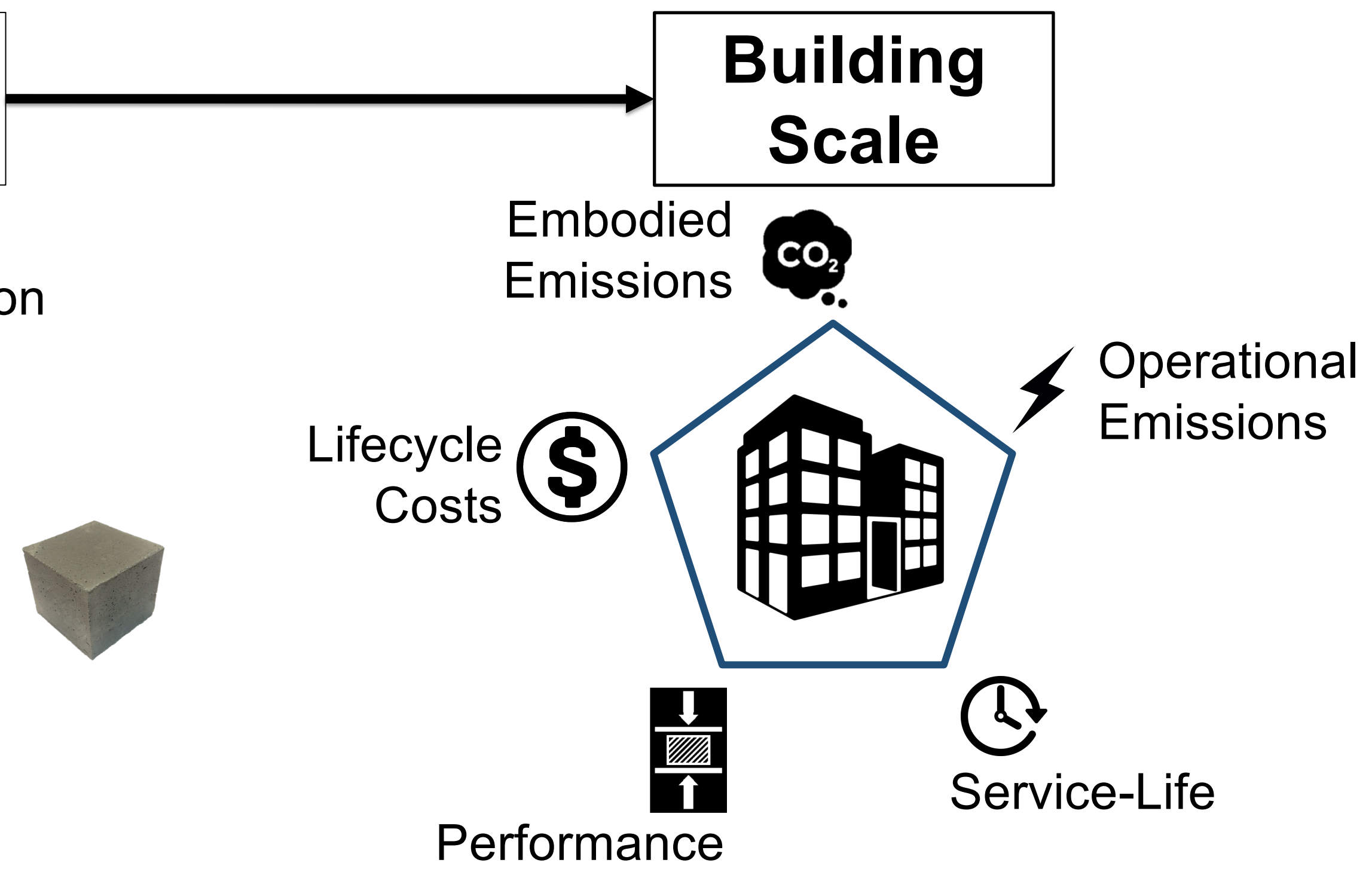
Motivation

40%	Today, the built environment contributes 40% of global carbon emissions [1].
150 billion	In 2010, 205 billion square meters of floorspace existed. By 2060, 356 billion square meters will be constructed to meet the needs of a growing population and urbanization [2].
49%	49% of the carbon emitted by buildings between 2020 and 2050 will be from manufacturing construction materials, while 51% of carbon emissions will be from operating buildings [1].

Evaluation Framework

Material Scale

- Synthesis
- Characterization
- Modeling
- Optimization



The Living Materials Laboratory at the University of Colorado Boulder, led by Prof. Wil Srubar, focuses on experimental and computational materials science research which integrates biology with polymer and cement chemistry to create responsive, biomimetic, and/or living materials for the built environment. The research focuses at two scales to evaluate how these natural and living construction materials have the potential to move the built environment towards *drawdown*. At the material scale, novel materials are synthesized and their properties characterized. The results from these experimental and computational investigations are used to model and optimize material performance at the assembly scale. Moving from the material to the building scale, the use of these materials are evaluated from five primary perspectives: embodied emissions, operational emissions, service-life, performance, and lifecycle costs.

Living Building Materials

What is a Living Building Material?

