BEST6

Low carbon insulation materials to reduce buildings' carbon footprint

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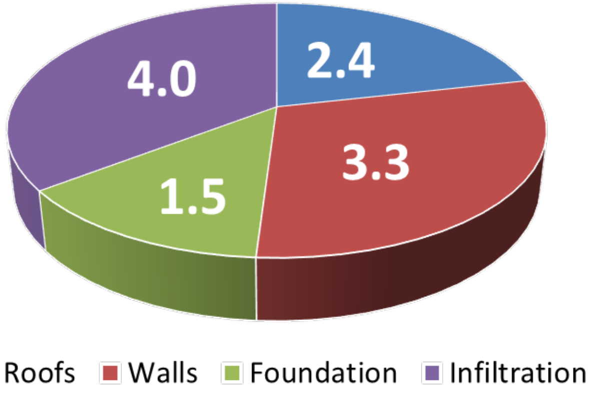
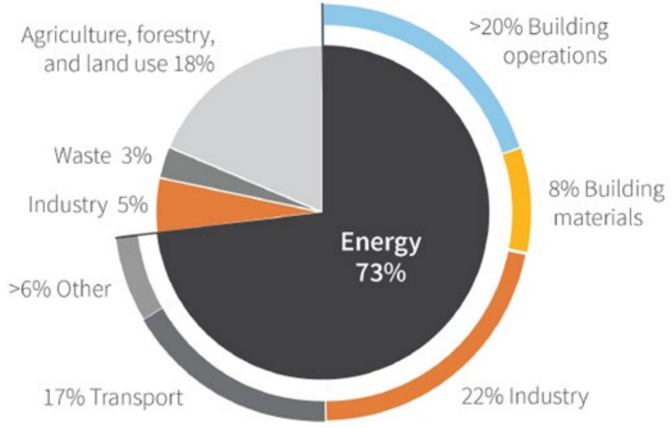
Background

- Primary energy consumption attributable to heat transfer through opaque envelope ~ 11 quads i.e., 25% of energy use in building.*
- Building materials are responsible for 8% of global CO_2 emission.**
- Insulations account for 15 to 26% of emissions from building materials.***
- The environmental impact from operational energy is declining. Hence, the embodied carbon of building materials are becoming a significant component of a building's carbon footprint.
- By 2050, it is estimated that more than 50% of building emissions will be associated with embodied carbon.
- High-performance and low carbon insulation can significantly reduce buildings carbon footprint.



Primary energy consumption attributable to building envelope components in the US, Quads *



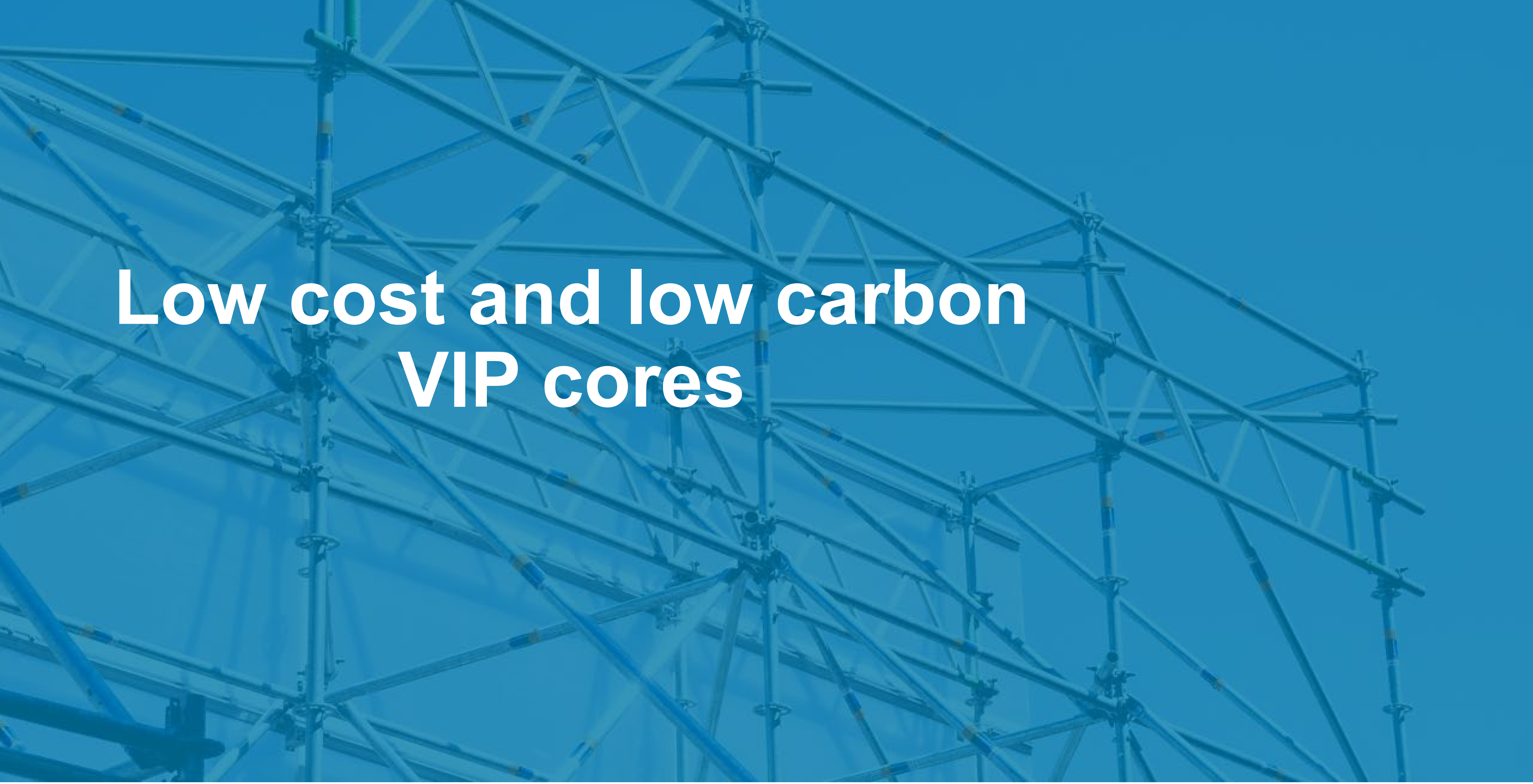
Global CO_2 emissions by sector**

* DOE, Research and Development Opportunities Report for Opaque Building Envelopes
** Carbon Leadership Forum - Embodied-Carbon-101
*** RMI - The Hidden Climate Impact of Residential Construction

Agenda

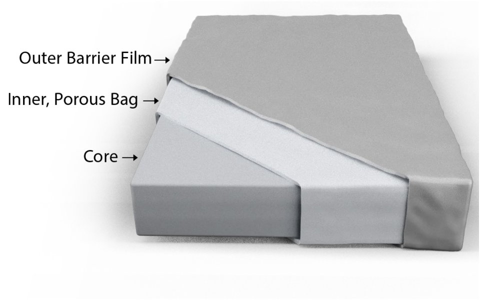
- ✓ Background
- ✓ Low cost and low carbon VIP cores
- ✓ Low-carbon, recyclable, biobased foam insulation
- ✓ Wood fiber insulation
- ✓ High performance insulation
- ✓ Flame retardants for low-embodied carbon materials
- ✓ Database of biobased materials used in building envelope applications

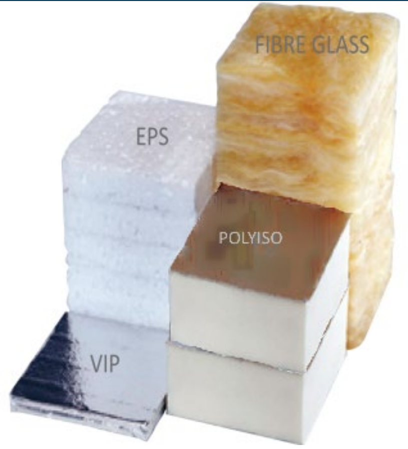
Low cost and low carbon VIP cores



Low cost and low carbon VIP cores

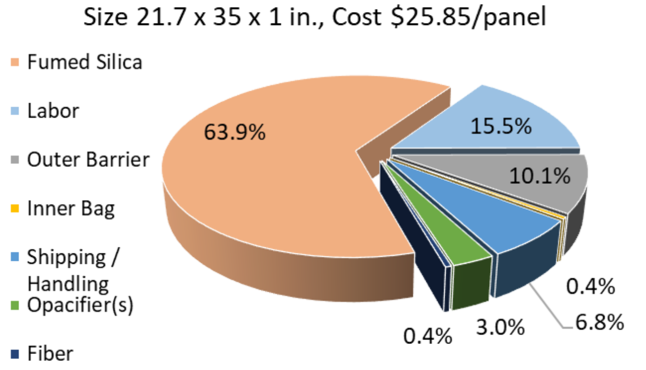
- Vacuum insulation panels (VIPs) can achieve > R35/in.
- IEA estimates VIPs can reduce building's operational CO_2 by ~8%.
- Fumed silica VIP cores are costly and have high embodied carbon → not widely used in buildings in North America.



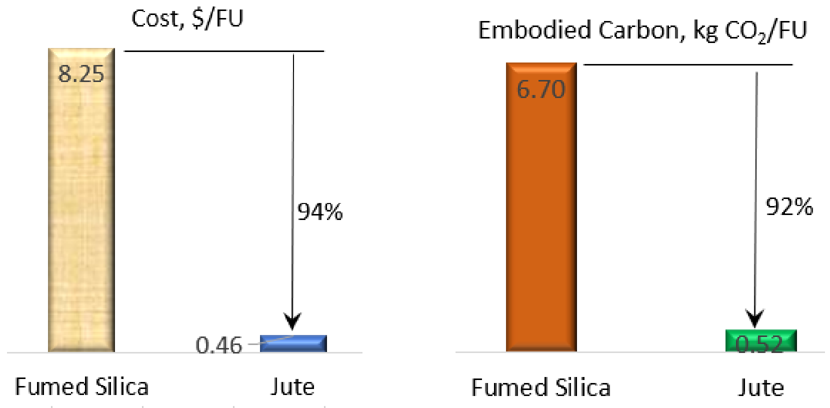


A solution:

- Natural fiber VIP cores with **50 to 80% lower cost** and **50 to 90% lower embodied carbon** but thermal resistivity comparable to fumed silica VIP cores.



A main cost component of VIPs comes from their core materials.



Shahaboddin Resalati, Christopher C. Kendrick & Callum Hill (2020). Embodied energy data implications for optimal specification of building envelopes, Building Research & Information, 48:4, 429-445, DOI: 10.1080/09613218.2019.1665980

A K Singh, M Kumar, and S Mitra. 2018. Carbon footprint and energy use in jute and allied fiber production. Indian Journal of Agricultural Sciences 88 (8): 1305–11, August 2018/Article

FU: functional unit (kg of material needed to cover a 1-m^2 area at a thickness providing an average thermal resistance of 1 $m^2 \cdot K/W$).

World production

- Jute 2,500,000 tons/year
- Cotton 25,000,000 tons/year

Identify candidate materials

Coupling effect on fibrous materials

$$k_{eff} = k_{solid} + k_{rad} + k_{air} + k_{coupling}$$

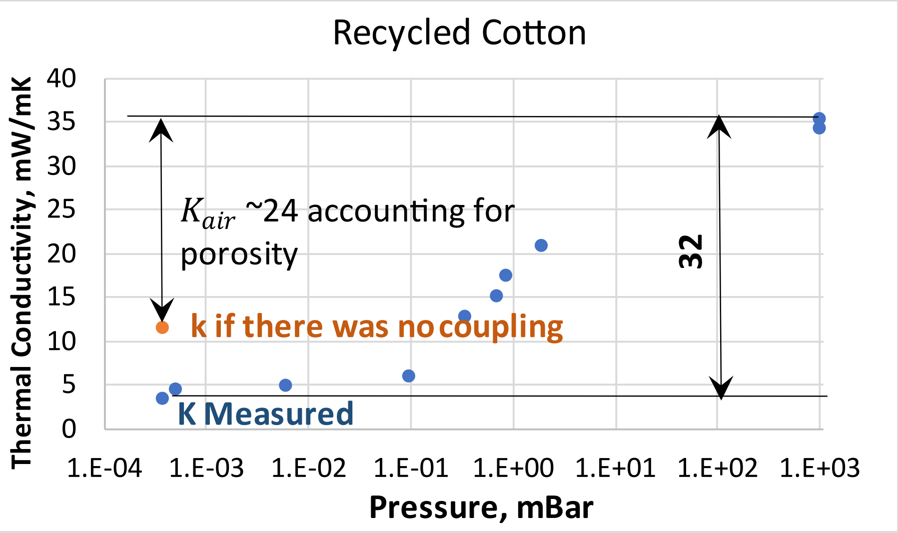
Recycled Cotton: k-value at vacuum	
If there was no coupling effect	Measured
12 mW/mK (R12/in.)	4 mW/mK (R36/in.)