Living building materials are materials made by nature and are characterized by their ability to grow, regenerate, and adapt. To create these materials, living organisms, such as bacteria, fungi, or algae are included with abiotic media to create a hybrid material. In the context of construction materials, living materials can be synthesized to replace conventional materials which are carbon-intensive to manufacture. In addition, because living materials can grow, regenerate, and adapt to the environment, they are well suited for dynamic environments in which buildings exist. The growth, and regenerative capacity of these materials are controlled by environmental switches. Furthermore, the at the end of service, the abiotic components of living materials can be recycled, which contributes to a circular economy. Figure 1 shows the lifecycle of a brick synthesized using bacteria as the biotic inoculum and a gelatin scaffold as the abiotic media.

Figure 1. Lifecycle of a microbial brick.

Microbial Mortars

One living material whose application is specific to the built environment is mortars composed of gelatin, sand and bacteria (Figure 2). The gelatin media with bacteria cells produces $CaCO_3$ which creates physical crosslinks with the sand aggregate. When the bricks are desiccated, their structural performance improves, yet also have regenerative abilities if the water content of the brick is increased.

While development of these mortars is in the early, they have the potential to replace cement-based mortars which contributed 0.66 $GtCO_2e$ to the atmosphere in 2016 [3].

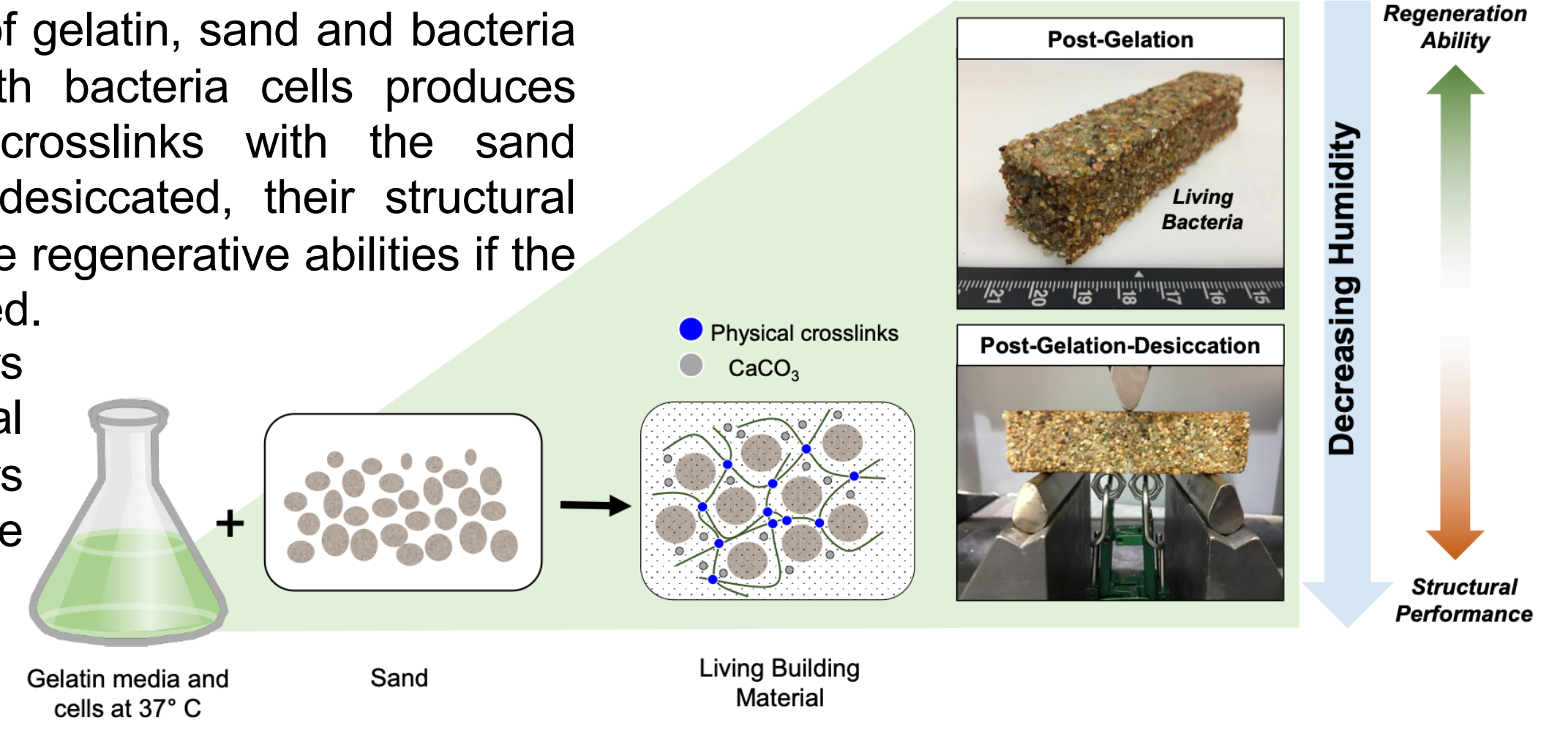
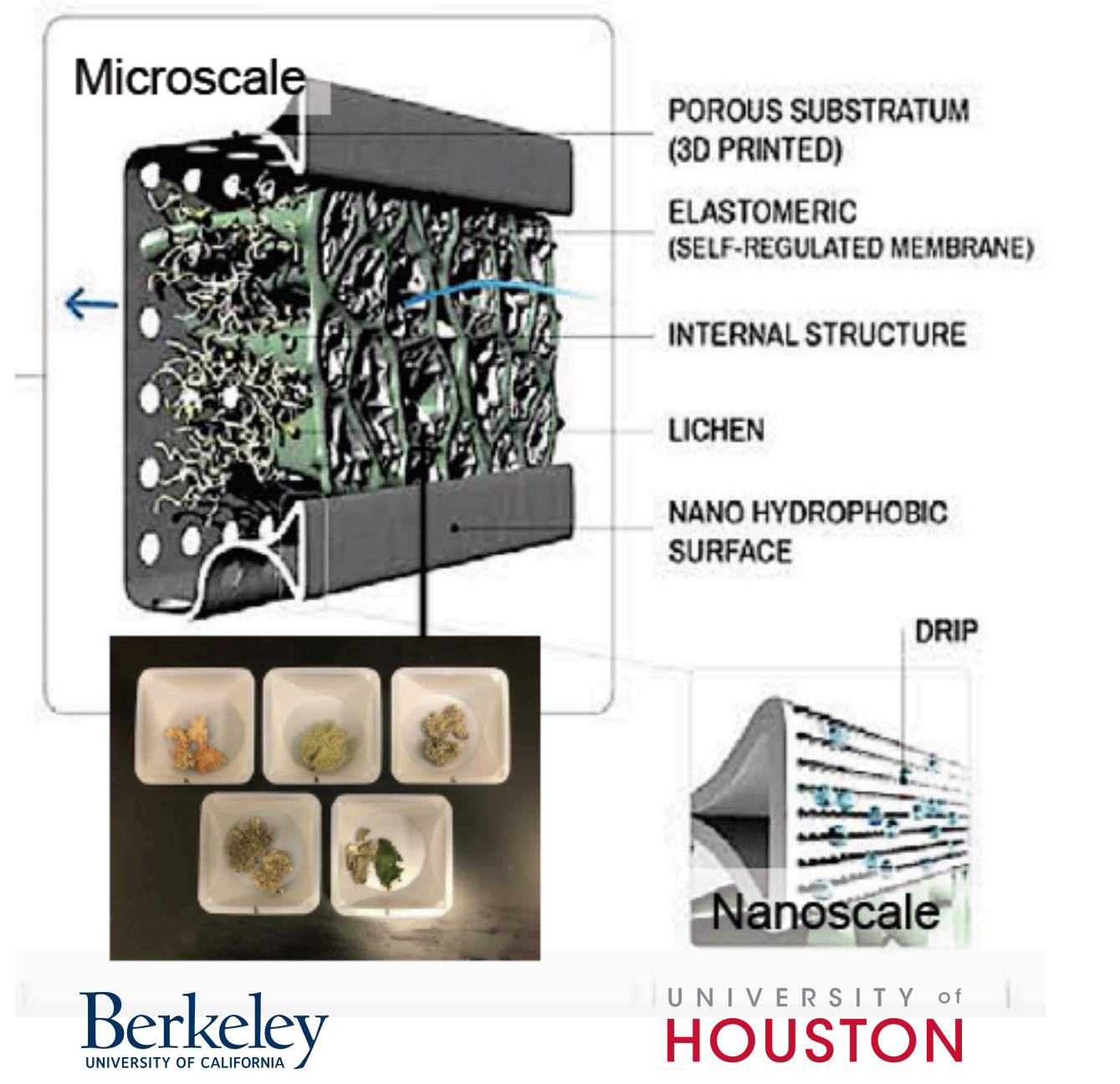