Coupling effect diminishes at vacuum

Selection based on

- Small fiber diameter
- k-value at ambient pressure < 50 mW/mK
- Availability

Identified several candidate materials

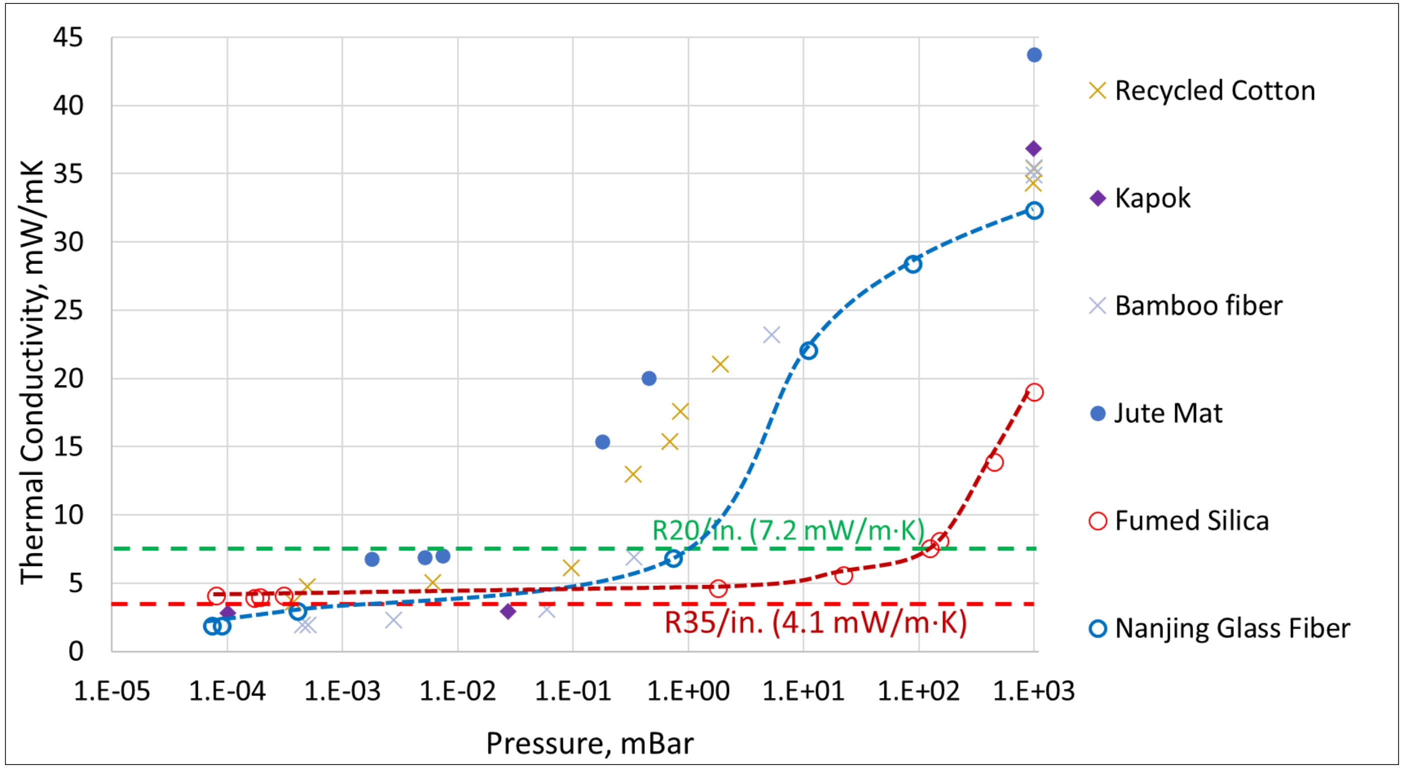


Pressure-dependent thermal conductivity

✓ Identified several candidate materials

Two issues:

- Rapid increase in thermal conductivity as pressure increases.
- When core is compressed during evacuation, k-value will likely be different than when measured in HFMA.



Some promising candidates

Some materials perform better than fumed silica at high vacuum likely due to lower density.

Challenge in measuring thermal conductivity

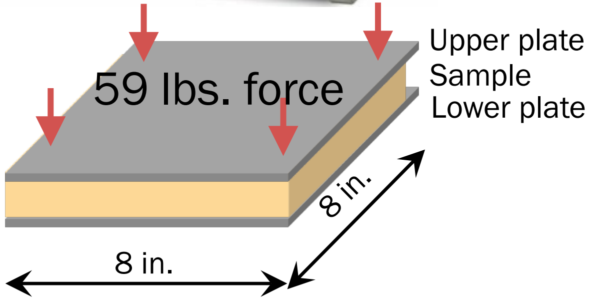
Thermal properties using a heat flow meter apparatus (ASTM C518) with vacuum capability

- HFMA limitation: compressive stress on the samples is only ~0.9 psi as compared to 14.7 psi when packaged in VIP barrier films. Density and K-value change at higher compression.

HFMA with vacuum

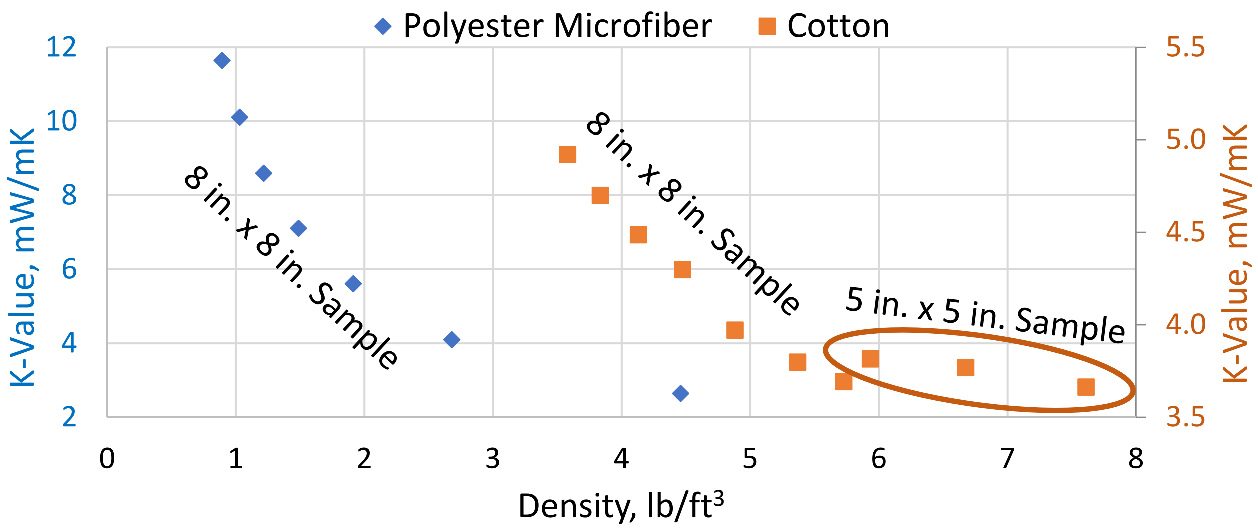
Experimental setup

Force exerted between upper and lower plate from stepper motors



Density-dependent thermal conductivity

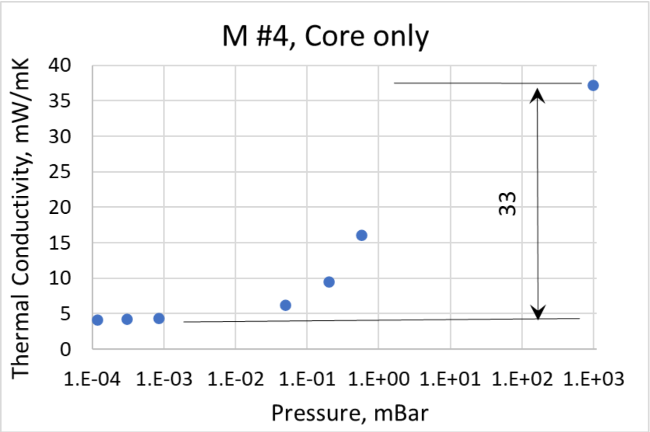
- Density increases as the materials are compressed
- Density of conventional VIP core ~ 12 – 16 lb/ft^3
- Density of natural fibers at 14.7 psi compression ~ 10 – 16 lb/ft^3



- K-value ↓ as density ↑ because decrease in radiation and conduction through gas dominated increase in solid conduction
- Yet to check if the trend continues up to density corresponding to 14.7 psi compressive stress

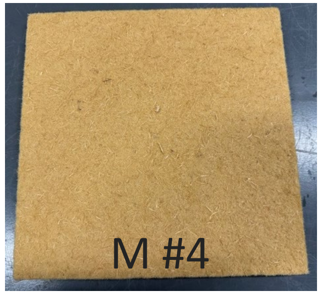
Established test methods to evaluate pressure- and density-dependent K-value

Sample results and next steps



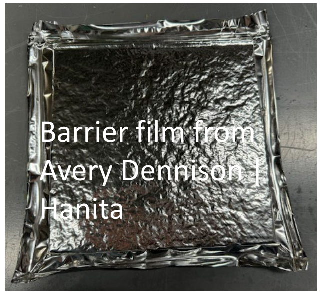
Wood fiber board

Before packaging



13.0 mm
4.4 mW/mK (R33/in.)

After packaging



12.1 mm
6.5 mW/mK (R22/in.)

VIP package machine

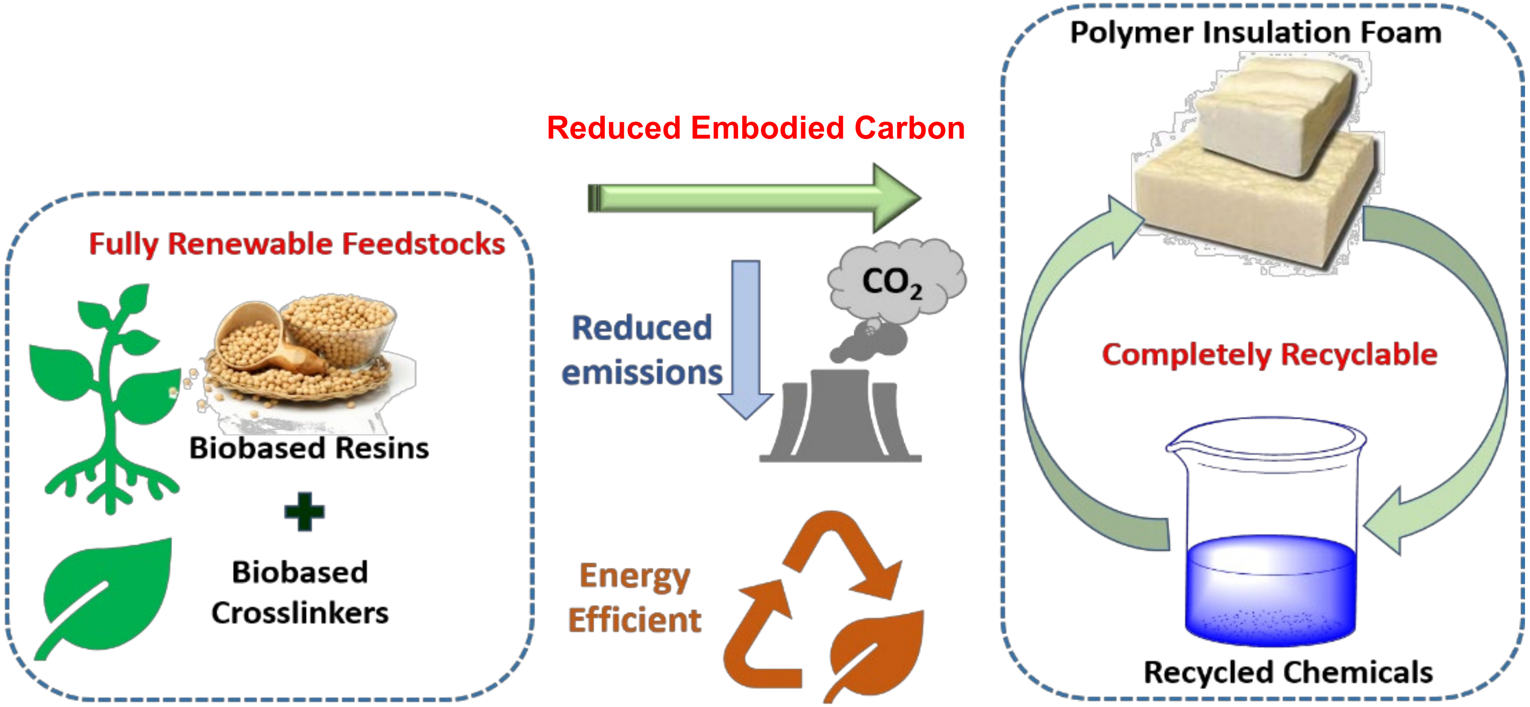
- Fabricate VIPs using additional natural fiber cores
- Evaluate their long-term performance
- Work with industry to overcome commercialization challenges

Low-carbon, recyclable, biobased foam insulation

Low-carbon, recyclable, biobased foam insulation

Goal: Reduce embodied carbon of thermoset foam insulation

- R-value ≥6/in. and meet common performance metrics
- ~50% lower embodied CO_2 than PU foam with low GWP blowing agents
- Nontoxic components and emissions
- Recyclable through low energy thermal processes



State-of-the-art and our target

Commercial PU biobased foams

- R-6 to 7/in.
- Uses isocyanate
  - Can cause skin sensitization, asthma, skin or mucous membrane irritation
  - Personal protective equipment needed
- ~22% biobased content
  - 20% max lower embodied carbon
- Non-recyclable

Biobased foams from the literature

- Examples
  - PU foams with biobased polyols
  - ~30% max lower embodied carbon
  - Extruded polylactic acid-based foam
  - Cellulose-based foams
- Challenges
  - <R4/in
  - <15 psi compressive strength
  - Non-recyclable

Do not meet R/in and compressive strength of commercial foams

Our target: low embodied carbon foams

- R- >6/in.
- ~85% biobased polymer content
  - Acrylated Epoxidized Soybean Oil
- Embodied carbon ~50% < PU foam made with low GWP blowing agent
- Recyclable through process with low energy intensity
- No toxic emissions, safe
- Compatible with current foam manufacturing practices
- Compressive strength ≥ 15 psi

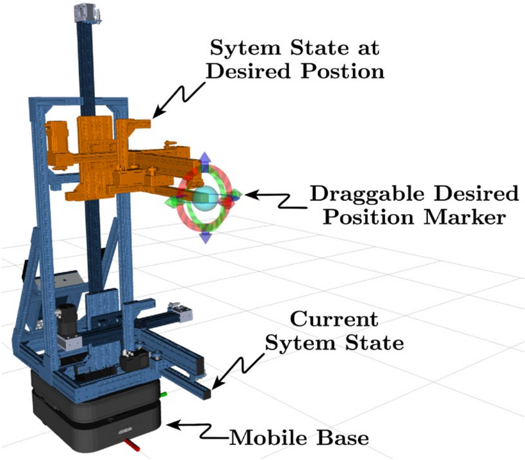
Next steps

- Improve thermal performance by tuning blowing agent, surfactant and catalyst.
- Develop formulation that require minimum changes to current manufacturing practices.
- Develop sprayable formulation.