Figure 2. Manufacturing and synthesis of a microbial brick

Living Lichen Membranes for Indoor Environments



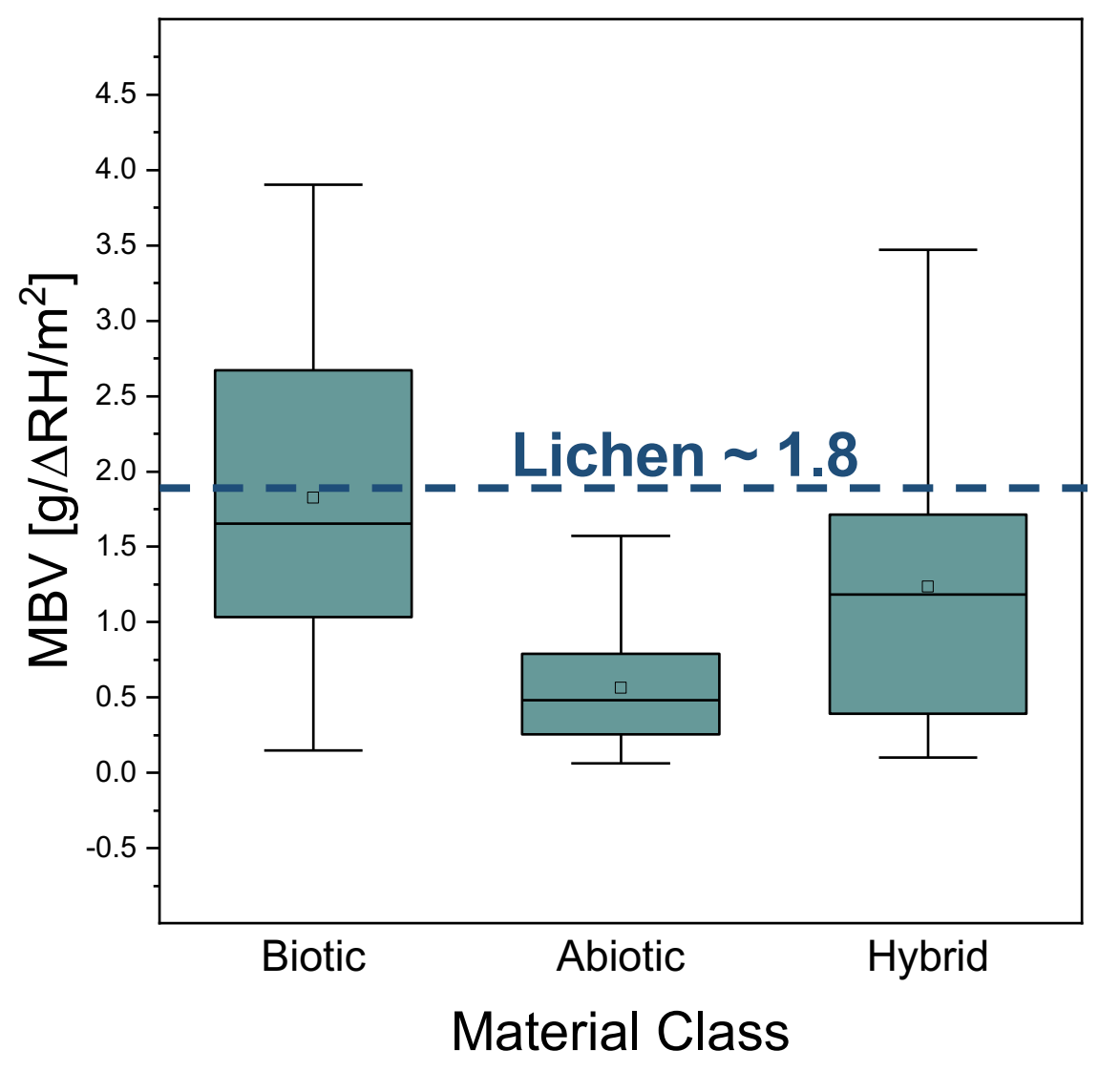
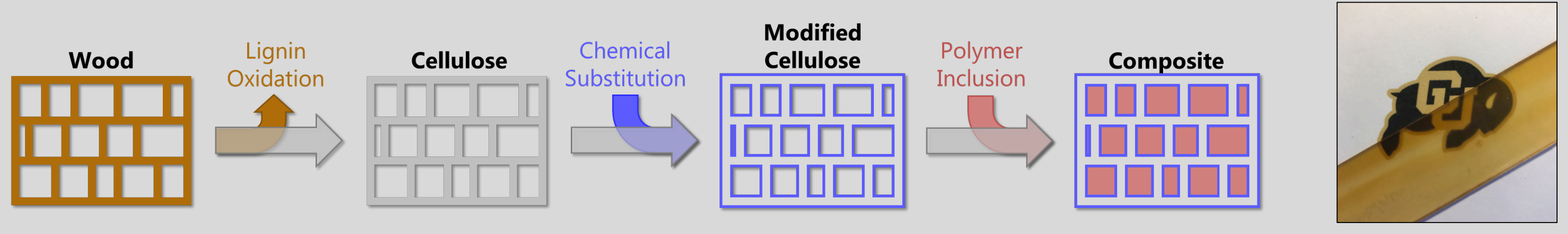


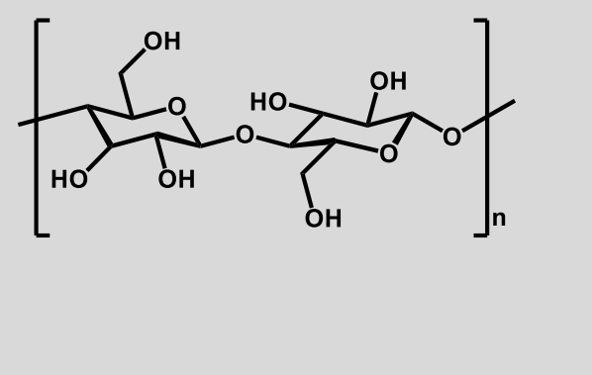
Figure 3. Moisture buffering value (MBV) for different material classes.

Lichenous materials are a living material consisted of an abiotic structure and a lichen-based material which benefit indoor environments through their moisture buffering capacity (see Figure 3), carbon sequestration, and bio-indication. Unlike plant-based materials, lichenous materials do not evapotranspire, yet interact with indoor relative humidity. Similar to thermal buffering effects, materials with high moisture buffering values (i.e. lichen) dampen relative humidity peaks. By reducing peak humidity loads, energy-expensive de-humidification can be decreased or even avoided. Additionally, these bio-based materials sequester carbon through photosynthesis and can be used as bio-indicators to monitor and improve indoor air quality [4,5].