- Integrate sprayable formulation with the autonomous spray foam robot

State of the Art

Autonomous Spray Foam Installer



Wood fiber insulation

Wood fiber insulation

https://www.timberhp.com/why-timberhp/healthy-planet

- Thermal resistivity R-3.4 to 4/in.
- High heat capacity (2.1 J/g·°C)
- Moisture carrying capacity >300% @ 100%RH
- Low thermal diffusivity
- Hygric buffering potential

- Mainly uses a feedstock of wood chips left over from lumber production.
- Carbon Storing
- Class A/B Flame Spread
- Nontoxic, Safe
- Highly Recyclable


Fill


Batt


Board

High performance insulation

High performance insulation to reduce operational energy

High-performance insulation can improve building energy efficiency but currently used insulation limits ~R-6/in.

A solution:

- Multi-scale simulations and machine learning guide the design and development of R10/in. foam → >60% better than commercially used foams.
- Cost comparable with commercially available foams in $/ft^2/R basis.
- High R/in. insulation can save >**1 quad energy/year**[*] (~**54 MMmtCO$_2$**, $10 billion in energy cost).

[*] DOE, Research and Development Opportunities Report for Opaque Building Envelopes

ThermoPI

Multi-scale model for $\lambda_{gas}, \lambda_{solid}, \lambda_{rad}$
https://thermopi.ornl.gov/calculate

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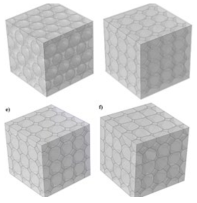

High-throughput finite-element

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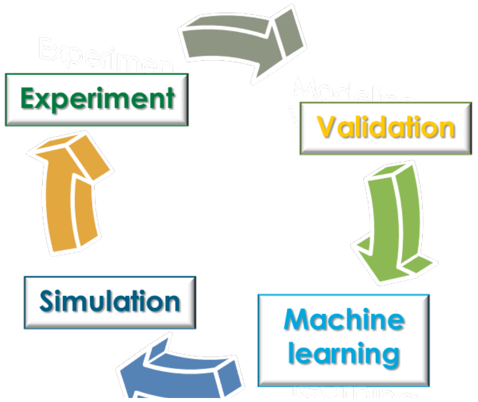
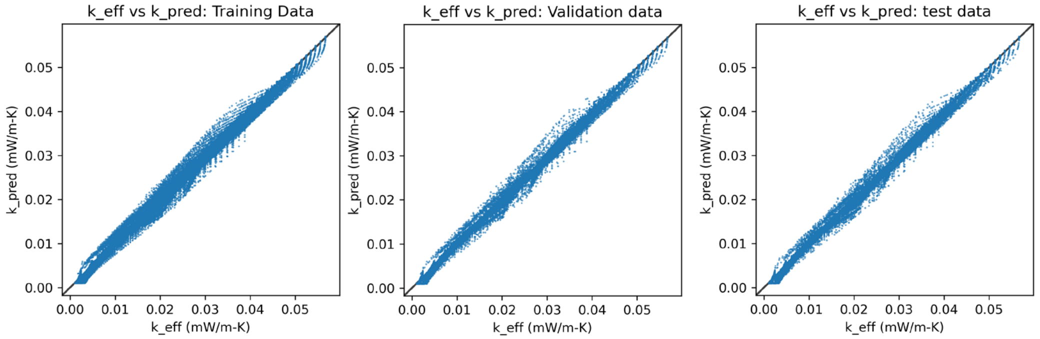
Synthesis

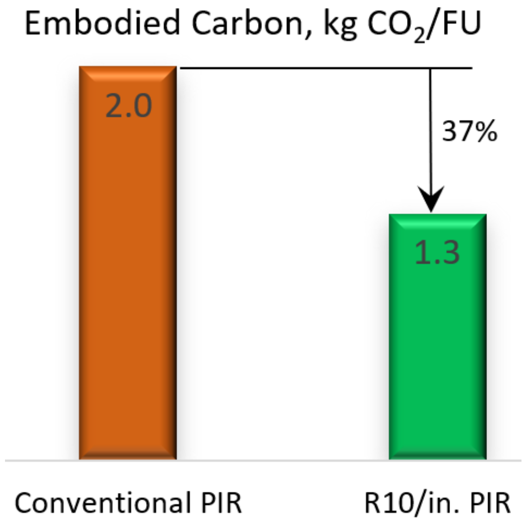




High performance insulation to reduce embodied carbon

A solution:

- High performance insulation to reduce embodied carbon per functional unit (kg of material needed to cover a 1-m^2 area at a thickness providing an average thermal resistance of 1 $m^2 \cdot K/W$).
- Polyisocyanurate (PIR) with R10/in. will have 37% less embodied carbon per FU compared to that of conventional PIR.*
- Minimal modifications to current manufacturing process.
- Cost competitive in terms of $/FU.



* Assuming 10% increase in embodied carbon per unit mass in PIR with R10/in. compared to that in conventional PIR

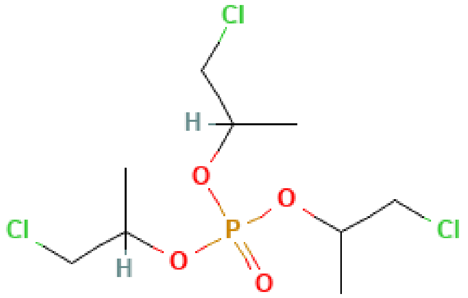
Flame retardants for low-embodied carbon materials

Low-carbon biobased polymeric flame retardant

Problem

Flame retardants is a $8B global industry that generates 2.25 million tones of hazardous materials.

Environmental and health effects for soil organisms, and humans such as cancer, hormone disruption and other adverse health effects have been linked to exposure to fire retardants.



Tris(chloropropyl) phosphate (TCPP)

Embodied carbon

The incorporation of low embodied carbon building materials in the enclosure is increasing the fuel load for fire, increasing the demand for fire retardants.

The industry is expected to grow to over $16B by 2030.

Biobased building materials

Goal

The goal is to leverage more environmentally friendly technologies to improve the fire resistance of low embodied carbon building materials.

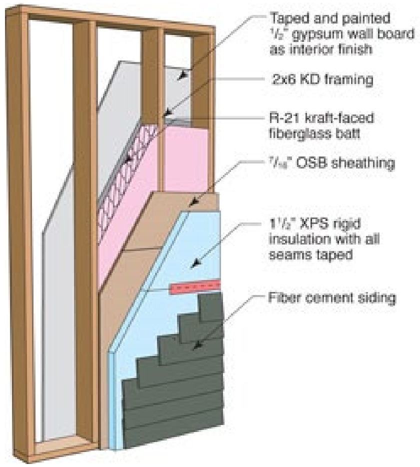
Improve properties such as ignition and flame spread.

Flame spread, ASTM E84

Result

Envelope system that is low-embodied carbon in form and function.

Impart fire resistance while preserving the property of low-embodied carbon.



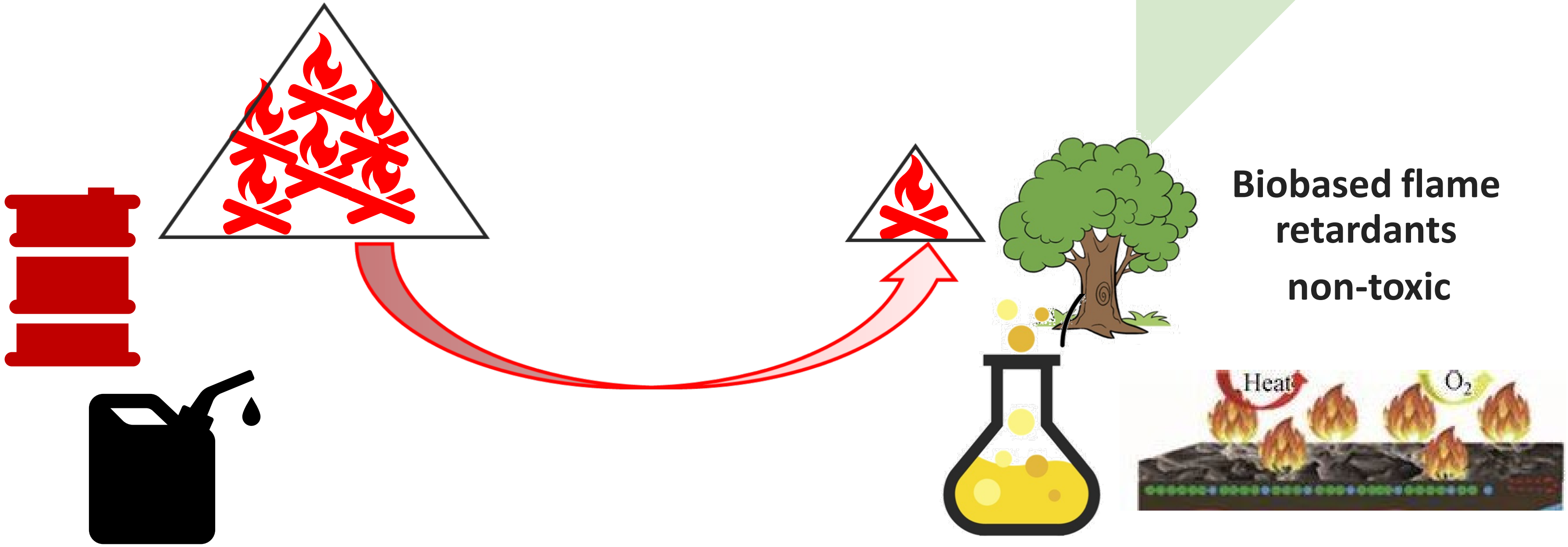
Building envelope

Our approach

Utilize Biobased Feedstock (Resin)