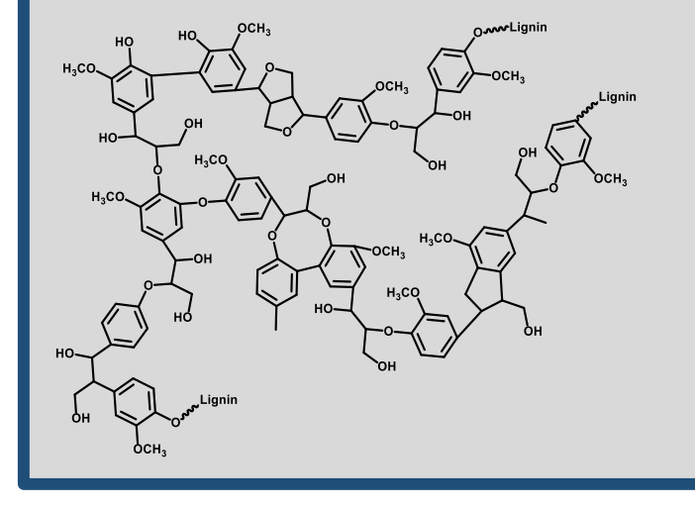
Natural Building Materials

Transparent Wood Composite Windows





Cellulose: 40-50%
- Structure
- Strength



Lignin: 20 – 30%
- Reinforcement
- Color

Transparent wood composites (TWCs) are a natural material that have the potential to replace silica-based glazing in buildings. TWCs are produced by removing the lignin within wood through an oxidation process. The cellulose scaffold is then modified and a polymer is infiltrated that matches the refractive index. The result is a transparent wood assembly that has a thermal conductivity of ~0.15 W/m/K (glass is ~1 W/m/K). This more insulative glazing, has the potential to reduce the energy consumed by space heating and cooling in buildings. Up to 33% savings in space heating and cooling can be achieved when retrofitting pre-1980 vintage office buildings with double-paned TWC-based windows (Figure 6) [6-8].

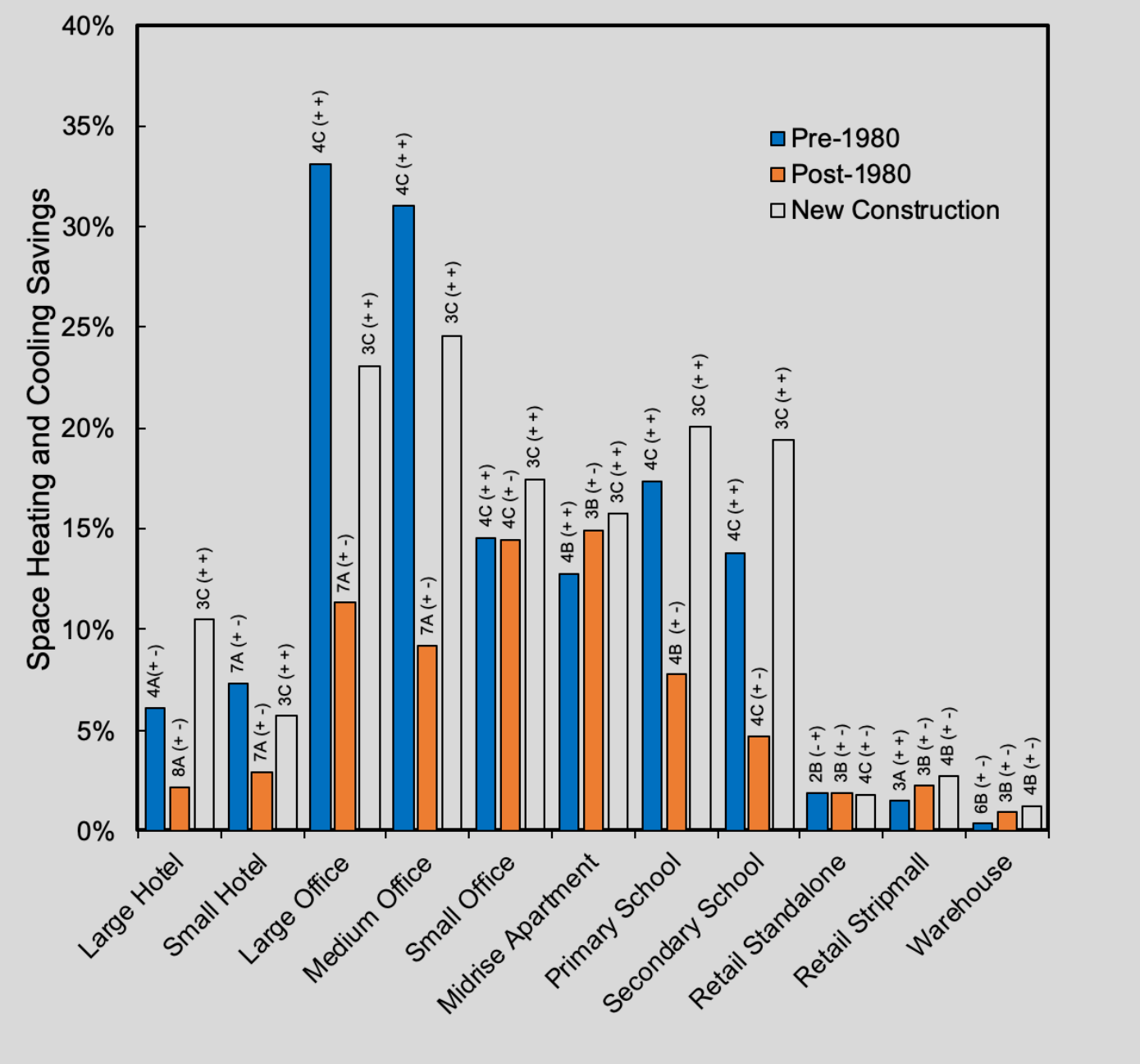
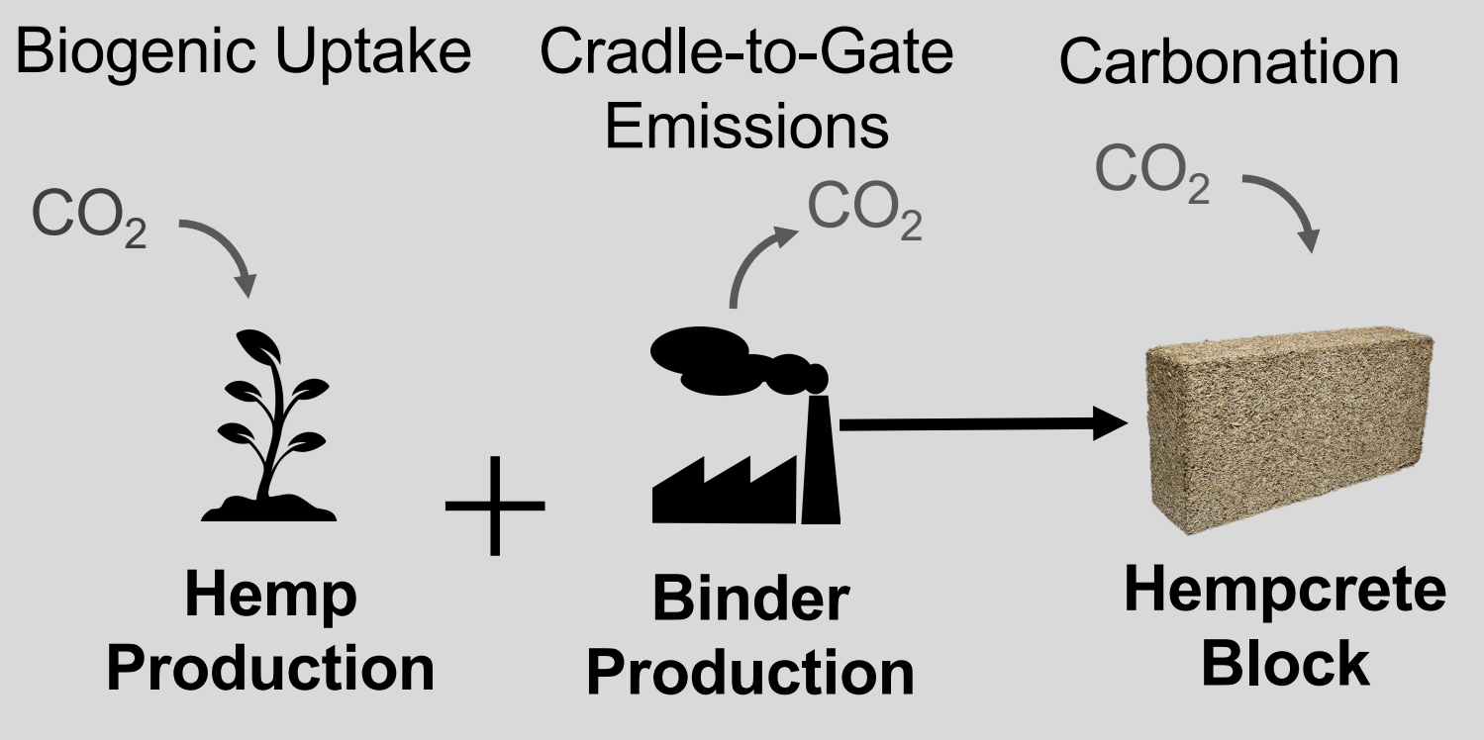


Figure 6. Space heating and cooling energy savings from TWC-based window retrofits.