Functionalize with Moieties to suppress flame spread

Reduce Flame Spreading and Improve Sustainability of New Construction Materials



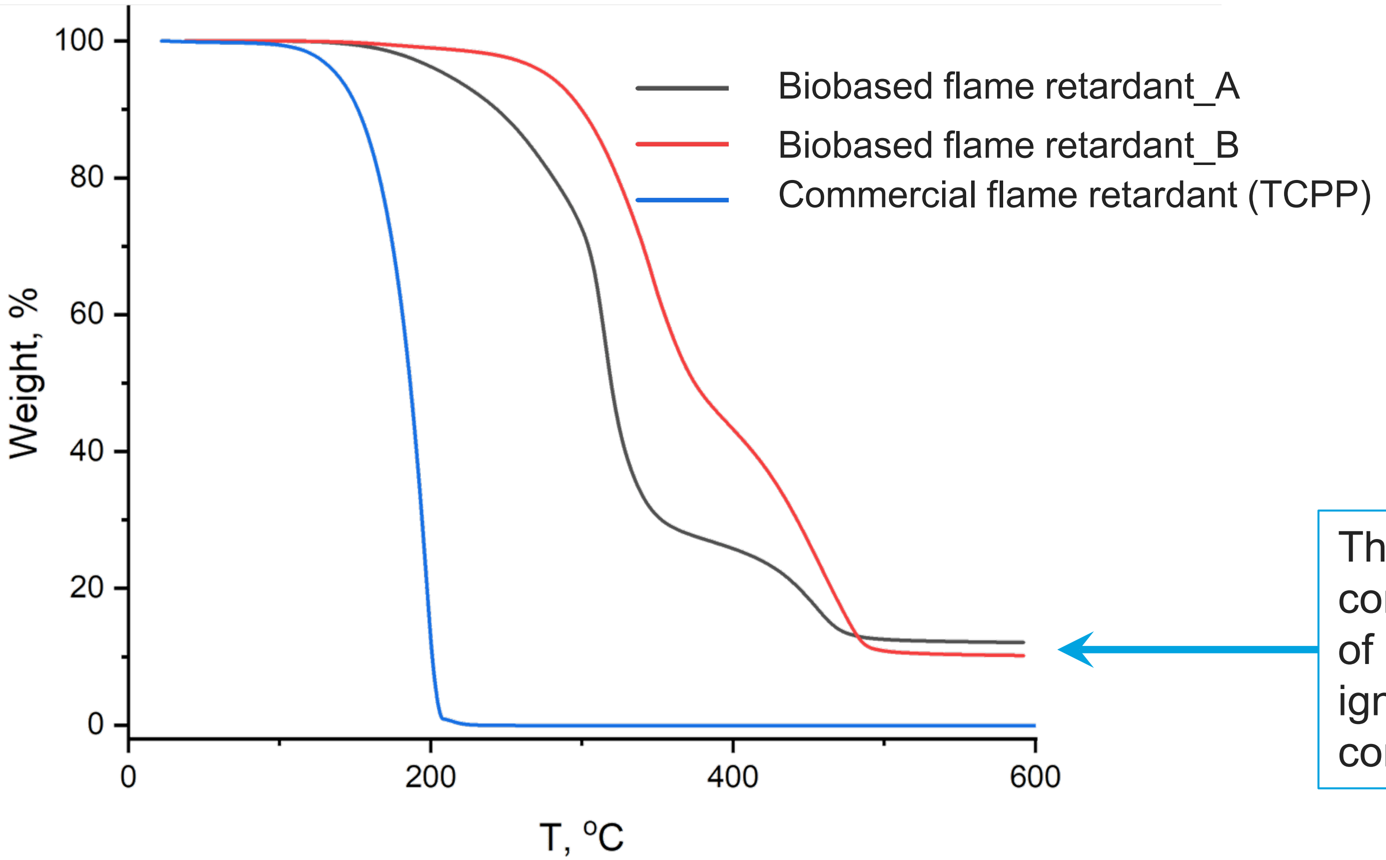
Biobased flame retardants

non-toxic

Petroleum-based flame retardants

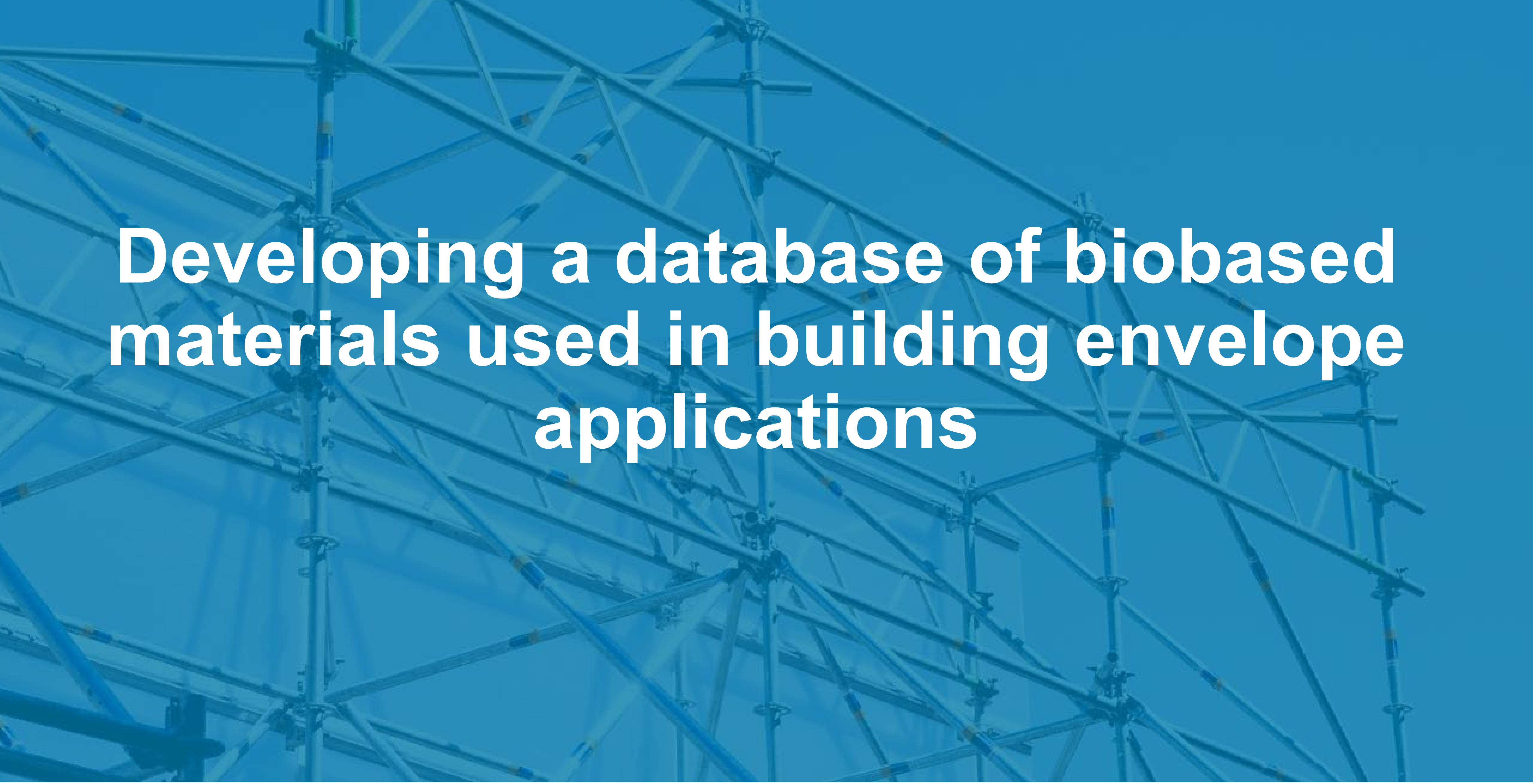
Formation of char layer →prevention of flame spreading

Thermal stability of flame retardants



Thermogravimetric analysis result

The biobased flame retardant is thermally stable compared to TCPP and results in the formation of char that potentially can provide resistance to ignition and flame spread – needs to be confirmed using large scale tests.

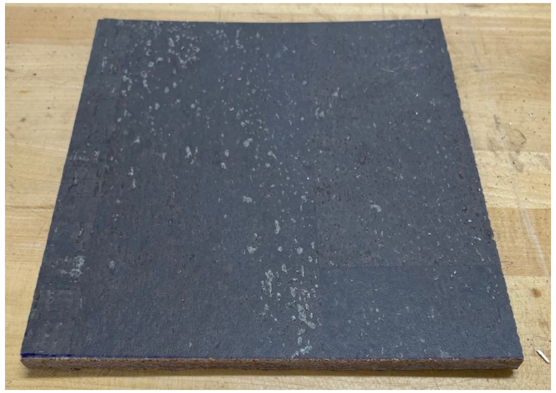


Developing a database of biobased materials used in building envelope applications

Emerging low-carbon building materials lack performance data

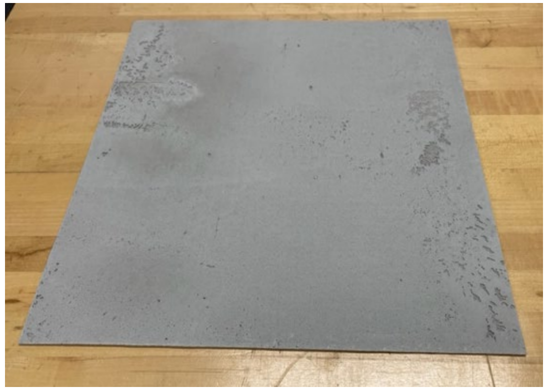
- **Problem:** Widespread acceptance of biobased materials for building envelopes is hindered by minimal availability of hygrothermal properties needed to run energy and hygrothermal simulations that can help predict moisture durability problems.
- **Goal:** Generate key material properties of biobased materials.
  - Heat capacity
  - Thermal conductivity as a function of temperature and moisture content
  - Moisture content dependent permeance
  - Sorption isotherm
- **Dissemination:** Supply database for addition to hygrothermal models and reference sources such as the ASHRAE Handbook of Fundamentals.

Materials being evaluated - 1



Cork flooring

Bamboo wall covering



Recycled rubber flooring

Molded cork interior cladding

Cork brick interior cladding

Recycled rubber roof tile

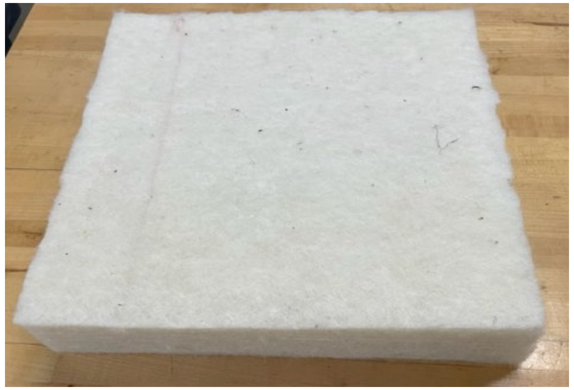
Bamboo board

MgO interior sheathing

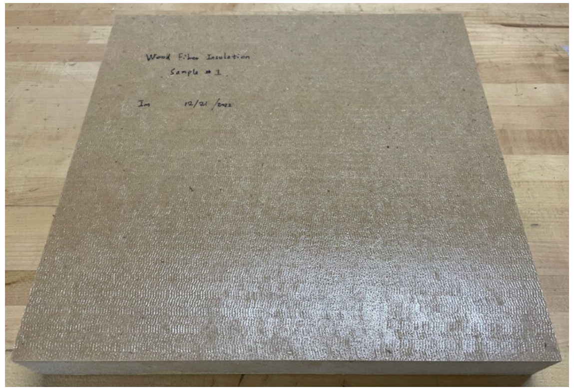
Materials being evaluated - 2

Low density sheep wool

Medium density sheep wool



High density sheep wool



Wood fiber sheathing

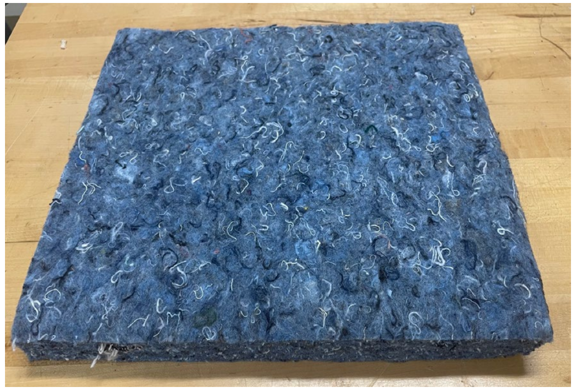
High density hemp

Low density hemp

Compressed earth block

Mycelium

Materials being evaluated - 3



Recycled blue jeans

CLT

Cedar wood shakes

Jute mat

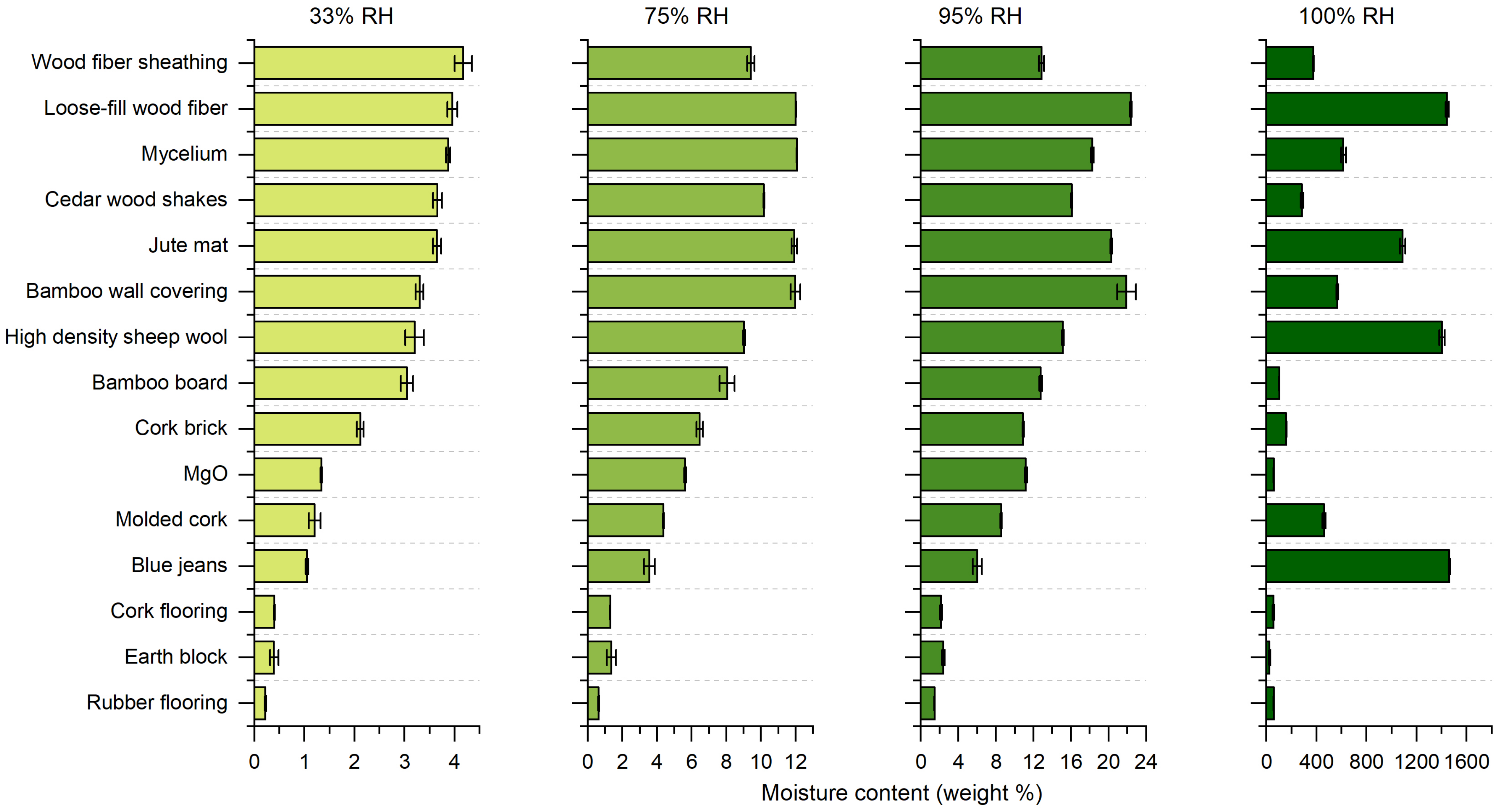
Loose-fill wood fiber

Wood fiber board

Hemp batt

Hemp board

Sample results



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Thank You

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