Carbon Storage Potential of Hempcrete



Carbonation Reaction:

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$$

Carbon Storage Potential:

$$\alpha_{CH} = \left[\phi_h\left(\frac{3}{2}\frac{K_{C_3S}}{MW_{C_3S}} + \frac{1}{2}\frac{K_{C_2S}}{MW_{C_2S}} - \frac{2}{1}\frac{K_{C_4AF}}{MW_{C_4AF}}\right) + \frac{K_{CH}}{MW_{CH}}\right] MW_{CO_2}$$

Hempcrete is a fiber-composite material composed of hemp shiv and a cementitious binder (a blend of hydrated lime and hydraulic of pozzolanic binders). Commonly used as an insulation material, hempcrete can take the form of both blocks and infill. The growth of the hemp shiv is a carbon storage process, while the production of the binder emits significant carbon emissions. Yet, during its lifetime, hempcrete recaptures many of those emissions through a carbonation process. The total recoverable CO_2 is expressed through α_{CH} (kg CO_2/kg binder) where K_x is the concentration of each mineral of the binder, MW_x is its corresponding molecular weight, and ϕ_h is the degree of hydration. The results of this model when implement in the lifecycle assessment (stages A1-A3 & B1) of a 1 m^2 wall with a U-value of 0.27 W/(m^2.K) are shown in Figure 7. When natural hydraulic lime (NHL) is used as a binder, up to 24 kg CO_2e can be sequestered from the atmosphere through both biogenic uptake and carbonation of binder [9].

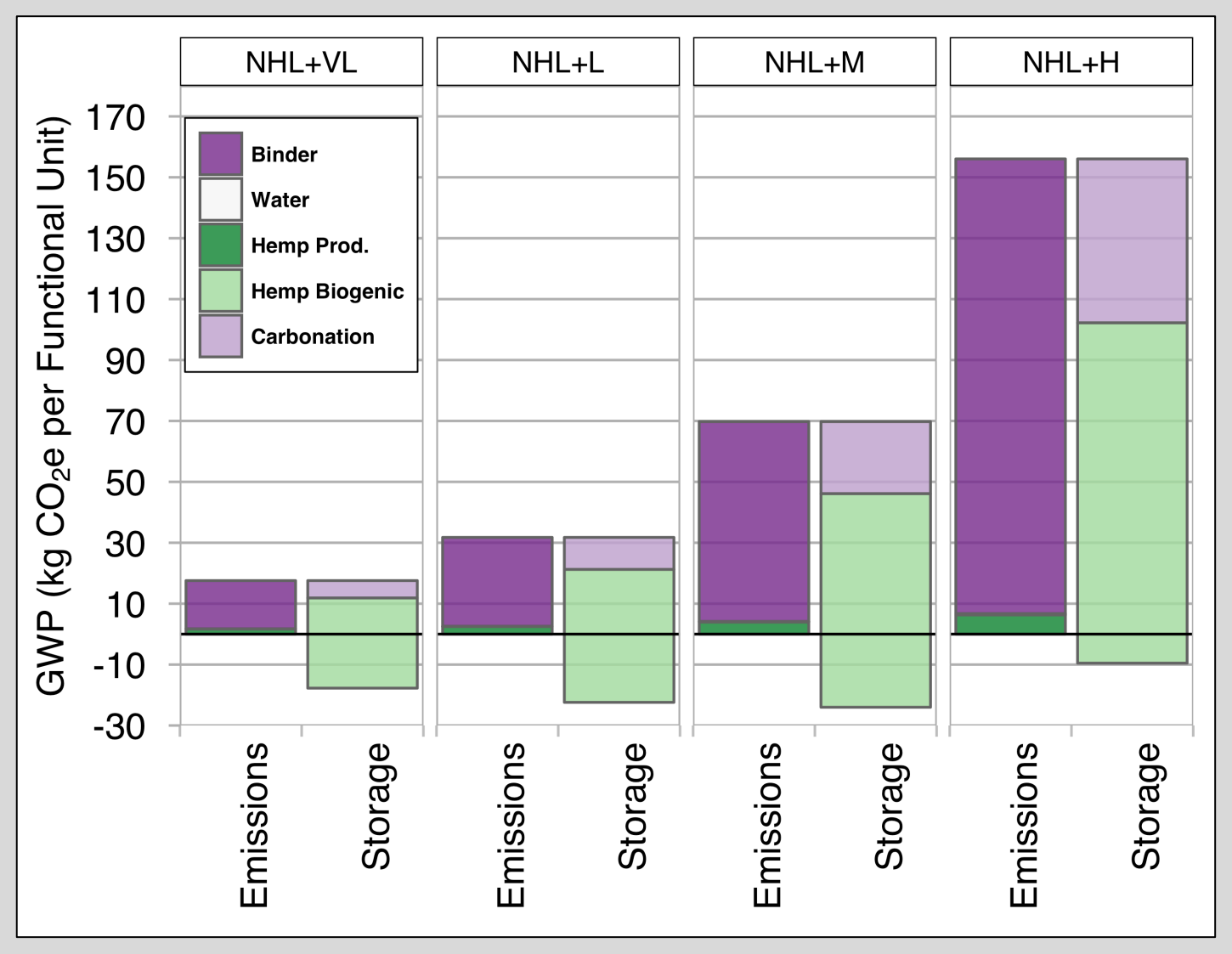


Figure 7. Carbon storage potential of hempcrete wall assemblies with natural hydraulic lime (NHL) for different densities (VL = very light, L = light, M = medium, H = heavy).

Biological Aggregate Production

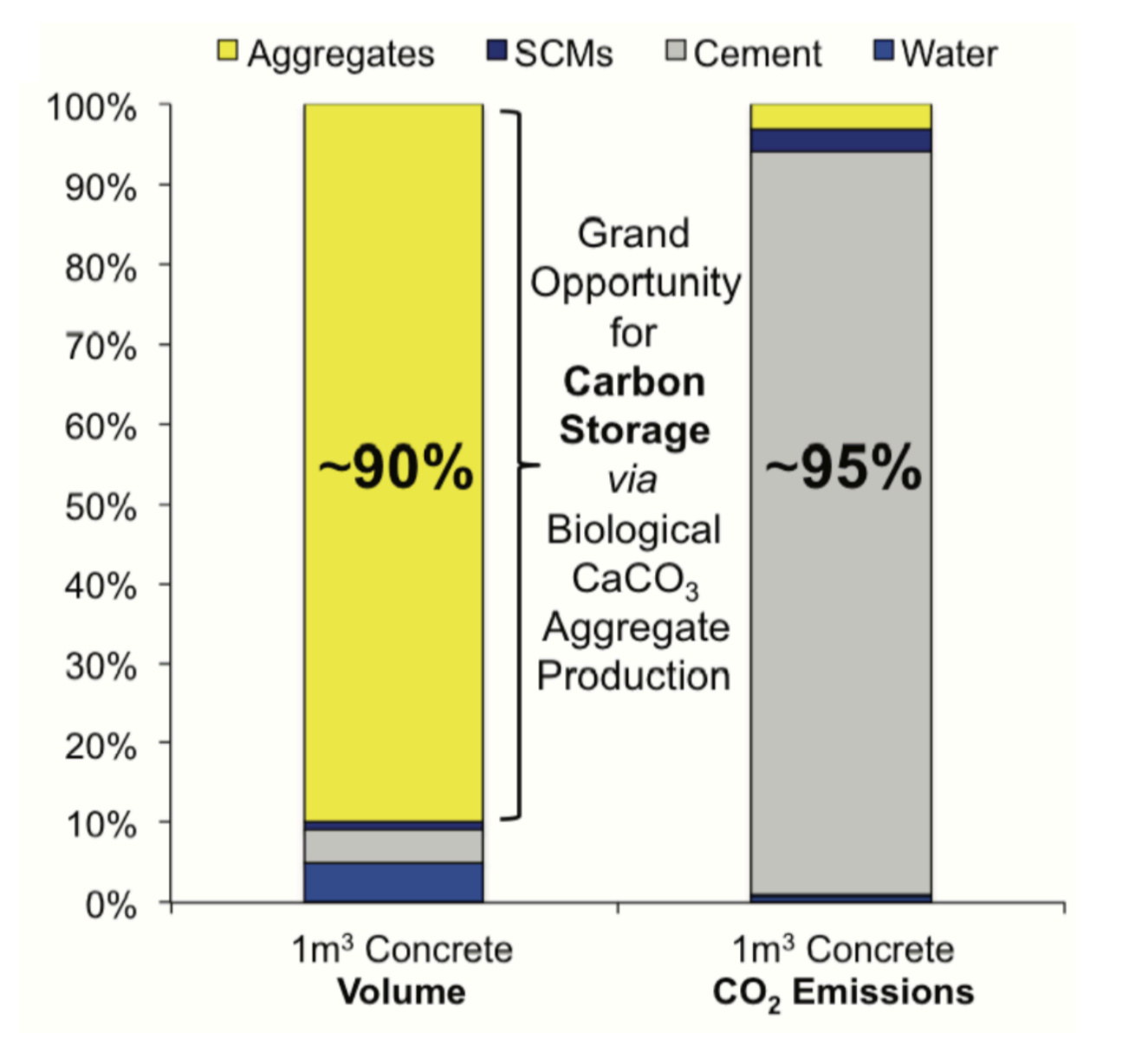


Figure 4. Opportunity for carbon storage via MICCP aggregate production.

The vast majority (~90%) of concrete volume is aggregate, yet the ~95% of emissions are due to cement production (Figure 4). Limestone is a common concrete aggregate and is composed primarily of $CaCO_3$ which is 44% (by mass) sequestered CO_2. Geological limestone deposits (and quarries thereof) formed over millennia predominately by the biological mechanism microbial-induced $CaCO_3$ precipitation (MICCP). By exploiting and accelerating MICCP using synthetic biology, limestone aggregates can be produced for use in concrete while simultaneously sequester CO_2.

Photosynthetic, carbon-sequestering bacteria, use calcium present in its growth media and CO_2 from the atmosphere to produce $CaCO_3$. Depending upon the calcium content in the growth media, the architecture of the precipitate can be controlled to create a particle suitable for use in concrete.

People of the Living Materials Laboratory

Work Supported by:

Engineering & Applied Science, University of Colorado Boulder; NSF; ARPA-E CHANGING WHAT'S POSSIBLE; DARPA; NCHRP NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

[1] Architecture 2030. (2014). *Roadmap to Zero Emissions*. Retrieved from The American Institute of Architects (AIA) website: https://unfccc.int/resource/docs/2014/smsn/ngo/418.pdf
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